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Protection of Jeita Spring

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Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

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Protection of Jeita Spring

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Authors:	Dr. Armin Margane, Philip Schuler, Dr. Paul Koeniger, Eng. Renata Raad, Jean Abi Rizk, Leonard Stoeckl (all BGR)
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List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
ALES	Association Libanaise d'Etudes Spéléologiques
asl	Above mean sea level
AFD	Agence Française pour le Développement
ASAGE	Advanced Global Atmospheric Gases Experiment
AVSI	Italian NGO
bgl	Below ground level
BMZ	German Ministry of Economic Cooperation and Development
CDR	Council for Development and Reconstruction
DEM	Digital elevation model
DST	Dead Sea Transform (Fault)
EIA	Environmental impact assessment
EIB	European Investment Bank
FAO	Food and Agriculture Organization
FC	Financial Cooperation
GNIP	Global Network of Isotopes in Precipitation
GW	groundwater
KfW	German Bank for Reconstruction and Development
LARI	Lebanese Agricultural Research Institute, Ministry of Agriculture
LRA	Litani River Authority
MAPAS	Company operating Jeita Grotto
MCM	Million cubic meters
MoEW	Ministry of Energy and Water
OEB	Office des Eaux de Beyrouth
PETM	Paleocene-Eocene Thermal Maximum
SCL	Spéléoclub du Liban
SWE	Snow water equivalent
TC	Technical Cooperation
UNDP	United Nations Development Program
UTM	Universal transverse Mercator
WEBML	Water Establishment Beirut and Mount Lebanon
WW	Wastewater
WWTP	Wastewater treatment plant

List of Reports prepared by the Technical Cooperation Project Protection of Jeita Spring

Report No.	Title	Date Completed
Technical Reports		
1	Site Selection for Wastewater Facilities in the Nahr el Kalb Catchment – General Recommendations from the Perspective of Groundwater Resources Protection	January 2011
2	Best Management Practice Guideline for Wastewater Facilities in Karstic Areas of Lebanon – with special respect to the protection of ground- and surface waters	March 2011
3	Guideline for Environmental Impact Assessments for Wastewater Facilities in Lebanon – Recommendations from the Perspective of Groundwater Resources Protection	November 2011
4	Geological Map, Tectonics and Karstification in the Groundwater Contribution Zone of Jeita Spring	September 2011
5	Hydrogeology of the Groundwater Contribution Zone of Jeita Spring	July 2013
6	Water Balance for the Groundwater Contribution Zone of Jeita Spring using WEAP including Water Resources Management Options and Scenarios	August 2013
7	Groundwater Vulnerability Mapping in the Jeita Spring Catchment and Delineation of Groundwater Protection Zones using the COP Method	February 2013
7b	Vulnerability Mapping using the COP and EPIK Methods	October 2012
Special Reports		
1	Artificial Tracer Tests 1 - April 2010*	July 2010
2	Artificial Tracer Tests 2 - August 2010*	November 2010
3	Practice Guide for Tracer Tests	Version 1 January 2011
4	Proposed National Standard for Treated Domestic Wastewater Reuse for Irrigation	July 2011
5	Artificial Tracer Tests 4B - May 2011*	September 2011

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Report No.	Title	Date Completed
6	Artificial Tracer Tests 5A - June 2011*	September 2011
7	Mapping of Surface Karst Features in the Jeita Spring Catchment	October 2011
8	Monitoring of Spring Discharge and Surface Water Runoff in the Groundwater Contribution Zone of Jeita Spring	May 2013
9	Soil Survey in the Groundwater Contribution Zone of Jeita Spring	First Draft November 2011
10	Mapping of the Irrigation System in the Jeita Catchment	First Draft November 2011
11	Artificial Tracer Tests 5C - September 2011*	February 2012
12	Stable Isotope Investigations in the Groundwater Contribution Zone of Jeita Spring	~August 2013
13	Micropollutant Investigations in the Groundwater Contribution Zone of Jeita Spring*	May 2012
14	Environmental Risk Assessment of the Fuel Stations in the Jeita Spring Catchment - Guidelines from the Perspective of Groundwater Resources Protection	June 2012
15	Analysis of Helium/Tritium, CFC and SF6 Tracers in the Jeita Groundwater Catchment*	June 2013
16	Hazards to Groundwater and Assessment of Pollution Risk in the Jeita Spring Catchment	June 2013
17	Artificial Tracer Tests 4C - May 2012*	~June 2013
18	Meteorological Stations installed by the Project	~September 2013
19	Risk estimation and management options of existing hazards to Jeita spring	August 2013
Advisory Service Document		
1	Quantification of Infiltration into the Lower Aquifer (J4) in the Upper Nahr Ibrahim Valley	May 2012
1 - 1	Addendum No. 1 to Main Report [Quantification of Infiltration into the Lower Aquifer (J4) in the Upper Nahr Ibrahim Valley]	June 2012
2	Locating the Source of the Turbidity Peaks Occurring in April - June 2012 in the Dbayeh Drinking Water Treatment Plant	June 2012
3	Locating the Pollution Source of Kashkoush	September 2012

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Report No.	Title	Date Completed
	Spring	
4	Preliminary Assessment of Jeita Cave Stability	April 2013
5	Preliminary Assessment of the Most Critical Groundwater Hazards for Jeita Spring	June 2013
Reports with KfW Development Bank (jointly prepared and submitted to CDR)		
1	Jeita Spring Protection Project Phase I - Regional Sewage Plan	October 2011
2	Jeita Spring Protection Project - Feasibility Study - Rehabilitation of Transmission Channel Jeita Spring Intake – Dbaye WTP	May 2012
3	Jeita Spring Protection Project - Environmental Impact Assessment for the Proposed CDR/KfW Wastewater Scheme in the Lower Nahr el Kalb Catchment	Draft June 2013 (BGR contribution)

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We would like to thank Dr. Farid el Khazen (Member of Parliament) for his continuous support, promotion of the idea of groundwater protection and participation in the awareness campaigns conducted by the project.

Many mayors and staff of municipalities in the catchment saw the opportunities which the project hopes to provide in the near future as a chance for development. Among those which very actively assisted the project we would like to highlight the municipalities of Ballouneh (Dr. Pierre Mouzawak, Simon Daou), Kfar Debbiane (Jean Akiki) and Jeita (Samir Baroud).

The hydrogeological investigations were conducted together with the University of Goettingen, Department of Applied Geology. The project is thankful for the good cooperation with Dr. Joanna Doummar (now lecturer at AUB), Dr. Tobias Geyer and Prof. Martin Sauter.

The project was made possible by grants of the German Government, allocated through the Ministry of Economic Cooperation and Development (BMZ). Our thanks therefore go to the staff of the BMZ, KfW and German Embassy. We experienced that this assistance is very much appreciated not only among the involved institutions and stakeholders but also the population living in the area.

0 Executive Summary

This report presents the results of hydrogeological field investigations carried out by the Technical Cooperation (TC) Project Protection of Jeita Spring (implemented by BGR and CDR) in the groundwater (GW) catchment of Jeita spring with the aim to protect Jeita spring, and other equally important water sources in the Jeita catchment used for drinking water supply, from pollution. These springs provide drinking water to the Keserwan district and the Greater Beirut Area, reaching almost half the population of Lebanon.

Using tracer tests and other hydrogeological investigation methods, the groundwater catchment of Jeita spring (405.6 km²) and other springs in the Jeita groundwater catchment: Afqa (101.5 km²), Rouaiss (65.8 km²), Assal (14.6 km²) and Labbane (9.5 km²), were delineated. The groundwater catchments are significantly different from the surface water (SW) catchments. The above mentioned springs discharging from the Upper Aquifer (C4) are part of the Jeita catchment as much of this spring discharge could be proven to infiltrate downstream into the Lower Aquifer (J4). Through continuous discharge measurements (20 minute intervals) the spring discharges of Assal (24 MCM/a), Jeita (172 MCM/a) and Kashkoush (70 MCM) could be determined. This is the first time that accurate discharge values are available for these springs. Kashkoush spring is not part of the Jeita catchment but has a separate catchment to the south of the groundwater Jeita catchment.

Groundwater recharge in the Upper Aquifer (Sannine Formation; C4) is estimated at 81% of precipitation, while groundwater recharge in the Lower Aquifer (Keserwan Formation; J4) is approx. 58%. A considerable proportion of surface water infiltrates into groundwater (~22-23 %). It is estimated that around 80 MCM (32 %) of Jeita spring discharge originate from riverbed infiltration, mainly from the C4. Most of this surface water comes from spring discharge from the C4 aquifer.

Comprehensive stable isotope analyses were conducted on spring water, rainfall, snow and Jeita cave stalagmite drip water. These confirm the reinfiltration of water from the Upper Aquifer into the Lower Aquifer.

Tracer tests, stable isotope and helium/tritium, CFC, SF_6 analyses show that groundwater flow velocity is relatively high (average flow velocity: 70-200 m/h; but up to around 2,000 m/h in large conduits) and mean groundwater residence time is only a few years.

Due to the short mean residence time, spring discharge is extremely sensitive to climate variations. The predicted future increase of temperatures due to climate change would have severe consequences for water resources availability as an upward orographic shift of the snow line would result in prolonged water shortages at the end of the dry season. The construction of managed aquifer recharge (MAR) dams was proposed to overcome already existing water shortages frequently affecting the water supply in the Greater Beirut Area.

Jeita spring shows a continuously high level of contamination. The main pollution sources are wastewater, gas stations, slaughterhouses, industries, hospitals, animal farms and quarries. Many of the contaminants can currently not be treated at the Dbayeh drinking water treatment plant. This health risk resulting from drinking water supply by Jeita and Kashkoush spring must be urgently mitigated.

A groundwater vulnerability map was prepared for the entire Jeita catchment, showing the high and very high vulnerability of the groundwater resources in more than 80% of the catchment. 64 MCM of annual discharge of Jeita comes from these areas. High vulnerability results from the high degree of karstification of the limestones dominating in the Jeita catchment and from the lack of a protective cover (open karst). The groundwater vulnerability map (protection zone 2 equivalent to area of high and very high groundwater vulnerability) was used in combination with groundwater travel times (10 days) to delineate groundwater protection zones. This, however, can not be effective for protection against non- or hardly degradable contaminants.

The implementation of the proposed groundwater protection zones could solve part of the problem. It requires that landuse planning concepts prepared by the Landuse Planning Department and the municipalities takes into the account water resources protection needs and does not allow landuse activities considered inconsistent with the protection zoning concept (MARGANE & SCHULER, 2013). It also requires the adoption of environmental-friendly production and landuse practices, which needs to be regularly controlled. The implementation of a wastewater scheme, supported by the German Government, is currently underway (MARGANE, 2011; MARGANE & MAKKI, 2012; GITEC, LIBANCONSULT & BGR, 2011). Although wastewater can be considered the main pollution source, there is a large number of other potential pollution sources which also endanger groundwater quality (RAAD et al., 2012, 2013).

Jeita spring is the most important drinking water source of Lebanon and there is currently no alternative to it. Its protection must be of national priority.

1 Introduction

The work presented in this report was conducted in the framework of the German-Lebanese Technical Cooperation project *Protection of Jeita Spring*, implemented on the German side by the Federal Institute for Geosciences and Natural Resources (BGR), the German geological survey. The partners in this bilateral cooperation are:

- the Council for Development and Reconstruction (CDR)
- the Water Establishment Beirut and Mount Lebanon (WEBML) and
- the Ministry of Energy and Water

The project was funded through a grant of the German Government (BMZ). It started in July 2010 and ends in December 2013.

The boundaries of the groundwater catchment had previously not been determined and the BGR project started under the assumption, voiced in the UNDP (1972) report, that the groundwater catchment of Jeita spring must be similar to its surface water catchment. For this reason the boundaries of the assumed catchment changed several times over the course of the BGR project, until in May 2012 the final catchment boundaries could be confirmed. Due to these frequent changes in the outline of the catchment also the boundaries of the geological mapping, vulnerability mapping, etc. had to be changed. This is why in older project reports, the Jeita catchment boundaries may appear different from those presented in reports prepared after May 2012. The determination of the groundwater catchment is a prerequisite for water resources assessments, however, until recently this had not yet been done in Lebanon for any catchment.

1.1 Objectives

The bilateral Technical Cooperation project aims to *'reduce major risks for the drinking water supply in the Greater Beirut Area by implementing measures to protect the groundwater contribution zone of the Jeita Spring from pollution'.* The project has four lines of intervention:

- <u>Integration of water resources protection aspects into</u> the investment <u>planning</u> and implementation process <u>in the wastewater sector</u> by providing geoscientific advice in the wastewater sector (site searching for wastewater facilities; EIA, BMP; reuse standard);
- <u>Integration of water resources protection aspects into landuse planning</u> (delineation of groundwater protection zones; inventory of GW hazards; risk assessment; awareness campaigns);

- Collection and use of monitoring data concerning quality and quantity of water resources (establish a monitoring network for all water balance components; assessment of available water resources; proposal of use options); and
- Support of the partner institutions concerning the implementation of urgent protective measures (proposal of an improved capture of Jeita spring and an improved water conveyance from Jeita to the treatment plant at Dbayeh).

The project worked in direct cooperation with another German funded project, the Jeita Spring Protection Project (JSPP), implemented as financial cooperation (loan) between Germany and Lebanon by KfW Development Bank and the Council for Development and Reconstruction (CDR). The aim of this project is to implement wastewater facilities in the groundwater catchment of Jeita spring, also with the aim to protect the water resources of Jeita spring from pollution. Together with this project, the optimal WWTP site, collector alignment and discharge location were selected (MARGANE, 2011; GITEC & BGR, 2011), an environmental impact assessment has been jointly prepared (LIBANCONSULT & BGR, 2013) and the construction of the wastewater facility will then be implemented, based on current planning in 2014.

Groundwater protection zones have been delineated using tracer tests and groundwater vulnerability mapping. A proposal for related landuse restrictions has been submitted and is waiting for implementation by the Lebanese Government (MARGANE & SCHULER, 2013).

The available water resources were assessed using previous and new data (SCHULER & MARGANE, 2013) and proposals for an optimized use (GITEC & BGR, 2011) were submitted to the partner institutions.

Several special groundwater investigation techniques were used within the BGR project to delineate the groundwater catchment and determine flow characteristics:

- tracer tests (Chapter 3.2.1; DOUMMAR et al., 2010a, 2010b, 2011a, 2011b, 2012a, 2013),
- long-term monitoring of physico-chemical parameters of springs using multiparameter probes (Chapter 3.9.1),
- long-term monitoring of spring discharge using stage – discharge correlations and direct flow measurements by Acoustic Doppler Current Profilers (ADCP) (Chapter 3.4; MARGANE & STOECKL, 2013),
- stable isotope analyses of springs, rainfall, snow and Jeita cave drip water (Chapter 3.9.4),
- He/^{3}H, CFC and SF6 analyses (Chapters 3.9.6 and 3.9.7), and

- differential flow analysis in surface water courses (to determine influent/effluent sections; MARGANE, 2012a, 2012b).

1.2 Study Area and Physiography

When the project started, the project area covered the surface water (SW) catchment of Jeita spring (blue line in Figure 1), because it was previously assumed (stated in the UNDP, 1972, report) that the groundwater (GW) catchment of Jeita spring must be similar to its surface water catchment. After 14 tracer injections, in May 2012, the groundwater catchment could finally be delineated as shown in Figure 1 (orange line). The SW catchment covers an area of 249 km², while the GW catchment has a size of 405.9 km².

The geology was mapped first in the SW catchment (HAHNE, 2011) and was later extended to the now determined GW catchment. Also the areas of mapping of karst features, GW vulnerability and hazards to GW had to be adjusted after each change in the GW catchment, i.e. when new information became available from tracer tests and other hydrogeological investigation techniques.

The now delineated GW catchment stretches in N-S direction from ENE of Tannourine el Faouka to Baskinta (approx. 28 km) and in W-E direction from Jeita to almost the eastern escarpment of the Lebanon mountain range (Upper Cretaceous plateau) (approx. 26 km). The elevation rises from 60 m asl at Jeita to 2628 m asl at Mount Sannine.

The project area covers the eastern part of the surface water catchment of Nahr Ibrahim (198.5 km² or 48.9 %) and the northern part of the Nahr el Kalb catchment (207.4 km² or 51.1 %). The southern part of the Nahr el Kalb surface water catchment, approximately following a line along the northern escarpment of Nahr el Kalb and Nahr es Hardoun, is not part of the Jeita GW catchment.

The Nahr el Kalb valley and its tributaries (Nahr es Salib, Nahr es Zirghaya) are deeply incised into the thick and uniform, massive Jurassic limestone sequence (J4) between Jeita and Faitroun and the difference in elevation between the escarpment and the valley bottom is typically around 300 m. In the Upper Nahr Ibrahim Valley this incision is much deeper, reaching differences in elevation of often more than 600 m between Yahchouch and Janneh.

The Upper Cretaceous limestone sequence is accompanied by a typical cliff (falaise). Between Faraya and Jebel Qana the difference in elevation between the escarpment and the valley bottom is more than 600 m, near Afqa it reaches more than 800 m.

The Upper Cretaceous plateau is very highly karstified and is covered by more than 2000 dolines in the GW catchment of Jeita (ABI RIZK &

MARGANE, 2011). Due to the extremely high rate of groundwater recharge (Chapter 3.1.1), it exhibits almost no surface water drainage pattern (Figure 2).

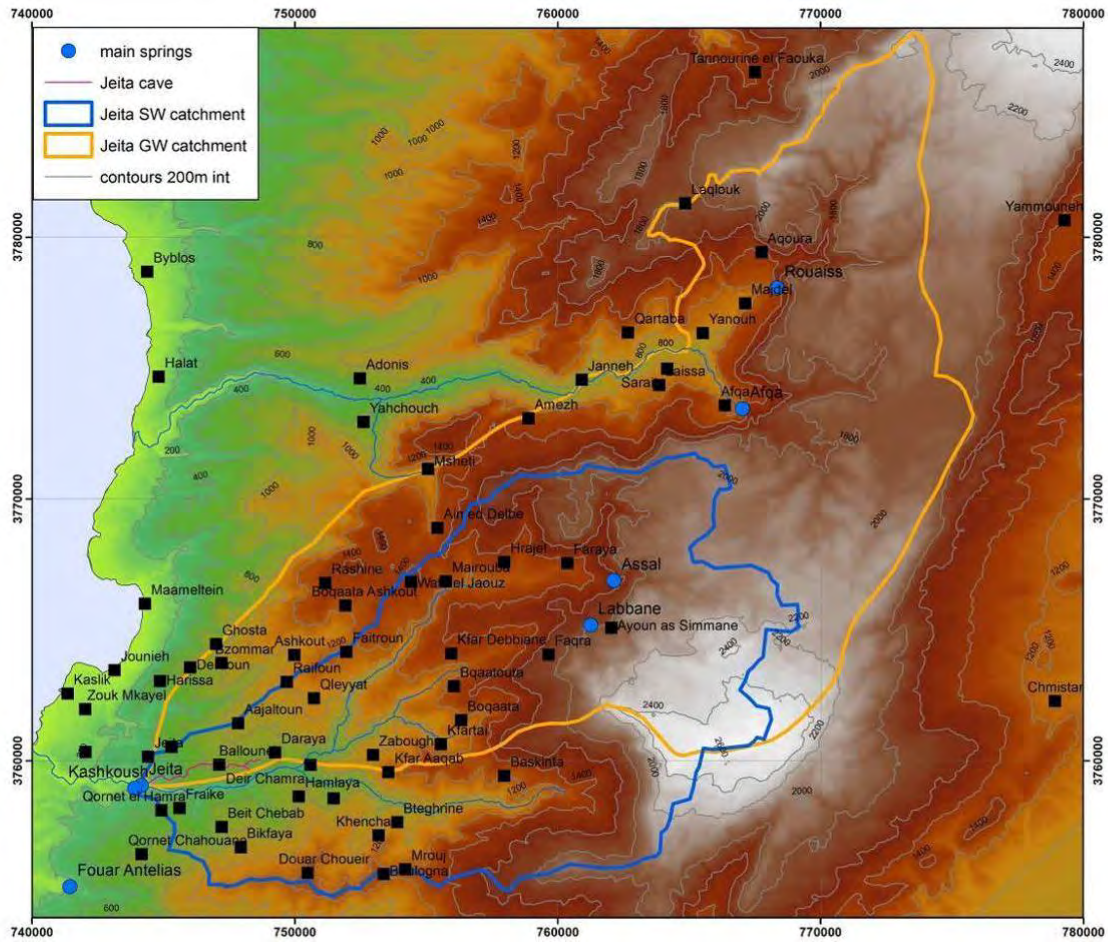


Figure 1: Digital Elevation Model of the Project Area using SRTM Data

Figure 2: Upper Cretaceous Plateau showing the Lack of a Surface Water Drainage Pattern (GE image 2005)

1.3 Population and Administrative Boundaries

Most of the groundwater catchment of Jeita spring is located in the Mount Lebanon Governorate (mohafazat), a small part in the extreme east in the Baqa'a Governorate (Baalbek district) (Figure 3). The southern catchment boundary almost follows the district (caza) boundary between Keserwan and Metn, so that only a small part, comprising the villages of Deir Chamra, Zabbougha, Kfar Aaqab, Ouadi el Qarm, Marj Biskinta, and Qana'at Baqeesh, is located in the Metn district. The administrative boundaries of the villages are displayed in Figure 4.

Keserwan constitutes the largest district within the Jeita catchment, covering the following municipalities:

Jeita, Sheile, Ballouneh, Aintoura, Ain el Rihane, Aajaltoun, Daraya, Harissa, Daraoun, Bzommar, Ghosta, Ashkout, Qaramoun, Qattine, Hayata, Maarab, Chahtoul, Delbta, Jour el Bawashek, Jouret el Hachich, Aghbe, Raashine, Nahr ed Dahab, Raifoun, Qleyyat, Mar Jerjis, Mazraat Mrah el Mir, Ain ed Delbe, Bqaatouta, Boqaata Kanaan, Faitroun, Mayrouba, Outa el Jaouz, Mazraat Kfar Debbiane, Ain el Mghayer (Hrajel), Faraya, Kfartay.

To the north, the Jbeil (Byblos) district, covering the villages in the Nahr Ibrahim area comprise:

Qehmez, Bhassis, Chouata, Laissa, Saraita, Mzarib, Ghabat, Afqa, Yanouh, Mghaira, Janneh, Majdel, Aaqoura, Laqlouq.

The extreme north of the catchment belongs to the Batroun district and is part of the villages of Tannourine et Tahta and Harissa.

The entire population living in the GW catchment of Jeita spring is estimated at 200,000 (pers. comm. with municipalities in catchment). Individual population numbers of villages in the catchment are given in SCHULER & MARGANE (2013) and GITEC, LIBANCONSULT & BGR (2011). Population numbers in Lebanon are, however, not very reliable. The last census in Lebanon dates back to 1932 and the Department of Statistics (DOS) has no correct population numbers of villages. Many households have two houses, one in Beirut, used in winter, and one in the catchment, used only during summer and may therefore be counted twice.

Figure 3: District Boundaries in the Groundwater Catchment

(green and blue lines; GE image)

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

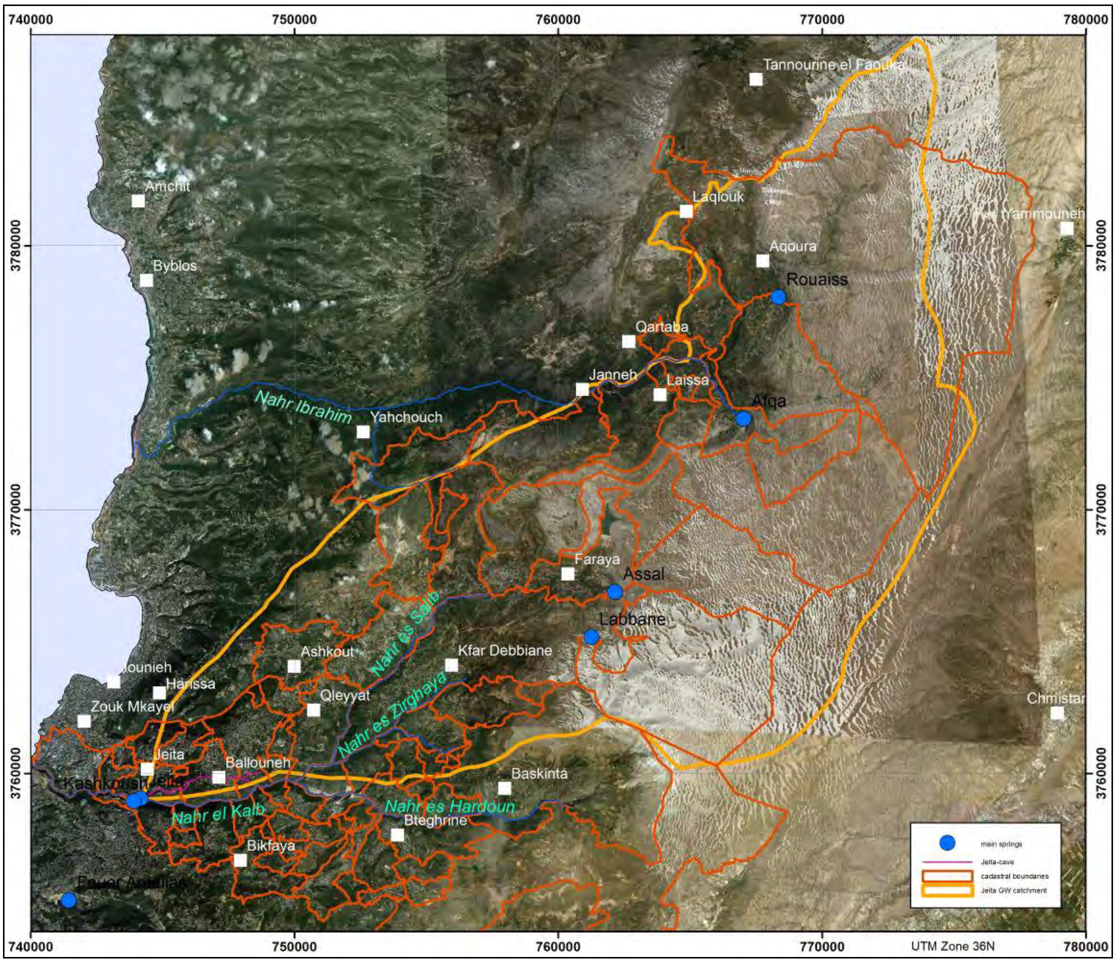


Figure 4: Administrative Boundaries (villages) in the Jeita Groundwater Catchment

(red lines)

1.4 Climate

With a total of 35 stations, the number of meteorological stations in Lebanon is extremely low (pers. comm. NMS), while Israel entertains more than 500 rainfall gauges (GOLDREICH, 2003), and Jordan (MARGANE & ZUHDY, 1995) monitors 80 stations equipped with automatic rainfall recorders, 240 stations equipped with standard precipitation gauges (manual daily measurements) and 40 stations equipped with precipitation totalizers (annual rainfall measurements). Data in Lebanon are collected by the National Meteorological Service (NMS), which is part of the Ministry of Public Works and Transportation. Also LARI (www.lari.gov.lb), which is part of the Ministry of Agriculture, currently monitors 40 operational weather stations in Lebanon but there is no data sharing and cooperation between both.

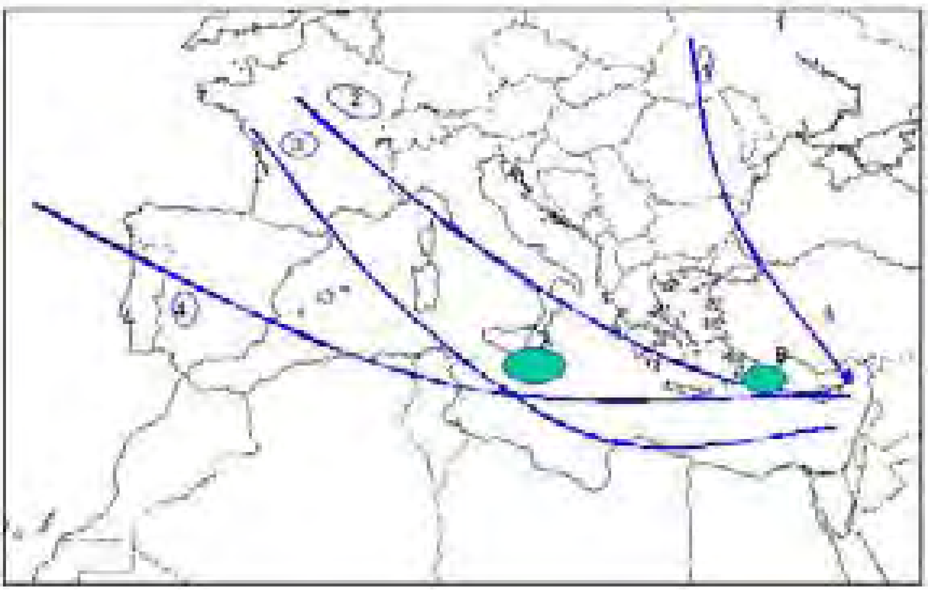


Figure 5: Trajectories of moisture sources in the Levant proposed by AOUAD-RIZK et al. (2005)

Rainfall

The long-term analysis of rainfall in the Levant (ZIV, et al., 2006; GOLDREICH, 2003) shows that rainfall in the eastern Mediterranean is strongly influenced by the Cyprus Low, which forms when cold air masses from Europe approach the region from the NW. Moving over the warm Mediterranean waters they gain moisture and become unstable, forming cyclones. AOUAD-RIZK et al. (2005) analyzed the moisture sources for single rainfall events in Mount Lebanon and suggested four main trajectories (Figure 5).

Using meteorological data gathered between 1939 and 1970, UNDP and FAO compiled a rainfall distribution map (UNDP & FAO, 1973). Rainfall distribution shown on this map was slightly modified (Figures 6, 8) based on interpretation of available satellite images as well as field observations and measurements of snow profiles in the snow covered area as it was recognized that snow accumulation is relatively high in the area north of the Mount Sannine escarpment and decreasing from there towards NE. Unfortunately there is no reliable detection of snow height yet through ground-based or satellite systems. Radar waves penetrate into the snow and the pixel size of e.g. the MODIS satellite system is much too large so that MODIS data cannot be used. The only reliable measurement of top of snow would have been conducting helicopter laser scans at different time intervals. This however would have been not feasible in Lebanon.

Rainfall distribution (Figures 6, 8) in the GW catchment reaches from slightly over 900 mm/a at Jeita to around 2,100 mm/a near Dome du Mzaar/Mount Sannine. Rainfall volumes for the entire GW catchment and for each individual spring catchment using this distribution are shown in Table 1. Details concerning rainfall and temperature in the catchment observed at the BGR meteo stations are listed in Annex 5.

Until the civil war there used to be a well operated meteorological network with nationwide around 100 stations. This has been reduced to 35 stations currently being operated (pers. comm.) by the National Meteorological Service (NMS), under the authority of the Ministry of Transport. Neither in the past nor nowadays any of these meteo stations was equipped with a heating system. However, snow plays an important role in Lebanon at elevations above 800 m asl. Therefore principally all current and previous rainfall measurements by Lebanese authorities are incorrect for elevations > 800 m asl. The currently existing meteo stations operated by NMS are shown in Figure 6.

NMS does not provide meteorological data for Lebanese governmental institutions, universities or development aid projects, such as the BGR/CDR project, free of charge but asks for advance payment of an unreasonable high amount. Due to the poor quality and data inconsistencies (pers. comm. MoEW), the NMS data were not purchased.

Because of this severe lack of meteorological data, several individual persons have installed their own meteorological stations for private weather forecast. There is a private weather station located in Aajaltoun at 825 m asl, operated by Joseph Kareh (www.meteokareh.com) since mid 2010 and there is a station located in Maarab at 755 m asl, operated by former BGR project staff Elias Saadeh (managed by meteokareh). Data from the Beirut airport weather station are available at: http://www.tutiempo.net/en/Climate/Beyrouth_Aeroport/401000.htm. Those data are available for download for the time period 1957-recent and have been used by the project. The Beirut airport station shows a fairly high interannual variation in the amount of rainfall (Figure 10).

The second edition of the 'Atlas Climatique' was prepared by the Ministry of Public Works and Transport in 1977 (NMS, 1977). It tried to establish an average for the period 1931-60 and uses data from 143 Lebanese and 23 Syrian stations, many of them covering data before or after the required period and only three stations with complete data were available for this time period. Even NMS thought it was not justified to directly compare those data and instead developed an algorithm to try to compare data (creating so-called 'normalized' data). The resulting map though shows that topographic effects, which clearly exist, were not considered and it was directly interpolated between data probably using Thiessen polygons (not explained in the report). Also the used normalization is highly suspicious. The resulting map of NMS (Figure 10) cannot be considered as representative for rainfall distribution in Lebanon and was therefore not used. On the other hand, the map prepared by UNDP & FAO (1973) uses topographic features for interpolation and the result seems much more realistic. In the absence of better data, the modified rainfall distribution map of UNDP & FAO was used. The average annual number of rainy days (Figure 12), presented in NMS, 1977 was used for individual hydrogeological studies, for instance the GW vulnerability map.

Before the start of the project only one governmental meteorological station was existing in the groundwater catchment. This station is operated by NMS in the village of Faqra Club (elevation 1690 m asl; part of the municipality of Kfar Debbiane). Another meteo station was installed a few years back by University of Saint Joseph near Chabrouh dam. The station, however, is located directly at an escarpment and therefore measurement of meteorological parameters cannot be representative because of ascending air currents.

In order to obtain some needed meteo data for purpose of validation of existing data and the possibility of future long-term monitoring, the project aimed to install meteo stations well distributed over the GW catchment. In the meantime 5 of the 6 stations purchased (Thies Clima; www.thiesclima.com) were established at the locations documented in Table 2 and Figure 6. However, an agreement has not yet been reached who would be in charge of monitoring these stations in the long-term, since non of the partner institutions of the BGR project is able to do so. All BGR stations are installed on properties of the government, at elevations ranging from 463 m to 1591 m asl. Results obtained so far are documented in Annex 5. Further details are contained in ABI RIZK & MARGANE (2013).

In addition, rainfall samplers were established to collect samples for stable isotope analysis every 10 or 15 days (Figure 7; Table 3). Rainfall amount during water year 2012/13 matches that of the BGR meteo stations (results of stable isotope rainfall sampling are documented in Annex 3; results of stable isotope rainfall sampling concerning amount, EC and chloride content are documented in Annex 5). Further details are contained in KOENIGER & MARGANE (2013).

Table 1: Rainfall Volumes and Average Elevations for all Spring Catchments in the Jeita Groundwater Catchment

Spring	Average Elevation [m asl]	Size of catchment [km²]	Average rainfall [mm/a]	Rainfall volume [MCM]
Jeita	1630	405.6	1529	620.3
Rouaiss	1919	65.8	1613	106.1
Afqa	2012	101.5	1613	163.7
Assal	2174	14.6	1807	26.4
Labbane	2171	9.5	1900	18.1

Table 2: Preexisting and New Meteorological Stations in and near the Groundwater Catchment of Jeita Spring

ID	Name	LAT	LONG	Altitude [m asl]	Institution	Year
	Kaslik university	33.982309°	35.618828°	40	NMS	
	Qartaba	34.095215°	35.852850°	1102	NMS	
	Hemlaya	33.938241°	35.706937°	790	NMS	
	Faqra Club	33.987469°	35.811718°	1690	NMS	
	Faraya	34.015412°	35.829295°	1555	USJ	
RS1	Aajaltoun AIS	33.95761°	35.67999°	821	BGR/CDR	2012
RS2	Baqeesh reservoir	33.949771°	35.788706°	1416	BGR/CDR	2012
RS3	Kfar Debbiane municipality	33.98113°	35.77111°	1307	BGR/CDR	2012
RS4	Shaile reservoir	33.955518°	35.653252°	463	BGR/CDR	2012
RS5	Chabrouh dam	34.025799°	35.834505°	1596	BGR/CDR	2012
WS1	Dome du Mzaar	33.965300°	35.840144°	2425	BGR/CDR	-

Table 3: Rainfall Samplers for Stable Isotope Data

ID	Name	LAT	LONG	Altitude [m asl]	Institution	Year
iA	Aajaltoun AIS	33.95761°	35.67999°	821	BGR/CDR	2012
iR	Raifoun BGR office	33.97662°	35.70658°	1036	BGR/CDR	2012
iK	Kfar Debbiane municipality	33.98113°	35.77111°	1307	BGR/CDR	2012
iS	Shaile reservoir	33.95552°	35.65333°	463	BGR/CDR	2012
iC	Chabrouh dam	34.02574°	35.83447°	1591	BGR/CDR	2012
iJ	Jeita restaurant	33.94311°	35.64445°	92	BGR/CDR	2012

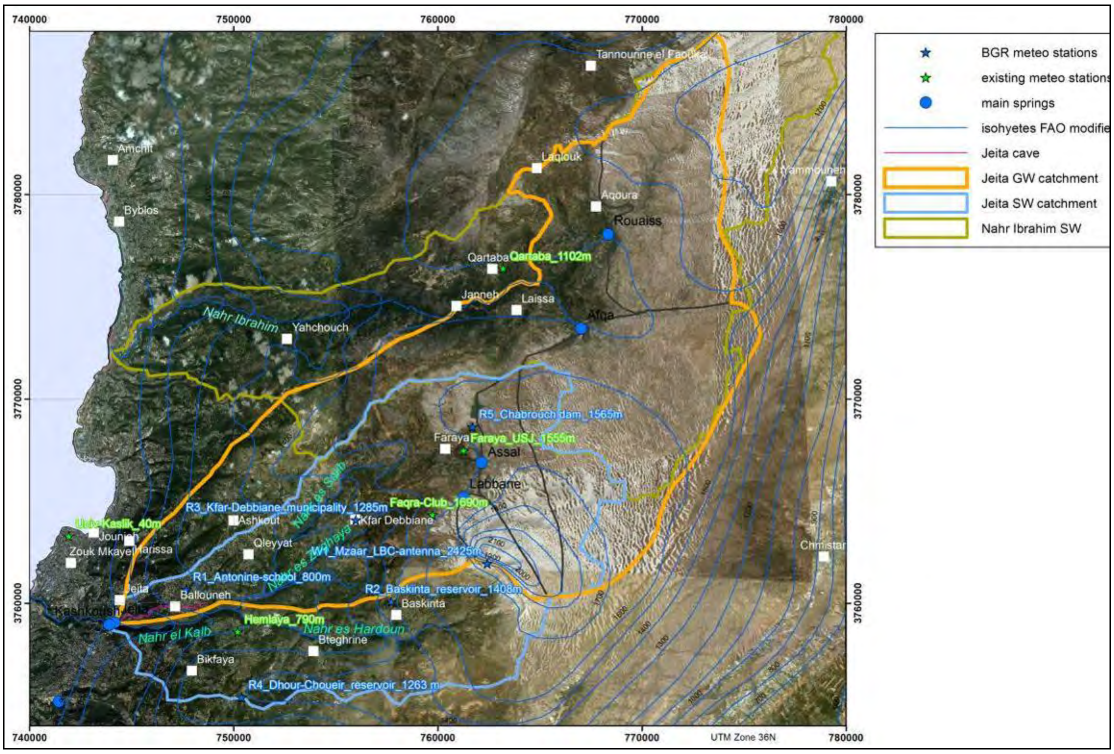


Figure 6: Preexisting and new meteorological stations installed by BGR in the Jeita groundwater catchment

Figure 7: Rainwater sampling sites for stable isotope analyses in the Jeita groundwater catchment

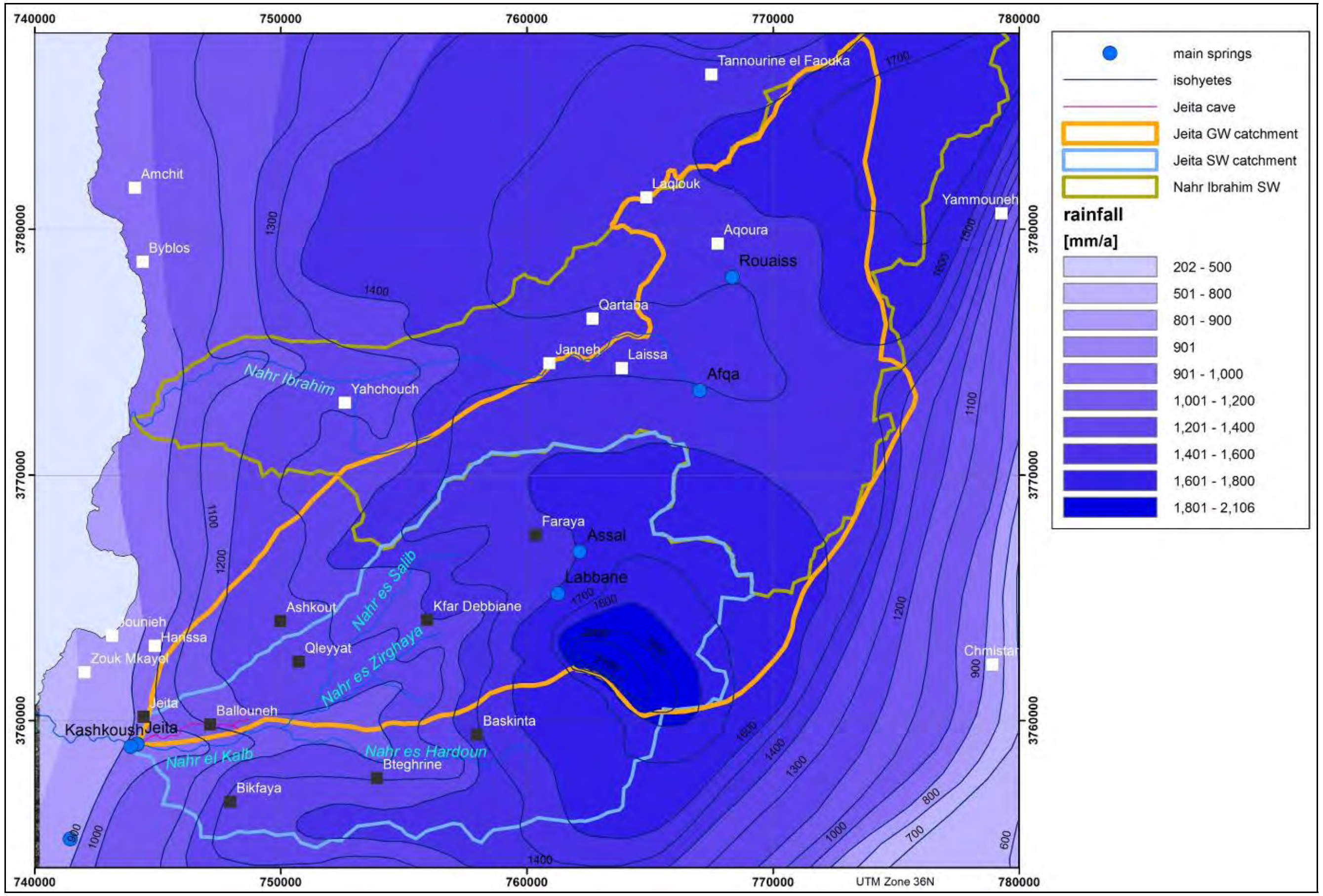


Figure 8: Spatial Distribution of Annual Precipitation
(modified after UNDP & FAO, 1973)

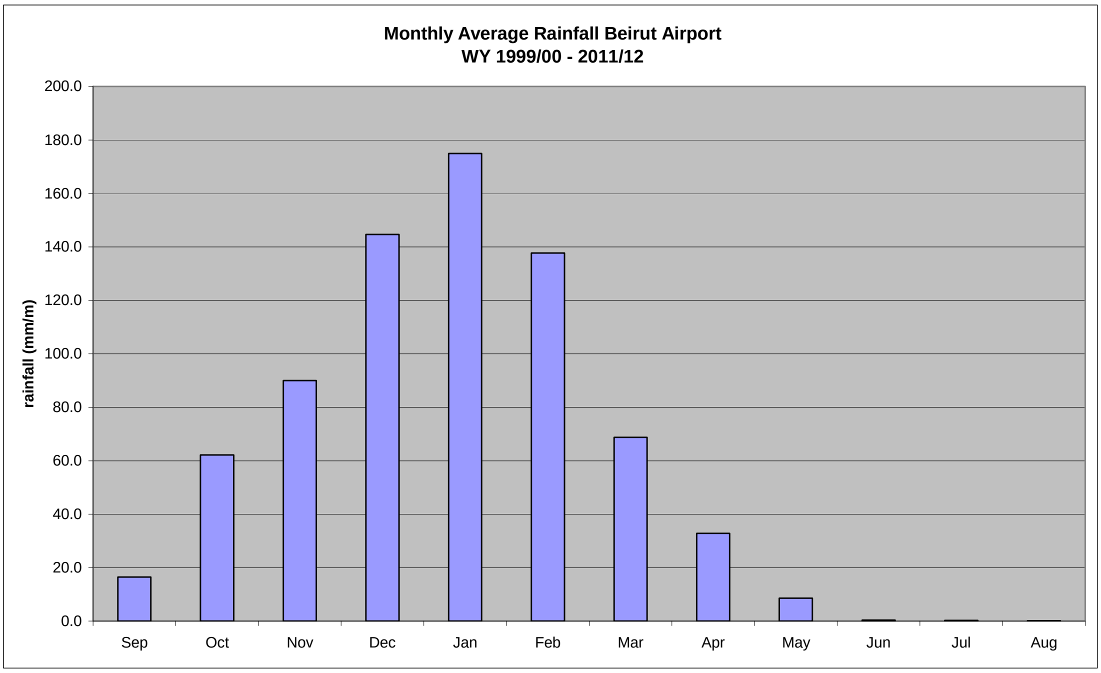


Figure 9: Monthly Average Rainfall at Beirut Airport

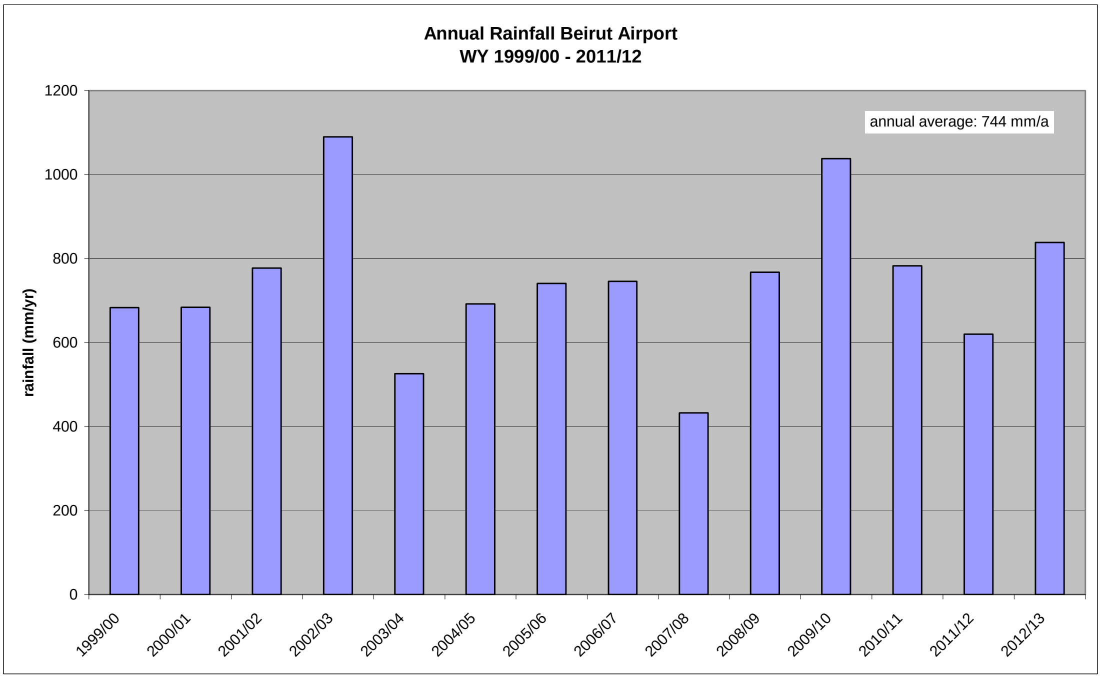


Figure 10: Variation in Annual Rainfall at Beirut Airport

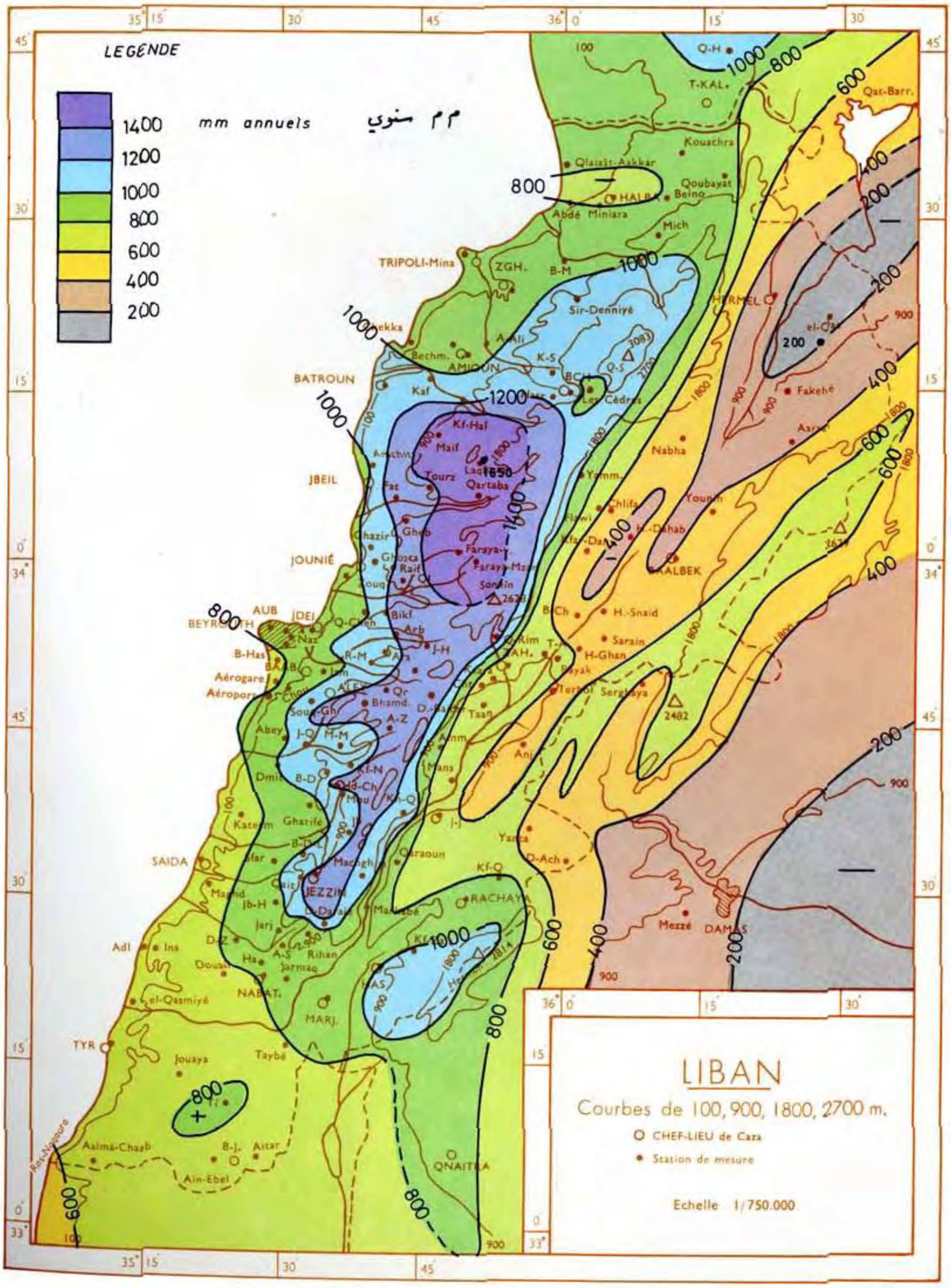


Figure 11: Spatial Distribution of Normalized Annual Precipitation (NMS, 1977)

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

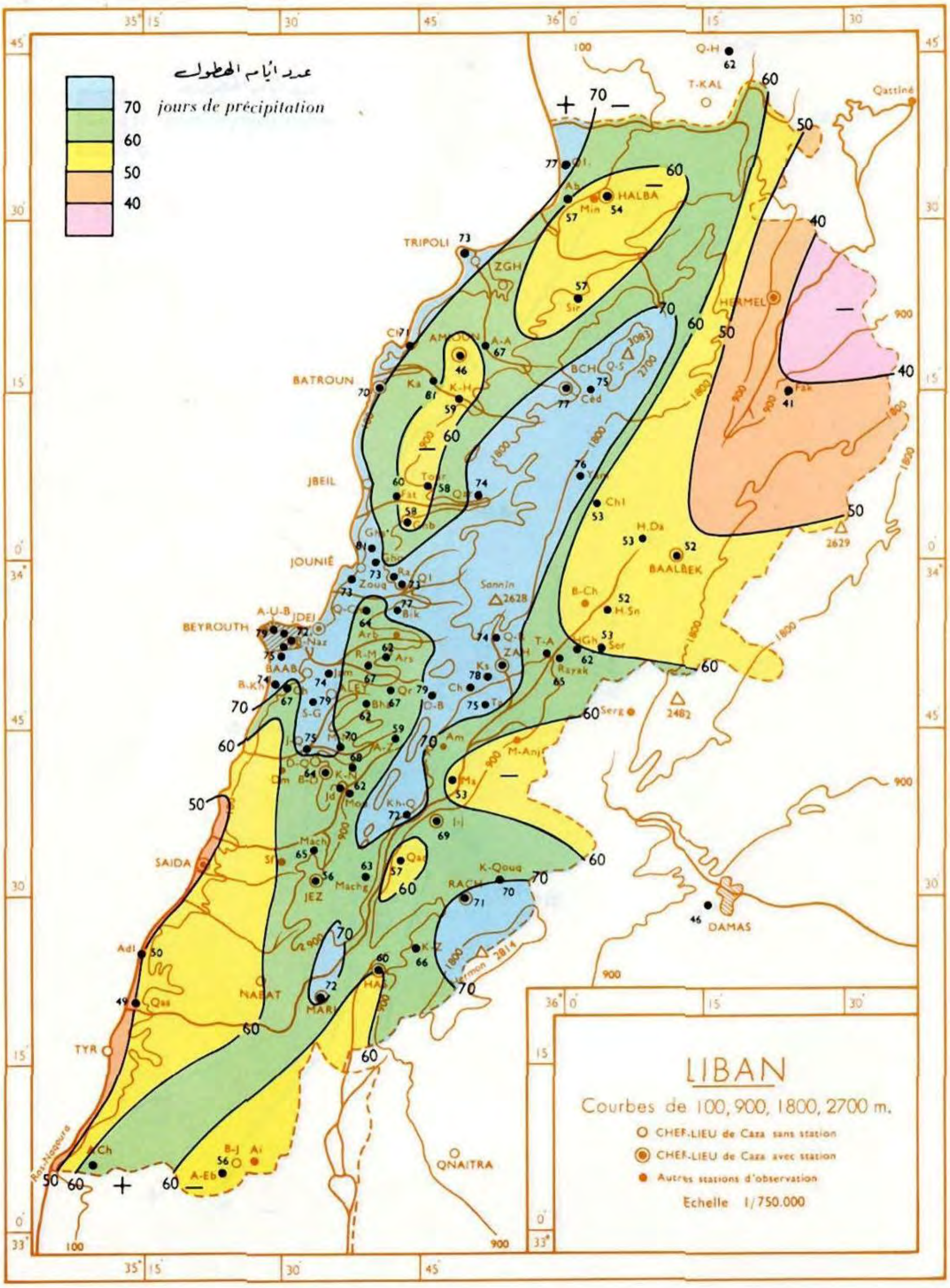


Figure 12: Spatial Distribution of Annual Average of Number of Rainy Days

(normalized data; NMS; 1977)

Temperature

Temperature was measured in the past (NMS, 1977) at the stations Zouk Mkayel (70 m asl; Figure 15), Ghosta (650 m asl; Figure 13), Qartaba (1140 m asl; Figure 16), Faraya-Mzar (1840 m asl; Figure 17), Laqlouq, Raifoun (no records in Atlas Climatique), and Bikfaya. Figure 13 shows the comparison of the average mean temperatures from four almost evenly spaced different elevations. Temperature gradients between stations are plotted in Figure 14, showing clear differences throughout the year (higher gradients in winter) and differences depending on the elevation (lower gradients at higher altitudes). The temperature gradient varies between 0.22 and 0.83°C/100 m. Daily average temperatures would be relevant for modelling of snow melt but are unfortunately not available.

Temperature measurements conducted at the new BGR meteo stations (ABI RIZK & MARGANE, 2013) show a high interdaily variation of daily mean temperatures of around 10°C (Annex 5). Temperatures measured at Kfar Debbiane (1307 m asl) show that at mid elevations minimum temperatures commonly fall only for a short period below 0°C (Annex 5.9).

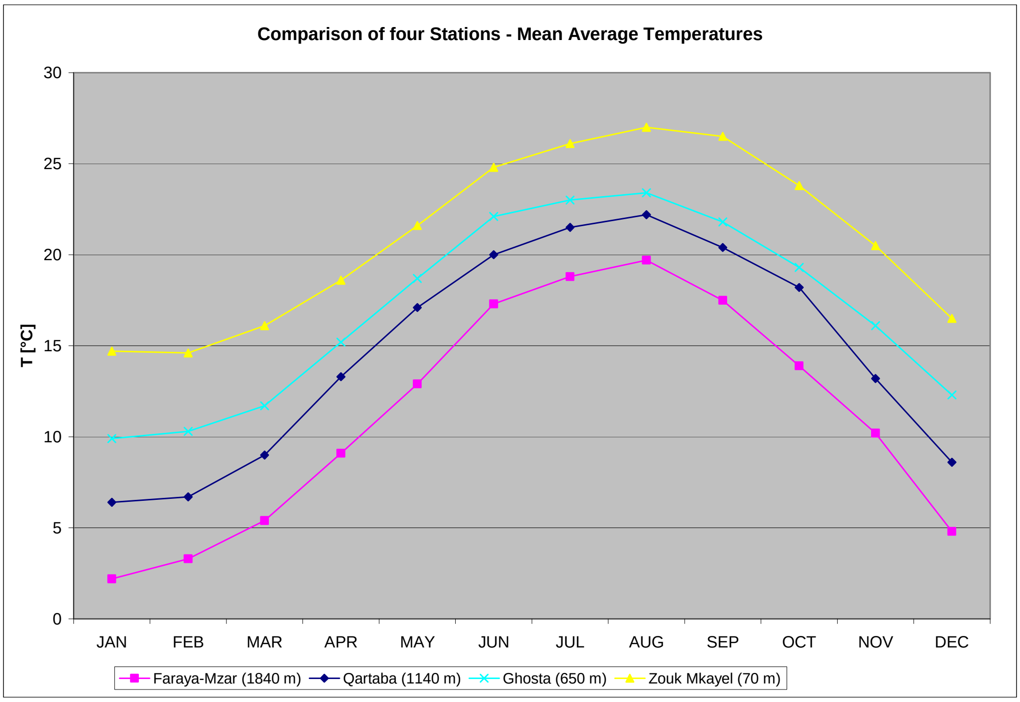


Figure 13: Averages of Mean Temperature for Stations in the Groundwater Catchment at different Elevations (based on NMS, 1977)

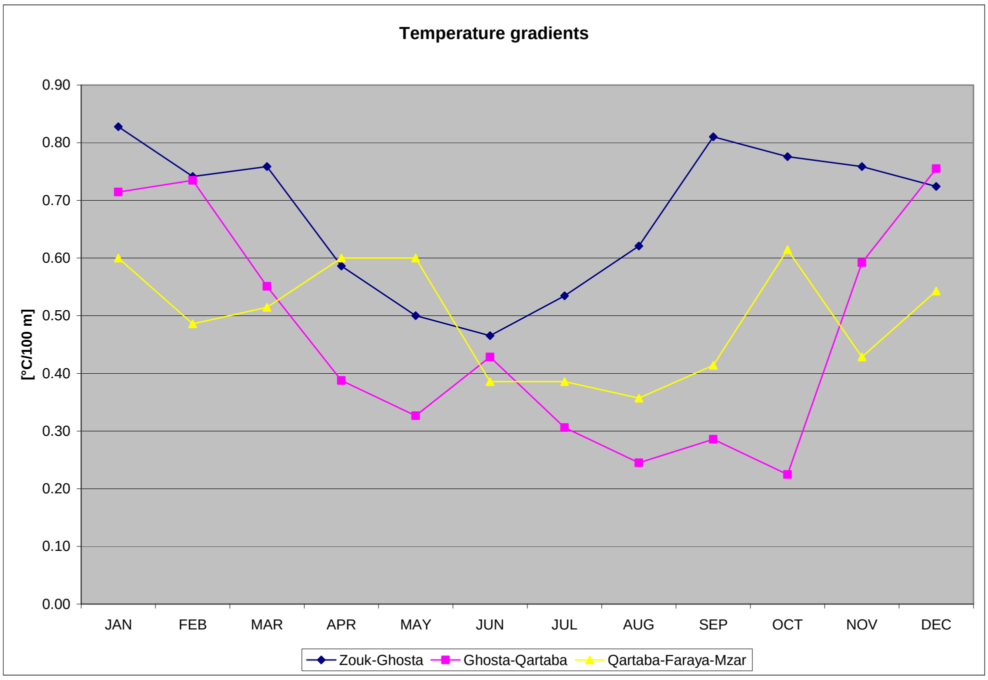


Figure 14: Temperature Gradients for Average Mean Temperatures of four Stations in the Groundwater Catchment (based on NMS, 1977)

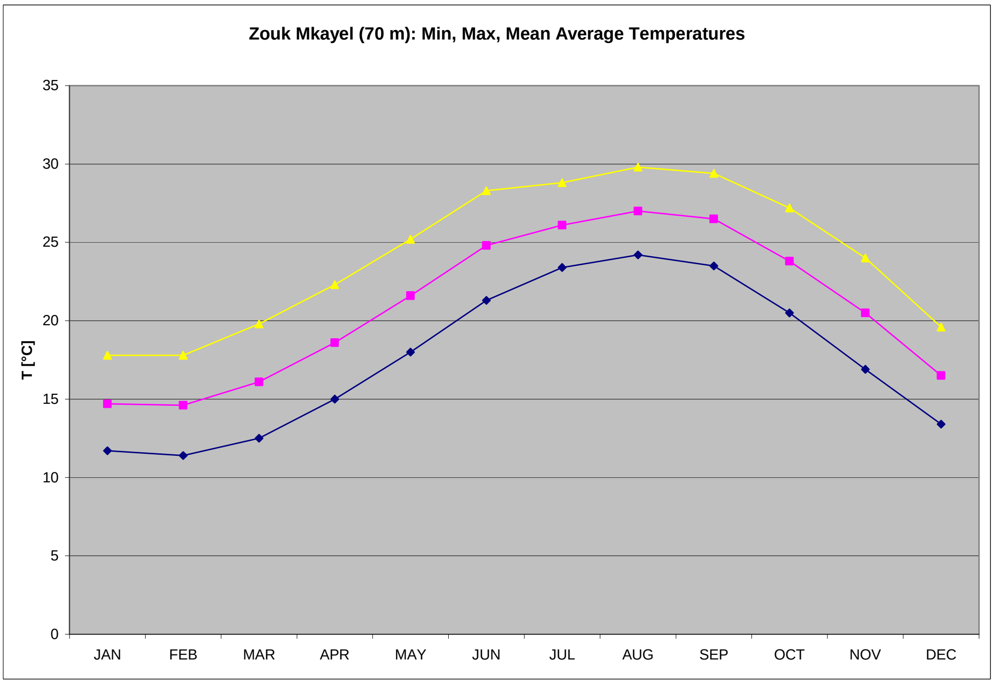


Figure 15: Temperature Averages for Station Zouk Mkayel (based on NMS, 1977)

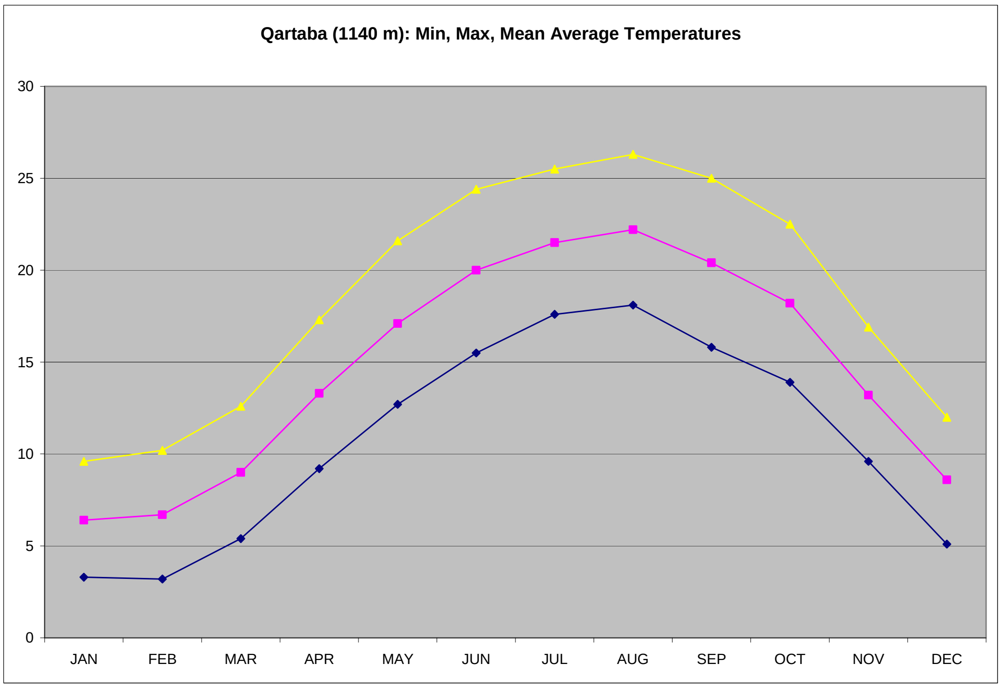


Figure 16: Temperature Averages for Station Qartaba (based on NMS, 1977)

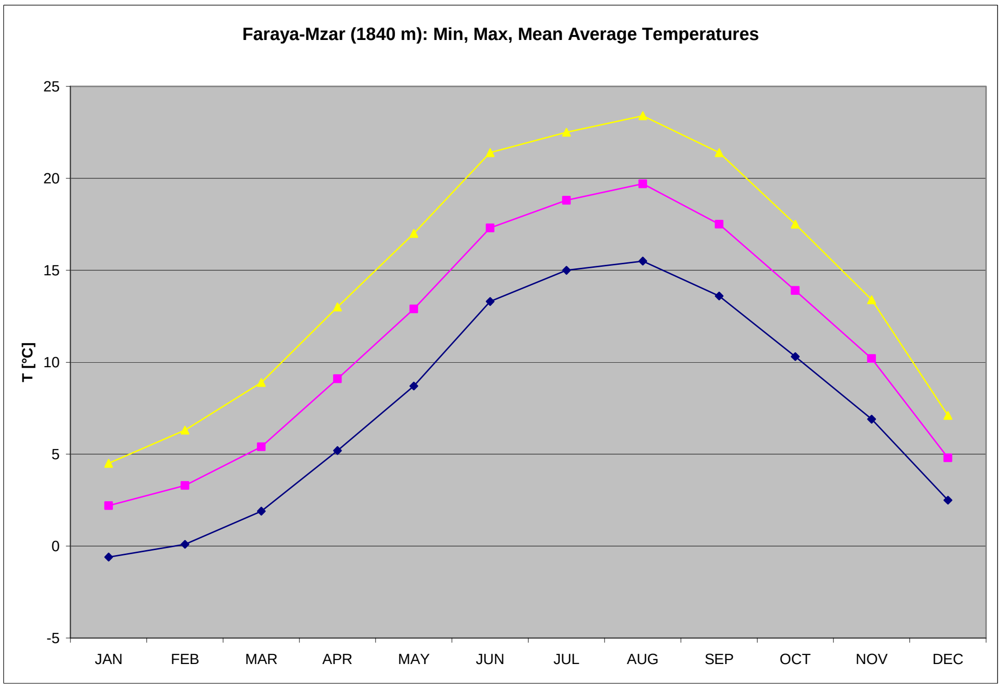


Figure 17: Temperature Averages for Station Faraya-Mzar (based on NMS, 1977)

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

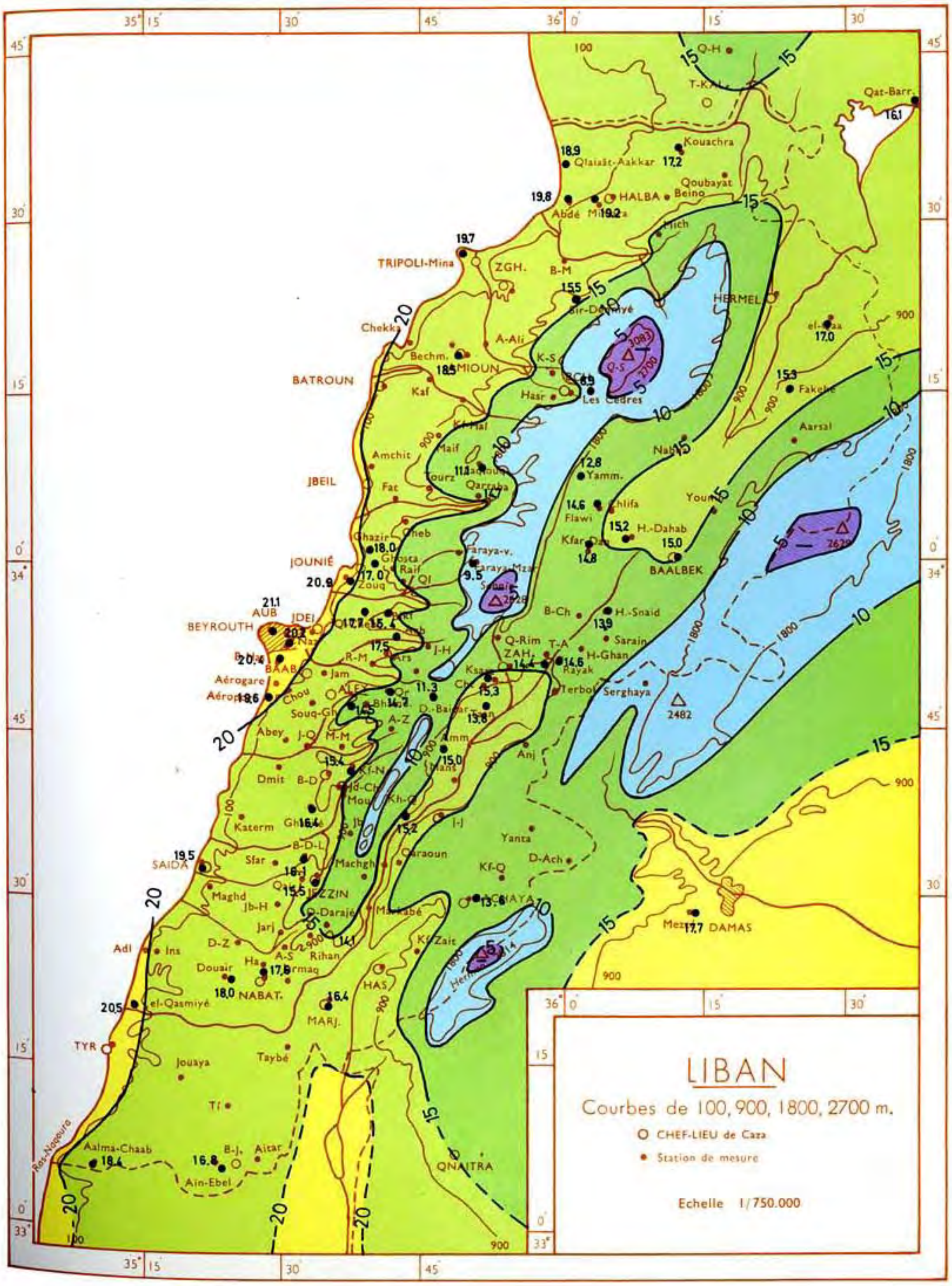


Figure 18: Average Annual Mean Temperatures (adopted from NMS, 1977)

Wind Direction and Speed

The second edition of the Atlas Climatique (NMS, 1977) contains maps of wind direction and speed, measured at 7 stations in Lebanon (Figure 19: annual distribution). There is one station of NMS in the project area, the groundwater catchment of Jeita spring, measuring wind speed and direction located at Faqra Club, however, it has no heating system and measurements in winter are therefore not accurate. Furthermore, the station is located at a more than 300 m high cliff so that ascending air currents will not be representative. Moreover, the valley at the bottom of the cliff is deeply incised and has a linear direction (~50°) so that wind will be channeled parallel to this prominent topographic feature. Wind direction and speed is also measured at the private station of MeteoKareh.com. The NMS map shows that the distribution is very different at the stations and probably depends on the local topographic situation. In general it is assumed that western wind directions prevail, as is the case also in Israel, where many more stations are available (GOLDREICH, 2003; ODEH, 2011). During winter, however, sometimes trajectories reach the Levant from Ukraine and Turkey (northern to northeastern winds), bringing snow (AOUAD-RIZK et al., 2005).

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Figure 19: Annual Distribution of Wind Direction and Speed in Lebanon (adopted from NMS, 1977)

Evaporation

Within the framework of the National Action Programme to Combat Desertification, the Ministry of Agriculture in cooperation with UNCCD reprinted the spatial distribution of potential evaporation as prepared by NMS in 1966 in its first edition of the Atlas Climatique (presented in: UNCCD & MoA, 2003; http://www.unccd.int/ActionProgrammes/lebanon-eng2003.pdf). The map (Figure 20) does not contain any reference points where potential evaporation would have been measured (e.g. by evaporation pans) and the original source was not available, even from NMS. Therefore the source and quality of information cannot be verified. Strangely, the second edition of the 'Atlas Climatique' (NMS, 1977), which was made available by NMS (scanned by BGR project), does not contain any information related to potential evaporation. Therefore the map shown below must be considered as hypothetical. It shows a potential evaporation of between 800 and 1100/a on the Upper Cretaceous plateau. The real evapotranspiration estimated by the project for this area, however, is less than 300 mm/a. It is pointed out that, due to the given physical conditions, there is a huge difference in the karst areas of Lebanon between potential evaporation and real evapotranspiration. The potential evaporation is therefore of little use for water balance assessments due to the high infiltration rates. In simple hydrological water resources assessments based on the curve number method this fact is commonly not considered.

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

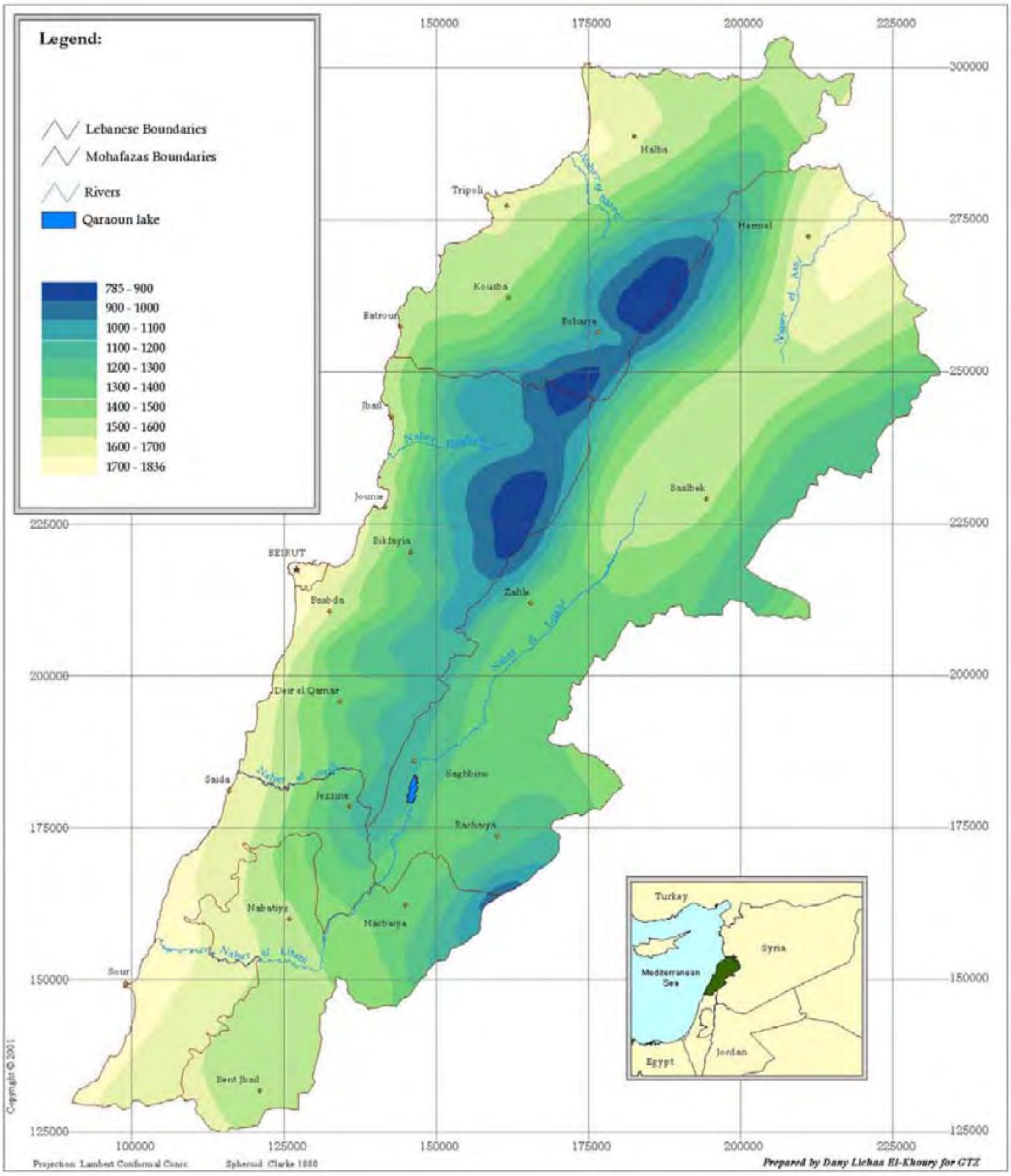


Figure 20: Potential Evaporation Map (adopted from MoA, 2003)

1.5 Hydrology

Streamflow is monitored in the Jeita GW catchment by the Litani River Authority (LRA). The river courses and existing monitoring stations are shown in Figure 21. Due to the high rainfall in the groundwater and surface water catchments and despite the high rate of groundwater infiltration in both, the Upper (GWR: ~ 81%) and Lower Aquifers (GWR: ~ 58%), large amounts of surface water are generated and run off unused to the sea (Table 4). There is a strong interannual variation of between 38 and 227% of runoff at the seamouth and of only between 36% and 164% at Daraya (Figures 22, 23).

The amount of surface water available in the Nahr el Kalb and Nahr Ibrahim surface water catchments has been assessed based on available streamflow data provided by LRA by MARGANE & STOECKL (2013). A proposal was made how to more efficiently use surface water (GITEC & BGR, 2011). It was suggested to construct dams for managed aquifer recharge (MAR) and storage in the Nahr el Kalb catchment (Table 5, Figure 24). The main purpose of MAR dams would be to facilitate infiltration of surface water into groundwater so that less water resources are lost to the sea and more groundwater would be available at Jeita and Kashkoush springs to reduce water shortages at the end of the dry season in the drinking water supply for the Greater Beirut Area.

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

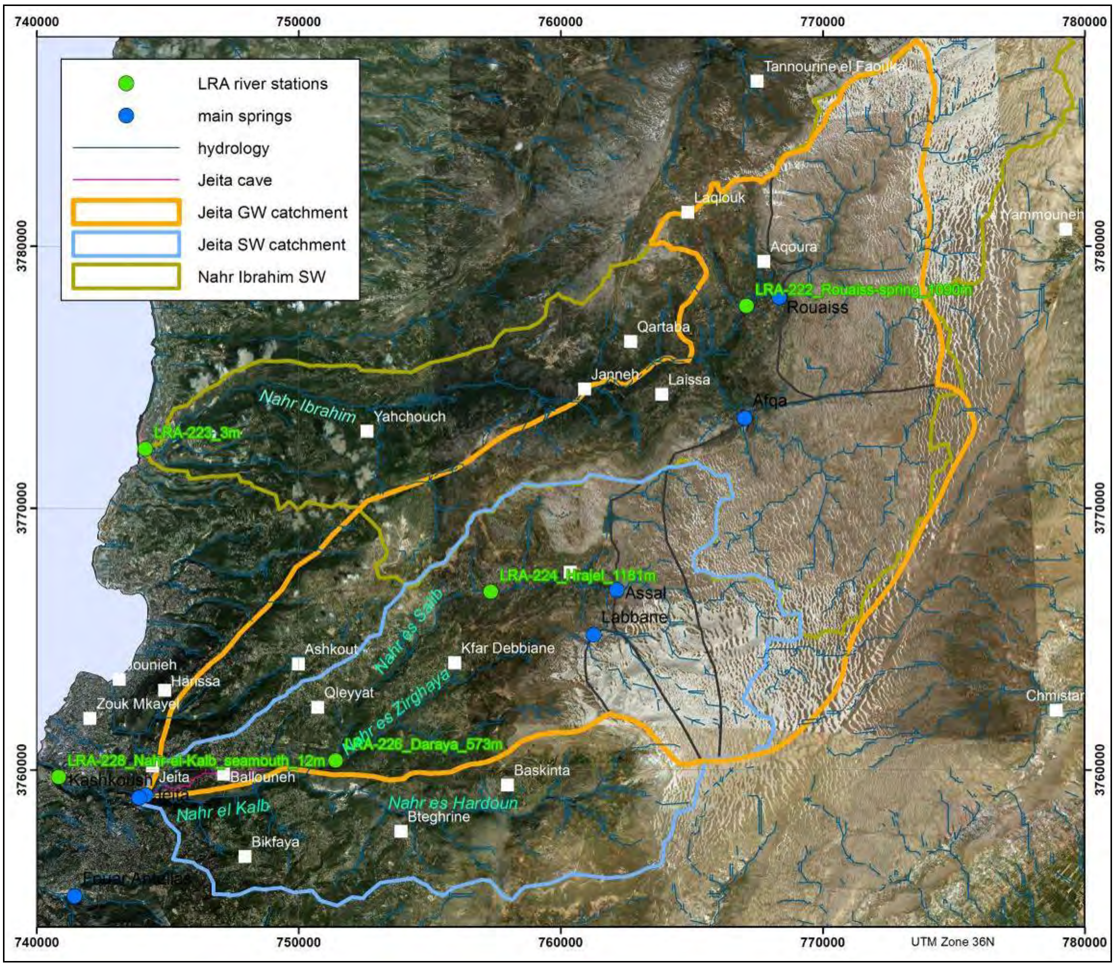


Figure 21: Existing Streamflow Gauging Station monitored by LRA

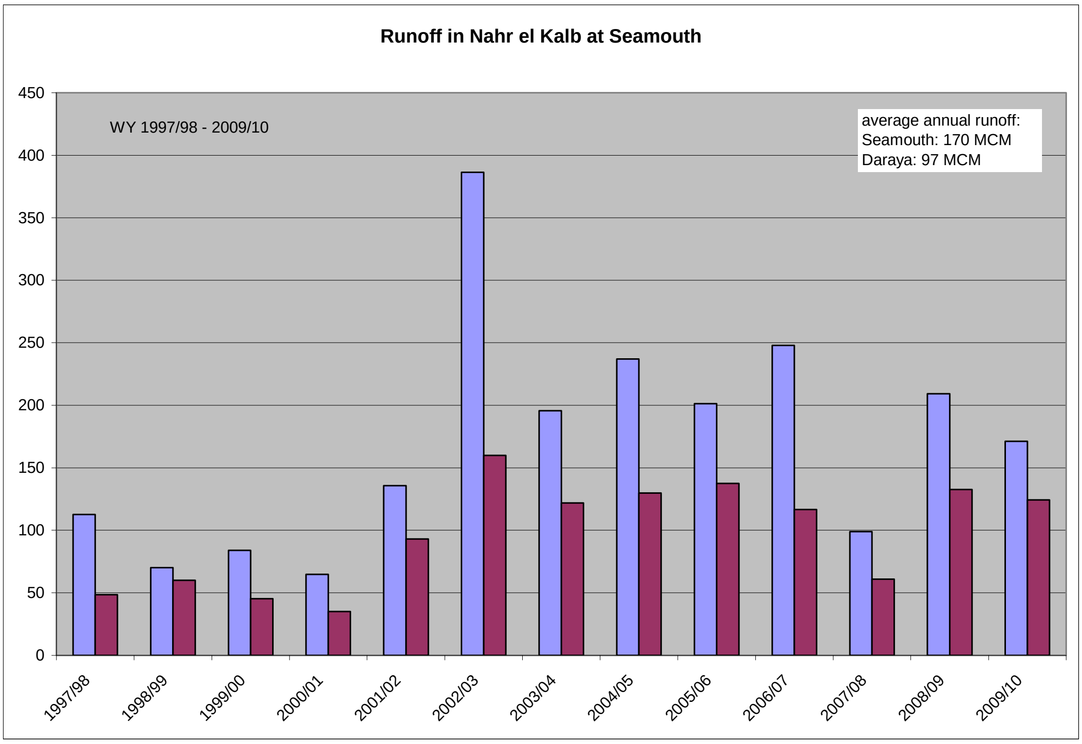


Figure 22: Annual Runoff in Nahr el Kalb at Seamouth and at Daraya

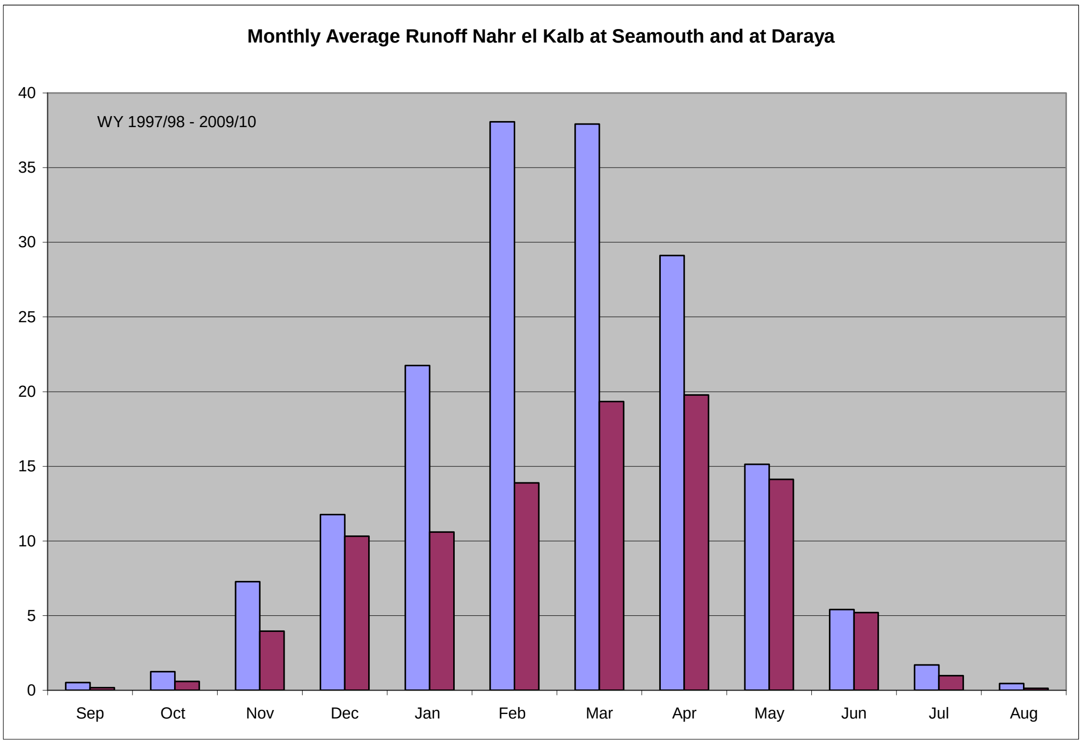


Figure 23: Monthly Average Runoff in Nahr el Kalb at Seamouth and at Daraya

Table 4: Runoff during Water Years 1997/98 - 2009/10 in the Nahr el Kalb Catchment

ID	Station	River section	Runoff [MCM]
228	Nahr el Kalb seamouth	Nahr el Kalb	170
226	Daraya	Nahr es Salib	97
-	-	Nahr es Hardoun	73*

* inferred, assuming that no surface water infiltration would occur between Deir Chamra and station 228

Figure 24: Proposed Dam Sites in the Nahr el Kalb Catchment

Table 5: Base Data of Proposed Dams

Name	UTM_E	UTM_N	Elevation [m asl]	Dam crest [m]	Storage [MCM]	Surface area [m²]	Surface Catchment [km²]	Rainfall [mm/a]	Rain volume [MCM/a]
Kfar Debbiane dam	752020	3761940	720	100	7.3	224,721	91.0	1,565	142.4
Faitroun dam	755210	3765710	1115	65	6.6	459,963	80.1	1,596	127.8
Boqaata dam	754200	3761500	900	80	4.1	198,025	16.8	1,442	24.2
Baskinta dam	759060	3758630	1035	100	6.0	157,730	28.5	1,659	47.4
Zabbougha dam	752120	3760710	635	100	3.0	104,976	46.9	1,454	68.2
Daraya dam	748720	3759500	320	100	9.0	235,215	222.0	1,494	331.7

Through tracer tests and other hydrogeological investigations it was proven that the extents of groundwater and surface water catchments are very different (Figure 25).

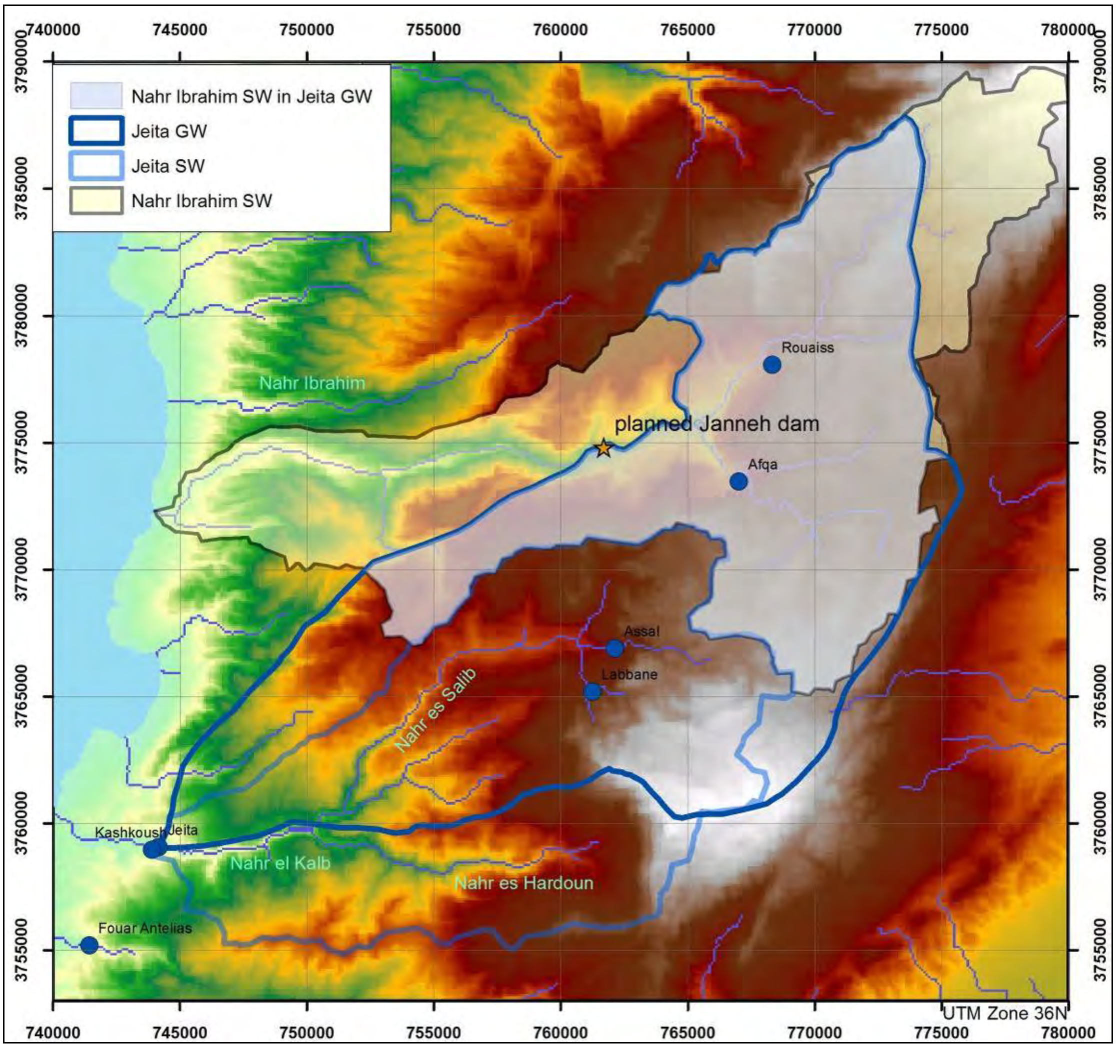


Figure 25: Part of Nahr Ibrahim Surface Water Catchment located in Jeita Groundwater Catchment

1.6 Previous Works

The Jeita surface water catchment is the area most intensively studied in Lebanon. This is due to the fact that Jeita spring is not only the largest spring in Lebanon but also the most important with regards to drinking water supply. However, until now, no real efforts have been undertaken to determine the groundwater catchment of Jeita spring, assess its discharge and propose options of water usage based on a comprehensive water balance as was done now by the BGR project.

The first tracer tests in the Jeita catchment (see also MARGANE, 2011) were done in the early 20th century (1913, 1923; KARKABI, 2009), near the village of Mayrouba. Later, altogether three tracer tests were conducted in 1965 and 1971, as documented in HAKIM et al. (1988), near Deir Chamra.

In his MSc, MAJDALANI (1977) investigated the geology and hydrogeology of the Faraya-Afqa area. He investigated Assal and Labbane springs and a number of small springs. This reference contains the discharge of Labbane spring, measured during 1960-1965 and Assal spring, measured during 1970-1972. However, it is not clear where and how measurements were done, especially since Assal springs has two exits. Also measurements were too scarce to account for the rapid changes in discharge.

UNDP carried out a study on Jeita spring ('Jeita - the famous karst spring of Lebanon'; UNDP, 1972). The study, however, entirely conducted by civil engineers, focussed mainly on the question of the exploitation potential of Jeita spring and not on characterizing groundwater flow in the Jeita spring catchment and the report admits openly in its introduction that 'no systematic exploratory work had been carried out on the groundwater'. The main idea behind the study was to provide water for Beirut from Jeita 140 through pumpage (190 m lift) from the 'Daraya tunnel' and the construction of another proposed tunnel connecting the Nahr el Kalb Valley with Nahr Beirut. The study used a groundwater catchment similar to the surface water catchment. As one of the main results, the study states that Jeita has an average discharge of 211 MCM/a (p. 262). However, this conclusion is based on measurements conducted between 1966 and 1971, only. As the report admits, these measurements (done by Office National du Litani - ONL, today Litani River Authority - LRA) were rather basic (p. 52; 0-5 manual measurements per month; not mentioned how flow was determined) and were conducted mainly in the Hrash canal, i.e. after diversion from Jeita spring and not at the spring itself. The canal has only a limited capacity (not mentioned) and commonly when flow exceeds approx. 6 m^3/s, excess water is directly discharged into Nahr el Kalb river. The report states: 'it might be said that the station upstream from Hrash controls about 90% of the flow of the Jeita spring' and that 'the actual discharge of the Jeita spring can be obtained by introducing an adjustment factor of about 1.146 in the figures recorded at the Hrash canal station' (p. 87). Based on our own measurements we can now say that these two statements are very wrong indeed and that the flow measurements previously conducted at Jeita spring and many others (Kashkoush, Assal, Labbane, Afqa, Rouaiss) are completely insufficient and incorrect.

Only 10 measurements were done by ONL inside Jeita spring and 2 inside Kashkoush spring, 4 measurements were done at siphon terminale of Jeita spring (referred to as Jeita 140) by ONL and 31 by Office des Eaux de Beyrouth (OEB) (UNDP study p. 97 and p. 152). Due to the fast recession observed in the measurements done by BGR (at 20 minute intervals), it is not justified using such random measurements for flow assessment of karst springs in Lebanon.

Flows at Jeita 140 (i.e. Daraya tunnel or siphon terminal) were correlated with the flows of Jeita 60 (i.e. Jeita spring) and flow of Jeita spring was then generated using a linear correlation. Recession curves were developed based on the conducted random (and highly insufficient and probably inaccurate) measurements.

As was found in 2005 by divers from Jeita Grotto, a submerged branch of Jeita cave enters the main underground river some 800 m upstream of the boat mooring. Flows determined in all three sections upstream and downstream by BGR show that around 15% of flow comes from this 'northern branch' (due to the difficult accessibility of the northern branch only 2 measurements during the low flow period could be conducted). It must be assumed that the flow path in the northern branch is very different from that in the main branch and therefore a linear regression between both is not possible. Also, due to the configuration of the weirs, flow determination at Jeita 140 was only possible for flows approx. < 6 m³/s. When flow exceeds this threshold, the second weir would start to flow, which is not monitored and at flows approx. > 8 m³/s the dam overflows in an uncontrolled manner. In winter and spring, flow frequently exceeds this level. Therefore previous measurements at the siphon terminal are highly inaccurate.

More importantly, a correlation of groundwater flow at Jeita 140 with surface water flow of Nahr el Kalb at Mokhada was established by UNDP (1972; pp. 262), believing that these behaved in a similar manner. However, the data at Jeita 140 were obviously artificially generated for the time period before the station even existed (UNDP: Figure 42, p. 263). Based on this 'correlation', flow of Jeita spring (Jeita 60) was generated. This mixture of measured data with artificially generated data and mixture of measurements periods must be considered as totally flawed. Also, as was found out now during the execution of the BGR project (Chapter 1.5; MARGANE, 2012a, 2012b), large amounts of surface water infiltrate into groundwater in the uppermost J4 geological unit and large shares of groundwater in Jeita spring come from such surface water infiltration located almost 30 km away from Jeita spring so that mean groundwater flow along this flow path takes around 2 months, while flow in the surface water flow path takes only around 1 day. The groundwater and surface water catchments of Jeita spring are completely different (Chapter 1.3) and the groundwater and surface water flow paths are therefore not comparable, which renders the concept of UNDP (1972) as completely incorrect.

For the above mentioned reasons, the flow determination of Jeita spring by UNDP (1972) is highly incorrect and must be outright rejected. The basic mistake of the UNDP study was not monitoring discharge of Jeita spring at the spring itself, at suitable time intervals and with appropriate means and the results of the study are therefore unfortunately rather useless.

The Beirut water utility, OEB, undertook several studies concerning the possibility of exploitation of Jeita, Kashkoush and Faouar Antelias spring, however, many of them are poorly documented and were not available in any archive or library. A coloration conducted by the Bureau Technique pour le Développement (BTD) in Jeita found no connection between Jeita spring and the OEB wells at Jeita and ruled out a link of the underground river of Jeita with Kashkoush spring (SAADEH, 1994; both statements are confirmed by all BGR tracer tests). Jeita cave was mapped by SCL (COURBON, 1989: in SAADEH 1994, p. 70).

SALIBA (1977) tried to recalculate, based on the same approach and data as UNDP (1972) the amount that could be extracted at Jeita 140. One option at the time was to build a tunnel from Jeita 140 to Beirut, but unfortunately the project concept is not explained in this document. Fortunately, this project was never executed.

Several explorations of the Jeita and Kashkoush caves were done by Lebanese and foreigners, documented in the journal of the Speleoclub du Liban (SCL), Al Ouat-Ouate, or the journal of ALES (Association Libanaise d'Etudes Spéléologiques), Speleorient.

In 1988 Associated Consulting Engineers (ACE), upon the request of CDR, analyzed the existing water conveyor from Jeita spring to Dbayeh and proposed four alternative solutions to improve water supply. The study points out the 'presence of a high degree of pollution, which renders the water unsafe for consumption without treatment'. In terms of water supply, this study is actually more complete compared to the UNDP (1972) study, although using the same data. The study also proposed using Kashkoush spring as an additional source of water for Beirut. Concerning the upgrading of the Jeita - Dbayeh conveyor, it was proposed to construct a new twin pipe system, replacing the channel. The proposals made by ACE (1988) are fairly similar to those made by the GITEC & BGR (2011). It shows that the need for an improved and safer conveyance system from Jeita spring to the Dbayeh drinking water treatment plant had been an issue for quite a while, however, despite the enormous risk for the population in the Greater Beirut Area, was not considered yet for some reason.

Several authors looked at water quality problems and the pollution sources in the Nahr el Kalb catchment. HAKIM (1993) investigated, in fulfilment of a contract with OEB, the Nahr el Kalb and Faour Antelias catchments and located pollution sources, finding that wastewater, gas stations, factories, hospitals, quarries and animal farms were the main pollution risks. This was confirmed by the recent survey of BGR (RAAD & MARGANE, 2013; RAAD el al., 2012). The number of pollution sources, however, has increased significantly since then. Bacteriological analyses of all major springs were done by HAKIM, showing that the level of contamination back then was also significantly lower than nowadays.

Almost simultaneously SAADEH (1994), in his MSc, studied the Jeita and Kashkoush springs and their quality (list of wells at Jeita: p.11, figure 7 (p. 68)). Saadeh conducted hydrochemical analyses on all major springs and wells near Jeita and Kashkoush and found that their composition varies with time in a similar pattern.

ACE (1995) prepared an environmental impact assessment for proposed water and wastewater projects in the Keserwan district. The water supply proposal comprised mainly the exploitation of the Madiq and Assal springs. The proposed wastewater system was intended to cover the coastal zone around Jounieh with a wastewater treatment plant (WWTP) at Tabarja. This concept was then used for a related European Investment Bank (EIB) project, which, however, is still not implemented although funds are available since that time. The main reason is that an agreement concerning the WWTP location could not yet be reached.

SCHULER (2011) prepared his MSc thesis in cooperation with the BGR project. He presented the first water balance for the Jeita groundwater catchment, known at the time. The water balance was made using the program WEAP. Due to the later modification of the GW catchment in May 2012, and the increased availability of data from the project for spring discharge, this report was later updated (SCHULER & MARGANE, 2013).

In the framework of the planning for the proposed Janneh dam, the geology, hydrogeology, and hydrology was examined by Khatib and Alami in order to come up with the final feasibility study. Planning of Janneh dam has been hampered by several shortcomings as pointed out by MARGANE (2012a, 2012b) and SAFEGE (2013) so that there are strong doubts concerning its feasibility.

VERHEYDEN et al. (2008) looked at the palaeoclimate in this region, based on the investigation of a 1.2 m long stalagmite from Jeita cave, covering an age of between ~1200 and 12000 BP. The isotopic records for $\delta^{18}O$ and $\delta^{13}C$ recovered from Jeita cave show some major differences with those recovered from the intensively studied Soreq cave (BAR-MATHEWS et al., 1999). Jeita cave provides immense opportunities to study the climatic archive of the Levant, preserved there over several hundred thousand years.

The leakage phenomenon at Chabrouh dam, built between 2002 and 2006, was investigated by BOU JAOUDE (2010).

The work of DOUMMAR (2012) for her PhD thesis was largely conducted in cooperation with the BGR project. The tracer tests were carried out either jointly or by the project and interpreted by DOUMMAR et al. (20101, 2010b, 2011a, 2011b, 2012a, 2013). All basic data for the GW vulnerability map prepared by DOUMMAR (2012b) was provided by the project. It provided the basis for the GW vulnerability map and GW protection zone delineation finally prepared by the project (MARGANE & SCHULER, 2013).

2 Geology

Many geologists studied the area of nowadays Lebanon and Syria during the late 19th and early 20th century and paved the way for the understanding of the geology and tectonics. Lebanon was first studied by BLANCKENHORN (1891). ZUMOFFEN (1926) prepared the first geological map at 1:200,000 scale, although not very accurate; and DUBERTRET conducted a comprehensive geological mapping at 50,000 scale (published between 1949 and 1951), later compiled into a countrywide geological map at 200,000 scale (published 1955) during and shortly after the end of the French mandate. However, discussions about the age dating of the individual sequences persist until today because only few and not entirely reliable age datings are available for the lithological units. WOLFART (1967) undertook a comprehensive review of all previous geological studies, coming to the conclusion that many age datings are uncertain and concluded that lithofacies changes are not well studied and documented.

A recent lithostratigraphic table was prepared by WALLEY (1997; Figure x), lacking, however, a comparison with the contemporary lithofacies in Syria, Southern Turkey and Jordan. Therefore the geological development, especially between the Triassic and Cretaceous in the region is still not entirely clear, while the Triassic and its depositional environment has been intensively studied in Syria (BREW, 2001; BREW et al., 2001) because of its particular importance for hydrocarbon exploration.

Unfortunately nothing is known yet about rocks of the Triassic sequence in Lebanon. Although the base of the Jurassic rocks can be assumed to be not very deep in many areas (e.g. in the Upper Nahr Ibrahim Valley; MARGANE 2012a, 2012b), the Triassic sequence has not yet been penetrated in boreholes or found at outcrop. The understanding of the Triassic is not only of importance for hydrocarbon exploration (in Syria major oil discoveries were made in carbonate-evaporite mega-cycles of the Triassic; LUCIC et al., 2010; SADOONI & ALSHARHAN, 2004) but also for the understanding of the most important aquifer in Lebanon, the Jurassic (herein named Lower Aquifer).

Also strangely no major efforts have been done yet to conduct a systematic age dating of the volcanic intrusions in Lebanon. Basaltic rocks occur as layers but also often in the form of dykes or massive intrusions (especially along or near major tectonic elements, such as in the Upper Nahr Ibrahim Valley or the Upper Nahr es Hardoun Valley). The direction of groundwater flow is often controlled by the location of basalt dykes and intrusions and therefore the knowledge about these, e.g. through geomagnetic surveys, would increase the understanding of the groundwater system.

The geological map (sheet Beirut) prepared by DUBERTRET in the Jeita catchment was not reliable and detailed enough so that the BGR project had to undertake a detailed geological mapping of the entire Jeita groundwater catchment based on extensive field work. The result is documented in HAHNE (2011) and in the attached map (ANNEX 1), which was later compiled for the remaining area, after the groundwater catchment of Jeita spring was finally established in May 2012 (Figure 26). Also the geology in the area west of the Jeita catchment was studied by BGR for the environmental impact assessment (EIA) of the Jeita Spring Protection Project (JSPP), implemented by KfW and CDR (LIBANCOSULT & BGR, 2013).

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

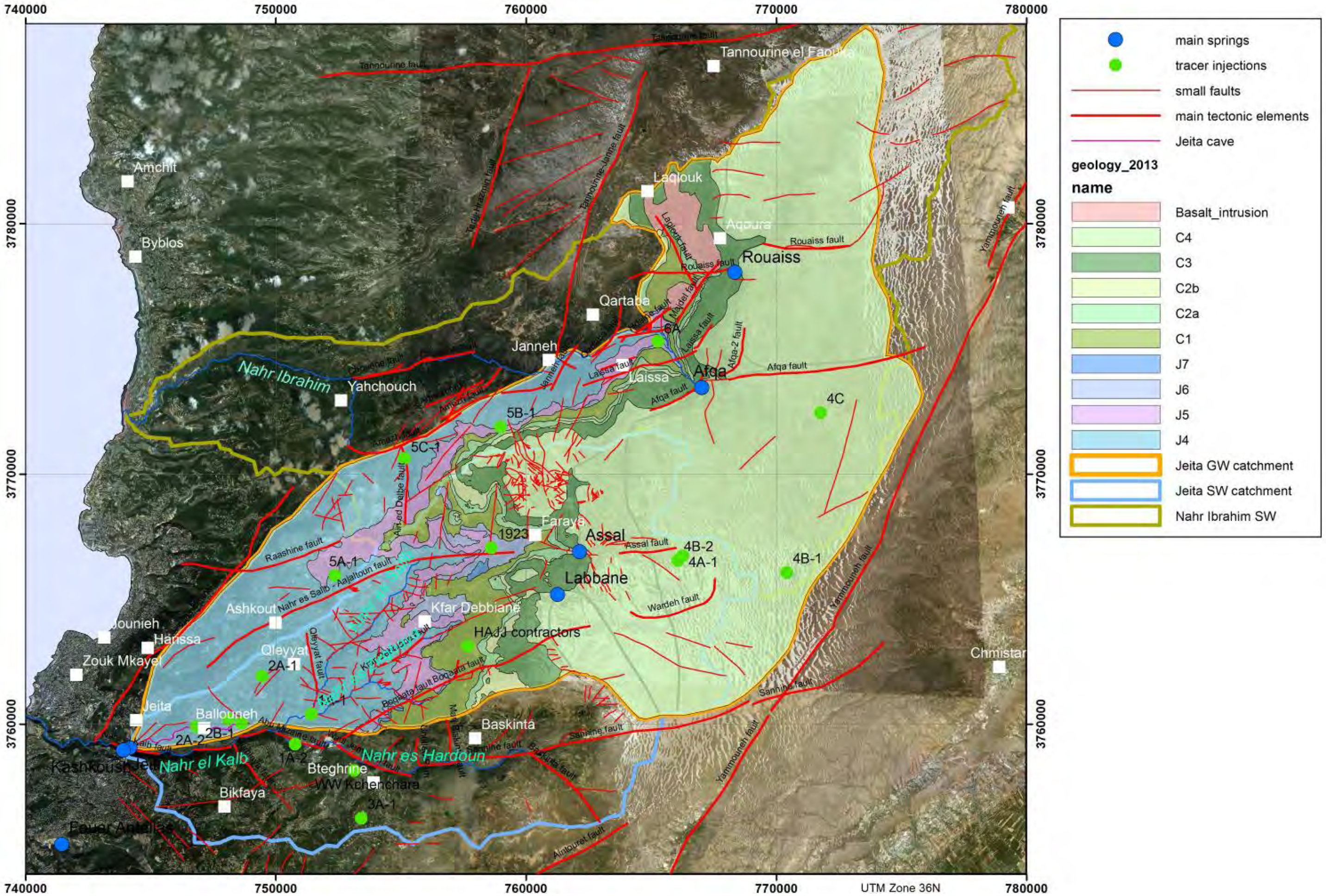


Figure 26: Geological Map of the Groundwater Catchment of Jeita Spring

2.1 Lithostratigraphic Units

A comprehensive overview on the geology in the Jeita GW catchment is given in HAHNE (2011). The new geological mapping undertaken by HAHNE for the project was based on the lithostratigraphy provided by WALLEY (1997) and own observations. The hydrostratigraphy (Figure 23) is based on these works and on the hydrogeological study carried out by BGR and presented in this report. The geological units from J5 to C3 were considered to act as an aquitard. They have a combined thickness varying between 500 and 800 m, the interbedded aquiferous units (J6, C2b) do not receive recharge, other than through downward leakage and have therefore no major discharge. Altogether the amount of downward leakage through this Aquitard Complex is considered to be negligible.

For the understanding of the hydrogeology the Triassic sediments are of major importance as they define the basis of the Lower Aquifer (J4). Unfortunately there has been no investigation of the Triassic in Lebanon yet. However, the regional comparison of the Triassic sediments and depositional environment (Figure 27) (BREW, 2001; BREW et al., 2001; LUCIC et al., 2010; SADOONI & ALSHARHAN, 2004; MAKLOUF, 2002; MAKHLOUF & EL-HADDAD, 2006) suggests that the Middle and Late Triassic in Lebanon largely consists of evaporites, including the deposition of thick salt layers (up to 800 m in the Palmyride Trough; the Palyride Rift developed between the Rutbah High to its south and the Aleppo High to its north and according to WALLEY (1998) extends to the modern coast of Lebanon), deposited following the Carnian Salinity Crisis. Extensive rifting during the Triassic led to the opening of the Neo-Tethys progressively from East to West. Shallow marine to continental Triassic sediments are found in Jordan and in southern Israel (MAKLOUF, 2002; MAKHLOUF & EL-HADDAD, 2006), while shallow marine carbonates and thick evaporites were found in Syria, especially in the Palmyride Trough (LUCIC et al., 2010), marking evaporite and limestone platform conditions during the Middle Triassic and tidal-subtidal evaporitic carbonate platform conditions during the Late Triassic (SADOONI & ALSHARHAN, 2004) during predominantly arid climatic conditions. The Palmyride Trough reaches into Lebanon. Based on seismic profiles interpretations, BREW (2001) presents a thickness of the Triassic near the Lebanese border of more than 2,000 m, with high thickness all along the Palmyride Trough.

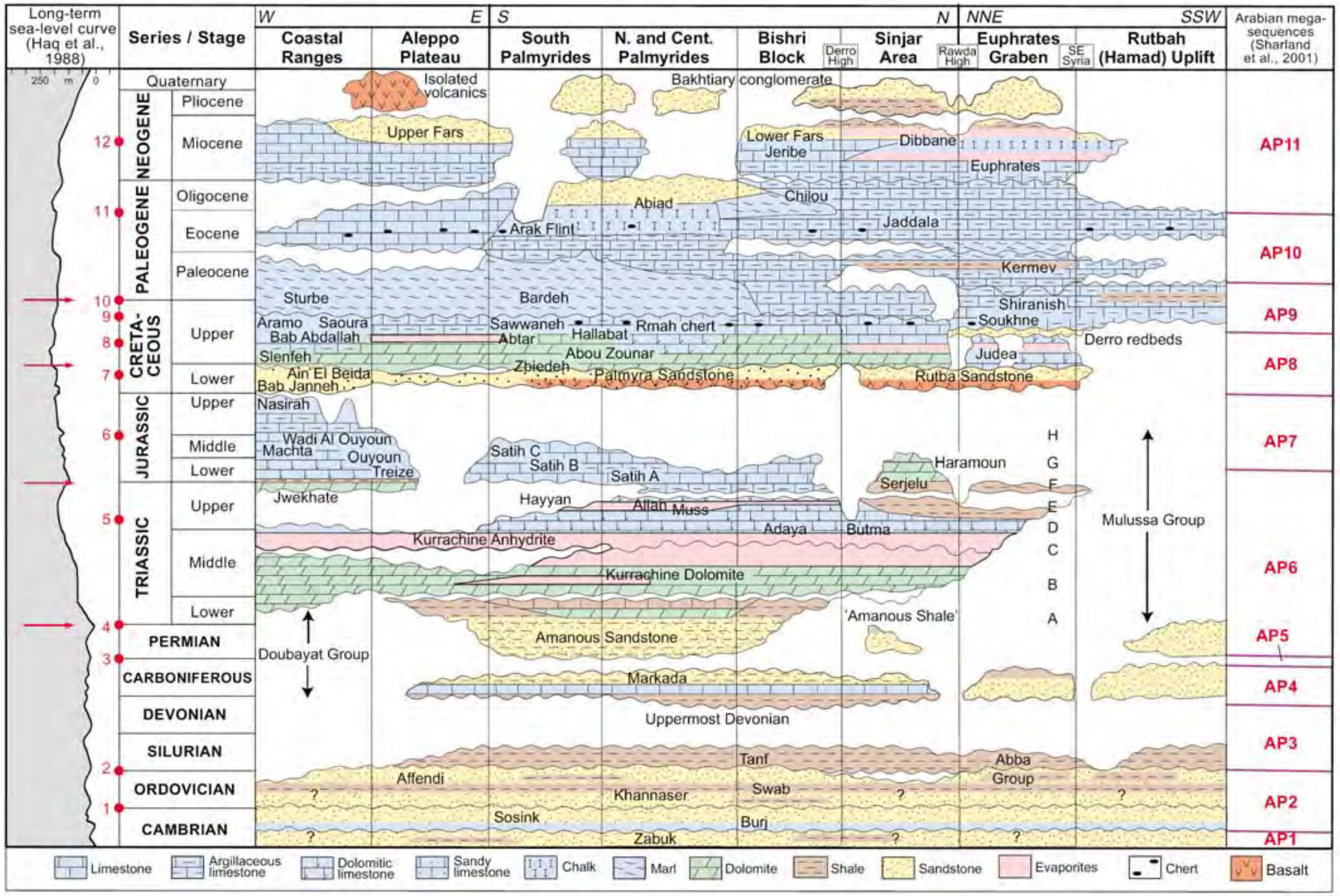


Figure 27: Generalized lithostratigraphy of Syria (BREW et al., 2001)

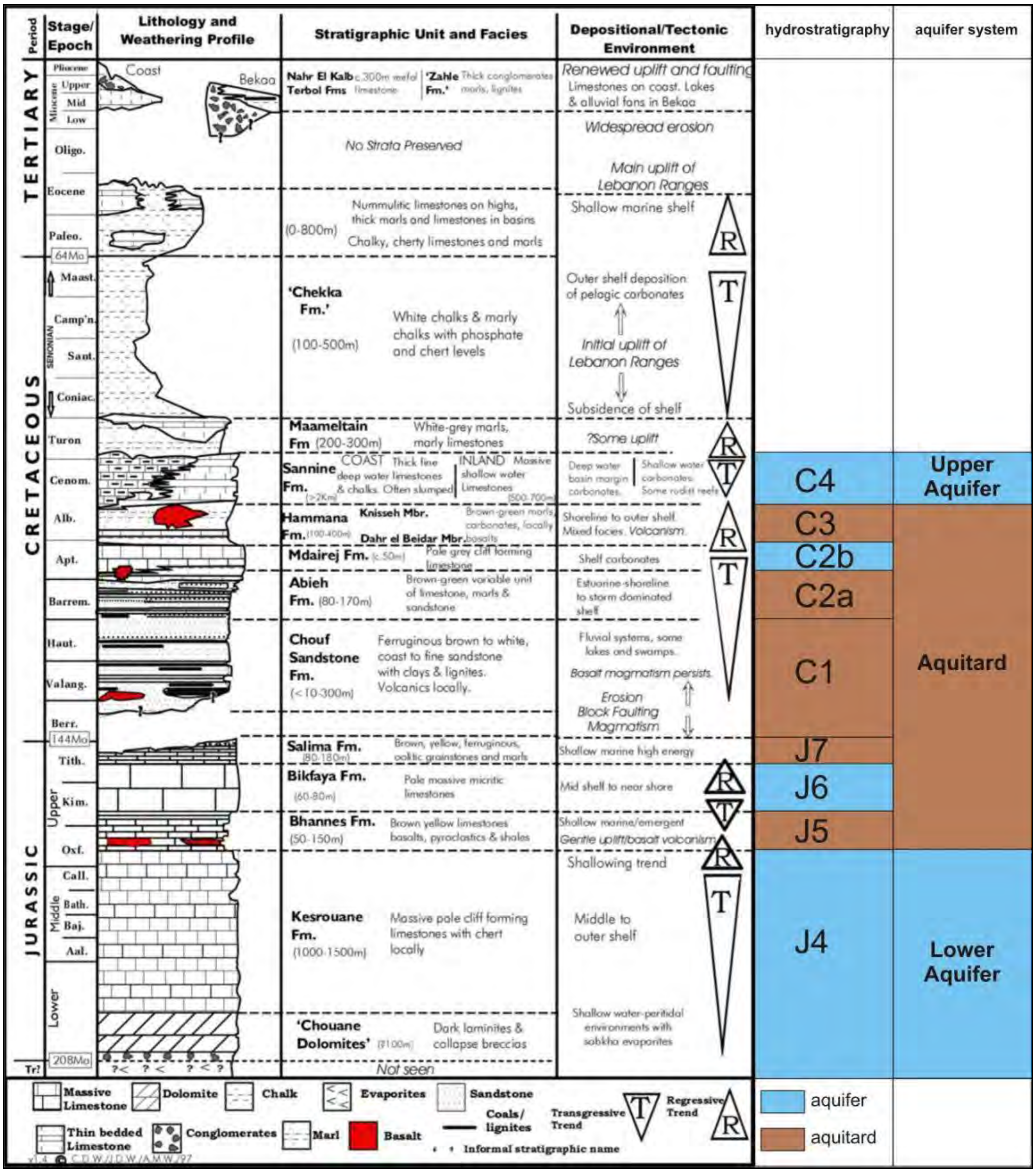


Figure 28: Lithostratigraphy and Hydrostratigraphy of Geological Units in the Jeita Groundwater Catchment (modified after WALLEY, 1997)

Keserwan Formation (J4)

The oldest geological unit found in the Jeita GW catchment is the Jurassic Keserwan limestone. It was described in detail by (HAHNE, 2011) and reaches a thickness of up to more than 1070 m. It consists mainly of massive micritic limestone and dolomite. Locally ooides occur in layers with shells. Fossil content consists mainly of bivalves (amongst others oysters), gastropods (amongst others *Nerinea*), corals and sponges. An otherwise uncommon occurrence of a thick chert layer was found east of Daraya. WOLFART (1967) notes the occurrence of sandstone and shale with lignite of Lower Jurassic age. A lignite layer of approx. 10 cm was found in the Daraya tunnel, some 50 m higher than the course of the underground river. Assuming the above mentioned thickness is valid also here, the level of the underground river (Jeita 140) may be close towards the base of the Jurassic limestone sequence. Because the Triassic has not yet been reached anywhere in Lebanon, it would be worthwhile drilling to the base of the Jurassic at Deir Chamra where it might be at a depth of around 150 m asl (i.e. approx. 400 m bgl). The base of the Jurassic is also presumably close to land surface in the Upper Nahr Ibrahim Valley (RENOUARD, 1955), west of the extended Tannourine-Janneh Fault, along which there is a vertical displacement of the Jurassic of partly more than 800 m (MARGANE, 2012a, 2012b). West of this fault, the Triassic is believed to be at an elevation of approx. 600 m asl or 100 m bgl.

The J4 geological unit partly consists of dolomite. Dolomitization is believed to be secondary, i.e. it took place after deposition. Dolomites cover large areas of the Upper Nahr Ibrahim Valley at different levels in the J4 sequence, while the J4 in the Nahr el Kalb Valley consists mainly of limestone. Here dolomites only occur along faults or at certain levels (e.g. the lower section in the Daraya tunnel, which is believed to be close to the Triassic/Jurassic boundary). The issue of dolomitization and possible dedolomitization (NADER & SWENNEN, 2004; NADER et al., 2008) is until now poorly investigated and needs further studies. Field observations (ABI RIZK & MARGANE, 2011) in the entire Jeita catchment show that dolomitization is not bound to layers or depth horizons but occurs mainly near major faults and is very extensive in areas with extensive basalt intrusions (which occurred either as dykes or in the form of layers), such as the Qamezh fault, the Qartaba, Hemlaya and Baskinta basalt intrusions. Basalts are commonly rich in Mg and the source of Mg in dolomite could therefore have been either rising hydrothermal water following basalt deposition or weathering of basalt.

Bhannes Formation (J5)

According to DUBERTRET (1955), the basalt of Oxfordian/Kimmeridgian age was deposited as the 'complexe volcanique' together with conglomerates, shales and limestone. For the J5 a total thickness of 50 - 150 is given by

WALLEY (1997). Higher thicknesses of up to 340 m were found near Bikfaya, Kfar Debbiane and Qartaba.

Bikfaya Formation (J6)

This formation consists of massive micritic limestone and often forms a typical cliff (falaise de Bikfaya) and is of Kimmeridgian to Middle Tithonian age. Layers of chert nodules are common especially in the middle and upper level of the formation and allow a clear distinction from the J4 unit. According to WALLEY (1997) the J6 has a thickness of 60-80 m, however, was observed to attain around 100 m south of Bikfaya. The J6 does not occur at outcrop in all areas due to overthrusting: e.g. north of Mayrouba, Zaghrine and Kfartay, east of Fraike and Kfar Debbiane, as well as W of Jeita and Sannine it is suppressed tectonically.

Salima (J7)

The Salima Formation is of Upper Jurassic and Tithonian age and, according to WALLEY (1997) has a thickness of 80 to 180 m. The J7 consists of mainly thin bedded, partly massive limestones, intercalated with red to purple claystone and siltstone, soft brown, yellow, green and grey marls. In the northern and eastern parts of the mapped area, the J7 is almost fully suppressed by thrust faults. In the south it is well developed and exposed except for a small part west of Bikfaya.

Chouf Sandstone Formation (C1)

The Lower Cretaceous C1 (Berriasian to Hauterivian) unit ranges from less than 10 to 300 m (WALLEY 1997). Between Kfartay and Baskinta a thickness of about 380 m is observed but may be fault related. At the base of C1 basalt is found at many locations, especially between Baskinta and Kfar Debbiane. Otherwise the formation starts with ochre cellular dolomites, followed by yellow limestone, grey marl and fine sandstone. Thick sandstone banks dominate the formation and are separated by thin claystone and siltstone layers. Sandstone varies in color from grey and brown to yellow, orange, red and pink. Cross-bedding and graded coarse- to fine bedding are common. Sulphur is often noticed accompanying lignite layers. The Chouf Sandstone Formation is often covered by pine forests and is therefore easy to recognize from afar.

Abieh Formation (C2a)

This formation is of Barremian to Lower Aptian age and consists of grey and ochre sandstones, alternating with green, brown, reddish and beige claystones and marls as well as ochre and light grey fossiliferous limestones. A thickness of 80 to 170 m is reported by WALLEY (1997) but in the Jeita catchment a thickness between 20 and 150 m has been found. Locally basaltic intrusions occur at the top of C2a.

Mdairej Formation (C2b)

The Mdairej Formation is of Aptian age and forms a typical cliff. A thickness of around 50 m for the massive, light grey, micritic limestone unit was given by WALLEY (1997) and was found also in the mapped area.

Hammana Formation (C3)

The Upper Ctretaceous (Upper Aptian to Middle Albian) C3 is a highly variable, mainly thin-bedded unit comprising green, grey, ochre, red and beige claystone and nodular, bioturbated marl alternating with brown, yellow and beige, often micritic, limestone. In the mapped area thicknesses from 110 m SE of Sannine to 350 m NW of Sannine were found.

Sannine Formation (C4)

The Sannine Formation is of Late Cretaceous (Upper Albian to Cenomanian) age. Its thickness reaches from 500 m to 700 m in the upper parts of the catchment and increases to more than 2,000 m at the coast (WALLEY, 1997). In the Jeita catchment, however, it reaches a maximum thickness of approximately 1050 m at the highest elevation of 2628 m at Jabal Sannine. It consists mainly of micritic light grey and beige limestone and is partly dolomitic. Chert nodules are frequently observed. At the base green and grey marl with bioturbation occurs.

Basaltic Intrusions

Basaltic intrusions are common at the bases of J5, C1 and C3. Basalt dykes have been found near the Upper Nahr Ibrahim Valley and along Nahr ed Dahab. In the area between Daraya and Zaghrine, basalt intruded discordantly into and through the J4 unit. North of Zaghrine this intrusion migrates into J5 and thus can be considered as one source of J5 intrusion. Another large intrusion was found at the southeastern edge of the mapped area along a major fault striking southeast towards the Bekaa Valley. This intrusion is most likely of Barremian / Aptian age as it affects the C2a formation. Basalt thicknesses in the Jurassic and Cretaceous units seems to be high especially in the areas along Sannine fault, such as the two intrusive basalt areas mentioned above, and the Qamezh fault, e.g. in the Qartaba area. These faults have a strike of around 80°.

2.2 Geological Structure

Unfortunately no boreholes have been drilled to the base of the Jurassic or Upper Cretaceous aquifer, although the base of the Jurassic must be expected to be near the land surface at several places in the GW catchment. Also no geophysical measurements, such as reflection seismic surveys or TEM soundings, have been conducted yet to determine the base of the Jurassic or Upper Cretaceous aquifers. One reason is that Lebanon is one of the few countries in the world without a geological survey, the other is that such equipment is not available in Lebanon and no local company can conduct such studies.

The geological structure is an important criteria for the groundwater flow pattern in karst aquifers. Therefore it was important to determine the base of the C4 and J4 geological units. In the western part of the Upper Cretaceous plateau, the base of C4 can be determined along the outcrop line. In the eastern part, however, there is a) a significant vertical displacement along the Yammouneh fault and b) a sudden change of dip, so that there is no possibility to determine the base of C4 in this area. In many areas the dip of the topographic slope can be used as a proxy for the geological dip. This was done for a tentative determination of the base of C4 in Upper Cretaceous plateau (Figure 29). The geological cross sections (Figure 30) were prepared using the thicknesses encountered in the project area.

<u>Geological cross section 1</u> (Figure 31): the profile is 25,860 m long and runs in NNE - SSW direction from the Upper Nahr Ibrahim Valley (Hdaine, Joe Marine) via Faraya, Marj Baskinta, Mrouj to Nahr Beirut near Mtein.

The profile shows a shallow anticline with its axis south of Nahr es Salib, where the Triassic comes up to around 100 m asl. J5 thickness is increasing towards Nahr Ibrahim. South of the axis, C1 thickness is increased in the Boqaata, Marj Baskinta area, reaching more than 300 m. While at the anticline axis top of J4 is at around 1,200 m asl, it drops towards south along the profile to around 800 m asl at Nahr Beirut. The profile is intersected by two major faults running in W-E direction (~ 80°), one crossing at Assal spring ('Assal fault'), the other in Nahr es Hardoun ('Sannine fault').

<u>Geological cross section 2</u> (Figure 32): the profile is 24,680 m long and runs in WNW - ESE direction from Souane via the Upper Nahr Ibrahim and Afqa spring to Beit Mchik in the Beqa'a Valley.

This section crosses several tectonic blocks. W of the Tannourine - Janneh fault, dip of strata is chiefly towards NW (~20°). Along the Tannourine - Janneh fault, which could be classified as an antithetic flexure or rollover anticline with a half-graben on the eastern part, there is a vertical displacement of partly more than 800 m (reference: top J4). Dip near Laissa is around 4° towards E, while the C4 on the Upper Cretaceous plateau inclines towards W (as was confirmed through tracer test 4C). At the Yammouneh fault (left-lateral shear fault) there is a vertical displacement of several hundred meters, with the eastern side being down-faulted. Dip on the eastern block is towards E.

<u>Geological cross section 3</u> (Figure 33): the profile is 41,800 m long and runs in SW - NE direction from Jeita spring via Kfar Debbiane and Assal spring to Flaoui in the Beqa'a Valley.

At the coastal flexure, at Jeita, the dip of strata is almost vertical. The dip is decreasing towards Faqra (axis of anticline). Further E a shallow syncline follows. The base of C4 cannot be determined at the Yammouneh fault, however, C3 must be close to land surface. E of the Yammouneh fault there is again a strong incline of the formations towards E.

<u>Geological cross section 4</u> (Figure 34): the profile is 25,680 m long and runs in NW - SE direction from the Lower Nahr Ibrahim Valley near Maaysra via Rashine, Faitroun and the Zirghaya monastery to Tarchich. The northwestern part shows the nearly vertical incline of strata at the coastal flexure. Near Rashine, dip is inverted and further along the profile towards SE, rocks dip at shallow angle towards Nahr el Kalb. In the part between Rashine and Nahr el Kalb, the profile is crossed by a number of E-W running faults with small vertical displacements < 50 m. Nahr el Kalb is accompanied by a fault (Sannine Fault) with probably significant vertical displacement, where the southwestern block is uplifted. The Sannine Fault probably forms a groundwater divide as the Triassic rocks might come up fairly high S of Nahr el Kalb (approx. 500 m asl near Mrouj). E of Mrouj an anticlinal axis is reached and further to the SW rocks start dipping towards SW. At the Tarchich Fault, in Nahr Beirut, the dip is again inverted and another small anticline follows.

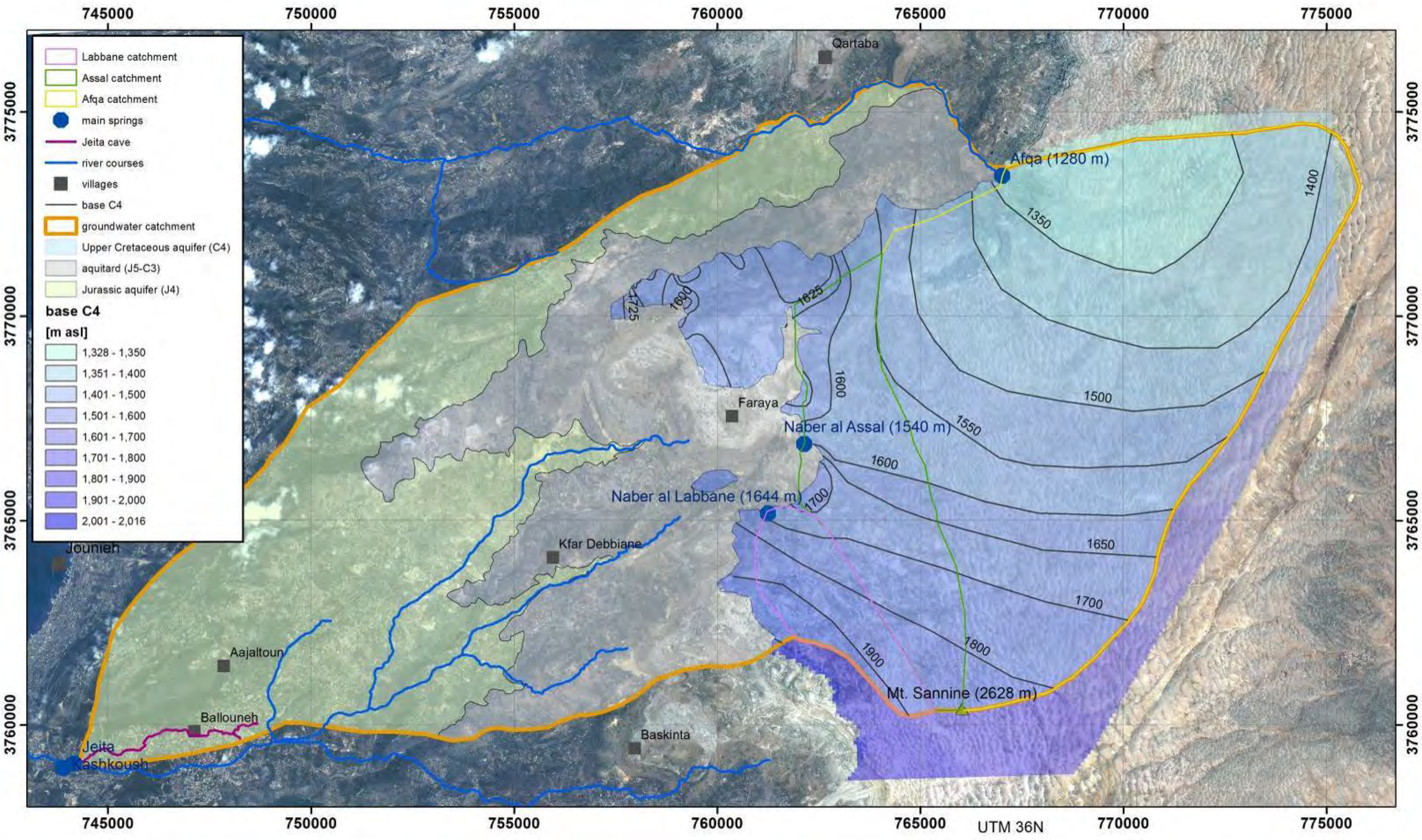


Figure 29: Tentative Structure Contour Map Base of C4 Geological Unit

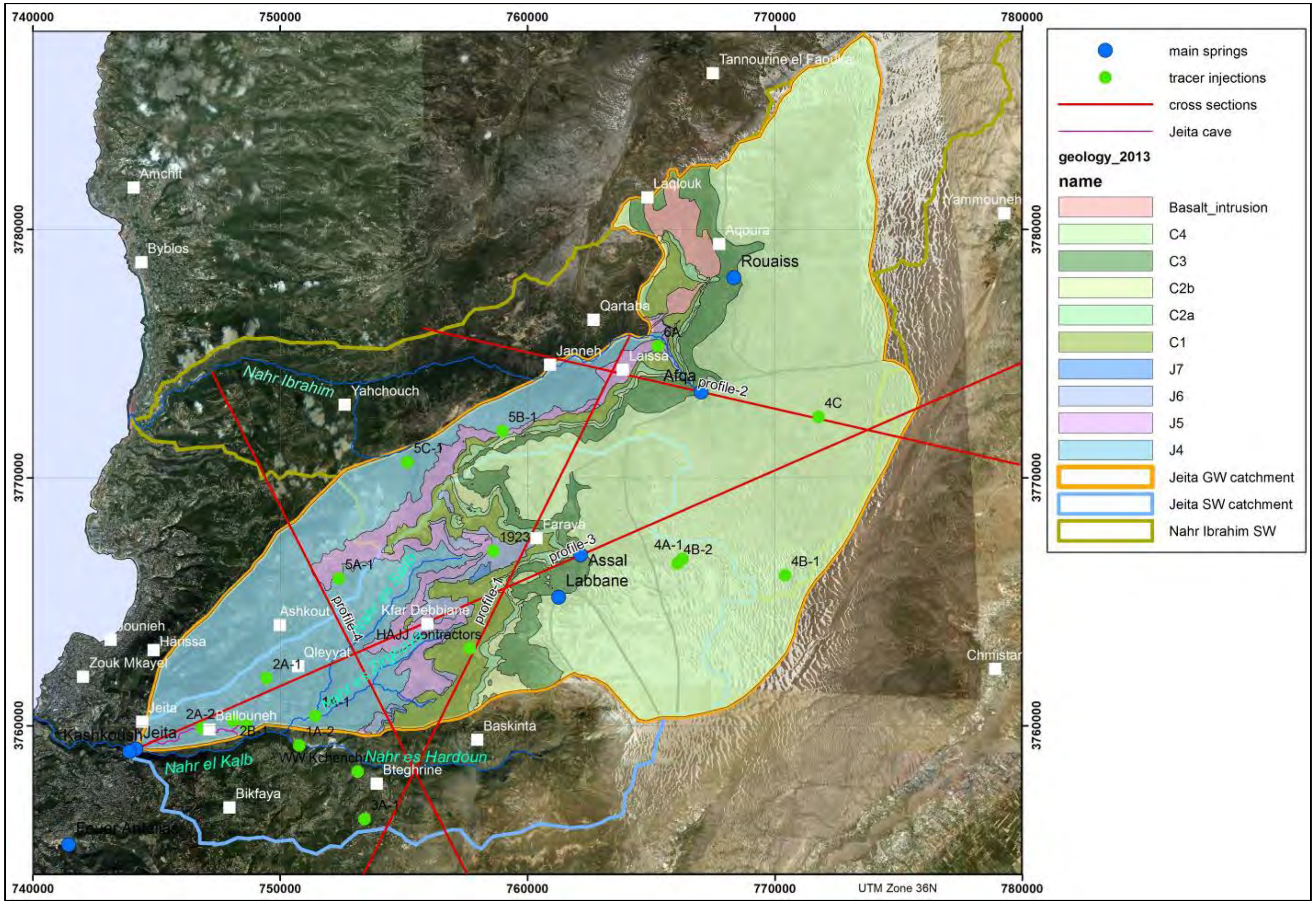


Figure 30: Locations of Geological Cross Sections

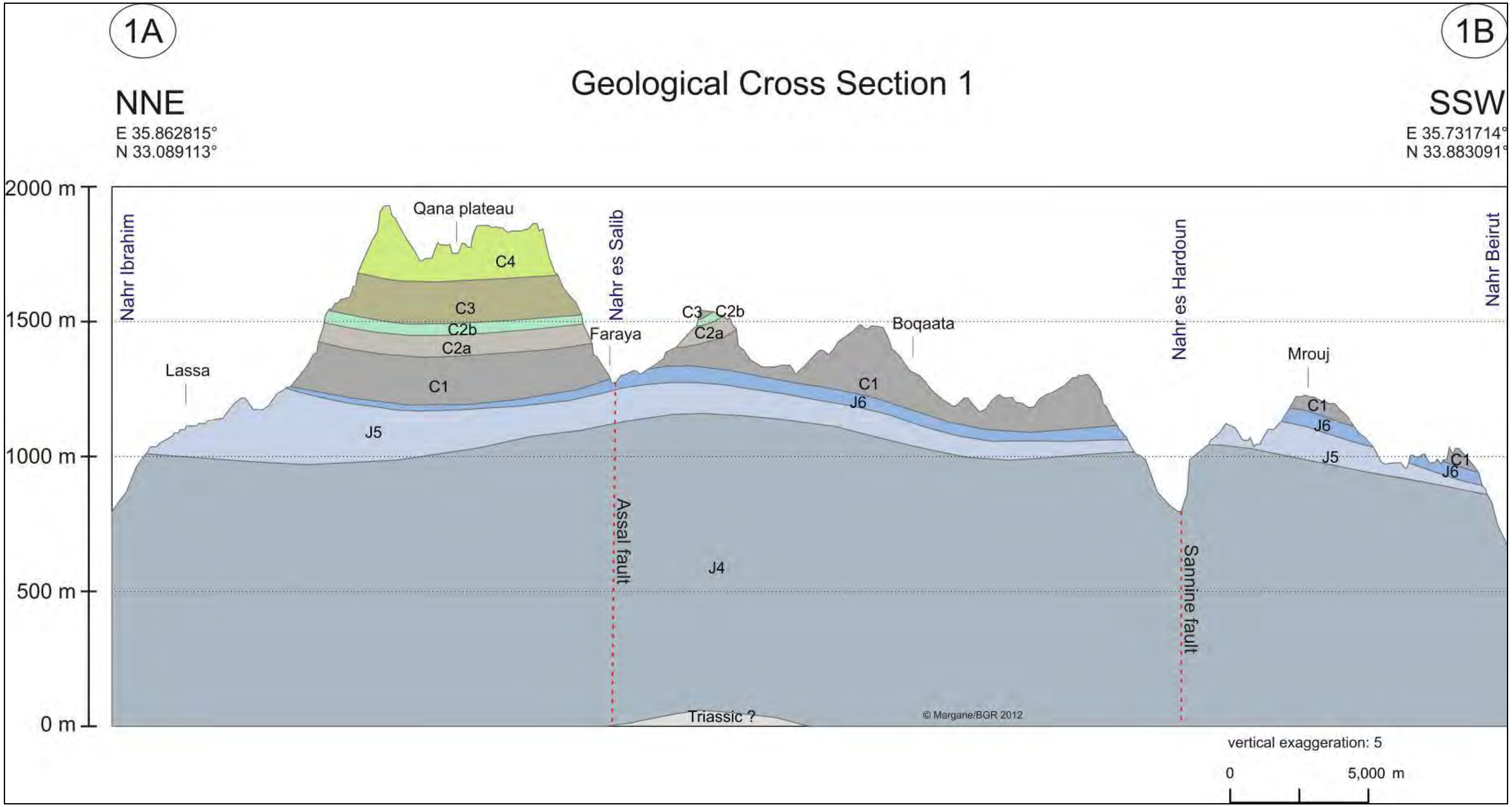


Figure 31: Geological Cross Section 1 - Upper Nahr Ibrahim - Nahr Beirut

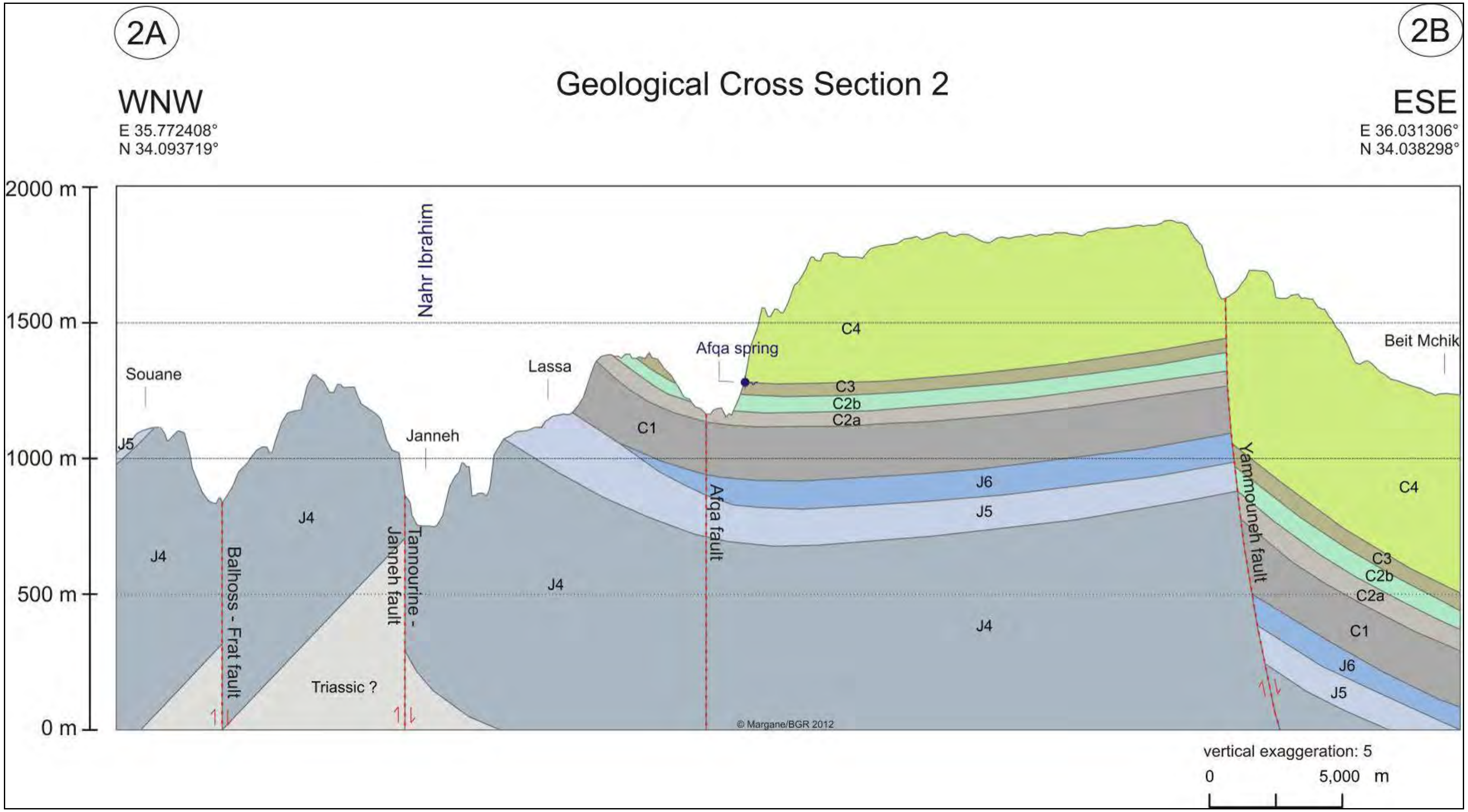


Figure 32: Geological Cross Section 2 - Nahr Ibrahim - Afqa - Beqa'a

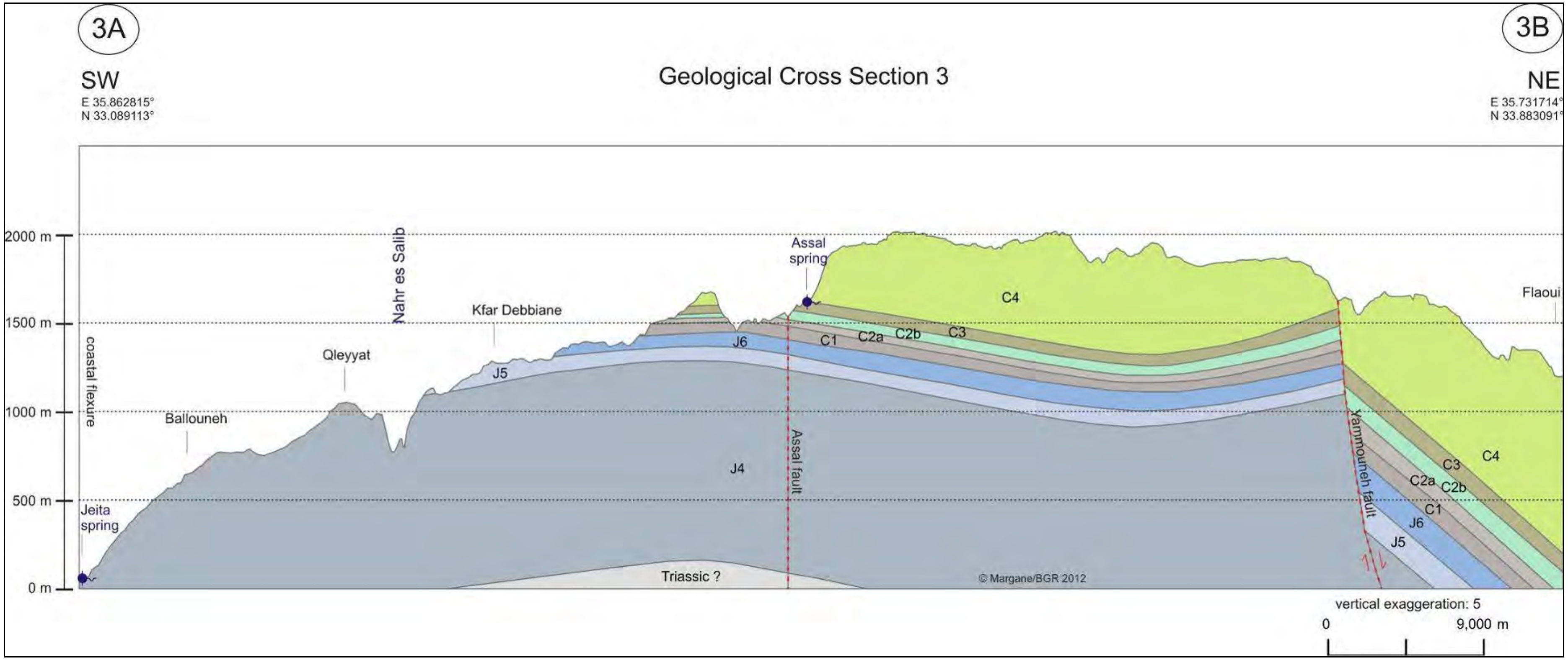


Figure 33: Geological Cross Section 3 - Jeita - Assal - Beqa'a

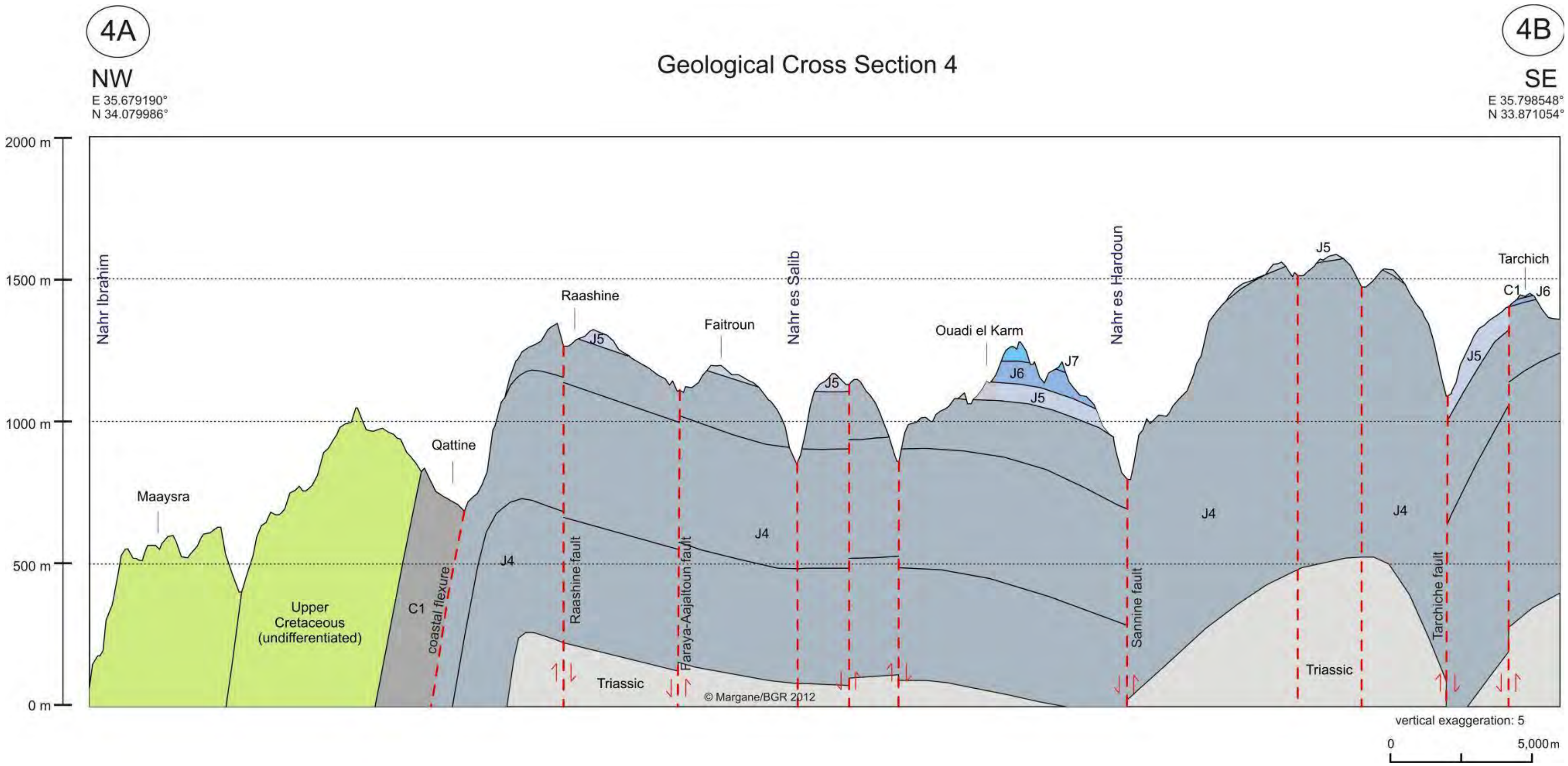


Figure 34: Geological Cross Section 4 - Lower Nahr Ibrahim - Faitroun - Tarchich

2.3 Tectonic Features

Onshore geophysical studies in Lebanon have not yet been conducted. Much of the following statements are therefore based either on observations along the Dead Sea Transform (DST) or related structures, mostly done between the Red Sea and the Hula basin, as well as in Turkey. The currently ongoing offshore seismic surveys in Cyprus and the Levant, conducted within the framework of hydrocarbon exploration, are hoped to expedite the knowledge about the tectonic development in the region.

Tectonic interpretation is also hampered by the lack of seismic observation points in Lebanon and Syria. There is only one seismic station in Lebanon (Bhannes). The seismicity map prepared by HUIJER et al. (2011) can only be considered as a first attempt to classify the earthquake risk in Lebanon.

A comprehensive inventory of the seismic events in Lebanon and the surrounding area is given in DAERON (2005: pp. 100).

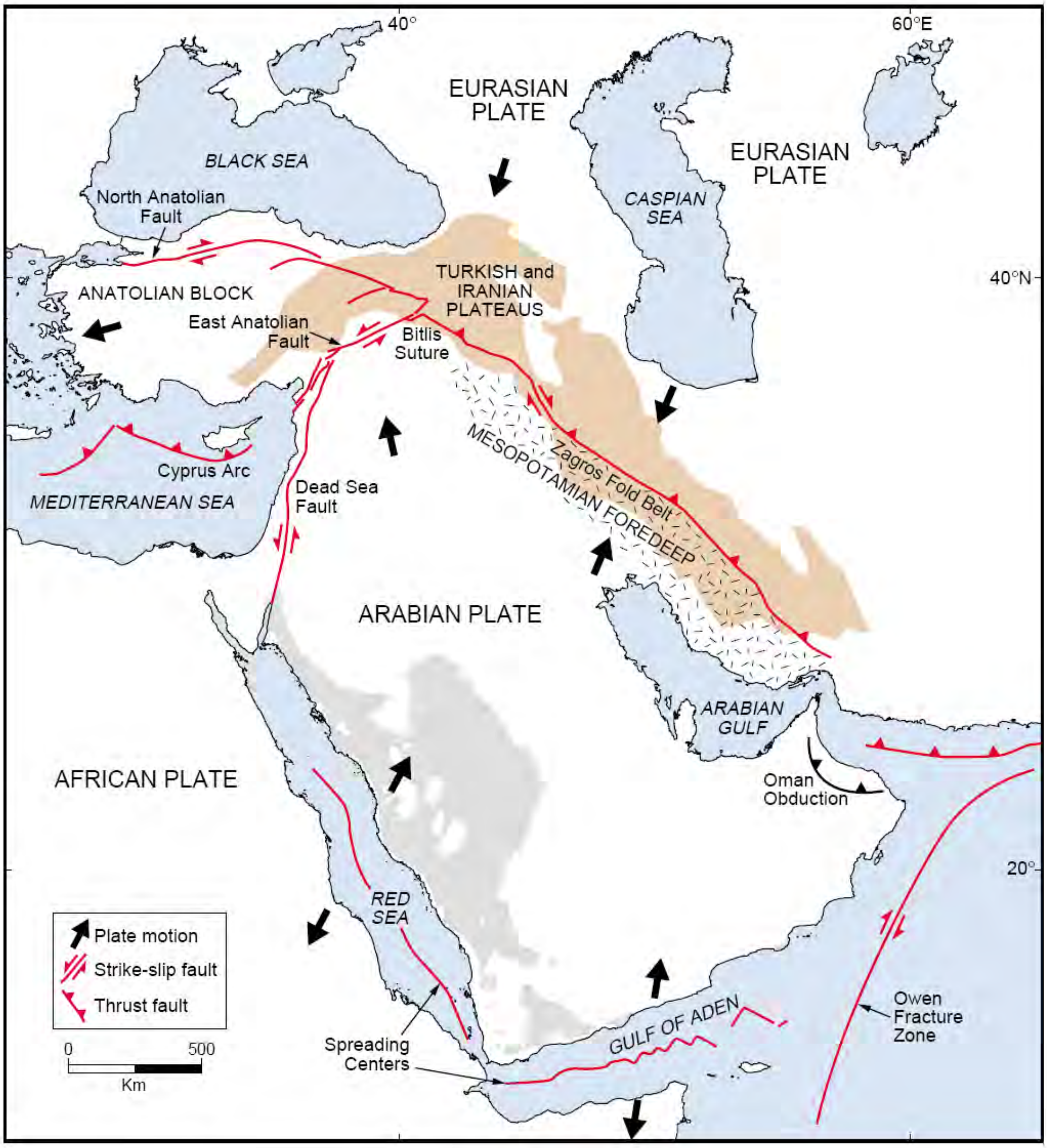


Figure 35: Regional Tectonic Regime (SEBER et al., 2000)

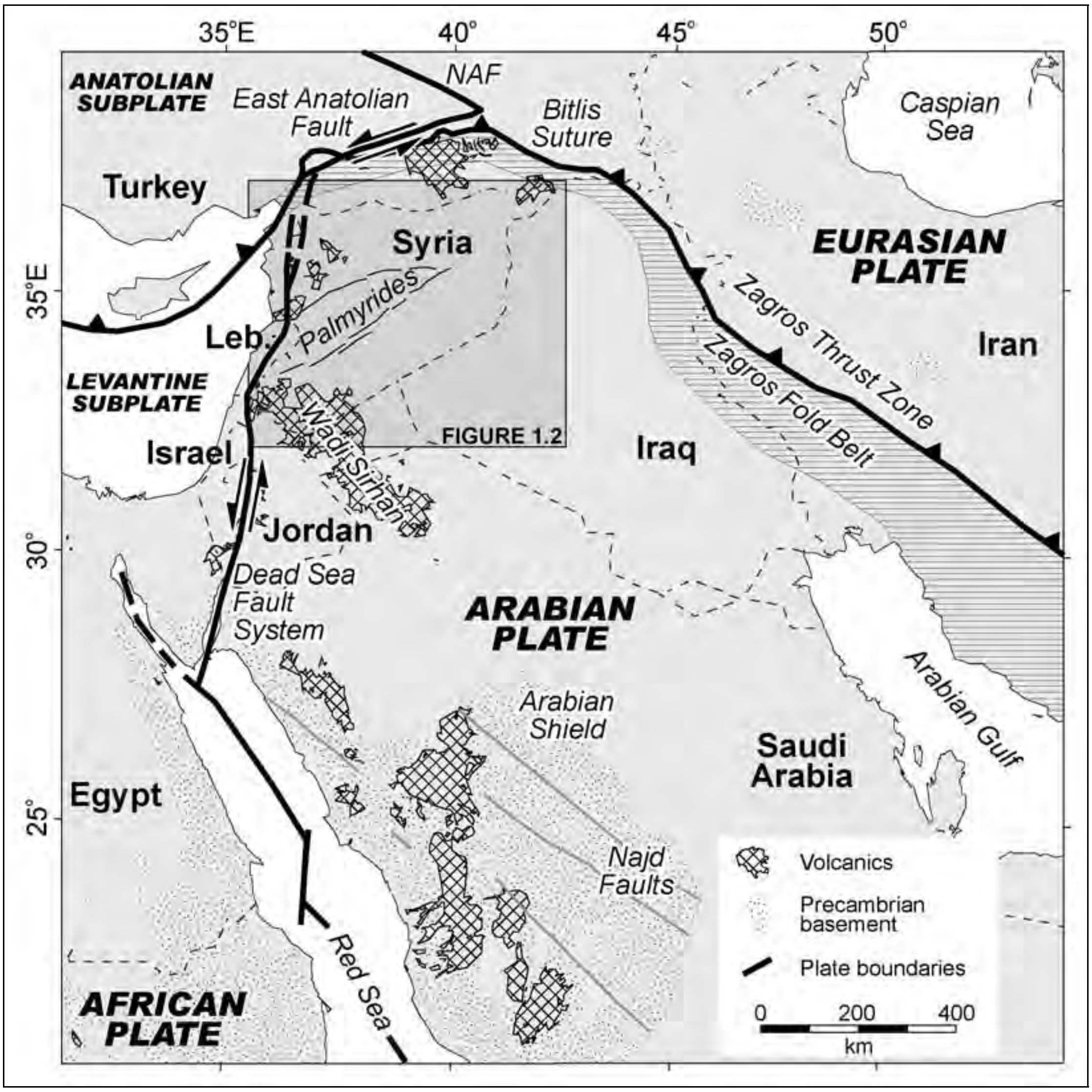


Figure 36: General Tectonic Setting in the Levant Region (BREW, 2001)

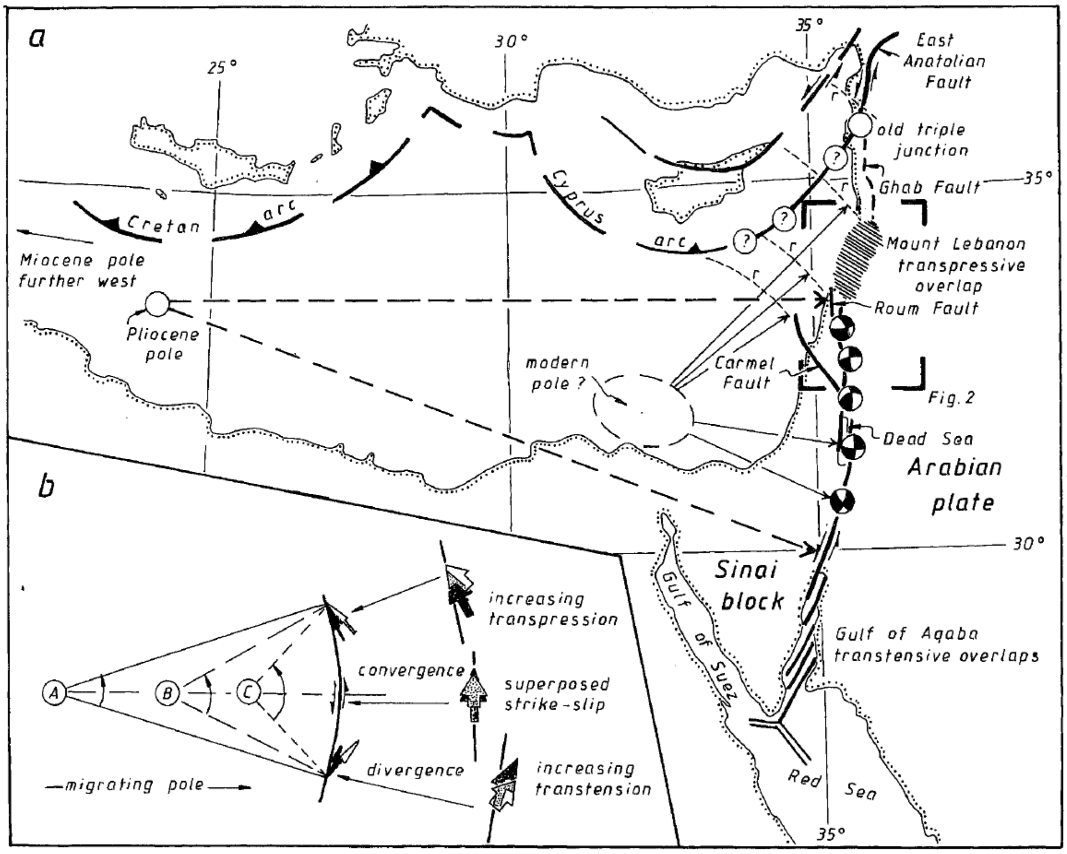


Figure 37: Historic and Modern Position of Rotation Poles and Locations of Pull-Apart Basins (BUTLER et al., 1998)

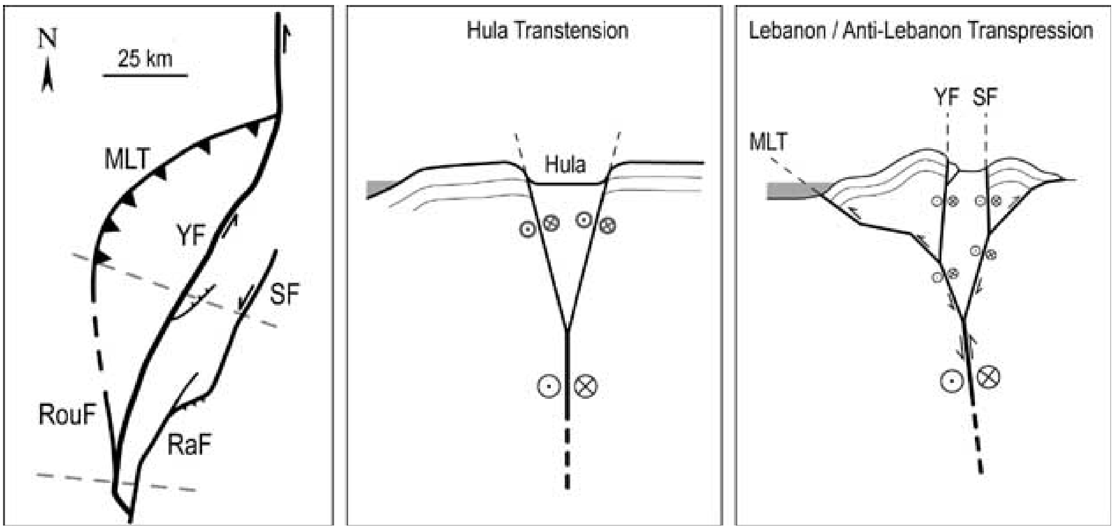


Figure 38: Assumed Structure of the Lebanese Restraining Bend (DAERON, 2005)

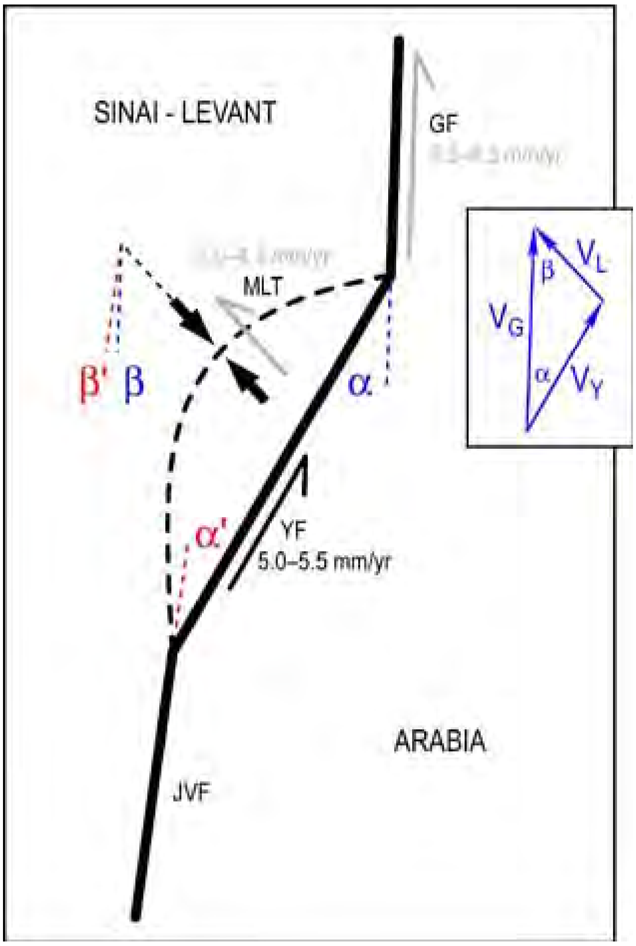


Figure 39: Geometric Tectonic Model proposed by DAERON (2005)

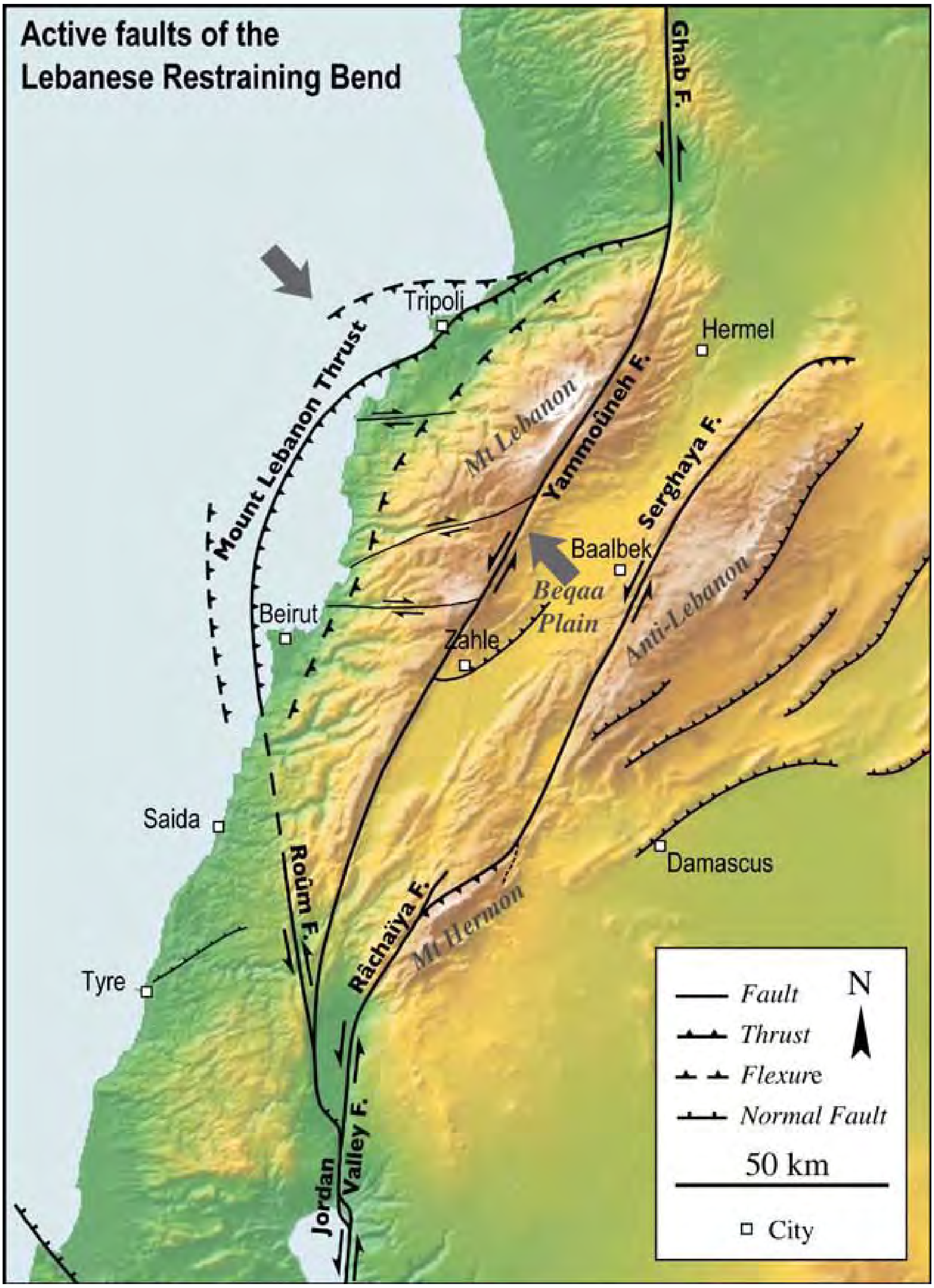


Figure 40: Dead Sea Transform Fault Splays caused by the Lebanese Restraining Bend (DAERON, 2005)

The structural and tectonic development of Syria was mainly investigated by Cornell University (e.g. BREW, 2001). The general tectonic setting in the boundary region between the Arabian, African and Eurasian plates are shown in Figure 31.

The dominant tectonic feature in Lebanon is the Yammouneh Fault, which is part of the approx. 1000 km long Dead Sea Transform (DST), extending from the Red Sea to the collision zone of the Eurosian plate with the Arabian plate in southern Turkey at the North Anatolia Fault (NAF) (Figure 36). In Jordan a left-lateral horizontal displacement of 105 km has been observed along the shear zone (QUENNEL, 1959). According to GARFUNKEL (1981), the DST is a transtensional deformation zone, resulting in the development of rhomb-shaped basins, so-called pull-apart graben structures (the Hula basin, the Lake Tiberias, the Kinneret - Beit Shean basin, the Dead Sea basin, and the Gulf of Aqaba/Elat; BEN AVRAHAM & TEN BRINK, 1989; HURWITZ et al., 2002). This model was also used by BUTLER et al. (1998) who located the rotation pole of the African plate south of Crete (Figure 37). In the area between the Hula basin in northern Israel and the Homs basalts in southern Syria, however, the otherwise rather uniform DST develops into an approx. 200 km long restraining bend (GOMEZ et al., 2007) and compressional forces split the DST into a splay of faults: the Roum (right-lateral shear fault), Yammouneh and Serghaya faults. In his PhD thesis DAERON (2005) proposes a split of the collisional forces between the Arabian plate and the Eurasian plate at the 'Lebanese restraining bend' into a smaller NW directed plate movement and a larger N directed movement. DAERON assumes a ‘Mount Lebanon Thrust Fault’, a near horizontal shear fault, that would explain the response to transpressional tectonic forces (Figures 38 - 40).

While hidden in the northern Beqa’a valley, the Missyaf Fault is again clearly identified in Southern Syria as a single plate boundary. It was suggested that the Yammouneh Fault may not have been active over the past 5 MY and it is under discussion whether the Roum Fault may constitute the currently active plate margin (GIRDLER, 1990; BUTLER et al., 1998). DAERON (2005) and DAERON et al. (2004) suggested a horizontal slip rate of 5.0-5.5 mm/a along the Yammouneh Fault. REILINGER et al. (2006) come to similar amounts of relative motion of the Arabian plate towards north (4-6 mm/a) and the sinistral movement along the DST (approx. 4±1 mm/a). ELIAS (2007) argue that earthquakes such as the catastrophic event that occurred in 551 AD, off the coast of Lebanon (epicenter approx. 20 km offshore Byblos), by thrusting at a submarine Mount Lebanon thrust ramp, caused a continued uprising movement in Mount Lebanon, which is still active.

According to WALLEY (1998) the West Lebanon Flexure, about 100 km in length in Lebanon, constitutes the northern continuation of the Carmel-Sinai hinge line (GVIRTZMAN & KLANG, 1972), which developed since the Early Mesozoic. It is several times dextrally offset along E-W striking faults. Marked facies changes and changes in thickness of the rock units are observed along this hinge line. While to the E of the flexure shallow marine and peritidal platform carbonates were deposited in the Middle Cretaceous, these develop into fine-grained deep-water carbonates, and further W into thin-bedded chalky limestones. WALLEY named this feature the Lebanon Hinge Line. According to WALLEY (1998) the Palmyrides extend to the modern coast of Lebanon. Subsidence began in the Late Permian and stopped in the Mid-Triassic. Crustal shortening (first Syrian Arc Deformation) started during Santonian-Campanian times, the major folding occurred during Mid-Eocene to Early Miocene (second Syrian Arc Deformation). Based on the left-lateral shear faulting dissecting the former Palmyrides structures along DST, starting in the Late Miocene, WALLEY argues that the sinistral displacement along Yammouneh Fault is approximately 47 km.

GARDOSH et al. (2008) reported a Neo-Tethyan rifting during the Triassic to Early Jurassic resulting in a system of horst and graben structures, the so-called ‘Central Levant Rift’ of approx. 45° strike. A connection with the Palmyride Trough of approx. the same strike is likely (GARDOSH: pp. 74). A NW-SE extension is assumed for the four main rifting periods, Permian, early Middle Triassic, Late Triassic and Early to Middle Jurassic. It seems, however, that oceanic crust was not formed during this rifting as the volcanics formed during the Triassic and Jurassic are not typical MORB volcanics. The margin of the carbonate platform during Jurassic and Cretaceous times can clearly be identified in the cross section shown in Figure 42.

The tectonic evolution in the region during the Cretaceous and Tertiary was well investigated in the framework of an ODP (ocean deep drilling) program conducted in the Eastern Mediterranean (ROBERTSON, 1998: pp. 769). Also the SHALIMAR marine exploration by the French institute IFREMER (http://www.ifremer.fr/ sismer/index_UK.htm) contributed to the understanding of the tectonics in the region.

The tectonic analysis carried out by the BGR project is shown in Figure 43. Fault names were assigned by the project, as most of these faults were not mapped before. The related local stress field is shown in Figure 44.

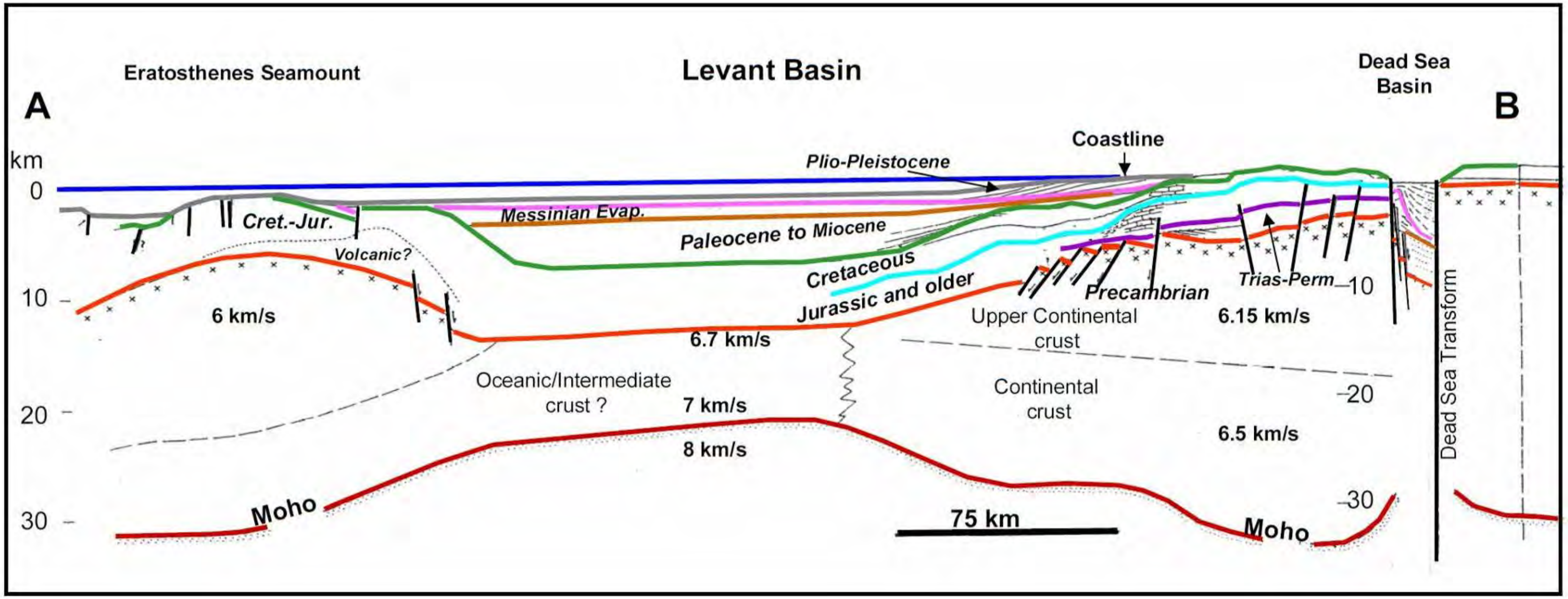


Figure 41: Seismic Cross Section across the Levant Basin from the Dead Sea Transform Fault to the Eratosthenes Seamount (GARDOSH et al., 2008)

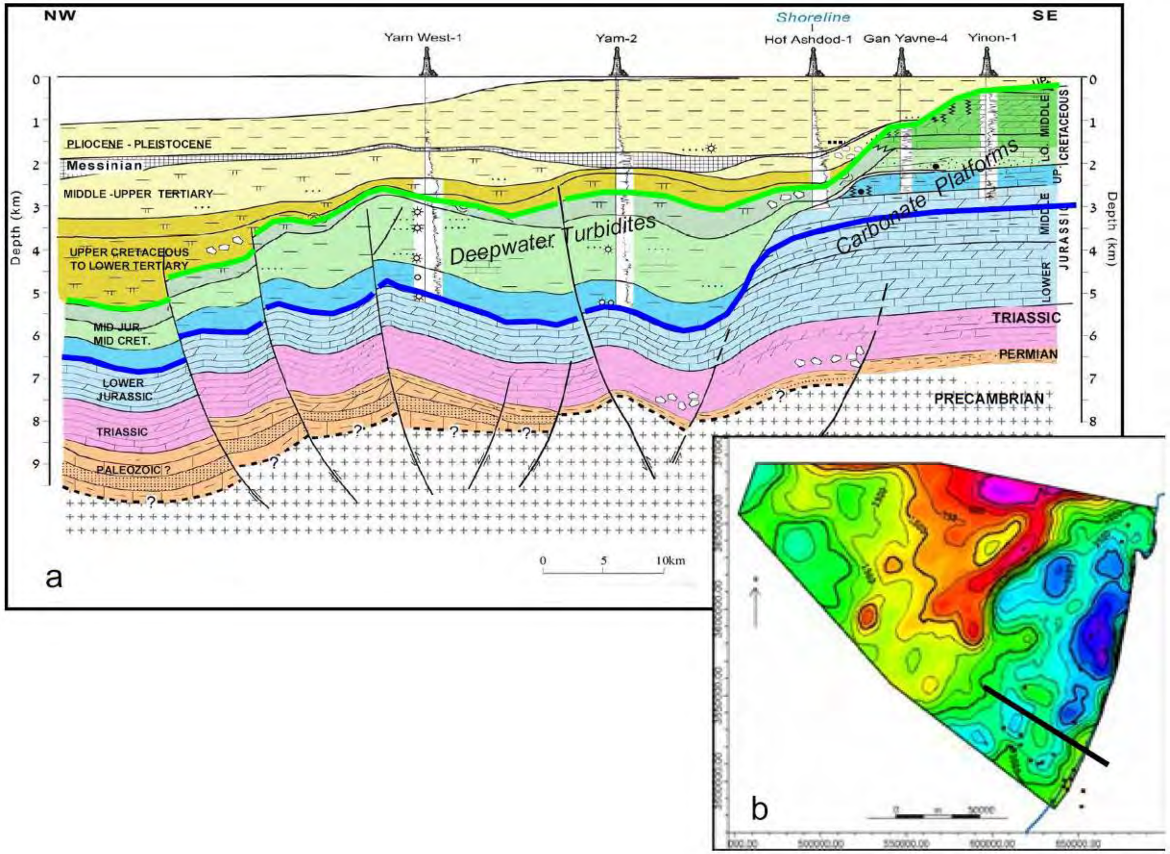


Figure 42: Tentative Cross Section across the Southern Part of the Levant Basin

(GARDOSH et al., 2008)

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

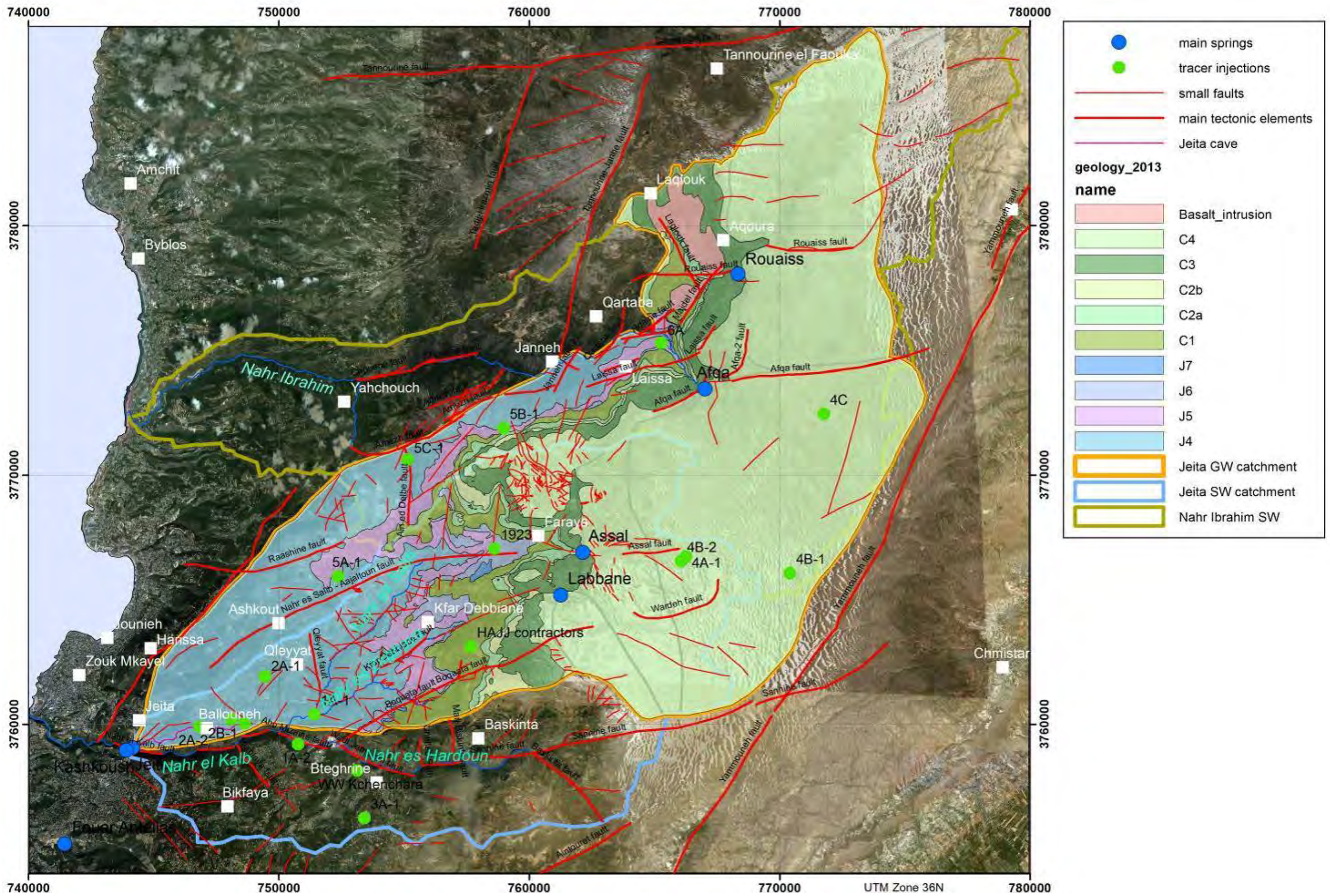


Figure 43: Main Tectonic Features in the Jeita Groundwater Catchment

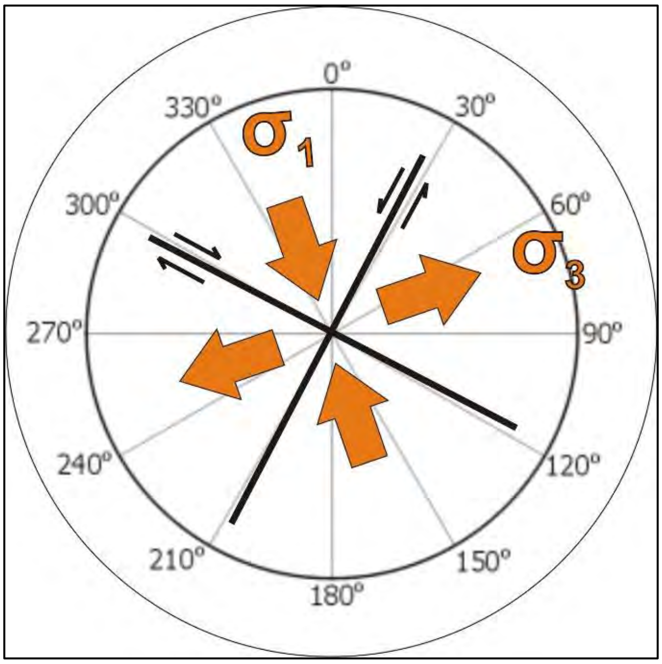


Figure 44: Assumed Local Tectonic Stress Field in the Jeita GW Catchment

2.4 Quaternary Glaciation

Esker-like structures were found throughout the groundwater catchment of Jeita spring and also further north but not south of the catchment (Figure 47). The structures consist of blocks of limestone measuring between 10 and 70 cm in diameter, often intensely weathered, accumulated along lines following the topographic gradient. Typically these structures are up to around 4 m high, 10 m wide and between 50 and 250 m long (Figures 45, 46). They are most abundant where the topographic gradient becomes steeper (at the escarpment) and often stop at the escarpment. Also these structures only occur at elevations between 800 and 1200 m and can therefore not be explained by landuse. Several authors have reported about Quaternary glaciations in Lebanon (DIENER, 1886; KLAER, 1957; MESSERLI, 1967; DAERON, 2005; MOULIN et al., 2011), however no systematic investigation of Quaternary glaciation landforms and extent has yet been undertaken in Lebanon.

It is believed that the maximum extent of Quaternary glaciations reached to elevations of 800-1,000 m asl (ABI RIZK & MARGANE, 2011; MARGANE & MAKKI, 2012). Similar extents of glaciations were reported from Greece (HUGES, 2004; HUGES & WOODWARD, 2008) and Turkey (ZREDA et al., 2006; SARIKAYA et al., 2011), however, not yet from Lebanon. Based on the new findings it is believed that large parts of the Mount Lebanon mountain range were covered by glaciers during the Quaternary glacial periods (Figure 47). This Quaternary glaciation has probably significantly promoted karst formation in the upper Mount Lebanon mountain range (ABI RIZK & MARGANE, 2011). In the southern Bekaa Valley there is evidence for a large Pleistocene lake reaching up to a level of around 970 m asl (WALLEY, 1998).

The reason why glaciations were so extensive in this area is that the Sannine area is the largest continuous high-plateau in Lebanon with elevations exceeding 1,600 m asl (Figure 48). This area is under modern climatic conditions continuously covered with snow over commonly 4-5 months every year. In comparison to other countries of this region, Syria and Israel/West Bank, Lebanon is in the unique situation that it receives much more rainfall and snow and stores snow over an elongated time period due to the high elevation of its mountains. Due to continental effects, however, the snow line is much higher in the Anti-Lebanon mountain range compared to the Lebanon mountain range (Figure 49). The Anti-Lebanon mountain range thus not only receives much less rainfall and snow it also cannot store it over such a long time period due to higher temperatures.

Figure 45: Esker near Zirghaya monastery

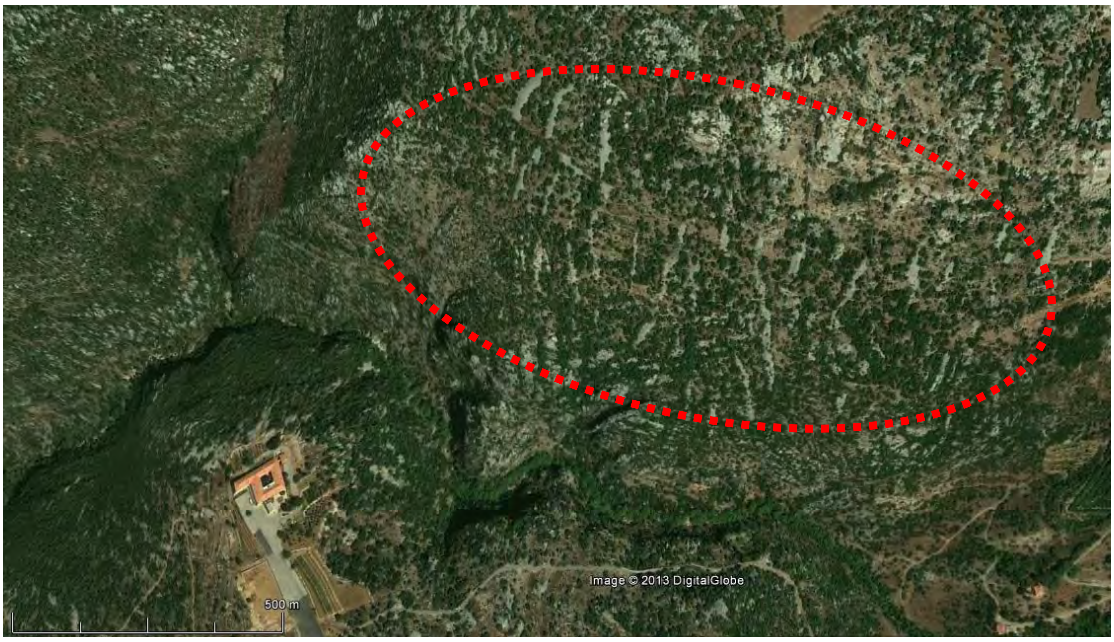


Figure 46: Eskers at Escarpment near Zirghaya Monastery

(GE image)

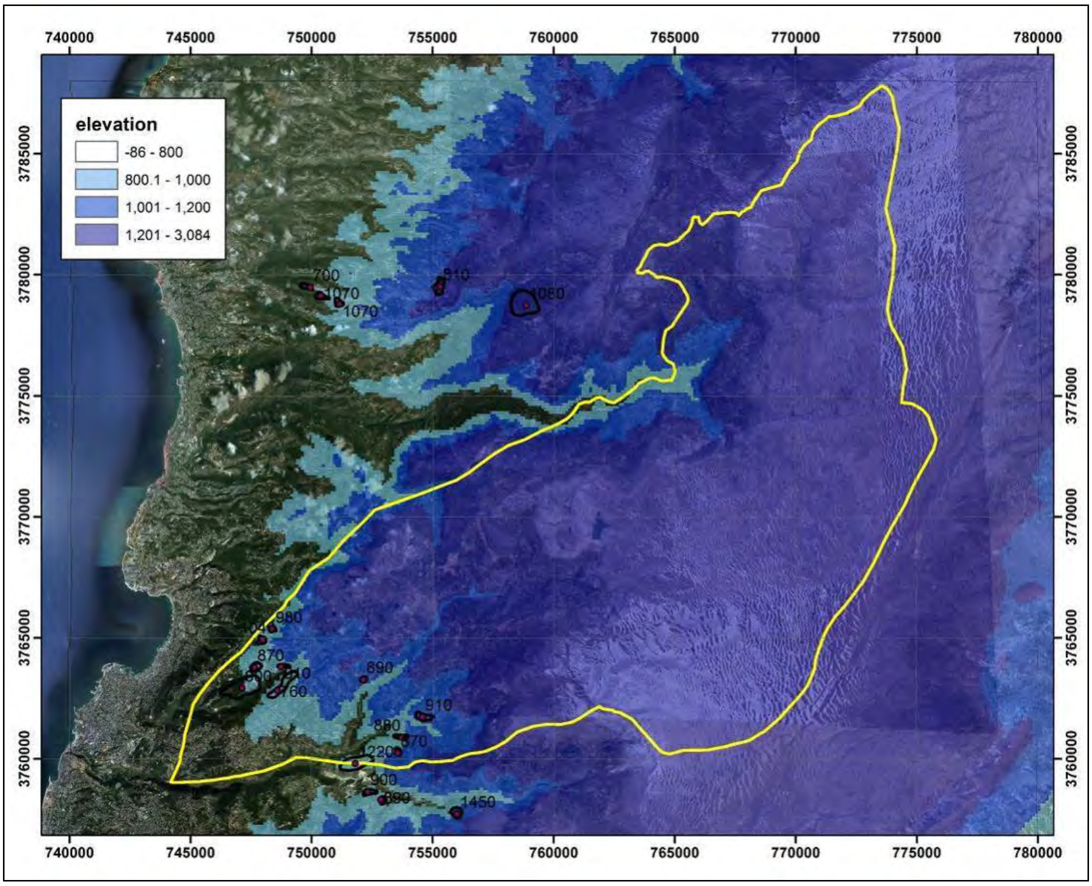


Figure 47: Location of Eskers with Elevations

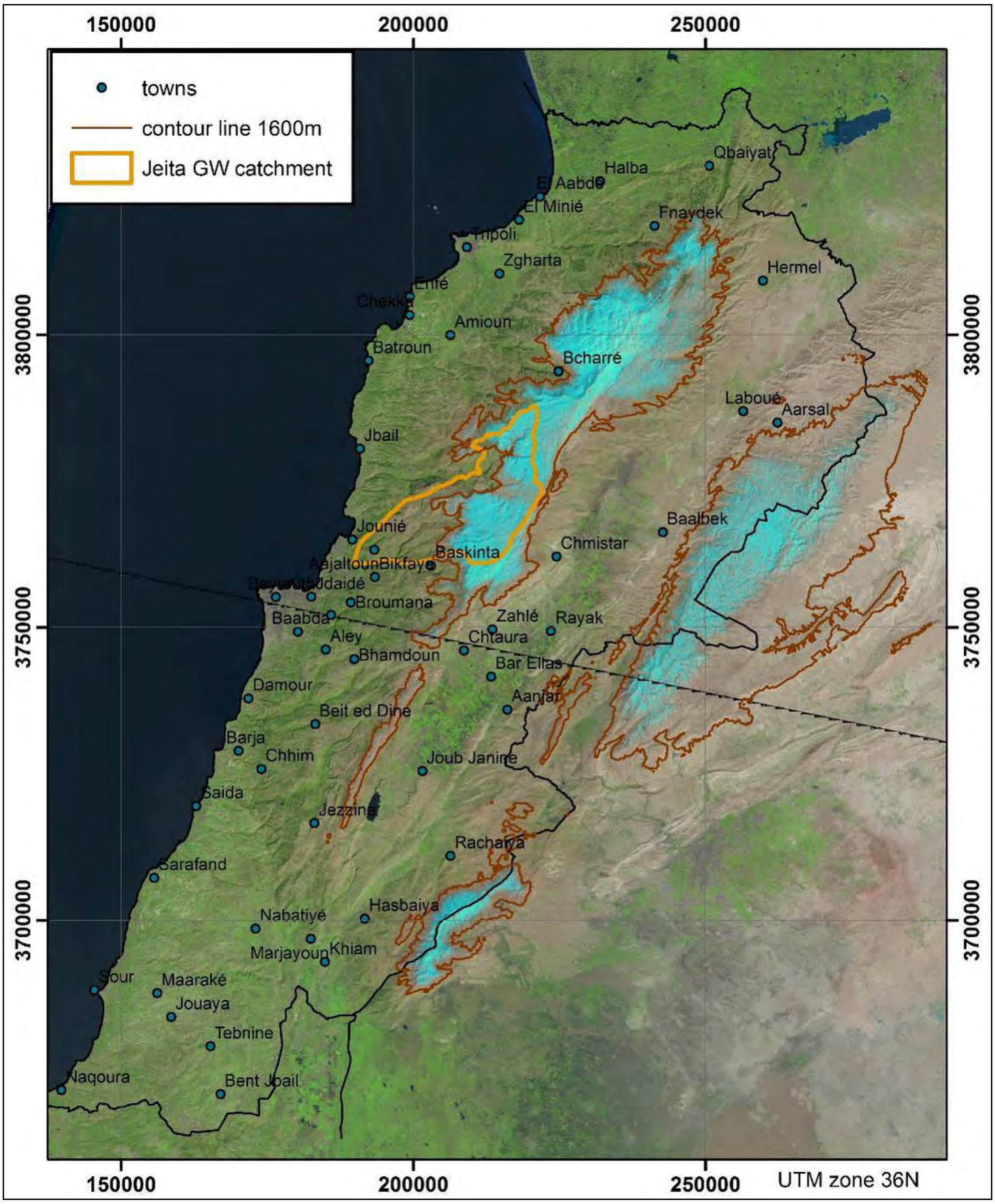


Figure 48: Landsat TM7 Image showing typical Snow Cover in Lebanon and Anti-Lebanon Mountain Ranges in Comparison to Elevation

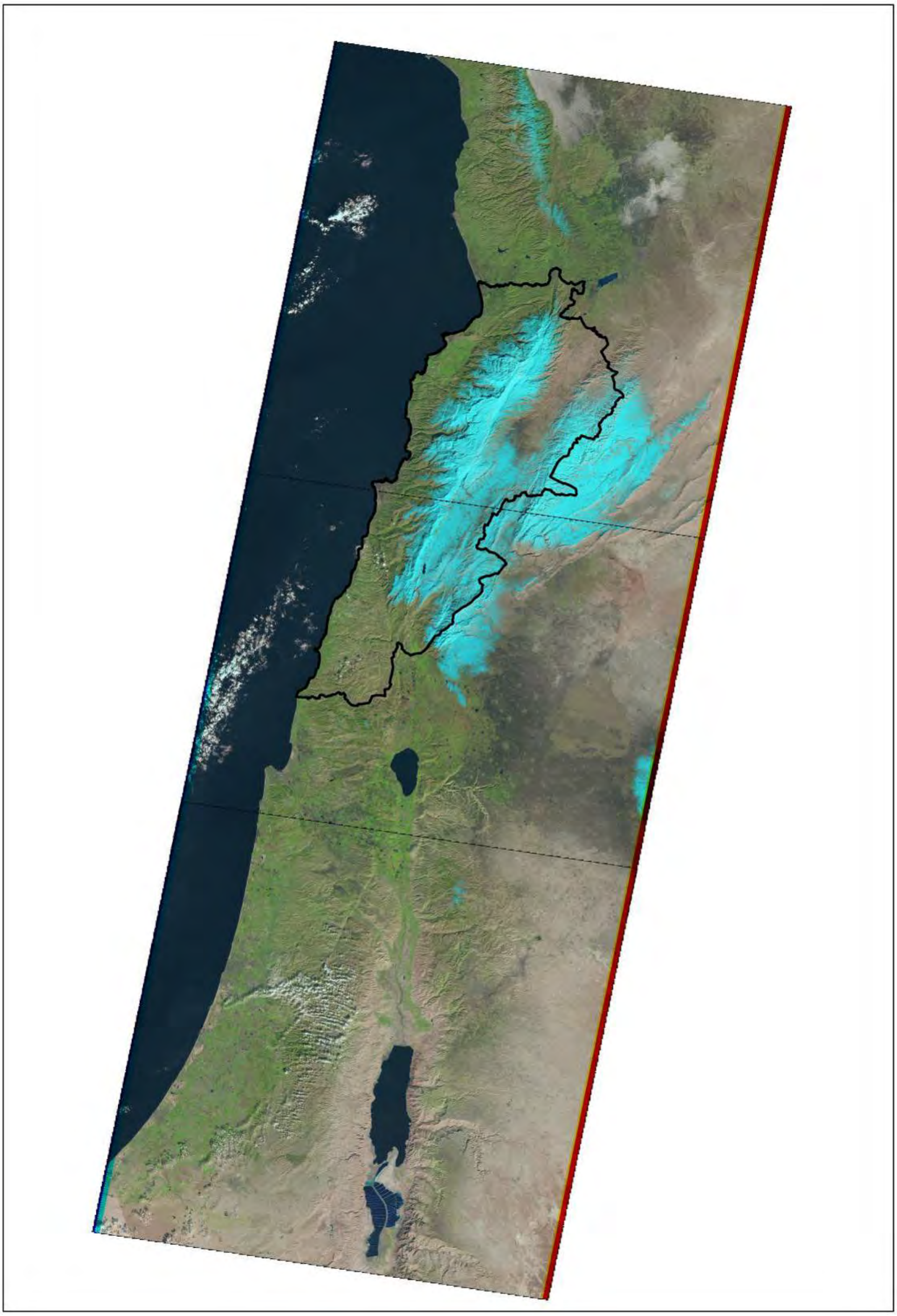


Figure 49: Landsat TM7 Mosaic of 19 January 2002 depicting Snow Cover in the Levant

3 Hydrogeology

3.1 Description of the Aquifer System

The aquifer system comprises mainly limestone units, most of which are highly karstified. The Jurassic Keserwan limestone (J4) has a thickness of 1,070 m (HAHNE, 2011). The base of this unit has not yet been penetrated in the Jeita catchment or anywhere else in Lebanon so that this thickness is only the minimum observed thickness. The Upper Cretaceous Sannine limestone (C4) has a similarly high thickness. The lithostratigraphic classification of geological units and their hydrostratigraphic subdivision in the Jeita catchment was explained in Chapter 2 and is shown in Figure 28.

Based on the results of the geological mapping, the groundwater system was divided into three main units (Figure 50):

- Upper Aquifer: C4 geological unit (highly karstified limestone), assumed thickness up to 1,050 m;
- Aquitard Complex: J5 to C3 geological units, assumed thickness: 500 to 800 m;
- Lower Aquifer: J4 geological unit (highly karstified limestone), assumed thickness up to 1,070 m.

The Aquitard Complex contains smaller aquiferous units, however these are on the overall scale (thickness, spring discharge) not relevant. Although the J6, C1 and C2b can produce water and locally even be of some limited use, the total amount discharged from these units is minimal (< 1%). This confirms that downward leakage from the Upper Aquifer to the Lower Aquifer is negligible.

Triassic sediments probably form the base of the Lower Aquifer. Unfortunately there is no knowledge about the Triassic in Lebanon although it is of major importance not only for oil exploration but also for the groundwater system.

Based on studies in Syria (BREW, 2001; BREW et a., 2001; LUCIC et al, 2010; SADOONI & ALSHARHAN, 2004), it must be assumed that especially Middle and Late Triassic sediments in central Lebanon contain evaporites (anhydrite and salt) and that the deeper part of the aquifer system, below the Jurassic, will most likely be brackish or saline, unless salt layers were already dissolved following the uplift of the Mount Lebanon mountain range. Triassic sediments are mostly found at greater depths, however, there are some areas in Lebanon where Triassic must be expected to be uplifted, such as the area W of the Tannourine-Janneh Fault (top Triassic at approx. 700 m asl; see geological cross section 2 in Figure 32), the area around Mrouj (top Triassic at approx. 500 m asl; see geological cross section 4 in Figure 34).

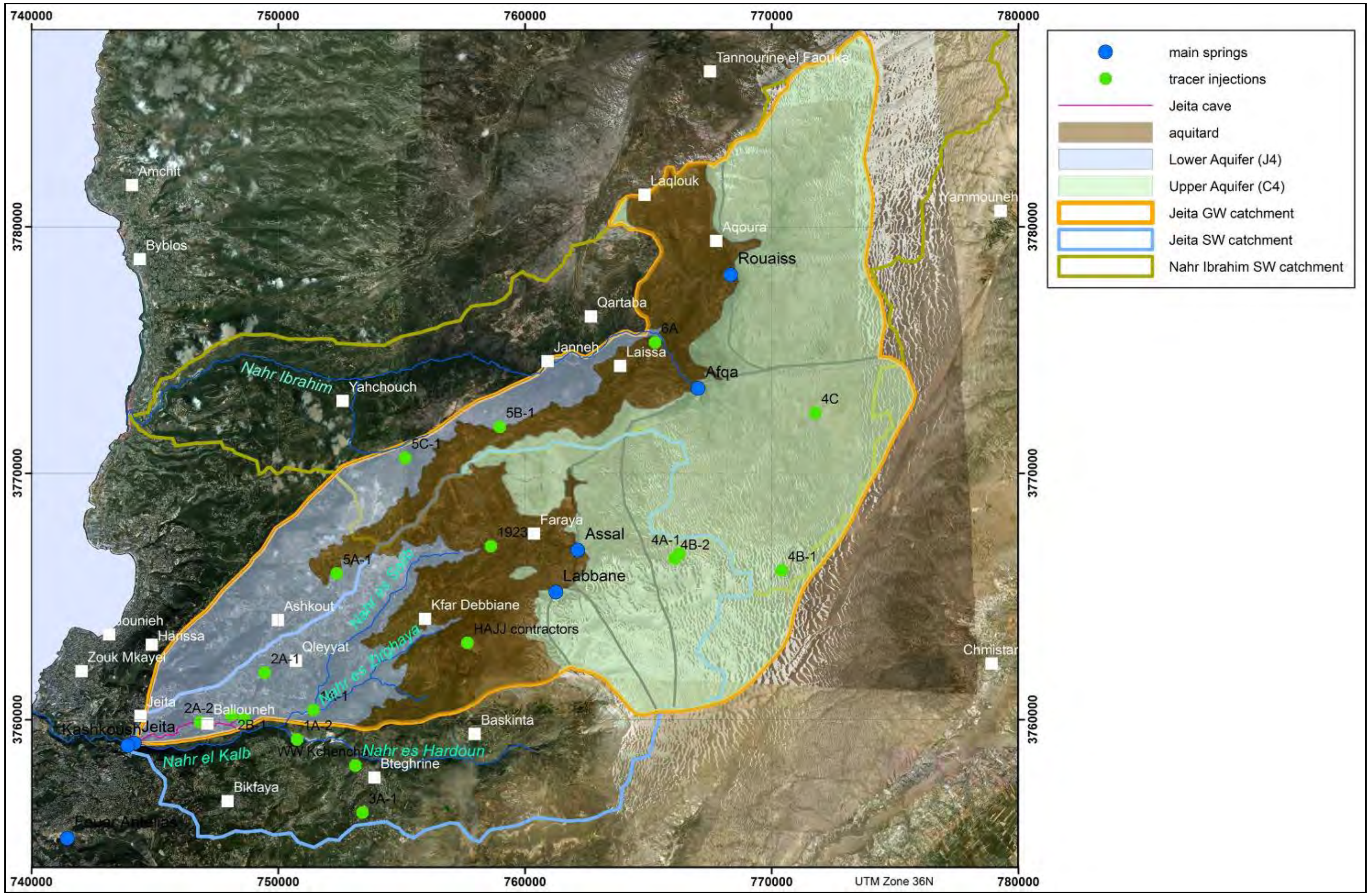


Figure 50: Subdivision of Groundwater System in Aquifer Units and Locations of Tracer Injections

3.1.1 Karst Formation

An extensive karst network has developed in the Jurassic and Cretaceous limestones over millions of years due to several reasons:

- limestone is the predominant rock type;
- both, the Jurassic and Upper Cretaceous limestones were exposed over a very long time period;
- during the Quaternary the areas higher than 800-1,000 m asl were covered by glaciers, leading to an intensive karstification, especially of the C4 and the uppermost J4 geological units (ABI RIZK & MARGANE, 2011; MARGANE & MAKKI, 2012);
- the entire Mount Lebanon mountain range is located in a tectonically very active zone and was affected by intensive tectonic movements; the predominating limestones are thus highly fractured;
- rainfall is relatively high at present and possibly in the past;
- topographic and hydraulic gradients are relatively high, leading to a high rate of erosion and thus a deep reaching limestone dissolution.

Several factors determine groundwater flow in this karst system:

- the geological structure (base of aquifer);
- differences in the level of karstification (width of conduits);
- tectonic elements and basalt intrusions (coastal flexure, Qamezh fault (basalt dyke), Tannourine-Janneh fault); and
- lithological differences (dolomitization due to basalt intrusions)/facies changes).

Geological Structure

The tops and bases of geological units play an important role for groundwater flow. It would be therefore critical to have structure contour maps at hand which display the depth (top) especially of impermeable layers. However, this has never been attempted in Lebanon. Since there has been no systematic exploration of the groundwater system using deep boreholes and geophysical investigations, the deeper geological underground is virtually unknown. Of particular importance would be structure contour maps showing the depth of the lower boundary of the aquifer system, i.e. the base of the J4 geological unit (Keserwan limestone). Due to the non-availability of geophysical surveys and even geophysical contractors in Lebanon that would be able to conduct such surveys, and the non-availability of deep boreholes, penetrating the J4 geological unit, the base of the Lower Aquifer is still unknown. Due to rapid facies changes and changes in thickness at the margin of the Arab plate, it is also not possible to infer from observations concerning a geological unit at one location to that at another location. What is urgently needed in this respect are W-E seismic transsects reaching to depths of at least 3 km, across the carbonate platform during Jurassic and Cretaceous times (Figures 41, 42). If such transsects are planned to be prepared for hydrocarbon exploration, it would be useful to design them in such a way that they could be used at the same time for groundwater exploration. The C4 geological unit is the only unit for which a tentative structure contour map could be prepared (Figure 29). The base of the C4 can be observed all along the western escarpment of the high plateau. To the east of the plateau, however, it is not visible because of the abrupt change of dip and vertical displacement at the Yammouneh fault (part of the DST).

Degree of Karstification

The degree of karstification depends on:

- access of water and soil air (open or buried karst; type of geological overburden);
- CO_2 content in water and air (dependent on temperature and global CO_2 air content; different throughout geological history);
- snow cover;
- vegetation cover and landuse;
- initial fracture porosity (intensity of fracturation, open/closed faults/fractures;
- lithological differences (formation of dissolution channel often follows weak zones along bedding planes).

Therefore the main factors controlling the degree of karstification are:

- lithological composition,
- tectonics and structural development,
- climate (present-day and palaeoclimate), and
- exposure.

The uplift of the Lebanon mountain ranges (Mount Lebanon and Anti-Lebanon) started in the Santonian of the Upper Cretaceous. However, until the Eocene a shallow marine environment prevailed and several hundred meters of predominantly marly sediments were deposited. The main uplift took place in the Eocene (56-34 MY ago) and thereafter (WALLEY, 1998). This is when the main erosion set in and karstification commenced. During the Eocene CO_2 levels were much higher than today (partly exceeding 2000 ppm (BEERLING et al., 2002), while today's CO_2 content of the atmosphere is only 390 ppm). Temperatures throughout the Tertiary were much higher compared to today. During the Paleocene-Eocene Thermal Maximum (PETM) sea-surface temperatures were more than 5°C higher than today (http://www.uta.edu/faculty/awinguth/PETM-Home.html; TRIPATI & ELDERFIELD, 2005). Both, higher concentration of atmospheric CO_2 and higher temperatures must have resulted in a higher rate of calcium carbonate dissolution and thus a very intensive karstification.

The Mediterranean Sea was formed in the process of continental collision between the African-Arabian with the Eurasian continent during the Tertiary, which led to the closure of the previous Tethys Ocean. In the Miocene, during the Messinian Salinity Crisis (6.0 - 5.3 MY ago; GAUTHIER et al., 1994), when the strait of Gibraltar was closed, the Mediterranean Sea dried up almost completely so that the drainage base level for the Mount Lebanon mountain range was several hundred meters lower than today. This might have caused an increased level of erosion.

During the Quaternary, large parts of the Lebanon mountain ranges (Mount Lebanon and Anti-Lebanon) were probably covered with glaciers (Chapter 2.4) at elevations exceeding 800-1,000 m asl. Content in carbonic acid in water is temperature dependent, due to the fact that more CO_2 can be dissolved in water at lower temperatures (Henry's law). Cold rainfall thus contains more carbonic acid at a given partial pressure of CO_2 compared to warm rainfall. Therefore the carbonic acid content in rainfall and snow during the glacial periods must have been higher, resulting in a more intensive karstification.

Karstification is most extensive where limestone had been exposed over a long period of time at elevations between 1,200 and 2,600 m asl and where actual rainfall is between 1,300 and 2,000 mm/a. The uppermost part of the Jurassic geological unit J4 exhibits large karrenfields, dolines and sinkholes at elevations between 1,000 and 1,400 m (Figure 51). The Upper Cretaceous Sannine Formation (C4) is exposed in the high plateau of the Mount Lebanon mountain range (> 1,800 m). There are practically no surface water runoff features developed on this plateau because rainfall and snow almost completely infiltrates into extended fields of dolines, proof for the high karstification in the C4 (Figure 52). The present day snow cover between December and May plays an important role for development of this extreme karstification of the Sannine Formation. But also Quaternary glaciations must have significantly increased karstification down to levels of 800-1,000 m asl. Soils were most probably completely eroded during these glaciations. Unfortunately there are few studies concerning Quaternary glaciation in Lebanon, however, the findings of the BGR project are supported by investigations in the region (HUGES, 2004; HUGES & WOODWARD, 2008; ZREDA et al., 2006; SARIKAYA et al., 2011) and by initial recent studies in Lebanon itself (MOULIN et al., 2011).

Figure 51: Intensive Karstification in the Uppermost J4 Geological Unit

Figure 52: Intensive Karstification in the C4 Geological Unit

Tectonic Elements

At mid elevations (800-1400 m), the Cretaceous and Upper Jurassic cover on the J4 geological unit was eroded since millions of years. The exposure of the J4 over large areas, combined with the high rainfall (1200-1500 mm/a), lead to an extensive karstification especially of the uppermost J4. Due to the missing cover, water could attack limestone preferably along tectonic weak zones, especially along the W-E oriented (70-90°) faults, following the general topographic gradient. In this respect karst dissolution facilitated erosion processes. This combined attack by physical and chemical weathering and erosion processes is the main reason why the rivers are so deeply incised in the W-E direction. Fractures are at outcrop often accompanied by a shatter zone (Figure 53).

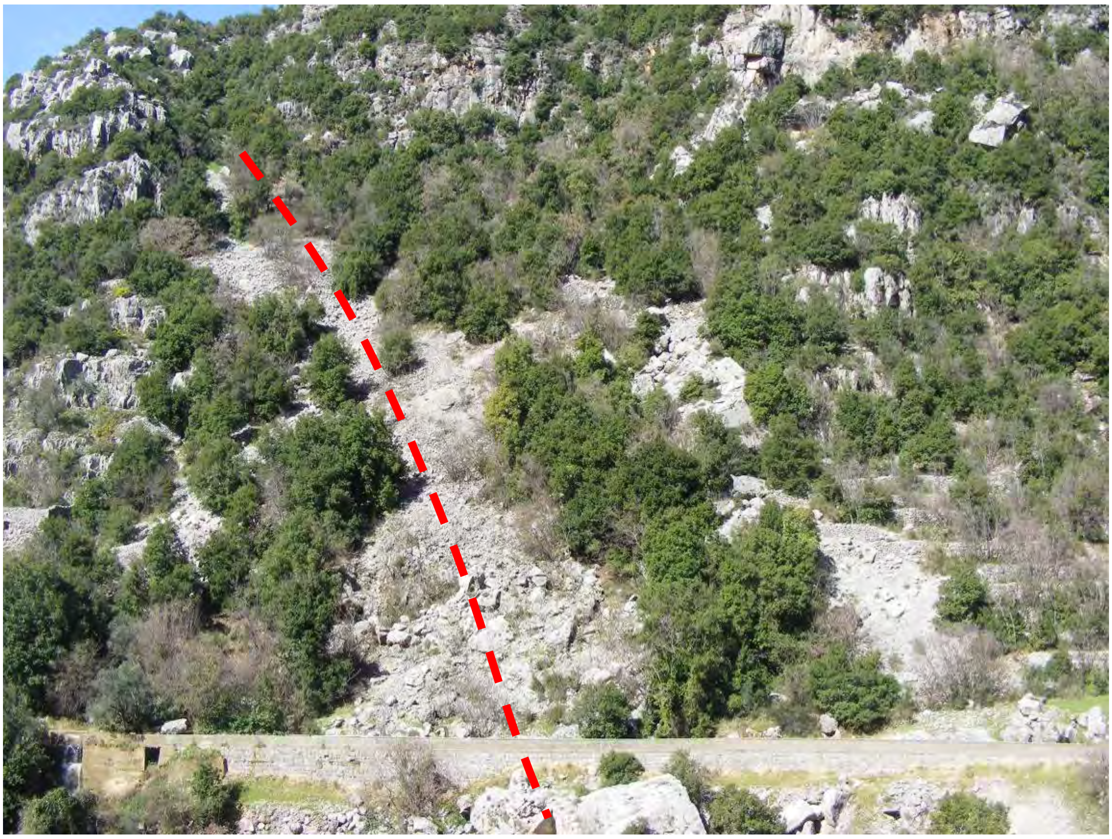


Figure 53: Shatter Zone accompanying Fault (red line) in Nahr es Zirghaya

Basalt Intrusions/Dolomitization

Basalt intrusion plays an important role concerning the dolomitization of limestone units, especially in the J4. Dolomitization is not bound to certain levels in the J4 but to faults and large intrusions of basalt. These occur especially in the Upper Nahr Ibrahim Valley, causing the most extensive dolomitization in the Jeita GW catchment but also near Hemlaya/Abu Mizaine and Baskinta. It is assumed that intrusion of hydrothermal waters lead to secondary dolomitization in the underlying J4. The leaching of magnesium-rich solutions from basalt weathering (J5) could be another Mg source.

Lithological Differences

Dissolution of limestone often follows weak zones in the rock such as lithological boundaries, e.g. bedding planes. This can be observed throughout the Jeita catchment in the J4 (Figure 54).

Figure 54: Exposed former Dissolution Channels following Bedding Planes in the J4

3.2 Delineation of the Groundwater Catchments

3.2.1 Tracer Tests

The groundwater contribution zone of Jeita spring was delineated using tracer tests, the results of the geological mapping and the results of the hydrochemical investigations.

Altogether 14 tracer injections in groundwater and 10 surface water tracer campaigns with several injections each were conducted between 2010 and 2013. The tracer tests were carried out and interpreted together with the Georg-August University Goettingen, Department of Applied Geology. The tracer tests are documented in the Special Reports series of the project (Tables 6, 8). ANNEX 2 shows the results of all groundwater tracer tests.

The project started under the assumption voiced in the UNDP (1972) report concerning Jeita that the groundwater catchment of Jeita spring must be similar to its surface water catchment. For this reason the boundaries of the assumed catchment changed several times over the course of the BGR project, until in May 2012 the final catchment boundaries could be confirmed. Due to these frequent changes in the outline of the catchment also the boundaries of the geological mapping, vulnerability mapping, etc. had to be changed. This is why in older project reports, the Jeita catchment boundaries may appear different from those presented in reports prepared after May 2012.

Table 6: Documentation of Tracertests

Tracer tests	Date	Report No.	Objective	Reference
1 1A-1 1A-2 1B	 19.04.2010 22.04.2010 28.04.2010	SR-1	Test 1A: Suitability of proposed WWTP site; Hydrogeol. connection of southern part of Nahr el Kalb catchment with Jeita spring; Tests 1A/1B: Flow velocity/path in Jurassic (J4) aquifer (lower part of catchment); Tests 1B Flow velocity in Jeita cave (test 1B repeated 20 times).	DOUMMAR et al. (2010a)
2 2A-1 2A-2 2B-1	 02.08.2010 02.08.2010 20.08.2010	SR-2	Permeability of Jurassic (J4) aquifer in lower part of catchment; Function of N/S faults	DOUMMAR et al. (2010b)
3	13.11.2010	-	Hydrogeol. connection of southern part of Nahr el Kalb catchment with Jeita spring; Flow velocity/path in Jurassic (J4) aquifer (central part of catchment).	-
4 4A 4B-1 4B-2	 16.03.2011 18.05.2011 18.05.2011	SR-5	Hydrogeol. connection of C4 aquifer with Jeita spring; Flow velocity/path in Upper Cretaceous (C4) aquifer (upper part of catchment) Test 4B-1: flow to Afqa spring	DOUMMAR et al. (2011a)

Tracer tests	Date	Report No.	Objective	Reference
4C	04.05.2012	SR-17	(N) or towards W/E ? Test 4B-2: flow to Afqa spring (N) or towards W ? Test 4C: flow to Afqa spring (W) or to Yammouneh spring (NE) or Rouaiss spring (N)	
5 5A 5B 5C	 23.06.2011 11.08.2011 16.09.2011	 SR-6 SR-11		DOUMMAR et al. (2011b) DOUMMAR et al. (2012a)
Tests by others or pollution tracing				
Hrajel 1923	03.09.1923	TR-1	Several historic tracer tests; injection at Hrajel, arrival at Jeita after ~6 days (distance 16,500 mm)	KARKABI (2009), MARGANE (2011)
Perte de Deir Chamra	12.07.1971	TR-1	Injection in Nahr es Salib, arrival at Jeita after 29.5 h (distance 6,150 m)	HAKIM et al. (1988); MARGANE (2011)
Attine Azar sinkhole	12.10.1996	SR-8	Injection at Attine Azar sinkhole, arrival at Faouar Antelias spring after 327 h (distance 18,000 m)	LABAKY (1998); MARGANE & STOECKL (2013)
HAJJ contractor	2010-2013	ASD-3	Tracing of turbidity peaks due to operation of HAJJ sandstone quarry, travel time 24 h (distance 13,500 m)	MARGANE & CHRABIEH (2012)
WW Kchenchara	June 2013	ASD-4	Tracing of pollution peaks due to injection of untreated wastewater in Kchenchara	CHRABIEH & MARGANE (2012)

Based on these tracer tests the groundwater catchments of all major springs in the Jeita GW catchment were delineated (Table 7). They are shown in Figures 55-59 (Chapters 3.2.3 - 3.2.8).

Only a small proportion of rain and snow falling on the Aquitard Complex can infiltrate due to the nature of the rocks and due to its water holding capacity, the Aquitard Complex is the main area used for agricultural cultivation. Therefore some part of the rainfall will evaporate through transpiration by plants. The main part, however, forms runoff to the downgradient Lower Aquifer, where part of it infiltrates. Especially the uppermost part of the underlying J4 is highly karstified facilitating riverbed infiltration.

Table 7: Groundwater Sub-Catchments of the Jeita Groundwater Catchment

GW Catchment	Aquifer	Size [km²]	Mean Elevation [m]	Mean Rainfall [mm/a]	Mean Discharge Measured [MCM/a]	Mean Discharge WEAP model [MCM/a]
Afqa	C4	101.5	2,012	1,613	123.2	131.2
Rouaiss	C4	65.8	1,919	1,613	-	89.4
Assal	C4	14.6	2,174	1,807	24.2	21.5
Labbane	C4	9.5	2,171	1,900	-	14.6
Jeita	J4	86.7	1,019	1,296	-	-
Jeita	C4+J4	307.1	1,701	1,541	166.4	171.3

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

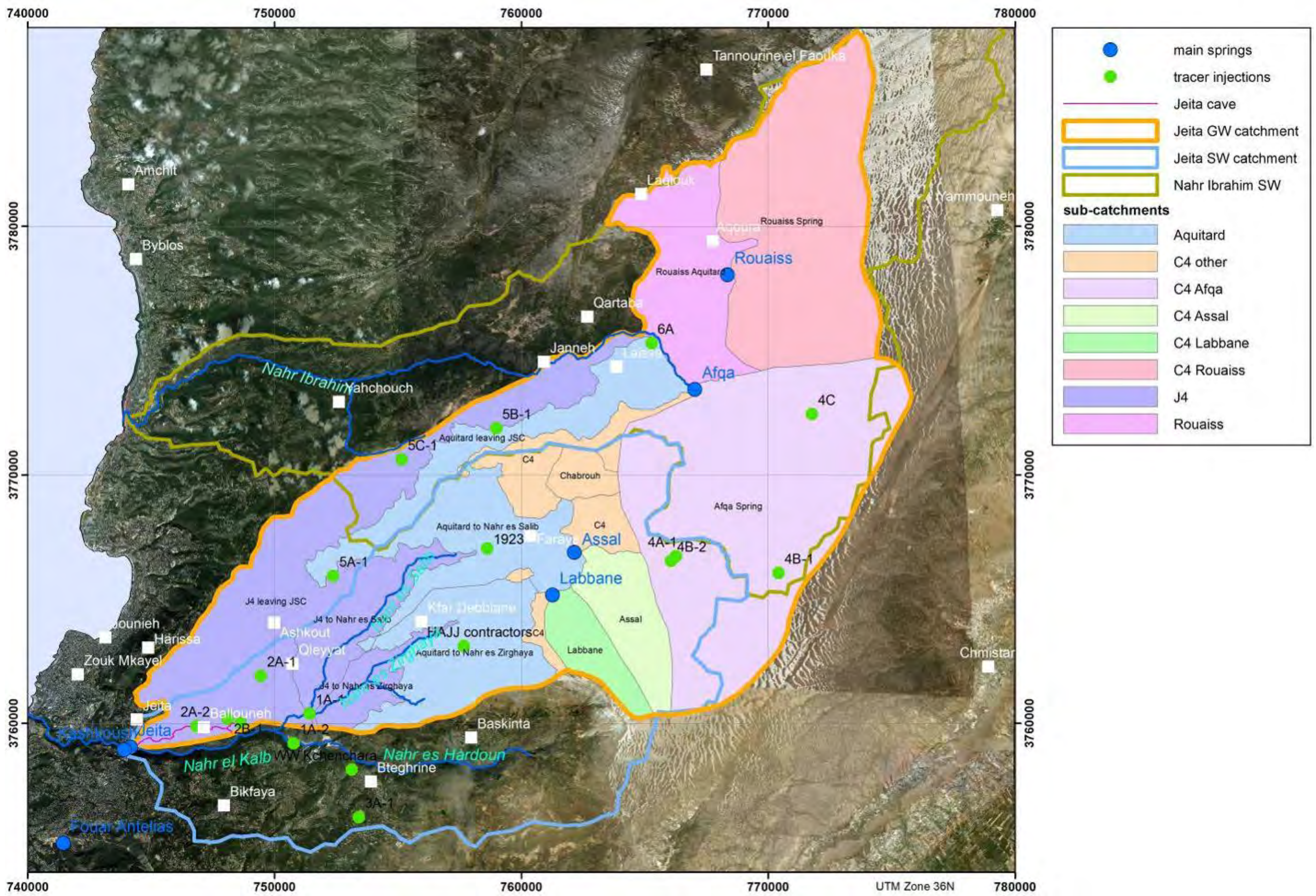


Figure 55: Sub-catchments of Jeita Spring

3.2.2 Hydrogeological Cross Sections

The same four geological cross sections presented in Chapter 2.2 are here below presented with their assumed approximate water levels (Figures 56-59). Although karst systems strictly do not have continuous water levels like porous aquifers, highly fractured karst behaves similar to a porous aquifer system. The karst aquifers of Jordan are a good example for that (MARGANE et al., 2002).

Due to the lack of adequate monitoring wells the water levels in the Jeita karst system are largely unknown. Based on the few control points available, cross sections with tentative water levels are presented below, which may be useful for planning purposes. However, a groundwater database and groundwater monitoring wells are urgently needed. Monitoring wells would allow observing seasonal and interannual changes water level in order to better characterize the response of the aquifer system to dry periods. Monitoring wells are the only means to quantify impacts of climate change on the groundwater system.

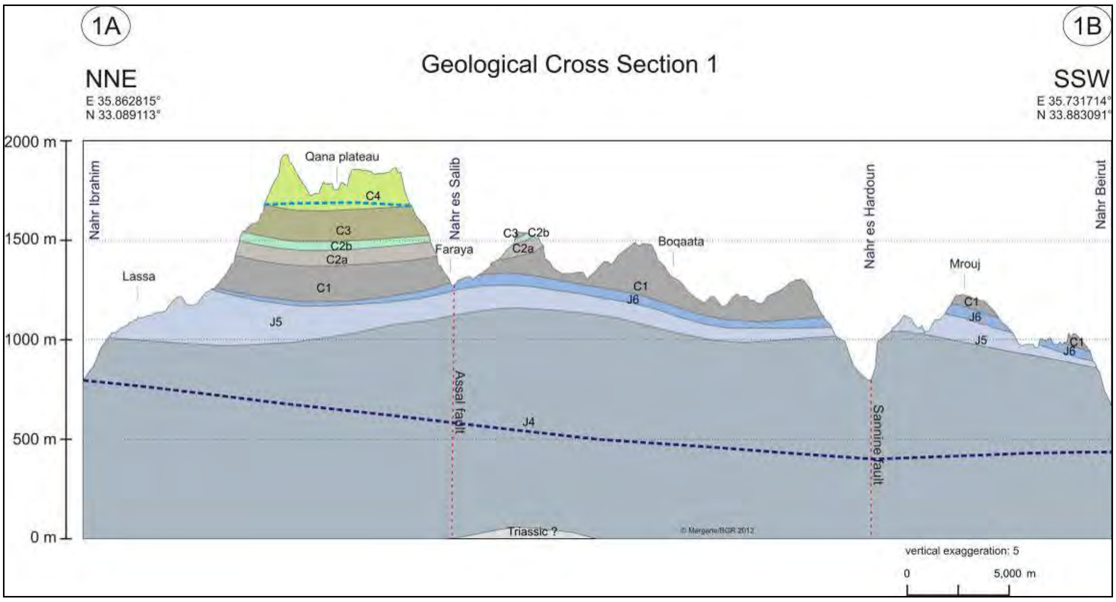


Figure 56: Hydrogeological Cross Section 1

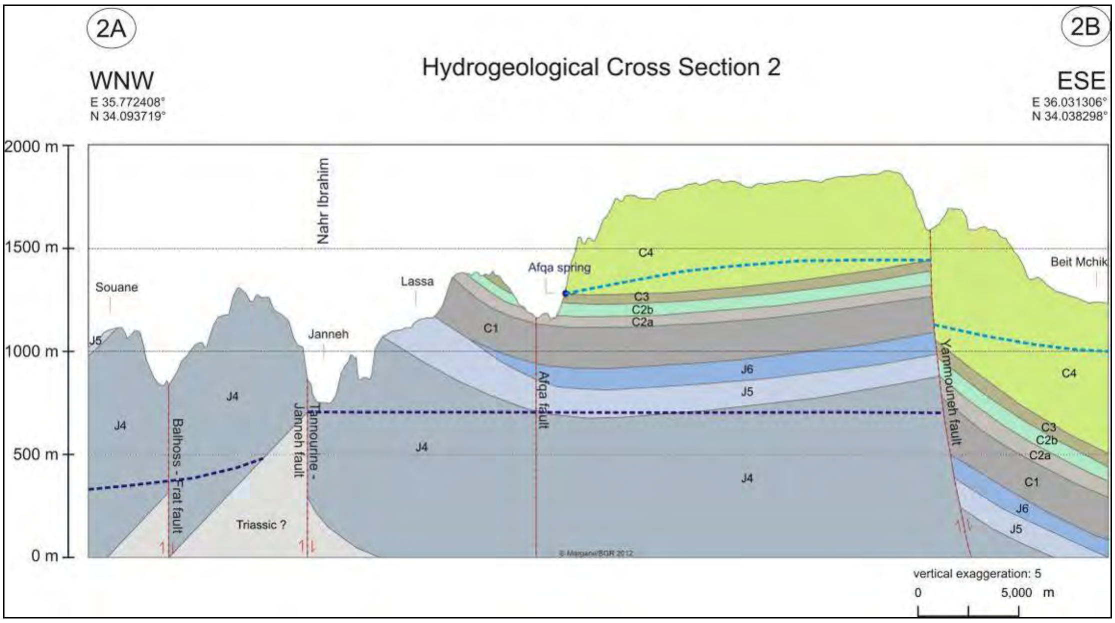


Figure 57: Hydrogeological Cross Section 2

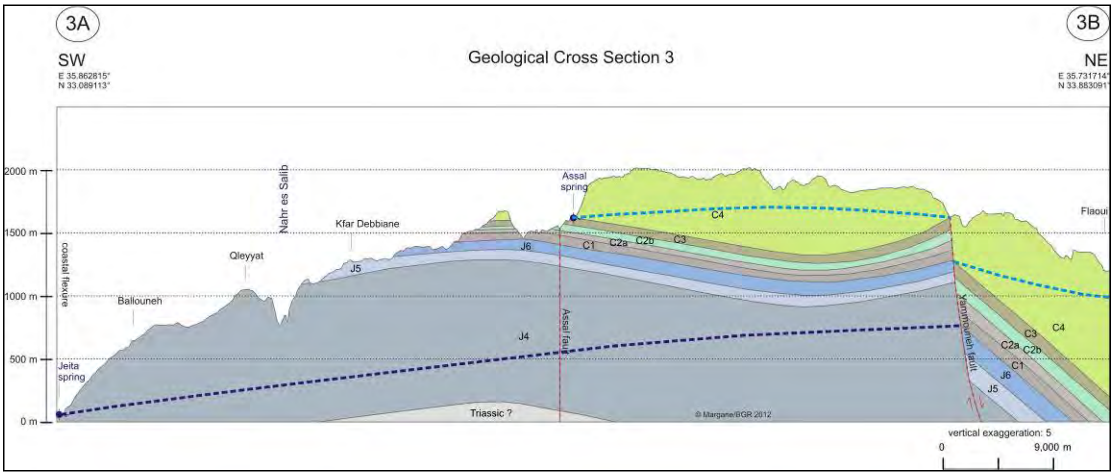


Figure 58: Hydrogeological Cross Section 3

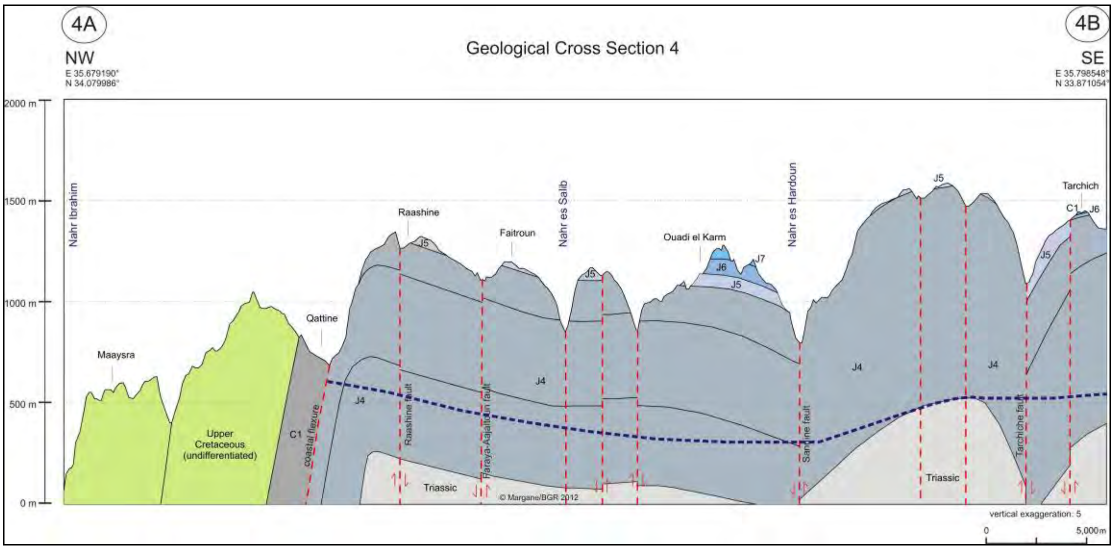


Figure 59: Hydrogeological Cross Section 4

3.2.3 Groundwater Catchment of Afqa Spring

The catchment of Afqa spring was delineated based on the tracer test results, the tentative geological structure contour map of the C4, tectonic elements, and the measured GW discharge. As GW recharge conditions are similar, also all neighboring catchments and spring discharges were taken into consideration, also that of Yammouneh spring.

The Afqa GW catchment (Figure 60) has a size of approx. 101.5 km².

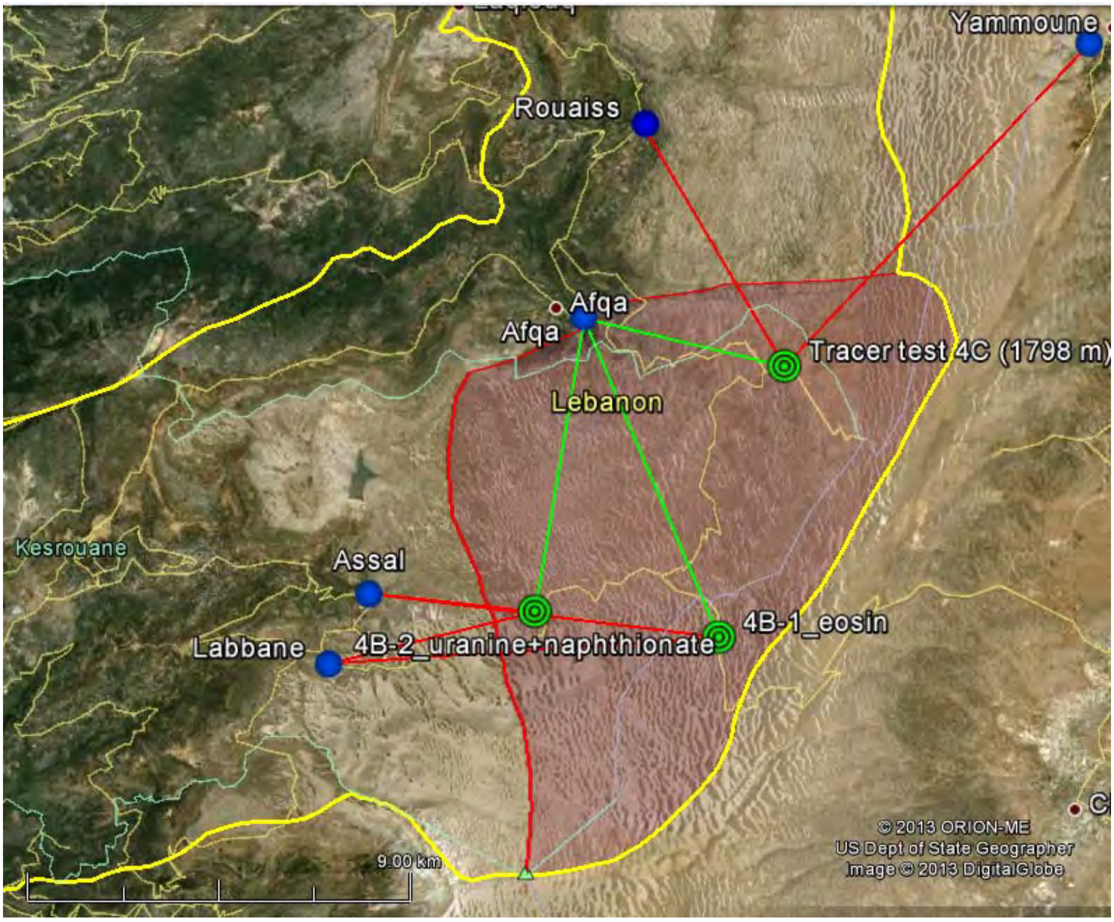


Figure 60: Boundary of Afqa Groundwater Catchment

remark: green circles: tracer injections with test number and tracer substance; green lines indicate a proven hydrogeological connection, red lines show that a link was proven not to exist

3.2.4 Groundwater Catchment of Rouaiss Spring

The catchment of Rouaiss spring was delineated based on the tentative geological structure contour map of the C4 and tectonic elements. The measured GW discharge could not be used because it is highly unreliable. As GW recharge conditions are similar, also all neighboring catchments and spring discharges were taken into consideration, especially that of Yammouneh spring.

The Rouaiss GW catchment (Figure 61) has a size of approx. 65.8 km².

Figure 61: Boundary of Rouaiss Groundwater Catchment (blue)

3.2.5 Groundwater Catchment of Assal Spring

The catchment of Assal spring was delineated based on the tracer test results, the tentative geological structure contour map of the C4, tectonic elements, and the measured GW discharge. As GW recharge conditions are similar, also all neighboring catchments and spring discharges were taken into consideration. There is a possibility that Assal spring is in hydrogeological connection with the catchment of Chabrouh dam and receives water from the dam. This could only have been proven by a tracer test in the dam itself and was therefore not done.

The Assal GW catchment (Figure 62) has a size of approx. 14.6 km².

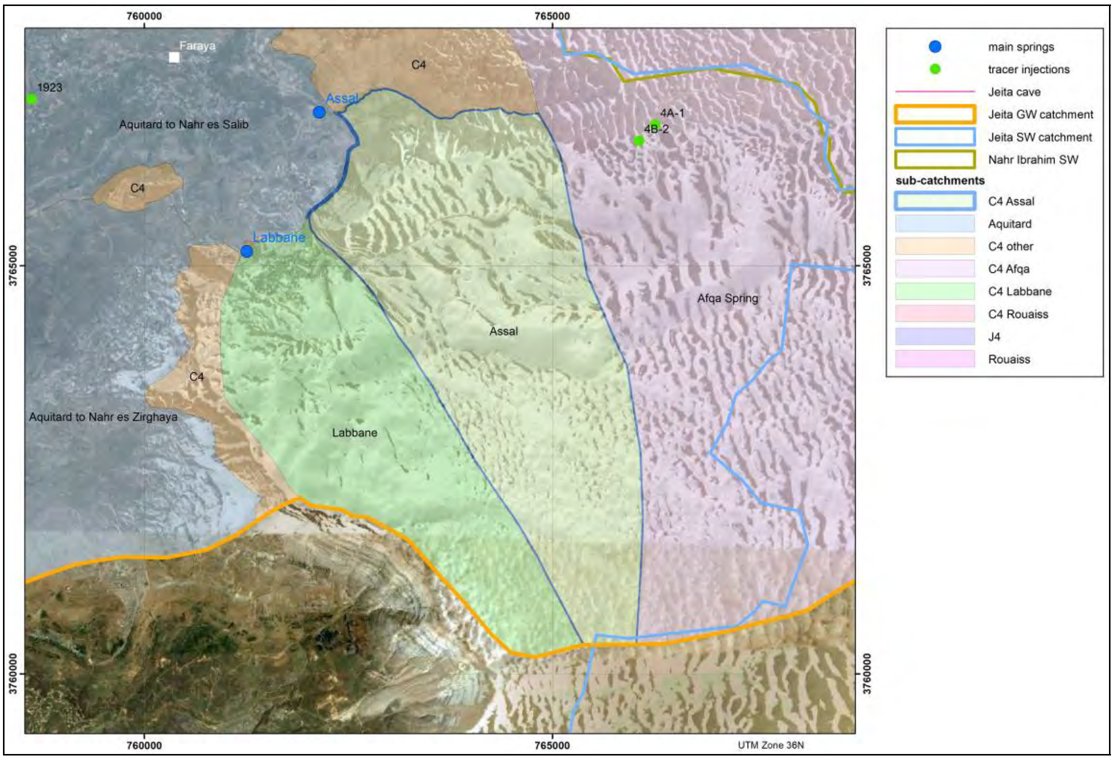


Figure 62: Boundary of Assal Groundwater Catchment

3.2.6 Groundwater Catchment of Labbane Spring

The catchment of Labbane spring was delineated based on the tracer test results, the tentative geological structure contour map of the C4, tectonic elements, and the measured GW discharge. As GW recharge conditions are similar, also all neighboring catchments and spring discharges were taken into consideration.

The Labbane GW catchment (Figure 63) has a size of approx. 9.5 km².

3.2.7 Groundwater Catchment of Jeita Spring

Details concerning the delineation of the Jeita catchment (Figure 64) are contained in Chapter 3.4. The size of the Jeita catchment is 405.6 km². It comprises the Afqa, Rouaiss, Assal and Labbane catchments as well as all parts of the Aquitard Complex which are drained at least in part to Jeita GW catchment.

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

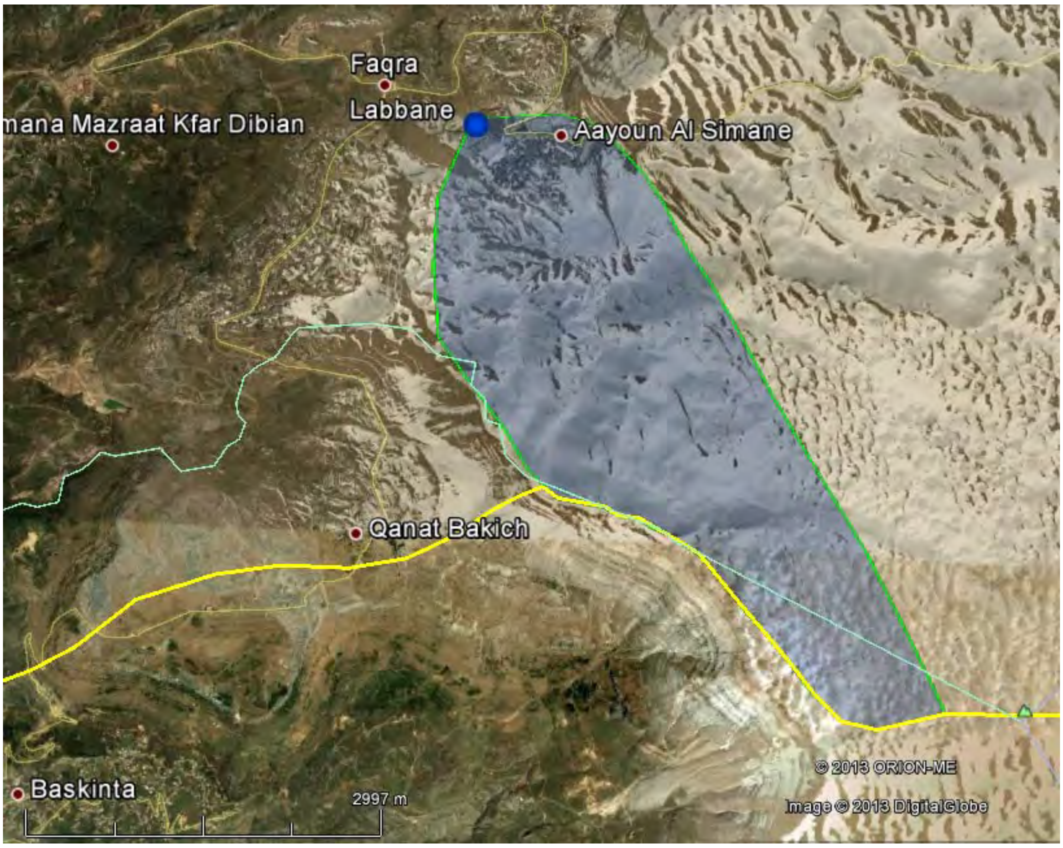


Figure 63: Boundary of Labbane Groundwater Catchment

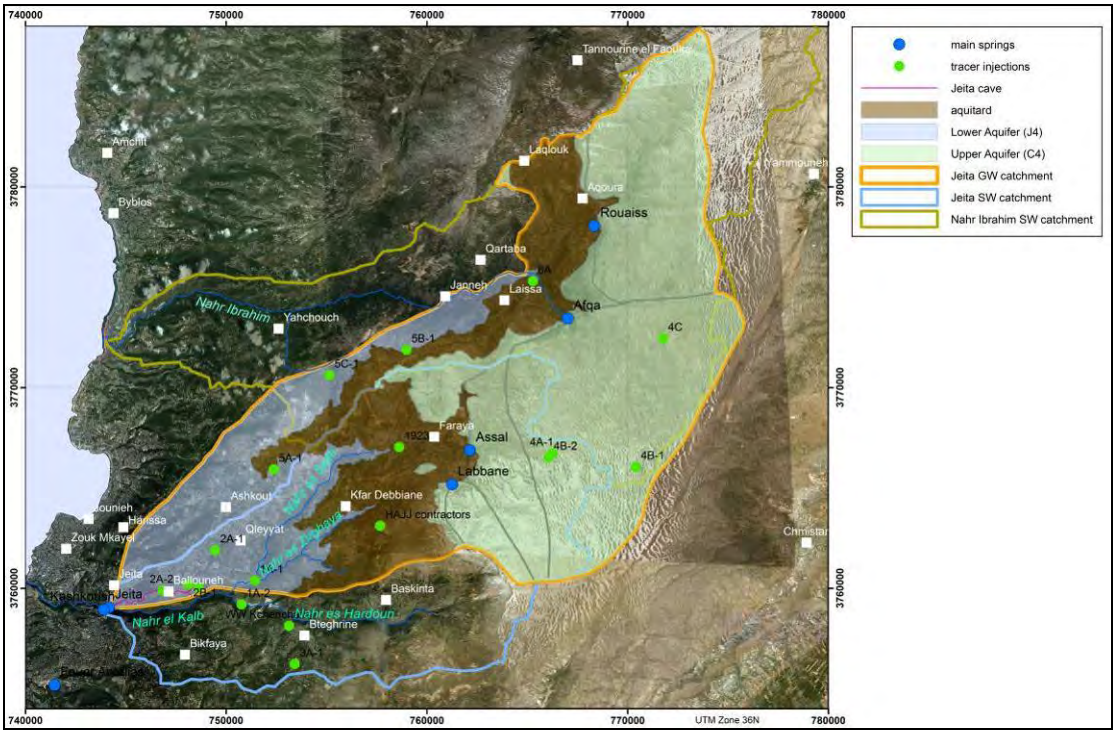


Figure 64: Boundary of Jeita Groundwater Catchment

3.2.8 Groundwater Catchment of Kashkoush Spring

The catchment of Kashkoush spring is completely separate from the Jeita catchment. While Jeita could be successfully delineated using tracer tests, no tracer substance ever arrived at Kashkoush spring. There are, however, some indications concerning the location of the catchment from other information. Kashkoush spring often shows a very high level of pollution by wastewater. During summer 2012 this pollution was so high that WEBML requested BGR to try to locate the pollution source. In a joint effort this source could finally be found downstream of Kchenchara, where untreated wastewater from the village was diverted to Nahr es Hardoun. Here wastewater must have infiltrated over several months unnoticed. At this time Nahr es Hardoun was dry so that wastewater directly infiltrated into the underlying J4 aquifer. The pollution had no effect on Jeita spring. This is also proof for the clear separation between the Jeita and Kashkoush catchments (CHRABIEH & MARGANE, 2012).

Before, between April and June 2012, several peaks of turbidity were observed in Jeita spring (MARGANE & CHRABIEH, 2012). These originated from the operation of the HAJJ contractors sandstone quarry in Bqaatouta. The same turbidity peaks, however, at a much lower magnitude were observed in Kashkoush spring. While there is infiltration along the Nahr es Zirghaya and Nahr es Salib branches of Nahr el Kalb with Jeita, as proven by tracer tests, there is no linkage of infiltration from this area to Jeita spring. The only explanation for an arrival at Kashkoush spring is infiltration in the upper Nahr el Kalb between Deir Chamra and Kashkoush.

The tracer test conducted by LABAKY (1998) in the Attine Azar sinkhole showed that there is a connection with Kashkoush spring, although only a very small amount of tracer (< 1%) arrived at Kashkoush spring.

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Table 8: Tracer Test Data

ID	Name	LONG	LAT	Elev	injection date+time	Injected substance 1	Amount (g) 1	Injected substance 2	Amount (g) 2
Test 1A-1	Deir Chamra WWTP	35.72076	33.95396	571	19/04/2010 12:11	uranine MKT	5000		
Test 1A-2	Abu Mizane WWTP discharge option 2	35.71441	33.94352	525	22/04/2010 15:59	AmidoG	5000		
Test_1B	Daraya tunnel siphon terminal	35.69101	33.95138	140	28/04/2010 11:42	uranine MKT	500		
Test_2A-1	fault zone @ road Daraya - Aajaltoun	35.70003	33.96811	846	02/08/2010 12:50	uranine ORCO	9233.3	Na-Naphthionate	9084.1
Test_2A-2	cess pit Joseph Nazzar house Ballouneh	35.67094	33.95063	668	08/02/2010 14:40	AmidoG	5749.1		
Test_2B-1	sinkhole Aajaltoun Valley housing project	35.68466	33.95321	667	20/08/2010 11:40	AmidoG	5000	Na-Naphthionate	5000
Test_3A	Khenchara sinkhole	35.74101	33.91605	1098	13/11/2010 10:57	uranine ORCO	10001.1	Na-Naphthionate	15010.8
Test_4A-1	Wardeh, near La-Cabane	35.88301	34.00743	2008	16/03/2011 11:30	uranine ORCO	5002.2		
Test_4B-1	Wardeh, Beka'a-road	35.92775	34.00031	2104	18/05/2011 10:35	eosin ORCO	10000		
Test_4B-2	Wardeh, near La-Cabane	35.88084	34.00573	1990	18/05/2011 13:35	uranine ORCO	5000	Na-Naphthionate	10000
Test_4C	Afqa	35.94441	34.05758	1798	04/05/2012 12:00	uranine ORCO	9000		
Test_5A	Boqaata Ashkout sinkhole	35.72794	34.00003	1184	23/06/2011 13:00	uranine ORCO	9373		
Test_5B	Qamezh sinkhole (Gouffre Albert)	35.80583	34.05570	1440	11/08/2011 09:04	uranine ORCO	14140		
Test_5C	Msheti well no. 1	35.76395	34.04536	1083	16/09/2011 09:52	uranine ORCO	10000	Na-Naphthionate	10000

3.3 Groundwater Flow Characteristics

The tracer tests conducted by BGR showed that mean flow velocities in the Upper and Lower Aquifer are fairly similar. The three positive tests conducted in the Upper Aquifer had mean flow velocities of between 129-163 m/h (Table 9), those conducted in the Lower Aquifer flow velocities of between 67-199 m/h.

However, the dilution tests conducted between Daraya tunnel (siphon terminal) and Jeita (+500) revealed that there is a huge seasonal variation in flow velocities (~1:10) of between 220 and 1,900 m/h in the main conduit (MARGANE, 2011; Figure 65). Therefore flow velocities generally depend on the season. It must also be assumed that, due to the different development of the karst network, especially higher up in the catchment, where the thickness of the unsaturated zone is extremely high (approx. 600 m in the area south of Qamezh), the water level fluctuation between dry and wet season reach more than 150 m. In dry years the water level can be more than 100 m deeper than in normal years (pers. comm. private well owners).

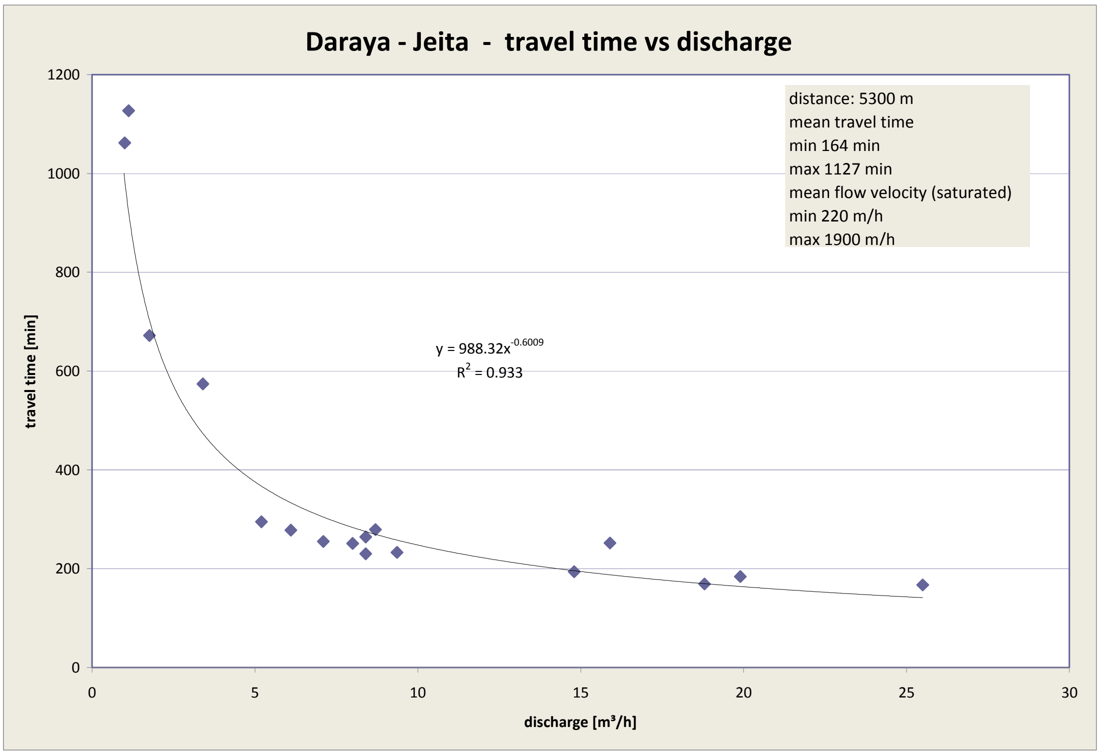


Figure 65: Variation of Groundwater Flow Velocity in the Conduit of the Underground River of Jeita between Siphon Terminal and Jeita (+500)

Mean groundwater travel times taken from all tracer tests conducted in the area are shown in Figure 66.

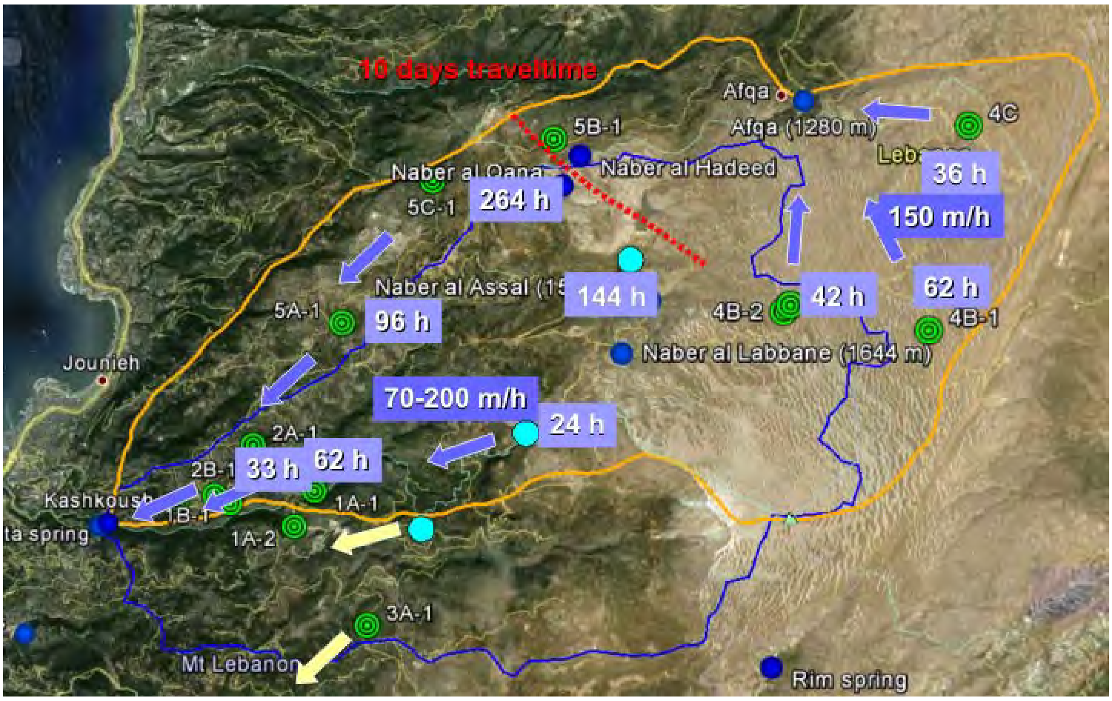


Figure 66: Mean Groundwater Travel Times based on Tracertests

Table 9: Parameter Characterizing Flow in the Karst Aquifer System

Aquifer	Test ID	Date	Distance (m)	Flow (m³/h)	Mean flow velocity (m/h)	Mean transient time (h)	Dispersion (m²/h)	Dispersivity (m)	Restitution (%)
Tracer Tests of the BGR Project									
Upper Aquifer (C4)	4B-1	18.05.2011	8,000	6.6	129	62	1480	11.5	1.5
	4B-2	18.05.2011	6,800	6.6	163	42	1840	11.3	95
	4C-1	04.05.2012	5,100	21.4	156	36	1850	18	28
Lower Aquifer (J4)	1A-1	19.04.2010	8,000	5.6	120	66	5070	41.9	13.3
	2B-1	02.08.2010	6,500	1.65	199	33	6050	30.4	75
	5A-1	27.06.2011	12,300	2.9	128	96	4750	37.1	22.2
	5C-1	16.09.2011	17,720	1.69	67.1	264	2970	44.3	9.1
Tracer Tests conducted by others									
Lower Aquifer (J4)	1923	03.09.1923	16,500			144			75
	Perte de Deir Chamra	12.07.1971	6150	2.94	208	29.5			24
	HAJJ contractors (pollution events)	Several recurring incidents during 2010-2013	13,500		562	24			

3.4 Groundwater Recharge

Groundwater recharge can be calculated if all water balance components of a well defined groundwater catchment are known:

$$GWR = P - R - ET - I + O \text{ (equation 1)}$$

where

GWR - groundwater recharge

P - precipitation

ET - evapotranspiration

I - inflow (including return flows from water supply facilities, wastewater facilities and irrigation)

O - outflow (including groundwater abstraction for domestic, agricultural and industrial purposes)

Inflow and outflow have to be considered in case of upward or downward leakage to or from the considered aquifer.

It must be distinguished between direct recharge, which takes place at the location of precipitation, and indirect recharge. Indirect recharge characterizes an infiltration process which takes place at a location of preferential infiltration to which precipitation is flowing by sheet flow, shallow concentrated flow or open channel flow. In karst systems indirect GW recharge takes place e.g. in sinkholes, dolines and sinking streams, which receive surface water runoff from a larger region.

In the case of a defined point of outflow of a catchment (spring) groundwater recharge is equivalent to spring discharge minus inflow plus outflow. Because inflow and outflow are zero in the Upper Aquifer (C4), GW recharge can be directly calculated comparing rainfall and spring discharge. Downward leakage is assumed to be minimal, which was confirmed by tracer test.

Groundwater Recharge in the Afqa Catchment

For Afqa spring the catchment boundaries were determined based on the structure contour map and based on four tracer tests (4A-1, 4B-1, 4B-2, 4C; compare Chapter 3.2; DOUMMAR et al., 2011; DOUMMAR et al., 2013). The determined catchment boundaries are shown in Figure 60.

The discharge of Afqa was measured by Litani River Authority (LRA). Spring discharge is 123.2 MCM/a during water years 2000/01 - 2009/10 (MARGANE, 2012a, 2012b; SCHULER & MARGANE, 2013; MARGANE & STOECKL, 2013). According to the WEAP model, annual discharge of Afqa is 131.2

MCM (SCHULER & MARGANE, 2013). The general characteristics of the catchment are shown in Table 7.

The size of the catchment is 101.5 km², long-term average rainfall (modified after UNDP & FAO, 1973) is 1,613 mm/a, mean elevation is 2,012 m asl. There is no inflow, and outflow in the form of downward leakage must be negligible because of the high thickness of the aquitard (tracer recovery in test 4B-2 was almost 100%). Groundwater abstraction is zero. Based on this assessment, total rainfall volume (P) is 163.7 MCM/a, so that considering an ET rate of 20% groundwater recharge (GWR) is 80 %.

Groundwater Recharge in the Assal Catchment

For Assal spring the catchment boundaries were also determined based on the structure contour map and based on the tracer tests conducted on the Upper Cretaceous plateau (Tables 6, 8; see references above). The determined catchment boundaries are shown in Figure 62.

The discharge of Assal was measured by Litani River Authority (LRA), however their discharge values (based on propeller measurements at monthly intervals) are much higher than the discharge determined by the BGR project. The BGR project determined discharge using a stage - discharge correlation (based on dilution tests; MARGANE & STOECKL, 2013) and ADCP flow measurements, both at 20 minute time intervals. LRA uses random propeller measurements and linearly interpolates between measurements over a very long time. Such interpolations are not justified, as the new measurements prove: response to rainfall and snowmelt events is commonly very fast.

Long-term spring discharge is estimated at 24 MCM/a (21.5 MCM in WEAP model; SCHULER & MARGANE, 2013). Groundwater abstraction is estimated at 0.14 MCM/a. Downward leakage through the thick aquitard sequence is believed to be negligible. The general characteristics of the catchment are shown in Table 7.

The size of the catchment is 14.6 km², long-term average rainfall (modified after UNDP & FAO, 1973) is 1,807 mm/a, mean elevation is 2,174 m asl. Based on this assessment, total P volume is 26.4 MCM/a, so that considering an ET rate of 18%, groundwater recharge is 82 %. The weak point concerning Assal spring is the catchment determination. It is assumed that the Assal catchment reaches farther to the north, to the eastern flank of Chabrouh dam. However, this could not be proven yet. It would require a tracer test to the east of Chabrouh dam, which is fairly impossible as there are no roads.

Groundwater Recharge in the Labbane Catchment

For Labbane spring the catchment boundaries were also determined based on the structure contour map and based on the tracer tests conducted on the Upper Cretaceous plateau (Tables 6, 8; see references above). The determined catchment boundaries are shown in Figure 63.

The discharge of Labbane was measured by Litani River Authority (LRA), however their discharge (based on propeller measurements at monthly intervals) is highly uncertain due to the difficulty to measure flow at Labbane spring. A weir was installed by the BGR project. Several dilution tests were conducted for this configuration and a multiparameter probe installed to measure stage at 20 minute intervals. The BGR project determined discharge using a stage - discharge correlation (based on dilution tests; MARGANE & STOECKL, 2013), however the weir was stolen so that flow measurements are only available for a rather short time period (Figure 52).

Flow at Labbane spring is considerably different from the flow at Assal. While Labbane spring usually falls almost dry during July/August (flow < 20 l/s), Assal spring never fell dry during the observation period (lowest flow: 60 l/s). Shortly after snowmelt, the flow of Labbane spring reaches approx. 10 m^3/s (estimation based on maximum stage and flow velocity). At Assal spring flow did not exceed 1.6 m^3/s during the monitoring period.

Based on LRA measurements, long-term spring discharge is 14.6 MCM. This is also the amount that is used in the WEAP model (SCHULER & MARGANE, 2013). Groundwater abstraction is estimated at 0.1 MCM/a. Downward leakage through the thick aquitard sequence is believed to be negligible. The general characteristics of the catchment are shown in Table 7. It is highly recommended to install an ADCP at Labbane spring to improve flow measurements. The project did not do this because of vandalism of the BGR weir by members of the Kfar Debbiane irrigation committee (Figure 52).

The comparison of temperature monitoring data from Assal and Labbane springs (Figure 68) shows that the average elevation of the Labbane catchment must be considerably higher than that of Assal. Following snow melt in spring 2011, the temperature of Labbane spring was about 1°C lower (assuming a temperature gradient of 0.6°C/100 m: approx. 150 m) than that of Assal. The comparison of electric conductivity monitoring data from Assal and Labbane springs (Figure 69) shows the same effect. With snowmelt continuously affecting higher regions in spring, the electric conductivity of Labbane spring drops to much lower values than at Assal spring. The reason is the decreasing chloride contents in rainfall/snow with increasing elevation and distance from the coastline (as determined by snow sampling and rainfall sampling by the BGR project).

The size of the catchment is 9.5 km^2, long-term average rainfall (modified after UNDP & FAO, 1973) is 1,900 mm/a, mean elevation is 2,171 m asl. Based on this assessment, total rainfall volume is 18.1 MCM/a, so that groundwater recharge is 81 %, considering an ET rate of 19%. The catchment determination of Labbane spring is not exact, however, it cannot be much larger than the mentioned size.

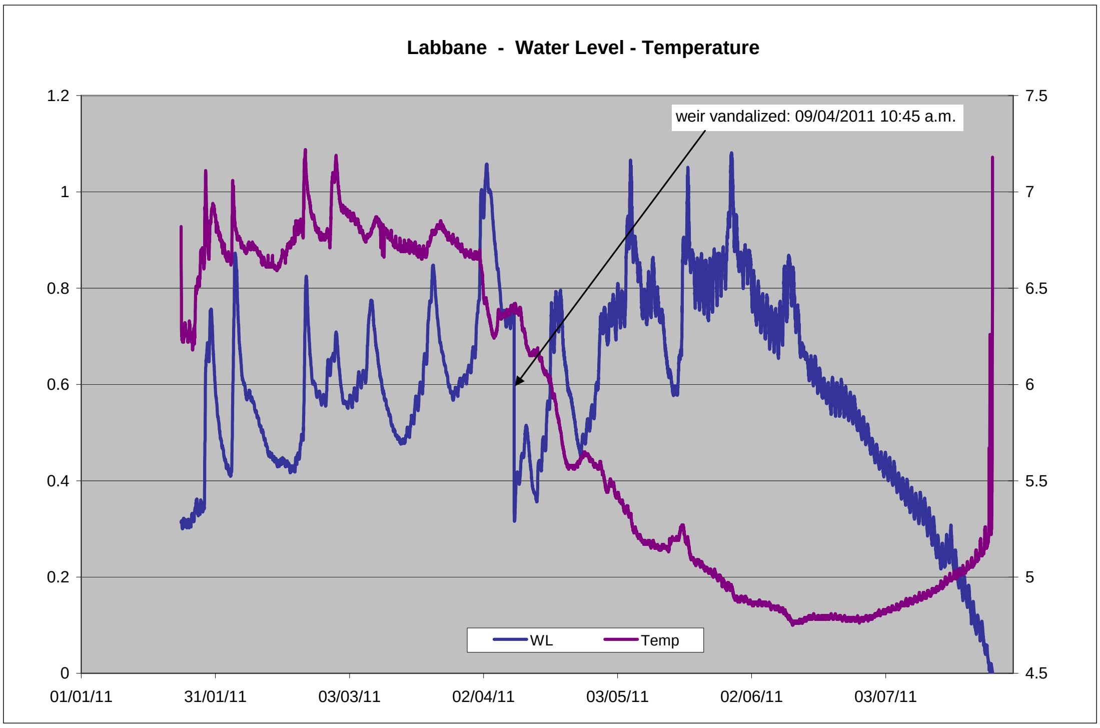


Figure 67: Measurement of Water Level and Temperature at Labbane Spring

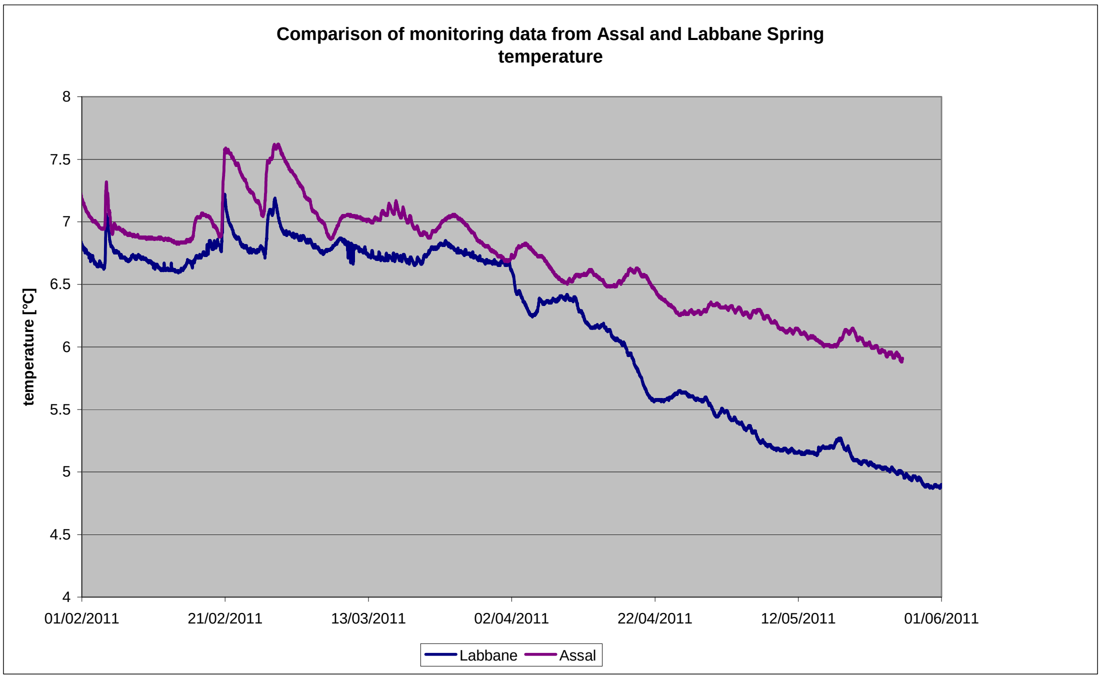


Figure 68: Comparison of Temperature Monitoring Data from Assal and Labbane Springs

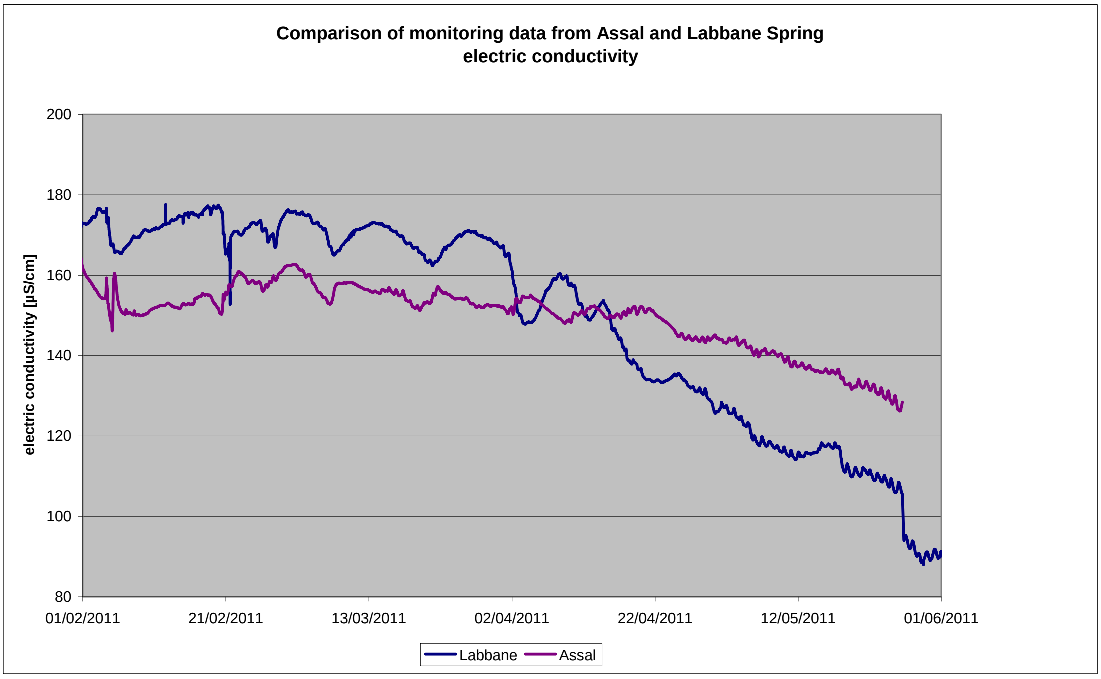


Figure 69: Comparison of Electric Conductivity Monitoring Data from Assal and Labbane Springs

Groundwater Recharge in the Jeita Catchment

Catchment boundaries in the J4 aquifer were defined based on the outcrop area of the J4, the assumed structure (see cross sections in Chapter 2.3), the tracer tests 1A-1, 1A-2, 1B-1, 2A1, 2A-2, 2B-1, 2B-2, 3A, the turbidity peaks observed in Jeita, Daraya tunnel and Kashkoush, the previous tracer tests conducted between 1913 and 1923 and the tracer tests conducted in the mid 1960s (see references in Table 9). The size of the outcrop area of the J4 within this catchment, however, is only 86.7 km² with an average elevation of 1,019 m and an average rainfall of 1294 mm/a. Such a small outcrop area cannot support the flow of Jeita. There must therefore be other inflows. There are only two possibilities for those inflows:

A) inflow from J4 aquifer from East of the Yammouneh fault (Beqa'a Valley), assuming a passage through this left-lateral shear zone (assumed horizontal displacement ~ 47 km) or

B) outflow from the Upper Aquifer (C4), flow as surface water over the Aquitard Complex and reinfiltration into the Lower Aquifer.

A) Groundwater in the J4 aquifer of the Beqaa Valley is confined under cover of Cretaceous and Tertiary sediments. The top of the J4 must be assumed to be mostly located below sea level. Below the Jurassic, there may be evaporitic sediments as found in Syria, Jordan and Israel. The DST is accompanied by evaporitic sediments (Lake Tiberias, Zemah-1 borehole, FLEXER et al., 2000; INBAR et al., 2010; diapirs in the Lisan peninsula). It must therefore be assumed that the mineralization in the J4 Aquifer of the Bekaa is substantially high. Any inflow through the Yammouneh fault, if it was possible, from the J4 would transfer water of high salinity to the Jeita catchment. As recharge of Jeita spring in the J4 occurs only in the winter months, also a high variation in electric conductivity would have to be assumed. However the electric conductivity of Jeita spring is relatively constant and ranges only between 320 and 380 µS/cm (Figure 70). This fact rules out the possibility of any significant amount of inflow through the Yammouneh Fault.

B) Moreover, differential flow measurements in the Upper Nahr Ibrahim Valley (MARGANE, 2012a, 2012b) and Nahr es Salib showed that extensive infiltration takes place in all deeply incised valleys cut into the J4. Karstification of the J4 is most extensive in the uppermost part of the J4 and surface water infiltration into the J4 aquifer is assumed to be most extensive in these areas (Janouh/Saraita; Hrajel/Mairouba; Zirghaya; south of Kfar Debbiane). The WEAP model (SCHULER & MARGANE, 2013) assumes an overall infiltration of 20% (Nahr es Salib and Zirghaya) and 23% (Nahr Ibrahim) of surface water runoff into the J4.

Infiltration is confirmed by the isotopic composition of springs which prove a large share of contribution from higher elevations (Chapter 3.10.4).

The electric conductivity encountered at Jeita can be explained by a mixture of water recharged on the J4 outcrop areas (300-500 µS/cm was encountered in stalactite dripwater of Jeita Grotto; Chapter 3.10.1) with water recharged over the C4 outcrop areas (100-200 µS/cm).

Electric conductivity and chloride content in rainfall decreases with elevation and distance from the coast (Chapter 3.10.5). Kashkoush spring has a chloride content (12-20 mg/l) which is almost twice as high as that of Jeita (8-10 mg/l). Kashkoush is mainly fed by groundwater recharge in J4 at low and mid elevations. Stable isotope contents are also higher than in Jeita (average catchment elevation: 1400 m).

Springs discharging from the Upper Aquifer (C4) have a low chloride content (2-6 mg/l). Again, the chloride content of Jeita can be explained as a mixture of local recharge on the J4, where chloride content in rainfall varies between 10 - 25 mg/l, and a large contribution from infiltration of surface water originating from the C4. Based on the very low chloride contents in Jeita, an inflow to Jeita from the Beqa'a, where chloride contents will be much higher, can be ruled out.

Even during the low flow period, spring discharge in Jeita never decreases below approx. 0.9 m^3/s. The observed minimum flow in the Upper Nahr Ibrahim Valley is around 1.5 m^3/s. Assuming that approx. 0.4 m^3/s infiltrate into the J4 and flow towards Jeita, the remaining 0.5 m^3/s must be attributed to slow flow components from the karst network in the J4 aquifer.

Based on the above it can be stated that there are two main components of flow to Jeita spring:

1) direct groundwater recharge on the Lower Aquifer (J4)

2) indirect groundwater recharge by surface water infiltration into the Lower Aquifer of water originating from a) runoff generated over the Aquitard Complex and b) runoff coming from the springs discharging from the Upper Aquifer (C4). This indirect GW recharge takes place mainly in the upper parts of the J4 outcrop in the Upper Nahr Ibrahim, the Upper Nahr es Salib, Nahr es Msann and Nahr es Zirghaya.

The respective flow paths of these components are all very different in length and flow from Nahr Ibrahim may take several weeks.

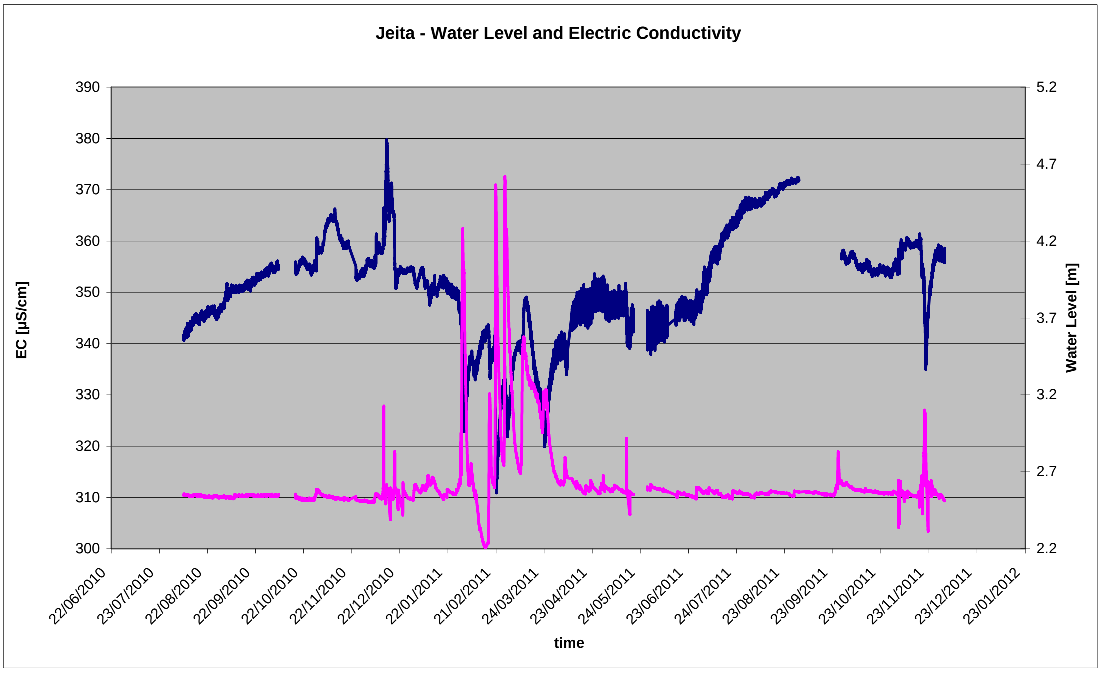


Figure 70: Monitoring of Electric Conductivity and Water Level at Jeita

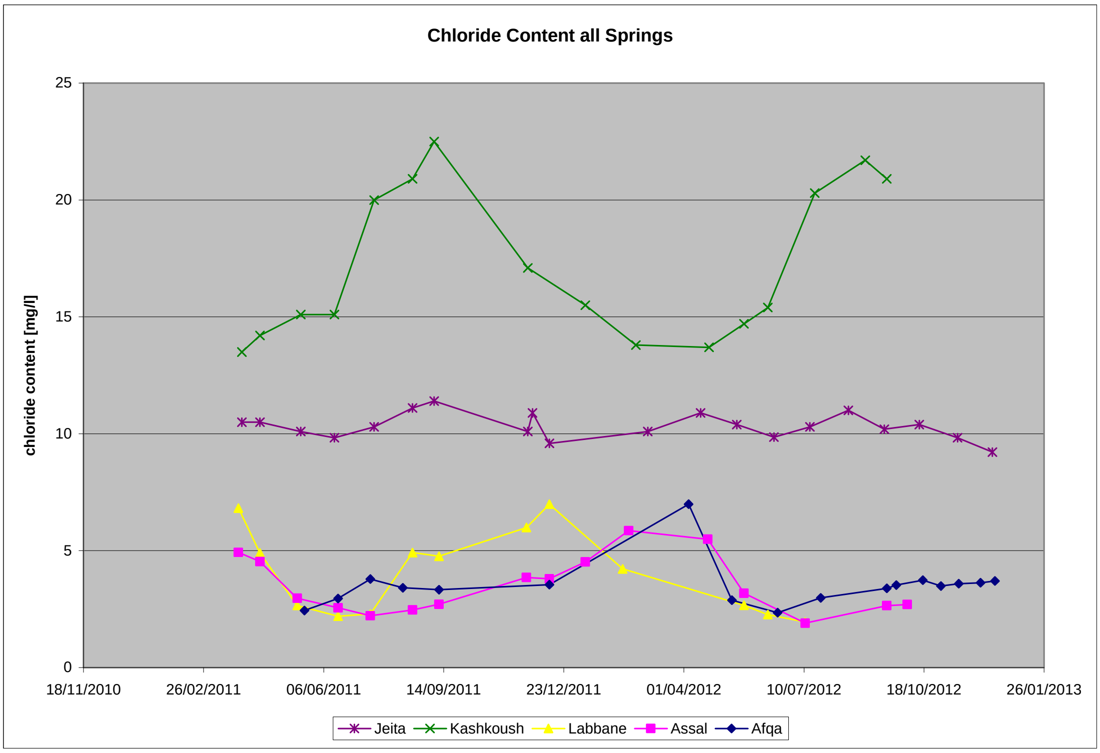


Figure 71: Chloride Content of Springs in and near the Jeita Catchment

3.5 *Groundwater Discharge*

Discharge from the Jeita GW catchment occurs at the springs in the Upper Aquifer, at Rouaiss, Afqa, Assal, Labbane as well as several small springs of minor importance (such as Qana, Maghara (J6), Hadeed), and as discharge from the Lower Aquifer at Jeita spring. The occurrence of a submarine spring in the Junieh Bay is reported but measurements seem not to have been carried out there. The catchment of this submarine spring is totally unknown and is likely not to be related to Jeita. Kashkoush spring has a GW catchment that is entirely different from the Jeita GW catchment (chapter 3.2.8).

Long-term annual groundwater discharge of the springs in the Jeita catchment is approximately as follows:

Table 10: Groundwater Discharge at Springs

Spring	Discharge [MCM/a]	Source of Information	Discharge in WEAP Model [MCM/a]
Afqa (C4)	123.2	MARGANE & STOECKL, 2013	131.2
Rouaiss (C4)	96.6	SCHULER & MARGANE, 2013	89.4
Assal (C4)	24.0	MARGANE & STOECKL, 2013	21.5
Labbane (C4)	14.4	LRA	14.6
Minor springs (C4+J6)	23.7	Estimated based on various sources	33.2
Total C4	270.2		290.0
Jeita (J4)	172	MARGANE & STOECKL, 2013	171.4

Groundwater discharge measured by BGR at the main springs in the Jeita catchment (and outside: Kashkoush) is shown below (Figures 72-75). Further details are contained in MARGANE & STOECKL (2013).

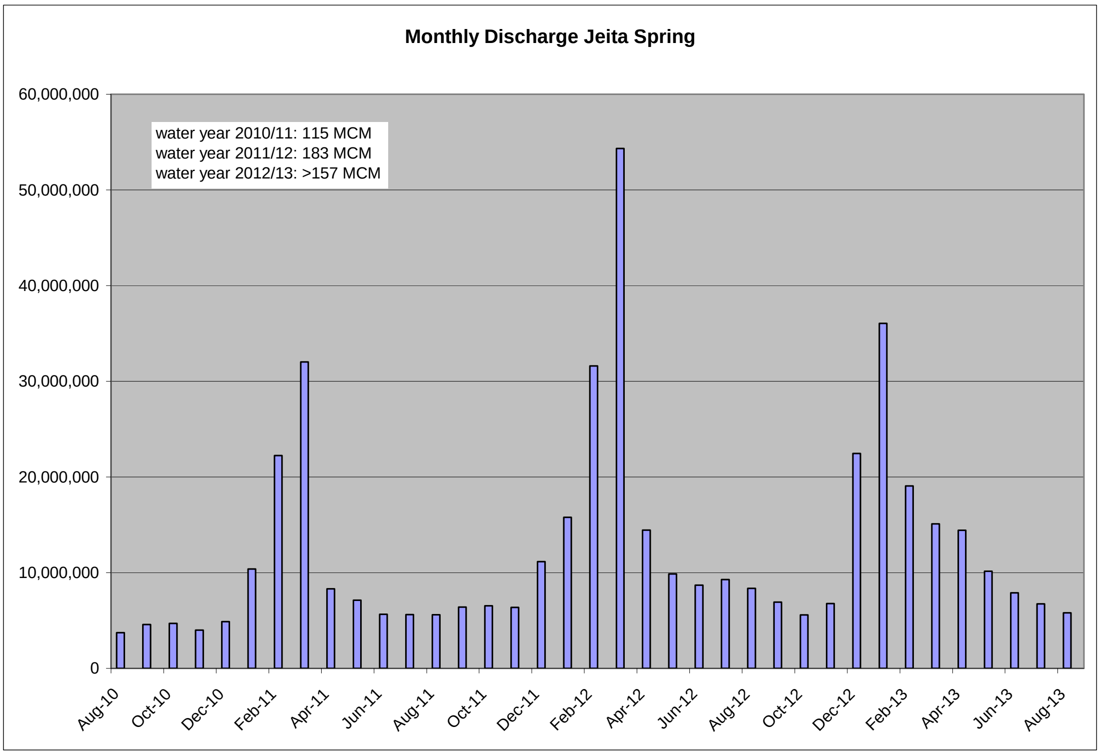


Figure 72: Groundwater Discharge at Jeita Spring (status 10.08.2013)

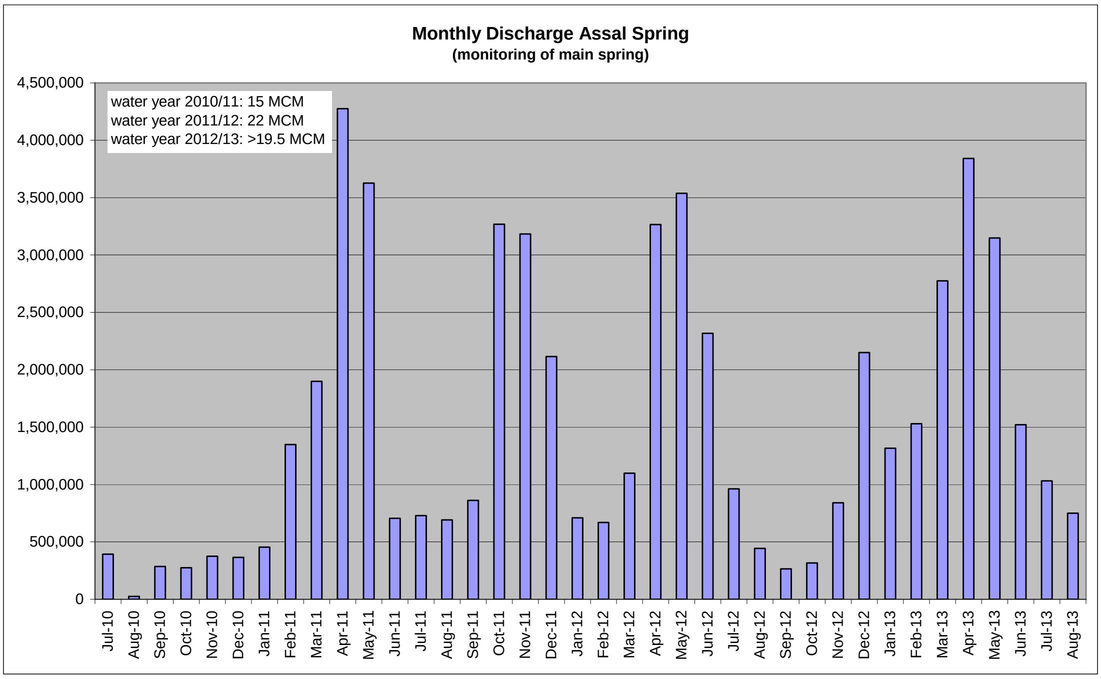


Figure 73: Groundwater Discharge at Assal Spring using Multiparameter Probe (status 10.08.2013)

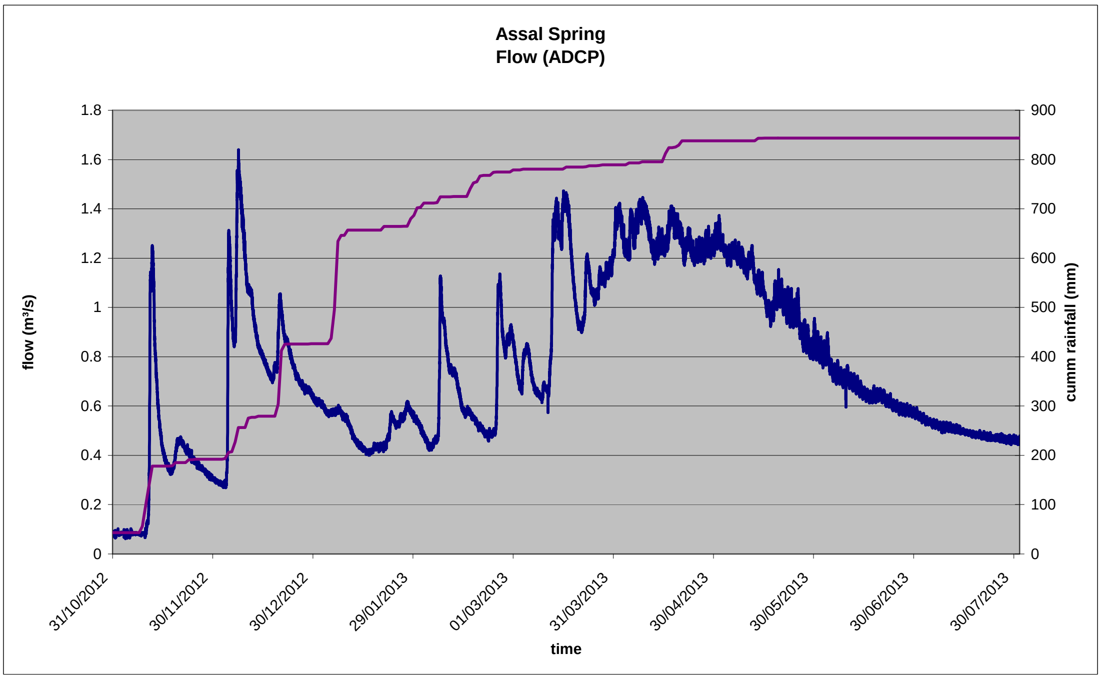


Figure 74: Groundwater Discharge at Assal Spring using ADCP (status 10.08.2013)

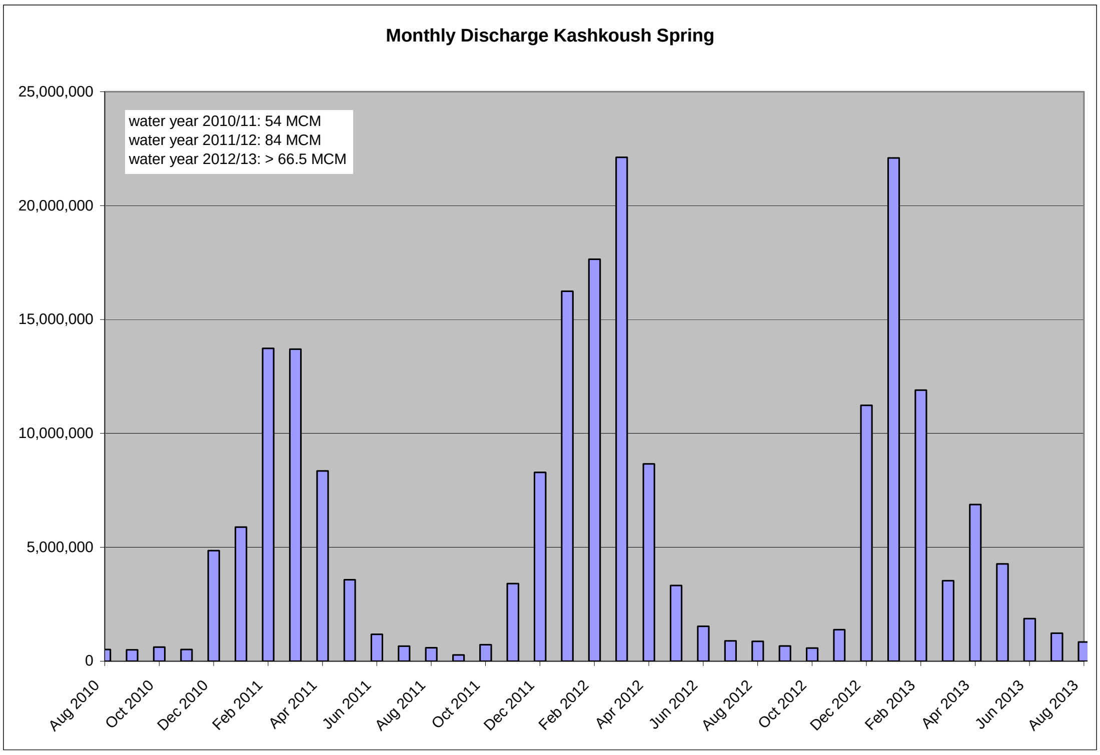


Figure 75: Groundwater Discharge at Kashkoush Spring (status 10.08.2013)

3.6 Groundwater Abstraction

There is currently no water well inventory or related database of any kind. Information seems to be either lost or spread over the different involved agencies, which do no share information. Currently the UNDP project Lebanese Centre for Water Conservation and Management (LCWCM) is setting up a database trying to overcome these difficulties. However, many fields are still blank as often not even the total depth (TD) or static water level (SWL) are known.

Groundwater abstraction for domestic water supply nowadays is of minor importance as since 2008 Chabrouh dam provides water to the entire region. Before that most of the water supply was covered by Assal spring. During the dry season or in remote areas water had to be supplied by water tankers.

There are a large number of private wells, for water sale (most of them are connected with gas stations) or for use in irrigation, however, most of these have not yet been inventoried and are not easy to get access to or obtain information from.

The following governmental wells exist in the Jeita GW catchment:

- Qamez wells (2 wells to 200/230 m TD (total depth) wells have almost no water);
- Msheti wells (2 wells to ~440 m TD; abstraction from J4; only used when no water can be supplied from Chabrouh dam);
- Wata Jaouz wells (2 wells; TD unknown; abstraction from J4; only used when no water can be supplied from Chabrouh dam);
- Hrajel wells (2 wells; TD unknown; abstraction from J4; ? not used anymore);
- Chahtoul well (375 m TD; abstraction from J4).

The available information on these wells is rather sketchy. For none of the wells a litholog could be found. WEBML stated that they don't have any detailed information to their wells. Neither could water analyses of these wells be found at the Dbayeh lab.

The following private wells were located:

Table 11: Private Water Wells in the Jeita Catchment

Well	LAT	LONG	Alt (m asl)	TD (m)	Year
Gerries Baroud well Jeita	33.953836°	35.641730°	362	?	?
Ballouneh park well	33.946750°	35.661353°	514	?	?
Simon Tabet, 7 wells	34.013818°	35.745514°	1358	540-670	Approx. since late 1970s
Saint Elias Monastery well	33.953000°	35.628712°	329	?	?
Sannine bottled water factory, 6 wells	33.969864°	35.793252°	1328	~250m	?

According to interviews with some of these operators, the seasonal water level changes in the central part of the catchment are approx. 150 m. In dry years, however, they can reach approx. 275 m.

Table 12: Governmental Water Wells in the Jeita Catchment

Well	LAT	LONG	Alt (m asl)	TD (m)	SWL (m)	Yield (m^3/h)	Annual Abstraction* [m^3]
Msheti 1 (Ain ed Delbe 1)	(34.045327°)	(35.763960°)	1070	427 (?)	380	108	240,000
Msheti 2 (Ain ed Delbe 1)	(34.044994°)	(35.763817°)	1070	?	350	100	
Wata Jaouz 1	(34.014640°)	(35.746981°)	1360	675	?	40	350,000
Wata Jaouz 2	(34.014800°)	(35.746855°)	1360		?	?	
Qamezh 1	34.055683°	35.818354°	1440	230	140	36	100,000
Qamezh 2			1440	200	140	36	
Hrajel 1	34.008894°	35.788964°	?	?	?	?	
Hrajel 2			?	?	?	?	
Chahtoul	34.03303°	35.728028°	980	375	?	54	480,000
Total							1,170,000

information based on official documents found and UNDP inventory; information acquired by BGR project in brackets or estimated (*)

The following wells are near the Jeita GW catchment but do not abstract from it:

- Kashkoush wells (6 wells to approx. 200 m; in winter artesian)
- Jeita wells (SAADEH, 1994: 8 wells to 20-250 m; currently only 2 wells used for pumpage to Qornet el Hamra via Jeita PS)
- Mokhada wells (at main road near bridge; discharge into Jeita-Dbayeh conveyor)
- Qartaba well

Based on available information about well yields and pumping schedule, a current groundwater abstraction from governmental wells of around 1.2 MCM/a is assumed. Of this amount only 0.5 MCM are used inside the GW catchment, while 0.7 MCM are used outside the catchment. Groundwater abstraction from private wells used to be high before the completion of Chabrouh dam but has decreased significantly thereafter. Public water supply is nowadays available in all villages, however, certain areas, located higher than the reservoirs are still dependent on water supply by tankers. Groundwater abstraction for this purpose will not be more than 0.5 MCM/a, as modeled in WEAP.

A larger share of groundwater is needed for irrigation because water supply from springs and surface water is not sufficient and irrigation canals are poorly maintained. The total amount of private groundwater abstraction for irrigation is estimated at 5 MCM/a.

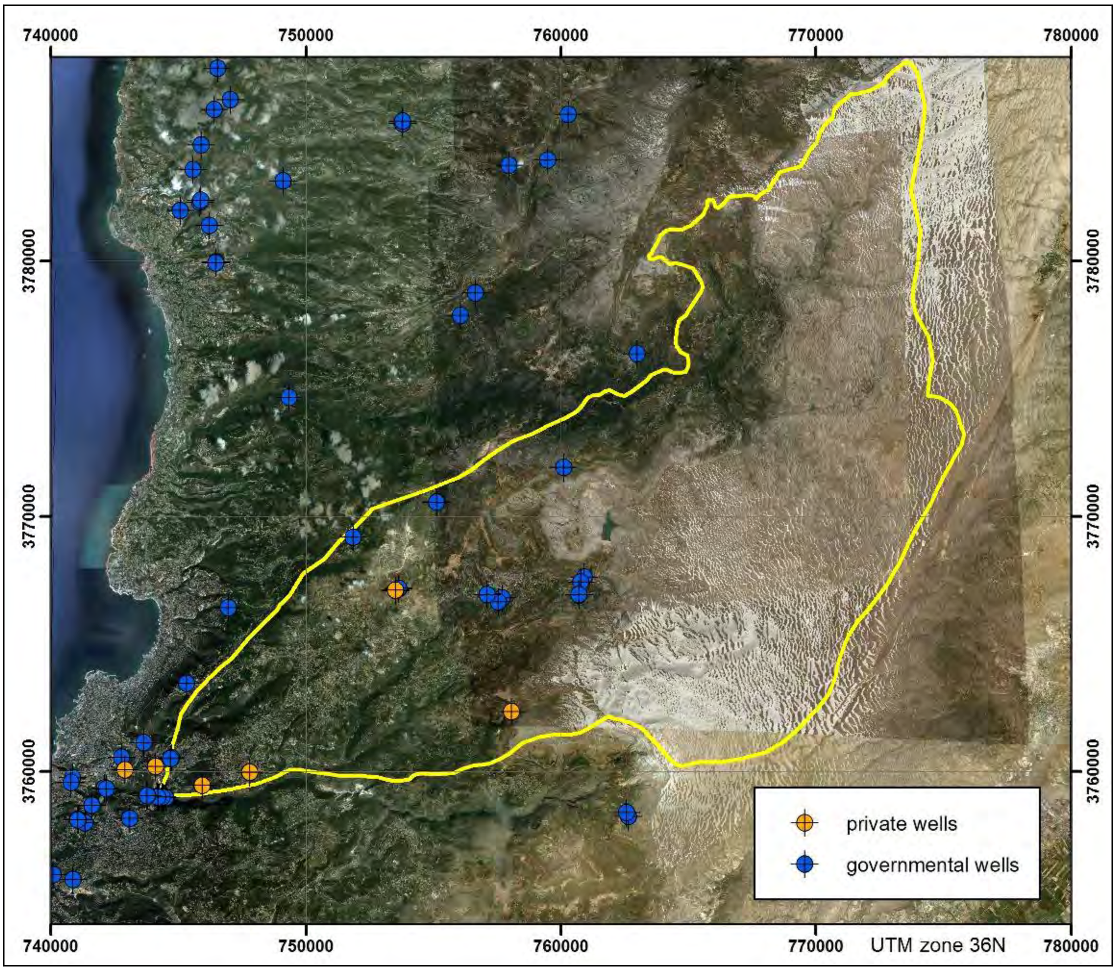


Figure 76: Water wells in the Jeita catchment
(modified after inventory by UNDP project)

3.7 Groundwater Use

It is the domestic and agricultural sectors, which are considered as water users in calculating the water balance. There is little industrial activity within the catchment, which also has no water intensive production. Therefore, industrial activity is considered as domestic supply in the water balance. The overall water balance is explained in Chapter 3.10 and was compiled using WEAP. Catchment IDs used in this chapter refer to those listed in Chapter 3.10 (Table 16).

3.7.1 Domestic Water Supply

Villages in the Jeita GW catchment receive their supply almost exclusively by the governmental supply system, which is mainly fed by Chabrouh reservoir and Assal Spring.

To assess the flows for domestic supply and its return flow, villages in the Jeita GW catchment are aggregated to demand sites, according to their proximity in space and their shared return flow destination. Domestic demand is defined as 51.1 m^3/cap/a (140 l/c/d), except for the demand sites Ayoun es Simane and Faqra Club, which are expected to have a higher demand of 60 m^3/cap/a (164 l/c/d).

There is a high seasonal fluctuation of present population in the catchment. Due to the existence of many summer residents, population records are much higher in summer than in winter. Figure 77 displays the intra-annual water demand of the domestic demand sites.

Annual domestic water demand is 6.6 MCM. During the winter months, which are considered to be January to March, total demand is 1.3 MCM, which corresponds to 0.4 MCM per month. In summer, demand raises up to 0.6 MCM per month or 5.3 MCM for the respective period.

Since demand is expected to be met, the demand equals the supply that is delivered to the demand sites. However, network losses account for 35%, which leads to a GWR of 3.4 MCM per year. Table 13 shows all demand sites, their annual supply delivered from the respective source and their contribution to GWR by return flow and network leakage in MCM.

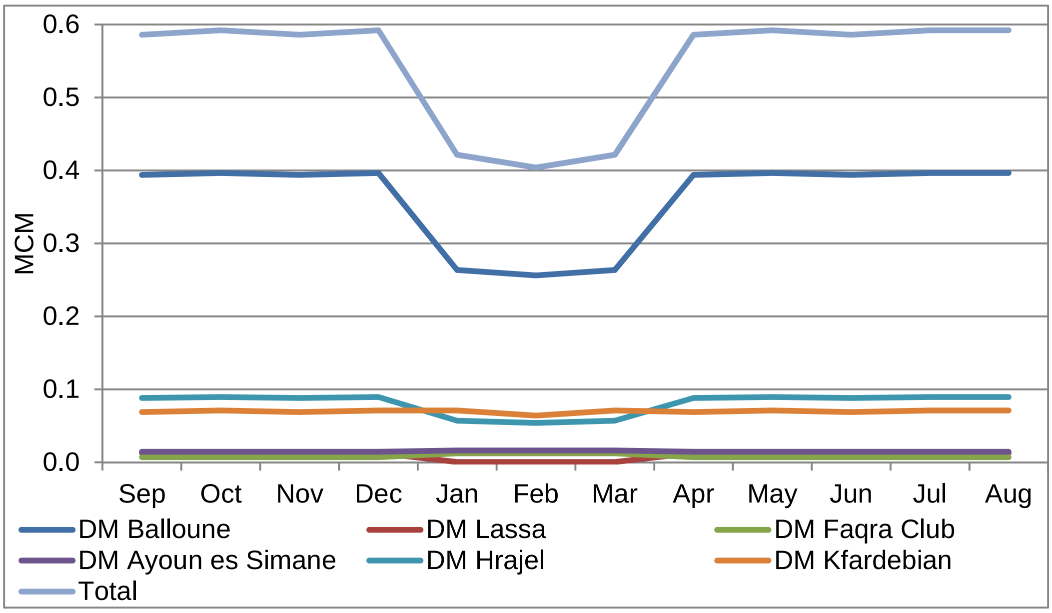


Figure 77: Monthly Water Demand in the Jeita Catchment

Table 13: Annual Inflow and Outflow of aggregated Demand Sites in the Jeita GW Catchment

Domestic demand site	Demand in MCM/a	Supply source		Network loss		Return flow	
		Conveyed in MCM/a	Source	in MCM/a	to GW	in MCM/a	to GW
DM Balloune	4.3	6.7	Chabrouh /Assal	2.3	J4	2.2	J4
DM Lassa	0.1	0.2	Afqa	0.0	Aquitard	0.0	Aquitard
				0.0	J4	0.0	J4
DM Faqra Club	0.1	0.2	Chabrouh /Assal	0.1	GW Labbane	0.1	C4 Springs
DM Ayoun es Simane	0.2	0.2	GW Labbane/ Chabrouh	0.1	Aquitard	0.1	GW Labbane
DM Hrajel	1.0	1.5	Chabrouh /Assal	0.5	Aquitard	0.5	Aquitard
DM Kfardebian	0.8	1.3	Chabrouh /Assal	0.4	Aquitard	0.4	Aquitard
Sum	**6.6**	**10.0**		**3.4**		**3.3**	

3.7.2 Agricultural Water Use

Agricultural activity takes place exclusively on the J4 unit and the Aquitard Complex. Agricultural activity is classified into the crops apples and tomatoes, with a respective seasonal variation of k_c values. Detailed results according to the crop classes can be found in SCHULER & MARGANE (2013).

Figure 78 displays the annual quantities of agricultural demand covered through precipitation (rainfed) as well as supplementary irrigation via canals and groundwater and irrigation fraction (additional supplied irrigation due to efficiency of 75%).

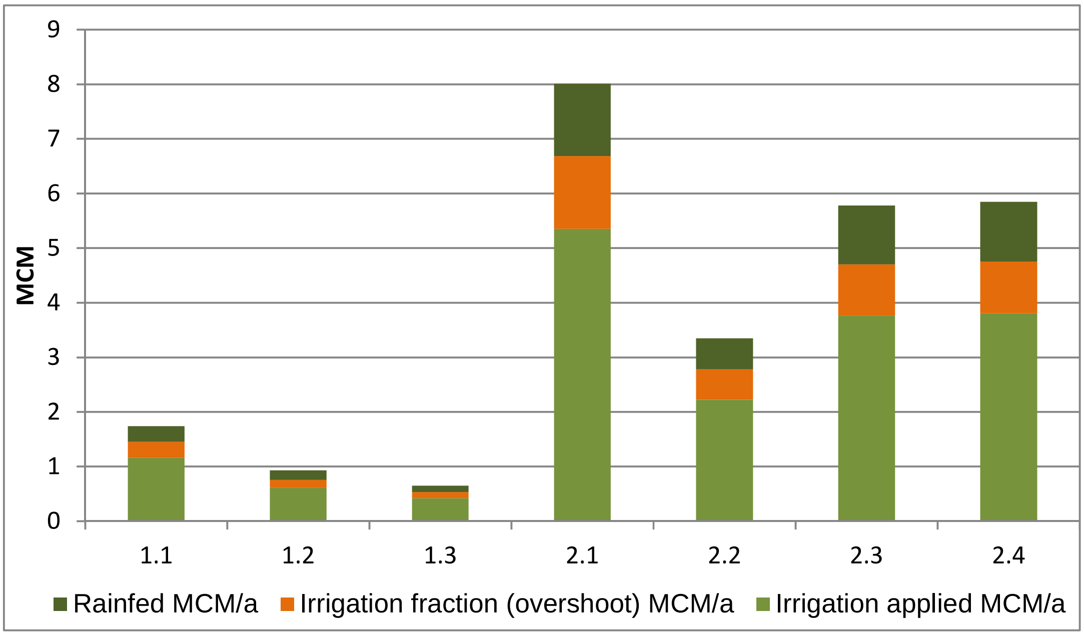


Figure 78: Annual Agricultural Demand per Sub-Catchment, covered by Rain, Irrigation and additional Irrigation Demand due to Irrigation Efficiency (75%)

The J4 aquifer accounts for 12.6% of agricultural demand, corresponding to 2.2 MCM of total agricultural demand. The Aquitard Complex is the main area of agricultural activity, demanding 87.4% or 15.4 MCM per year.

The total water demand for the agricultural sector, including rainfall and irrigation (75% efficiency), is 22 MCM, of which 18 MCM reach the crop. Therefore, 4 MCM account for irrigation overshoot, which is subject to GWR but mainly surface runoff (Figure 79). Due to the karstification of the J4 and resulting high groundwater recharge rate, irrigation overshoot is much more prone to GWR than to surface water runoff. In turn, above the Aquitard Complex, GWR by irrigation overshoot is negligible in comparison to the high rate of surface runoff towards streams. Table 14 gives an overview about the total annual demand of each sub-catchment, as well as the specific sources of supply.

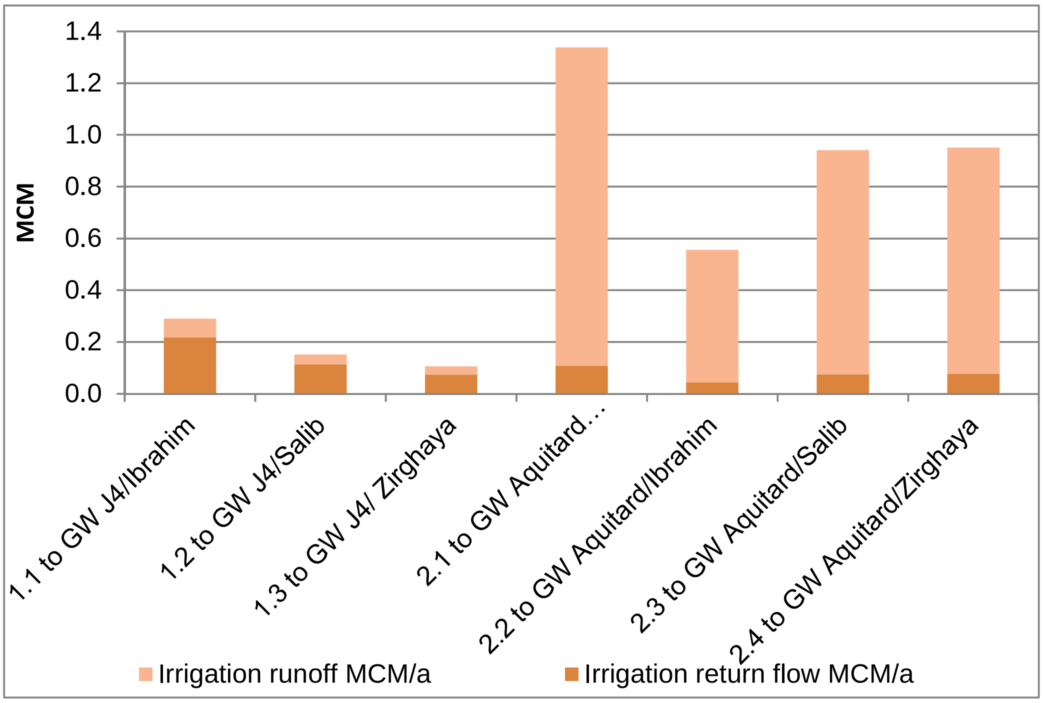


Figure 79: Annual Overshoot of Irrigation per Sub-Catchment and resulting Flow to Groundwater/Surface Water

Table 14: Annual Agricultural Demand of each Sub-Catchment

Agricultural demand site	Demand in MCM/a	Source of supply
1.1	1.2	GW J4, irrigation canal
1.2	0.6	GW J4, irrigation canal
1.3	0.4	GW J4, irrigation canal
2.1	5.3	GW Aquitard Rouaiss, irrigation ponds, Rouaiss spring
2.2	2.2	GW Aquitard, irrigation canal, C4 Springs
2.3	3.9	GW Aquitard, irrigation canal, C4 Springs
2.4	3.9	GW Aquitard, irrigation canal, C4 Springs

All catchments receive resources from their connected groundwater system. Besides this, irrigation canals throughout the Jeita catchment provide 4.4 MCM per year, mainly by Assal and Labbane Spring and a minor share by Chabrouh reservoir. All sub-catchments above the J4 and Aquitard Complex, except SC 2.1 are connected to the irrigation canal system. Sub-catchment 2.1 receives resources from irrigation ponds, which have altogether an approximate static storage capacity of 1 MCM. Also, Rouaiss spring provides water to SC 2.1.

Minor C4 Springs are providing water to the central sub-catchments of the Aquitard Complex, namely 2.2-2.4.

3.7.3 Proposal for Optimized Groundwater Use

According to the water resources assessment in the Jeita catchment (SCHULER & MARGANE, 2013), surface water resources are largely unused. Only a small part still contributes to irrigation. At the same time the water supply in the Greater Beirut Area, which is mainly based on Jeita spring (~75%), experiences shortages at the end of the dry season, between October and December. During this time discharge from Jeita spring decreases to a minimum of around 1 m^3/s. However, due to leakage losses from the Jeita-Dbayeh conveyor, only around 60,000 m^3/d arrive at the Dbayeh drinking water treatment plant. This amount is not enough to meet the demand in the Greater Beirut Area.

Surface water runoff commonly stops during June/July. Due to the high karstification in the J4 geological unit through which the rivers mainly pass, storage of surface water runoff is rather difficult. Storage may be enhanced by dolomitization processes which took place in part of the J4 probably due to basalt intrusion and subsequent invasion of hydrothermal waters (ABI RIZK & MARGANE, 2011; MARGANE, 2012a). This can be observed especially along the main E-W directed faults between Nahr el Kalb and Sannine mountain, the Nahr el Kalb - Sannine Fault Zone. Here a major dolomitization has taken place and it might therefore be possible to store water over an extended period, although with a relatively high infiltration rate. The BGR project has proposed to build the 'Daraya dam' which would be able to close part of the supply deficit (GITEC & BGR, 2011).

Another possibility would be to construct simple Managed Aquifer Recharge (MAR) dams (GITEC & BGR, 2011), the sole purpose of which would be to facilitate infiltration of surface water into groundwater and thereby to increase the discharge of Jeita spring during the dry season. These dams could be built by dumping construction waste and subsequent compaction during the dry season at specific places with limited coating of the dam side facing the reservoir. This simple construction could significantly reduce the costs. Large blocks of limestone would need to be included to increase stability. This would not only address the water shortage issue but also provide a solution for the random dumping of construction waste.

Five locations for MAR dams were proposed (GITEC & BGR, 2011).

3.8 Return Flows

The following return flows exist in the Jeita GW catchment (Table 15):

- return flows from water supply facilities (mainly the network);
- return flows from wastewater facilities (mainly open cesspits and injection wells);
- irrigation return flows.

Return flows from the water supply network and from wastewater will mainly go to the J4 aquifer. Water supply network loss almost completely contributes to GW recharge. It is estimated that at least 35% of piped water is lost in the network. With an annual actual water supply of 6.6 MCM, a total of 10.0 MCM is conveyed, from which estimated 3.4 MCM are lost from the supply network by leakage and contribute to GWR. Return flow from leaking cesspits or intentionally injected wastewater by the domestic sector is estimated at 50% of the supplied amount, i.e. 3.3 MCM/a. The other 50% are considered as ET.

Irrigation efficiency is 75%, thus, the 25% overshoot is available for catchment processes, i.e., it is split into GWR and surface runoff. Return flow from agriculture on the J4 is 14% of applied irrigation and 2% on the Aquitard Complex.

Table 15: Estimated Return Flows

Type	Coming from	Amount [MCM/a]	Going to
Water supply	C4 springs/Chabrouh	2.3	J4 aquifer
Wastewater	Water supply	2.2	J4 aquifer
Irrigation	C4 springs (irrigation canal)/GW Aquitard	0.3	Aquitard
	C4 springs (irrigation canal)/GW J4	0.4	J4

3.9 Dams

Hydrological features related to dams were partly already documented in Special Report No. 8 (MARGANE & STOECKL, 2013).

Chabrouh dam was built between 2004 and 2007 by Coyne & Bellier and Libanconsult. The dam is a bituminous face rockfill dam (BFRD; Figures 80, 81). It required extensive grouting along more than 60,000 m of drilled boreholes, up to 90 m deep. Despite this fact, it still shows considerable leakage through the earthfill dam on the western shoulder.

The dam receives only little direct runoff from the surrounding catchment (mostly C4 geological unit) and most water stored in the dam is transferred to it by a channel and closed pipe from Labbane spring. The transfer system from Labbane has a maximum capacity of 1.5 m³/s, which is far less than the maximum discharge after snowmelt (around 10 m³/s). Chabrouh dam provides drinking water for the Keserwan district between Faraiya and Junieh.

Storage in Chabrouh dam is 9.0 MCM. The dam crest is 63 m high, located at 1618 m asl. The treatment plant immediately downstream of Chabrouh dam has a capacity of 60,000 m³/d. Operation began in 2008.

Due to the small internal catchment size and the nature of the rocks (limestone, marlstone) silt accumulation in the dam is expected to be much less than in the two other dams currently under construction, Boqaata and Janneh.

The Janneh dam was planned already in the 1950s with the support of US (USBR) and French engineers. A new planning was done starting in 2004 by Khatib and Alami, finalized in 2012. The dam is currently under construction. Janneh dam has a surface water catchment of 242 km². It will have a dam height of 100 m (842 m asl) and a static storage of 30 MCM. Dynamic storage is calculated to be around 90 MCM, of which 85 MCM are intended to be used for domestic water supply of all Jbeil villages below 900 m. For irrigation 5 MCM will be used. A hydropower generation of 40 MW is projected. The dam will be built as RCC (roller compacted concrete) dam.

The entire dam is located on the J4 geological unit, partly highly karstified, especially in the upper part. Geological dip is around 4° towards E. While the J4 near the dam crest consists mainly of dolomite and dolomitic limestone, the entire eastern part consists of limestone (Figure 83). Extensive caves are found in this upper part. A surface water infiltration zone was located by the BGR project at around 800 m asl (Figures 82, 83; MARGANE, 2012a, 2012b). It is assumed that the infiltrating water contributes to Jeita spring. The existence of a karst network in this upper part was also proven by a well drilled at Saraita by WEBML in spring 2013.

The Boqaata dam is currently under construction as RCC dam. The aim is to have a static storage of 6 MCM and a dynamic storage of 12 MCM in a catchment of 16.5 km². The dam crest will be 71.5 m high (1011.5 m asl). Once completed it shall provide drinking water for approx. 260,000 inhabitants in Metn (all villages between Btegrine, Ain Saade, Douar-Choueir). It is, however, also located partly on highly karstified J4 geological unit and the same location was therefore proposed by the BGR project as MAR dam to increase groundwater recharge to Jeita spring (Figure 84; GITEC & BGR, 2011). Silt accumulation in Boqaata dam will be extensive because of nearby C1 sandstone quarries and erosion of volcanic tuff (J5) in Boqaata.

Besides Boqaata Dam, several other reservoirs were proposed by the project. Kfar Debbiane Dam is one MAR option for the J4 aquifer. with the dam has a static storage of 7.3 MCM and is located on the J4 unit. Its theoretical coverage extents over mainly unpopulated area, making it a favorable option. Assuming a leakage of 20% of storage/month if storage exceeds 1.5 MCM, Kfar Debbiane Dam could increase discharge of Jeita by ~17 MCM/a (SCHULER & MARGANE, 2013).

The dams existing in the area and currently under construction are shown in Figure 85.

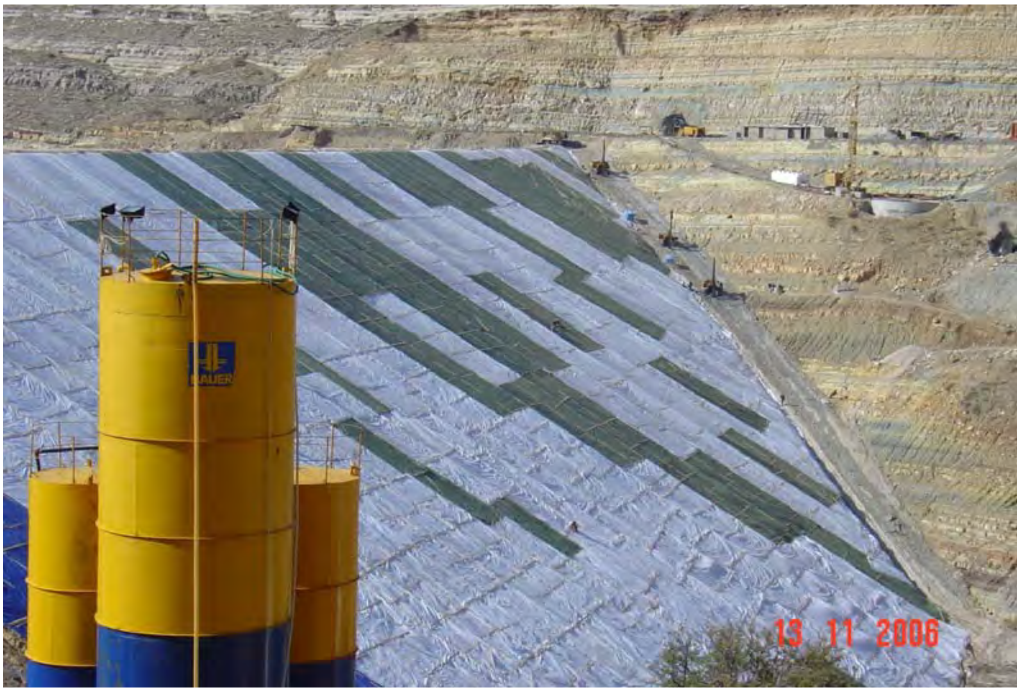


Figure 80: Construction of Chabrouh dam

Figure 81: Chabrouh Dam with Overflow Structure in February 2011

Figure 82: Location of Janneh Dam (under construction)

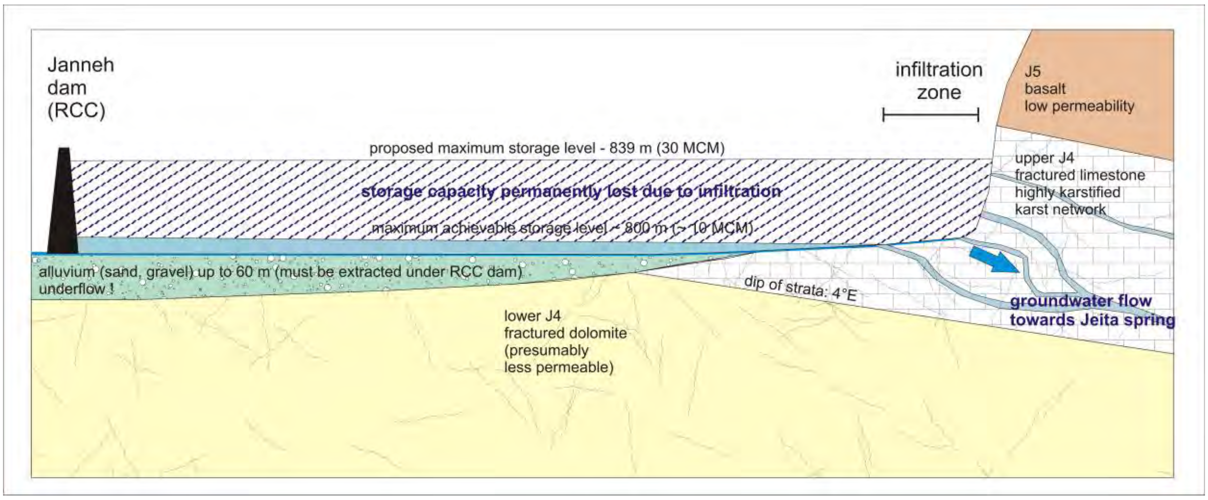


Figure 83: Geological Underground at Janneh Dam (under construction)

Figure 84: Location of Boqaata Dam (under construction)

(blue symbol: MAR dam proposed by BGR; GITEC & BGR, 2011)

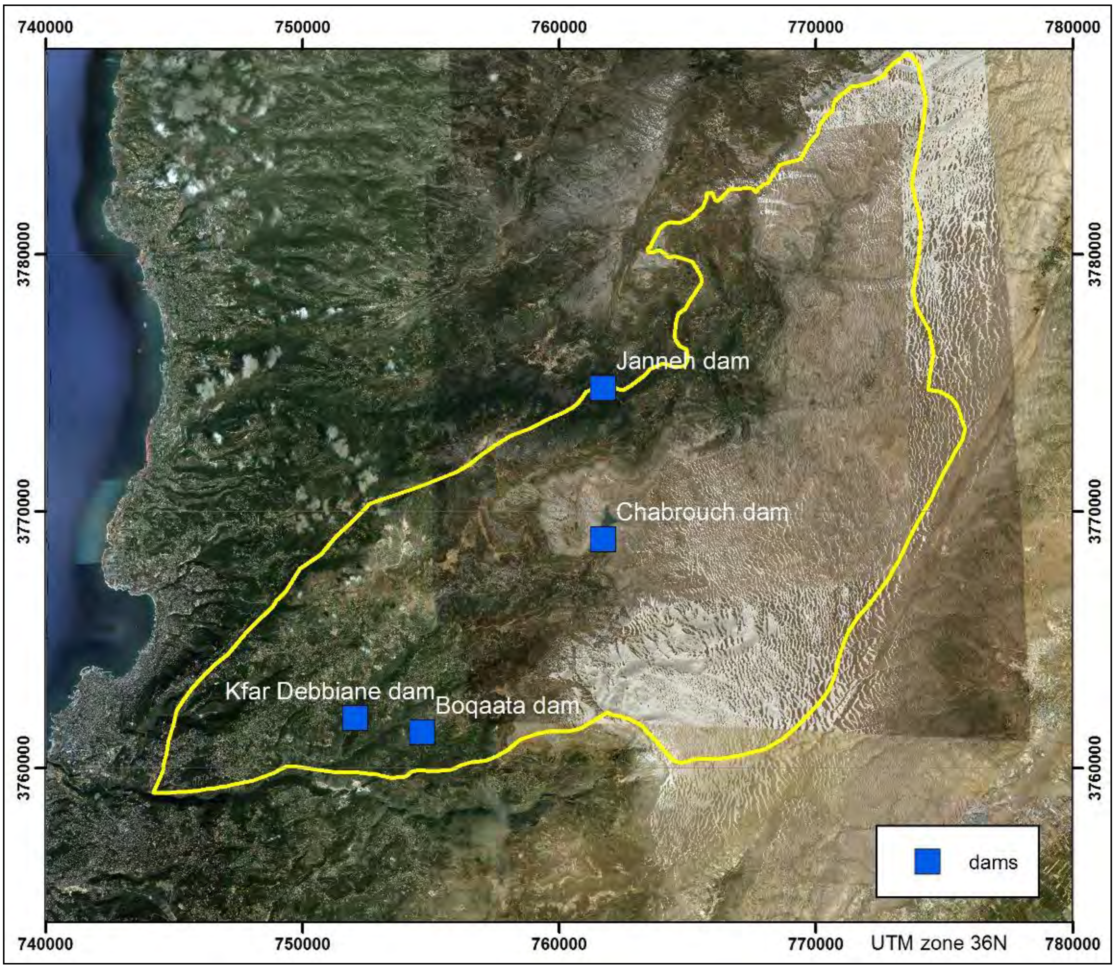


Figure 85: Dams in the Jeita Catchment

3.10 Groundwater Balance

To assess the absolute in and outflows of the Jeita GW catchment, a WEAP (Water Evaluation and Planning) (SEI, 2011) has been established (SCHULER & MARGANE, 2013). WEAP is commonly used to model a surface water catchment, however, as proven, WEAP is also applicable to quantify a groundwater balance.

The model is based on the basic hydrologic formula for a system (equation 1; Chapter 3.4) without any GW in and outflow.

As previously outlined, the physical setting of the catchment is characterized by a high degree of spatial variation in:

- relief and elevation;

- climatic conditions, due to orographic lifting of the eastwards moving weather front along the elevation gradient of western exposed mountain range of the Lebanon Mountains;
- infiltration/percolation rates depending on the rock type and its specific permeability, as well as the overlying soil cover.

The groundwater catchment is divided into 13 sub-catchments (SC) (Figure 86, Table 16), based on the characteristics of the considered area: (a) hydrogeology: Upper Aquifer (C4), Aquitard Complex (C3-J5), Lower Aquifer (J4), (b) GW catchments: C4 spring/reservoir catchments and (c), SW catchments (direction of surface runoff). Each sub-catchment is represented by one catchment node. There are three catchment nodes in the J4: ID 1.1 where SW runoff is directed towards outside the GW catchment (C J4 West), ID 1.2 where SW runoff is directed towards Nahr es Salib (C J4 Nahr es Salib) and ID 1.3 where SW runoff is directed towards Nahr es Zirghaya (C J4 Nahr es Zirghaya). Four catchment nodes represent the Aquitard: ID 2.1 and ID 2.2 where SW runoff is directed towards Nahr Ibrahim (C AT Rouaiss and C AT North West), ID 2.3 where SW runoff is directed towards Nahr es Salib (C AT Nahr es Salib) and ID 2.4 where SW runoff is directed towards Nahr es Zirghaya (C AT Nahr es Zirghaya). The C4 is split into six catchments: the GW catchments of the four main springs, ID 3.1 Rouaiss spring (C C4 Rouaiss), ID 3.2 Afqa spring (C C4 Afqa), ID 3.3 the catchment of the Chabrouh reservoir (C C4 Chabrouh), ID 3.4 minor springs draining the C4 (C C4 Springs), ID 3.5 Assal spring (C C4 Assal), and ID 3.6 Labbane spring (C C4 Labbane).

In order to be able to model snow accumulation and snowmelt in the C4 outcrop area, all respective catchments were modeled using the soil moisture method. The catchment nodes of the Aquitard Complex and Lower Aquifer (J4) were modeled using the simplified coefficient method.

The model runs on monthly time steps, modeling one water year.

For a detailed overview about the schematic and methodology applied, see SCHULER & MARGANE (2013).

Table 16: Data for WEAP Sub-Catchments

Catchment node	Catchment ID	Size in km²	Mean elevation (m asl)*	Mean annual rainfall**
C J4 West	1.1	63.3	1,019	1,296
C J4 Nahr es Salib	1.2	15.8	1,124	1,333
C J4 Nahr es Zirghaya	1.3	7.6	1,003	1,232
C AT Rouaiss	2.1	23.4	1,422	1,525
C AT North West	2.2	22.7	1,385	1,501
C AT Nahr es Salib	2.3	24.5	1,440	1,521
C AT Nahr es Zirghaya	2.4	27.9	1,409	1,430
C C4 Rouaiss	3.1	65.8	1,919	1,613
C C4 Afqa	3.2	101.5	2,012	1,613
C C4 Chabrouh	3.3	4.5	1,771	1,613
C C4 Springs	3.4	24.4	1,771	1,585
C C4 Assal	3.5	14.6	2,174	1,807
C C4 Labbane	3.6	9.5	2,171	1,900
J4		*86.7*	*1,019*	*1,297*
Aquitard		*98.6*	*1,407*	*1,492*
C4		*220.3*	*1,970*	*1,635*
Total		**405.6**	**1,630**	**1,529**

Source of data: * SRTM DEM; ** modified after UNDP & FAO, 1973

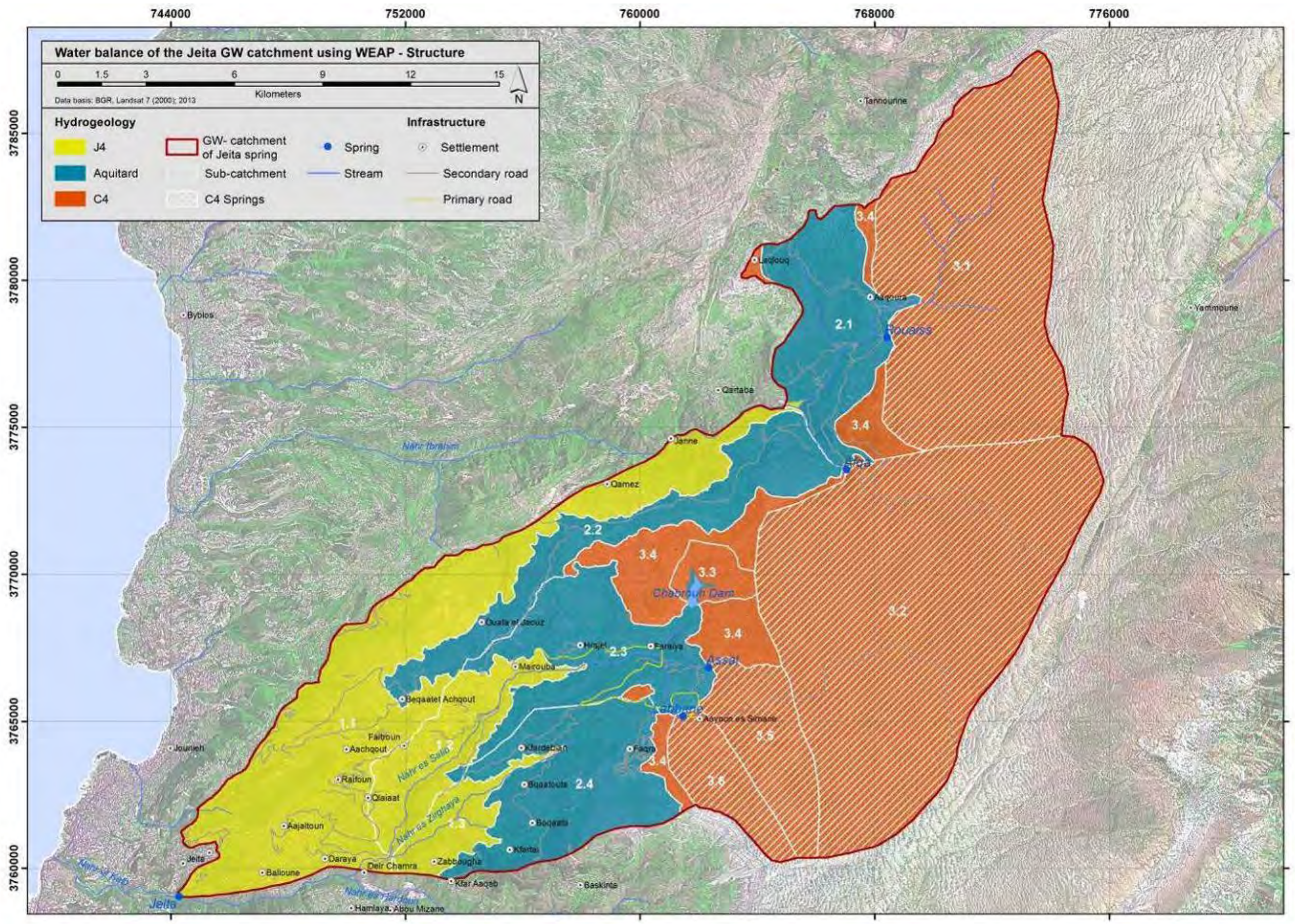


Figure 86: Sub-Catchments of WEAP Model for the Jeita Groundwater Catchment

3.10.1 Natural Water Balance

The natural water balance refers to the assessment of water flows, counting each drop only once (pre-development). Therefore, anthropogenic supply and demand is not considered in this calculation, since any conveyance can only happen after precipitation has been subject to runoff, infiltration or evapotranspiration. This calculation is important because it reveals the actual GW recharge rate for each sub-catchment, which is important for validation/calibration of the model.

Figure 87 displays the annual precipitation (P) input (outer ring) and groundwater recharge (GWR), evapotranspiration (ET) and surface runoff (SR) (inner ring) for each hydrogeological unit.

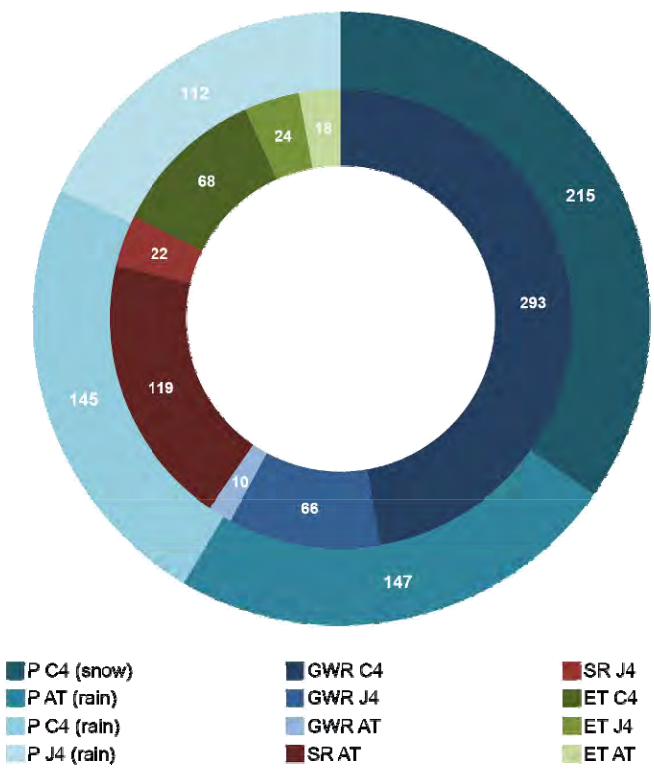


Figure 87: Natural Annual Water Inflows and Outflows of the Hydrogeological Units in the Jeita GW Catchment

GWR = groundwater recharge, P = Precipitation, SR = Surface runoff, ET = Evapotranspiration

In total, the catchment receives annually 619.8 MCM precipitation of which 34.7% (215.3 MCM) fall as snow and 65.3% (404.5 MCM) as rain. Due to the extent of the C4 (with regards to elevation and areal extent), this hydrogeological unit receives the largest share of annual P (58.1%), leading to 293.4 MCM GWR per year. Due to the high degree of karstification of the C4 and large number of dolines, surface runoff does not occur in this unit. The J4 unit generates 66.0 MCM/a GWR (58.7% of P) and the Aquitard Complex generates 10.3 MCM/a (7.0% of P). The overall GWR rate of each hydrological unit is calculated by weighting the GWR rate of each sub-catchment according to its catchment size (Table 17).

Table 17: Groundwater Recharge, Surface Water Runoff and Evapotranspiration as Share of Precipitation in each Hydrogeological Unit

Hydrogeological Unit	GWR in %	SR in %	ET in %
Upper Aquifer (C4)	81.3	0.0	18.7
Aquitard Complex	7.0	80.8	12.2
Lower Aquifer (J4)	58.7	20.0	21.3

The more GWR is generated, the less SR will be. The J4 generates 20% (22.5 MCM/a) of its P as surface runoff, while above the Aquitard, 81% (118.8 MCM/a) of P runs off towards streams.

ET is calculated, depending on landuse/landcover, the potential ET and the availability of water. The rate of ET is the highest above the J4 unit because the J4 is largely covered by land classes with a relatively high crop coefficient (k_c) value. The k_c value expresses "*the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions.*" (ALLEN et al., 1998). It is therefore a specific value for a certain land class that ranges according to the potential availability of water. It is applied for vegetation, as well as for non-vegetative land classes. Total annual ET accounts for 18% of total annual precipitation, summing up to 109.6 MCM.

3.10.2 Anthropogenic Water Balance

The anthropogenic water balance includes water conveyance, thus, water resources may be counted several times.

Figure 88 shows the total annual output of Jeita's GW catchment, considering agricultural and domestic water demand and ET losses.

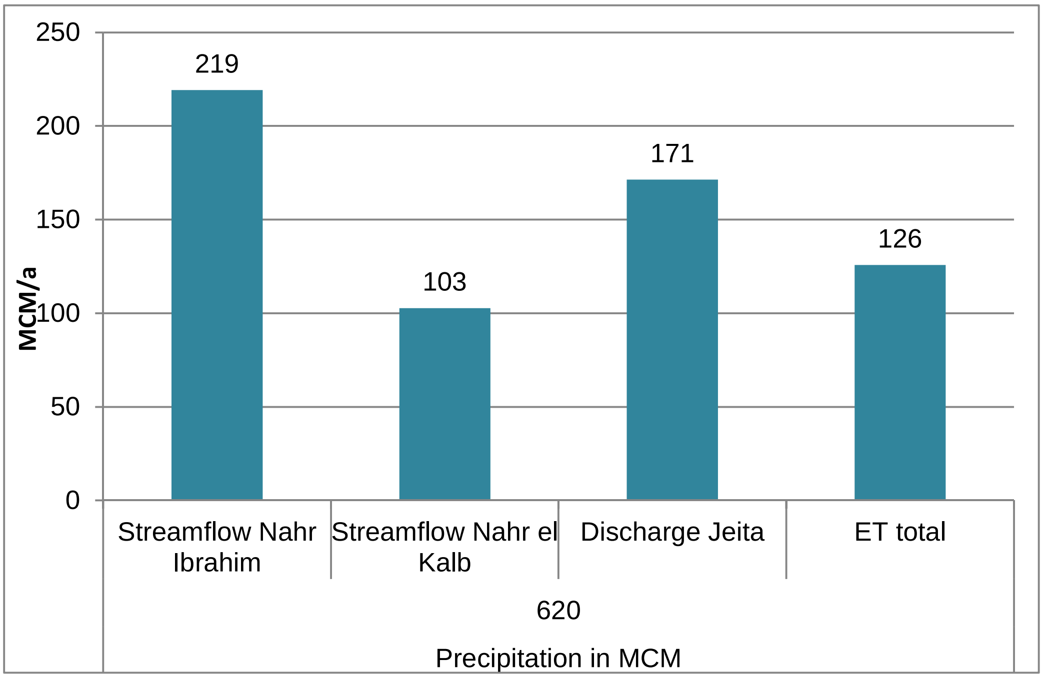


Figure 88: Annual Output from the GW Catchment of Jeita Spring

Surface water leaves the catchment either via Nahr el Kalb or via Nahr Ibrahim. The share of Nahr el Kalb accounts for 102.8 MCM/a, which fits to the measured records of LRA at Daraya gauging station for the period 1967-1974 (Figure 89).

For Nahr Ibrahim, no measured records of a suitable station are available, so no comparison between measured and modeled records can be done. However, considering all in and outflows of the river, 219 MCM leave the catchment this way. Nahr Ibrahim receives a total inflow of 275 MCM from the Jeita catchment. The highest inflows come from Afqa and Rouaiss Spring, which contribute by 47.5%, 31.6% respectively, summing up to 217 MCM per year (Figure 90). In addition, Rouaiss Aquitard (SC 2.1) adds another 25.6 MCM (9.3% of total inflow) to the streamflow. As proven by MARGANE (2012a, 2012b), a large share of the river flow infiltrates into the J4 aquifer, explaining the large annual discharge quantity of Jeita Spring of 171 MCM (Figure 91). River bed infiltration of Nahr Ibrahim accounts for 23%, summing up to 56 MCM per year.

Results of MARGANE (2012a, 2012b) indicate that with a decrease in streamflow of Nahr Ibrahim also the rate of infiltration decreases, which implies a seasonal variation of infiltration. Thus, discharge of Jeita depends on the discharge regime of Afqa and Rouaiss spring.

Downstream of this infiltration point, another 32 MCM concentrate towards Nahr Ibrahim, explaining the total annual discharge of 219 MCM.

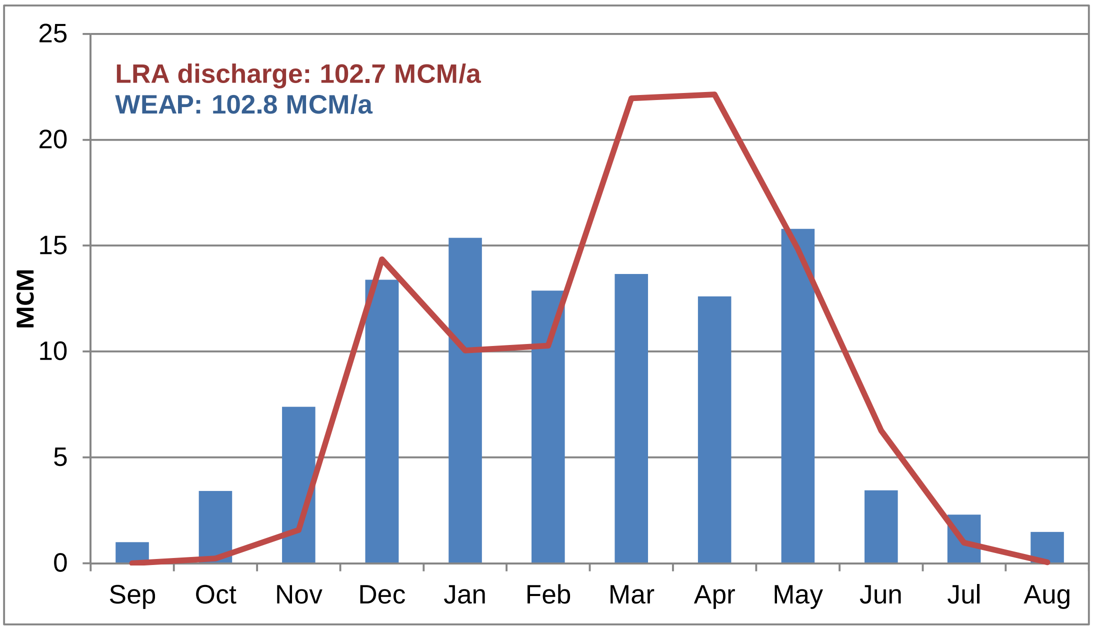


Figure 89: Average Monthly Streamflow of Nahr el Kalb at Daraya Gauging Station (Station 226) during Water Years 1967/1968- 1973/1974 as measured by LRA (red line) and Modeled Streamflow (blue columns)

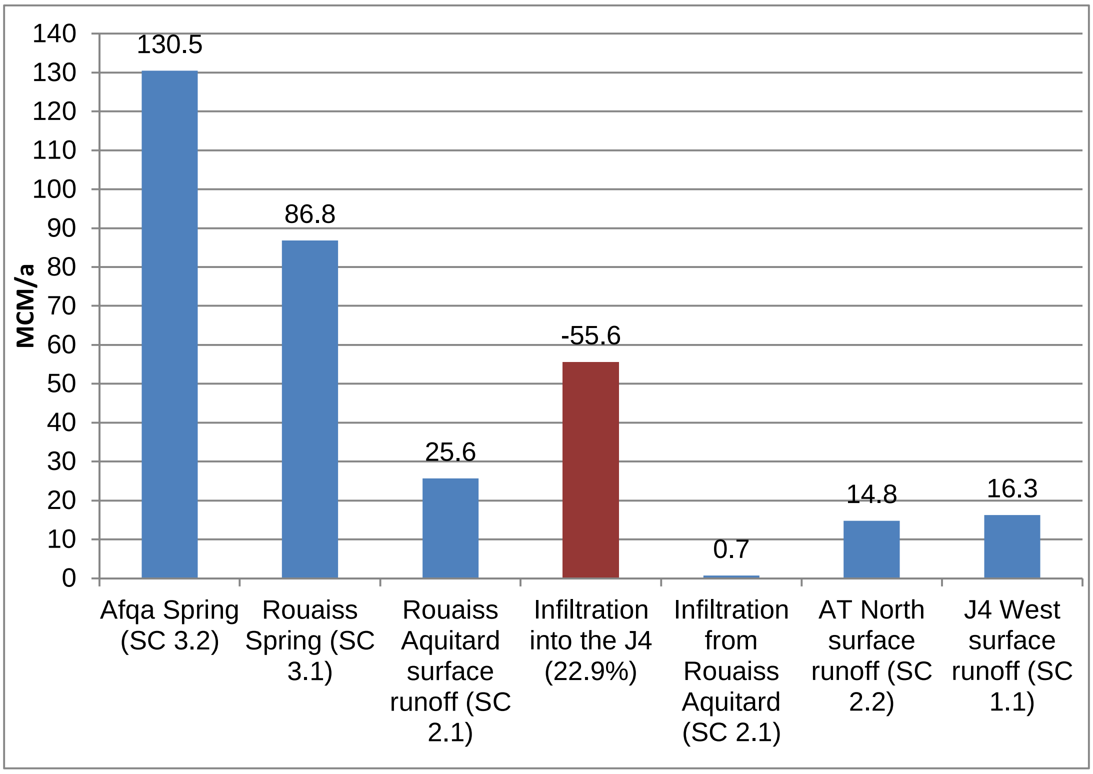


Figure 90: Annual Inflow (blue bars) and Outflow (red bar) of Nahr Ibrahim

(SC = sub-catchment)

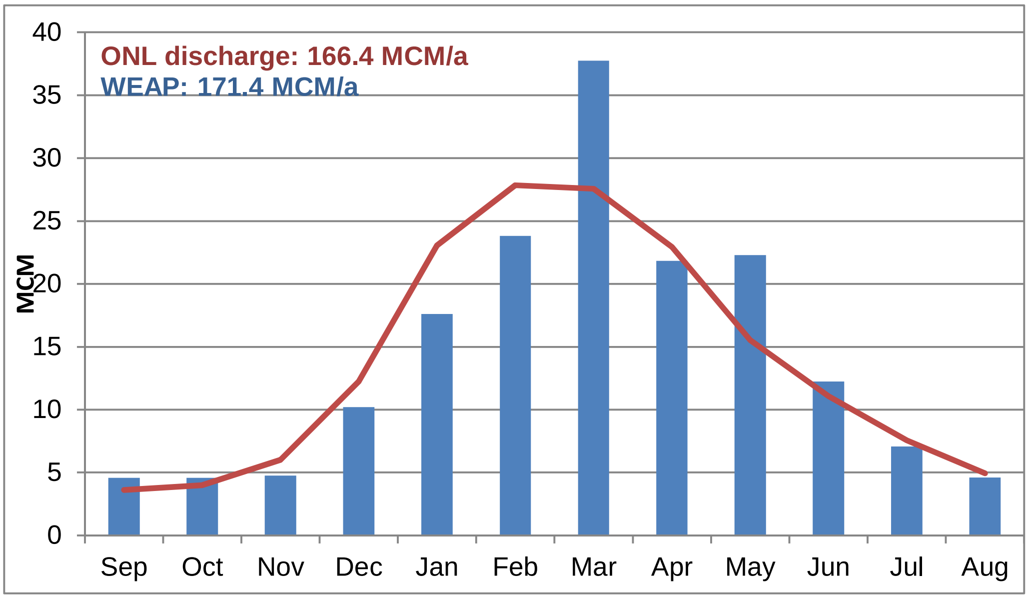


Figure 91: Historical Discharge of Jeita Spring (red line) during Water Years 1966/1967 – 1970/1971 (excluding 1968/1969) as measured by LRA and Modeled Spring Discharge (blue columns) of Jeita Spring

Total surface water outflows of Nahr el Kalb and Nahr Ibrahim amount to 322 MCM/a, while total GW outflow at Jeita spring is 171 MCM/a (Figure 91). According to the historical data of ONL (Office National de Litani) (UNDP, 1972), the annual discharge varies heavily, which is also related to the insufficient measurement intervals and uncertain methodology. According to these data, Jeita spring discharged 307.5 MCM in the water year 1968/1969. This figure is unrealistic, and is therefore not considered in the calculation and display of the average monthly discharge records for the period 1966/1967 – 1970/1971, resulting in an average discharge of 166 MCM. This figure must be corrected for GW abstraction at the time (~ 6 MCM/a), so that total discharge was approx. 171/172 MCM/a (MARGANE & STOECKL, 2013; SCHULER & MARGANE, 2013). These numbers fit better to the present measurements that have been conducted by the project (Chapter 3.5; Figure 72). According to the WEAP model, discharge of Jeita accounts for 171 MCM per year, with a maximum in March of 37.8 MCM (14.1 m^3/sec) and a minimum in October of 4.6 MCM (1.7 m^3/sec).

ET account for 126 MCM. From these 126 MCM, 3.3 MCM (2.6% of total ET) account for domestic ET, 4.6 MCM (3.7% of total ET) for rainfed agriculture, 13.0 MCM (10.3% of total ET) for irrigation that is supplementary applied to meet agricultural demand and 104.8 MCM (83.4 % of total ET) for ET from vegetation and sealed surfaces (Figure 92).

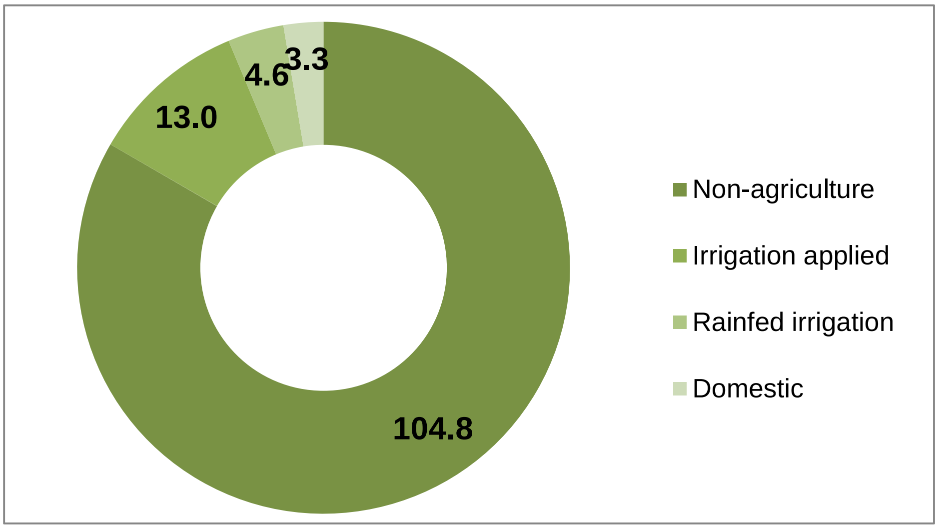


Figure 92: Annual Evapotranspiration from different Sources in MCM

Total groundwater recharge sums up to 475 MCM/a (Figure 93).

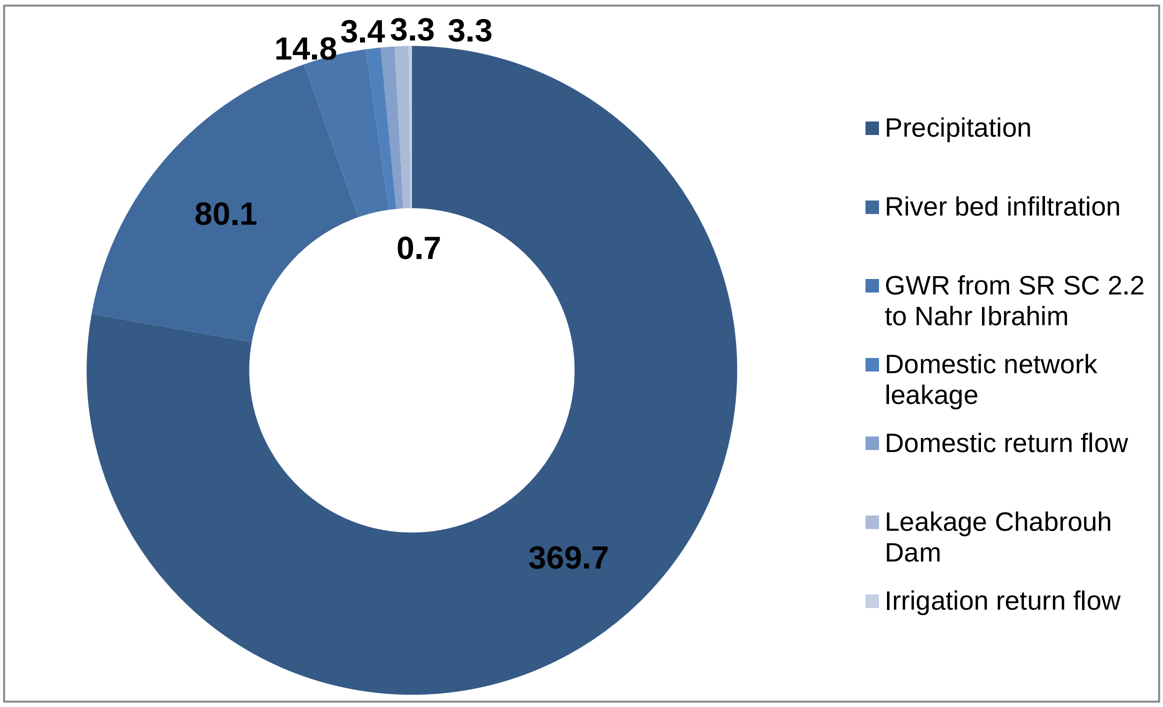


Figure 93: Annual Groundwater Recharge (GWR) in the Jeita GW Catchment in MCM

The smallest share, 0.7 MCM (0.2% of total GWR) originates from irrigation return flow. Leakage of Charrouh Dam towards GW C4 Springs accounts for 3 MCM/a (0.7% of total GWR). GWR from domestic supply accounts for 6.7 MCM (3.3 MCM domestic return flow and 3.4 MCM leakage from network), which corresponds to 1.4% of total GWR (0.7% domestic return flow and 0.7% leakage from network). 15 MCM of GWR are generated by SR, which concentrates from SC 2.2 towards Nahr Ibrahim. The generated surface runoff passes over the highly karstified SC 1.1, from where more than 50% of the surface runoff infiltrate towards the J4. Total riverbed infiltration accounts for 80.1 MCM (16.9% of total GWR), where Nahr es Zirghaya accounts for 9.2 MCM, Nahr es Salib for 15.2 MCM and Nahr Ibrahim for 55.6 MCM. Direct GWR from precipitation is by far the largest figure, 369.7 MCM, which corresponds to 77.8% of total GWR.

Most surface water runoff originates from the discharge of the C4 springs. Runoff generated on the Aquitard Complex and J4 is 145 MCM, from which 3.6 MCM (2.5% of total runoff) are generated from irrigation runoff.

For intra-annual analysis, Figure 94 displays the monthly inflows (positive records) and (out-)flows (negative records) of the Jeita GW catchment. Between October and end of April the catchment receives almost 600 MCM (97%) of its annual precipitation in the entire catchment. During this period 384 MCM fall as rain and 215 MCM fall as snow. Snow accumulation occurs exclusively above the C4, between November and end of March.

The very low precipitation regime in summer explains the need of 13 MCM of applied irrigation per year (excl. irrigation overshoot of 75%) (Figure 92) between May and end of September. Irrigation return flow accounts for 0.7 MCM, considering an irrigation efficiency of 75 %. According to this, GWR from irrigation return flow is 14% on the J4 and 2 % on the Aquitard Complex.

Return flow from domestic water supply sums up to 3.3 MCM (total domestic demand 6.6 MCM), since consumption rate is defined as 50 %. Network losses account for 35% of the conveyed quantities and add another 3.4 MCM as recharge to groundwater.

Natural groundwater recharge by rainfall and melting snow reaches its monthly peak in April, due to intense snowmelt, reaching 154 MCM in this month alone. Snowmelt lasts for three months (from March to the end of April) and is of utmost importance for GWR to the Upper Aquifer springs.

C4 springs drain the Upper Aquifer before feeding streams, such as Nahr es Salib, Nahr es Zirghaya and Nahr Ibrahim. As previously outlined, the latter one is of high importance for Jeita spring/J4 aquifer due to the large quantities of riverbed infiltration from Nahr Ibrahim into the J4 Aquifer (MARGANE, 2012a, 2012b; KOENIGER & MARGANE, 2013).

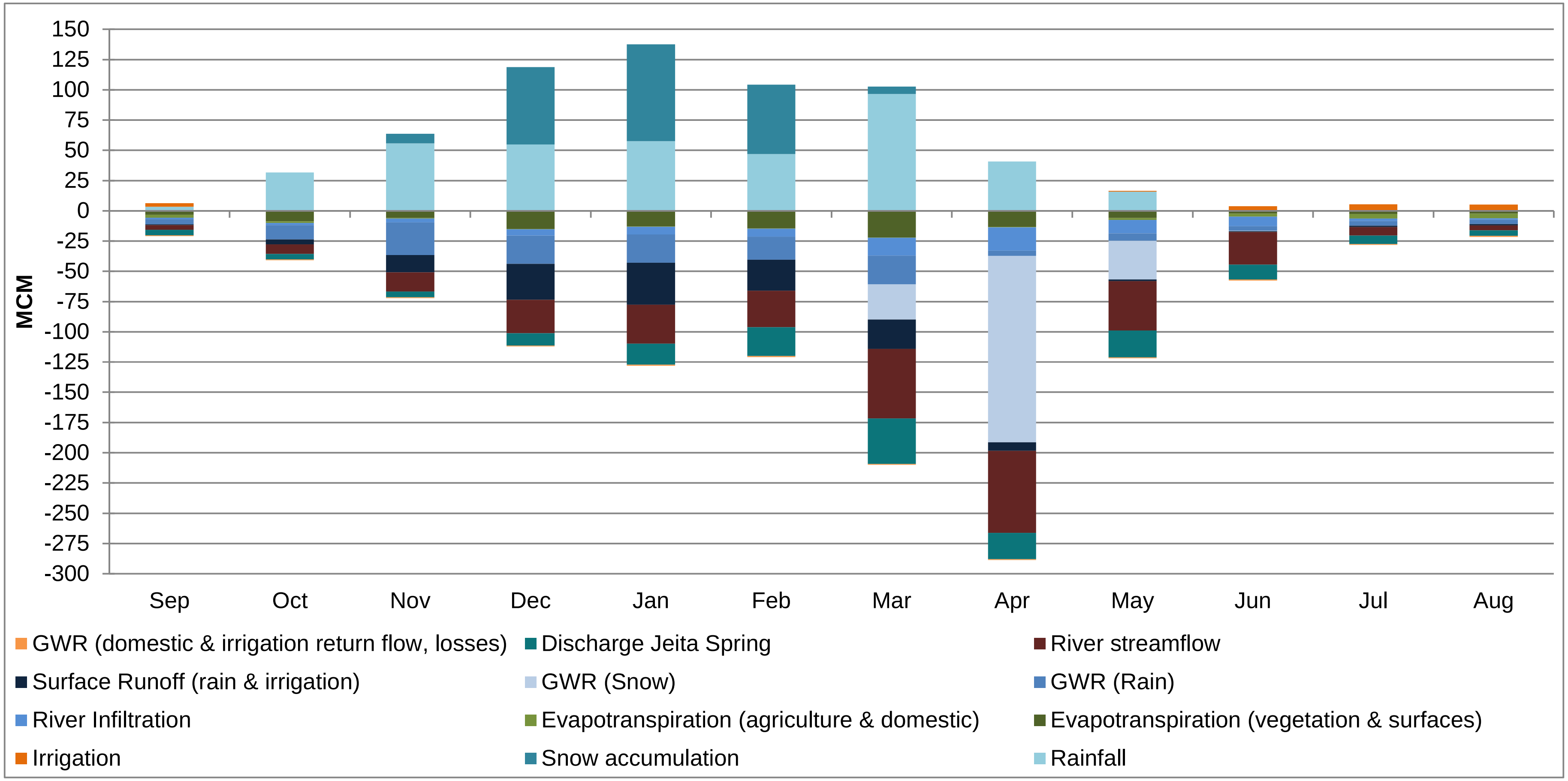


Figure 94: Monthly Inflow and Outflow of the Jeita GW Catchment

High karstification, similar to the intensity of Ibrahim Valley, occurs also in other parts of the catchment, namely in the upper J4 and in the respective river valleys of Nahr es Zirghaya and Salib Valley. A specific quantity of infiltration has not been proven so far by any tracer tests, however, repeating events of surface water pollution in Zirghaya Valley were detected 24 hours later in Jeita Grotto, indicating a high probability of a hydrological connection between the surface water in the related catchment and the J4 aquifer. Thus, Zirghaya and Salib River are also defined as loosing streams in this WEAP model, which accounts for an infiltration rate of 20.2%, considering the concentrating surface runoff of the sub-catchments above the J4 (2.3, 2.4, 3.4-3.6). This infiltration is not only needed to reach the annual discharge of Jeita spring but also to fit the annual streamflow of Nahr el Kalb to the modeled output (Figure 91).

In total, total river bed infiltration of all three loosing streams towards the J4 sums up to 80.1 MCM/a, which corresponds to 46.2% of the total annual inflow towards the J4.

3.10.3 Sources of Jeita/J4 Aquifer

The Lower Aquifer (J4) aquifer, receives its major share of inflow from riverbed infiltration. WEAP allows to identify the quantity of each possible flow path towards a certain flow point in order to illustrate the origin of respective resources, which is important in order to know where GW protection is most needed.

Total annual inflow towards the J4 sums up to 173.1 MCM; the difference between the input and the output is abstracted to directly cover agricultural and domestic water demand in sub-catchments 1.1 to 1.3 and to convey resources towards outside the catchment from the Msheti and Chahtoul wells.

Table 18 displays the absolute and relative share of the three hydrogeological units contributing to the J4 Aquifer.

Table 18: Sources of Flow to the Lower Aquifer (J4)

Hydrogeological Unit	Flow to J4 in MCM/a	Flow to J4 in %
Upper Aquifer (C4)	67.5	39.0
Aquitard Complex	39.5	22.8
Lower Aquifer (J4)	66.0	38.2

About 39% of flow at Jeita spring originates from the C4, with the largest share of 30 MCM (17%) coming from the catchment of Afqa spring (17 MCM or 56% are generated through snowmelt in the Afqa catchment).

Rouaiss Spring contributes by 20 MCM, from which 11 MCM (55%) are generated by snowmelt. Figure 95 displays the origin of water resources in the Lower Aquifer (J4), including the annual (natural) hydrological balance for each sub-catchment in MCM.

The Aquitard Complex contributes 40 MCM (23% of the annual discharge), mainly via surface runoff that concentrates towards streams from where it partly infiltrates into the upper J4.

66 MCM (38% of the annual discharge) of contribution stems from the J4, where 58.7% of rainfall recharge the aquifer.

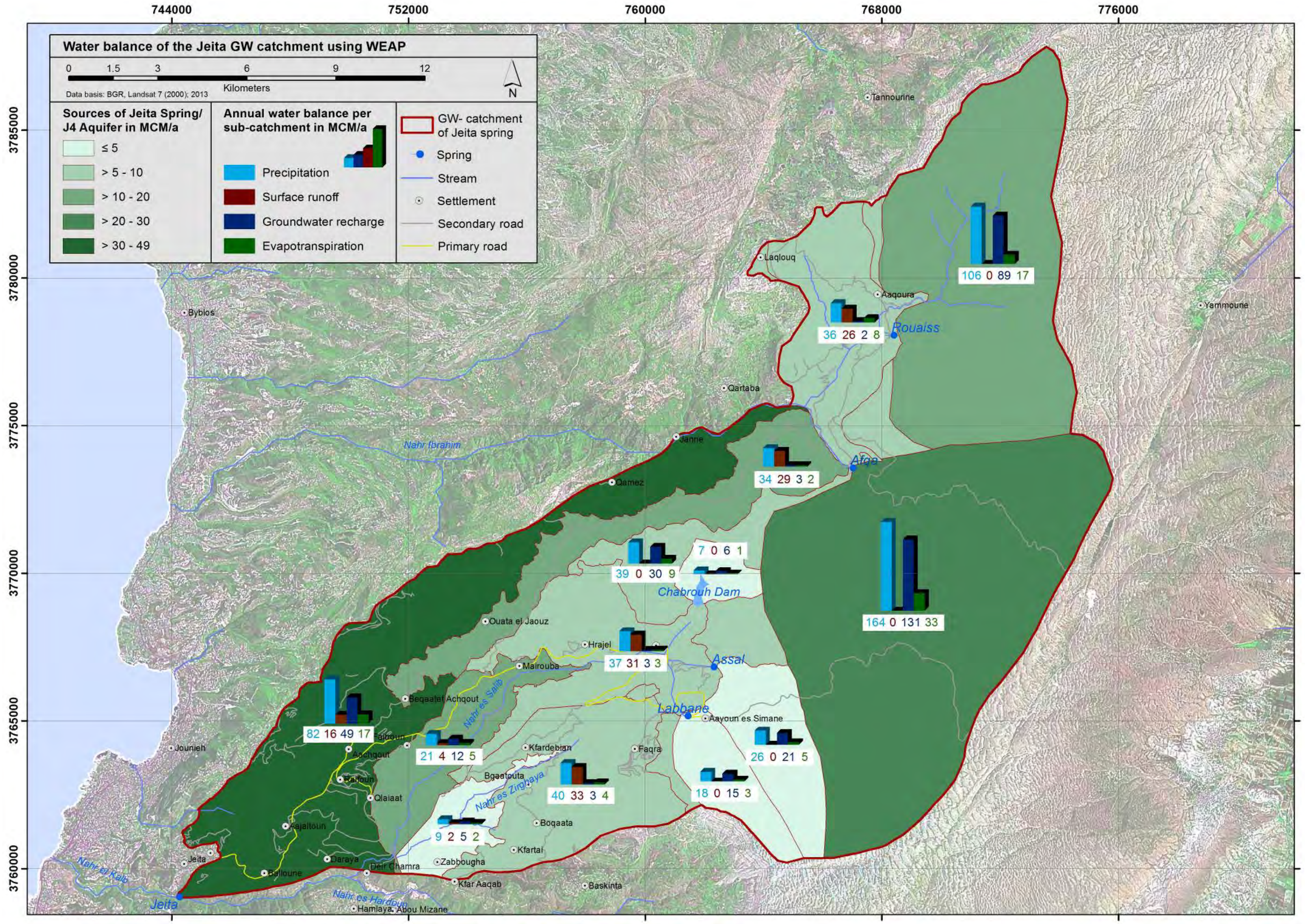


Figure 95: Origin of Flow Contributions to Jeita Spring in MCM/a and simplified Water Balances of all Sub-Catchments

3.10.4 WEAP and Groundwater Vulnerability

Combining the GW vulnerability (MARGANE & SCHULER, 2013) with the WEAP water balance (Figure 95) serves two purposes: First, it is a way to validate the WEAP and COP methods. Only catchments with a high infiltration rate, as modeled in WEAP, will contribute to major GW recharge. Karstification of the rock matrix, as is the case for the J4 and C4 units, allows rapid infiltration in the unsaturated zone and fast flow in the saturated zone. These catchments, however, coincide with a high vulnerability of GW. Fast transport of pollutants from the land surface to the groundwater are therefore likely if intense GW recharge occurs. Thus, comparing the spatial distribution of COP vulnerability and generated water resources by catchments allows to identify this interaction.

Secondly, GW protection measures can be prioritized according to the quantity of generated resources or according to the flow paths (e.g. if groundwater-surface water interaction is existent), when it is known where which quantities come from. It could be argued that the higher groundwater flow in an aquifer is, the less important GW protection measures become due to dilution (and in fact, this is considered in the COP method). However, this argument would not only be cynical and open way for continued GW contamination, it would also neglect that, due to the geological nature of the GW system, the aquifer rapidly depletes and GW flow reaches very low levels during the dry season so that the impacts of contamination become much more noted during this time period.

To assess the quantity of flow to Jeita spring with respect to GW vulnerability in the areas of origin, the Spatial Analyst in ArcGIS was used.

Table 19 displays the respective quantities per vulnerability class and Figure 96 illustrates the spatial distribution of origin by increasing darkness indicating increasing quantities of origin. It shows that although the flowpath from the Upper Aquifer may take longer, the contribution is considerable. If this area was developed and long or hardly degradable substances would infiltrate in the C4 catchments, they could cause tremendous impact at Jeita spring. Fortunately this is not the case until now.

Table 19: Sources of Flow in the Lower Aquifer and Groundwater Vulnerability in the Areas of Origin

COP vulnerability		Flow to J4 in MCM/a	% of total flow to J4
0-0.5	very high	111.0	64.1
0.5-1	high	29.1	16.8
1-2	moderate	1.8	1.1
2-4	low	0.6	0.3
4-10.0	very low	30.6	17.7

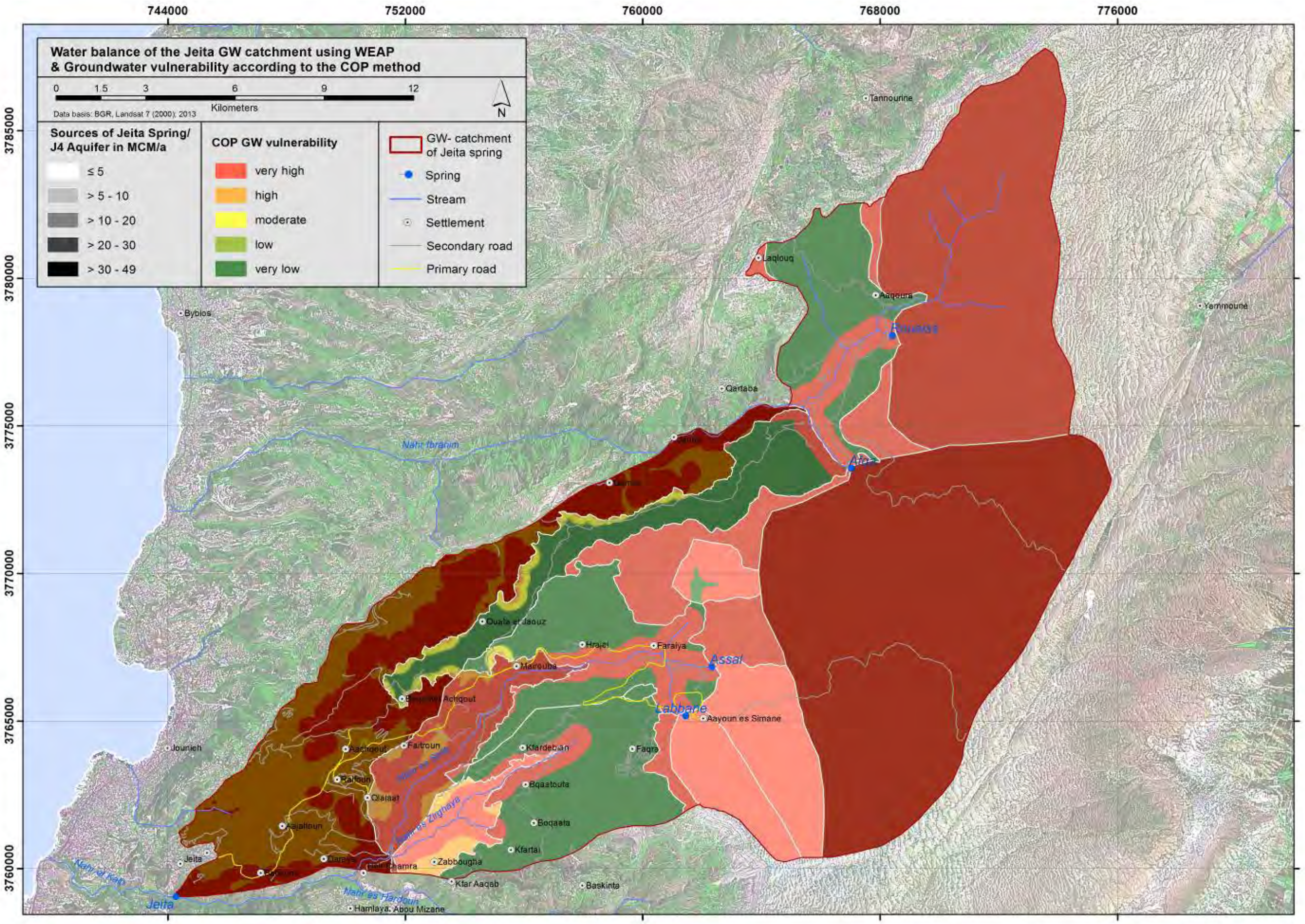


Figure 96: Origin of Flow Contributions to Jeita Spring and Groundwater Vulnerability in the Areas of Origin

3.11 Hydrochemical Groundwater Properties

Unfortunately there is no comprehensive analysis of water quality in the Jeita catchment. Only a few small studies are focusing on certain springs or done for certain purposes were conducted in the area. These are mentioned further below. Due to the lack of laboratory capacities in Lebanon the BGR project had to abandon plans to carry out a comprehensive water quality investigation in the Jeita catchment. Instead selected parameters were analyzed (physicochemical long-term monitoring) and individual campaigns very conducted (micropollutant survey).

3.11.1 Results of Physicochemical Monitoring

Multiparameter probes were installed at the following sites:

- Jeita spring
- Jeita siphon terminal (Daraya tunnel)
- Kashkoush spring
- Assal spring
- Labbane spring

These multiparameter probes registered water level (WL), electric conductivity (EC), pH, temperature (T), dissolved oxygen content (RDO) and oxidation-reduction potential (ORP) at 20 minute time intervals. Part of these measurements is already documented in Special Report No. 8 (MARGANE & STOECKL, 2013) but measurements will be continued and again documented.

Assal Spring

Assal spring is fed by direct groundwater recharge from rainfall and snowmelt in the Upper Aquifer (C4). Because of the relatively low mean residence time in the aquifer and the lack of evaporitic deposits in the C4, mineralization of all C4 springs is relatively low. Land cover is mainly barren land with few bushes and there is almost no human landuse activity so that there are no human induced hydrochemical constituents. Karstification is extensive leading to calcium-bicarbonate type water. Due to the high elevation and distance from the coast, chloride content of rainfall is low. Due to the lack of other sources, the Cl-content of springs is similar to that of rainfall/snow (Figure 100; Annex 5).

Assal spring water is well oxygenated, with dissolved oxygen contents of between 9.9 and 10.6 mg/l. Oxygen content decreases during winter, reaching its lowest level during snow cover. Oxygen content rises following snowmelt (Figure 97).

Development of temperature and electric conductivity are concordant. Temperature varies between 5.3 and 7.7°C. EC varies between 105 and 180 µS/cm (Figure 98). Both rise during winter, reaching their peak in March. They decrease quickly during snowmelt. The increasing conductivity is a response to increased residence times of water released from parts of lower permeability (slow flow component) and thus higher mineral content due to higher dissolution of carbonates.

Turbidity usually remains below 30 NTU, commonly rising after snow melt, when soil is washed down into the large dissolution channels underlying the dolines. This effect is even higher, when precipitation falls as rain on the high plateau, as in November 2012 (Figure 99).

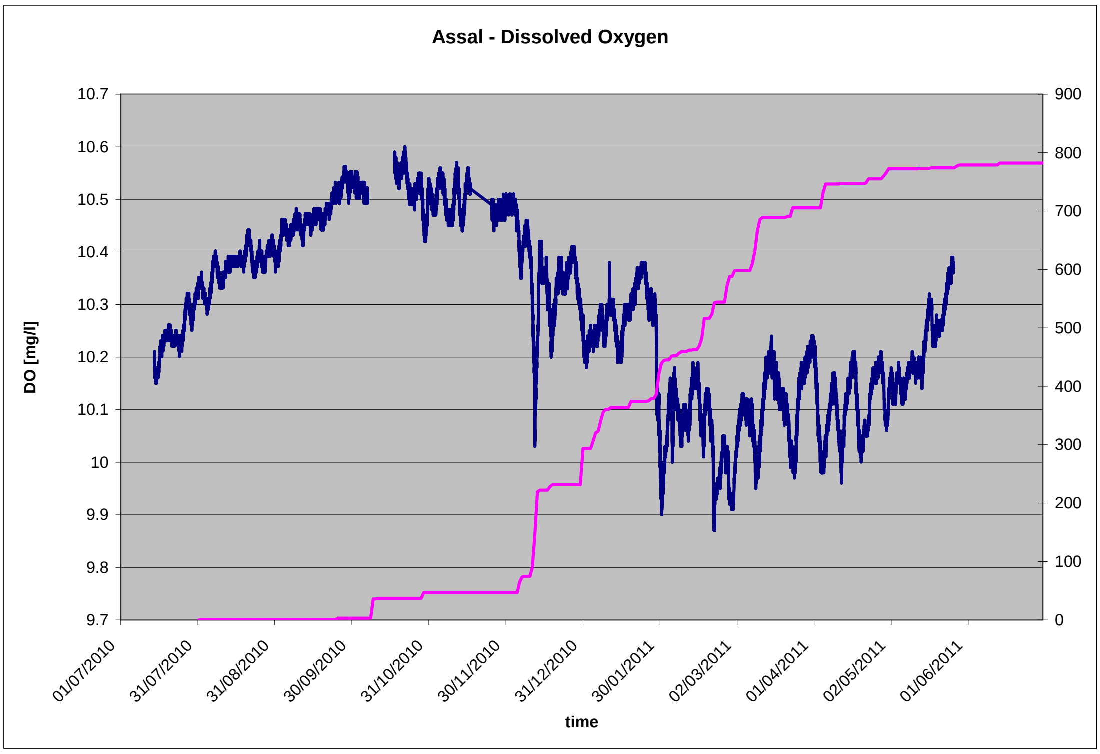


Figure 97: Long-term Dissolved Oxygen Monitoring of Assal Spring

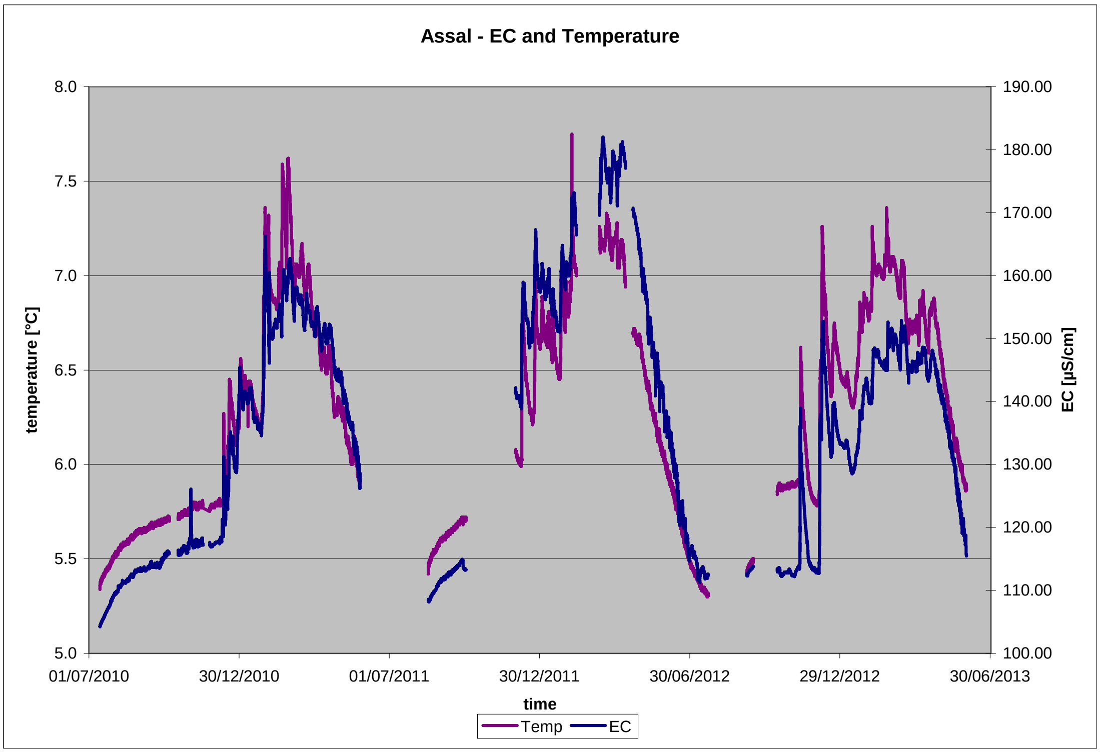


Figure 98: Long-term Temperature and Electric Conductivity Monitoring of Assal Spring

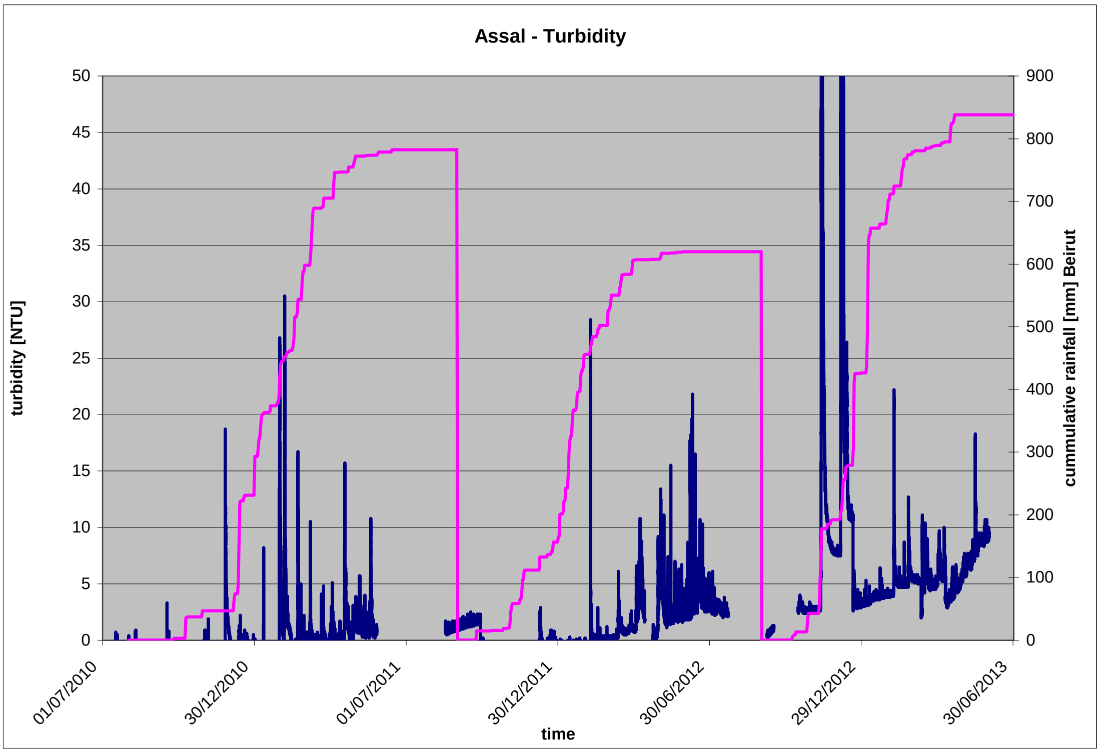


Figure 99: Long-term Turbidity Monitoring of Assal Spring

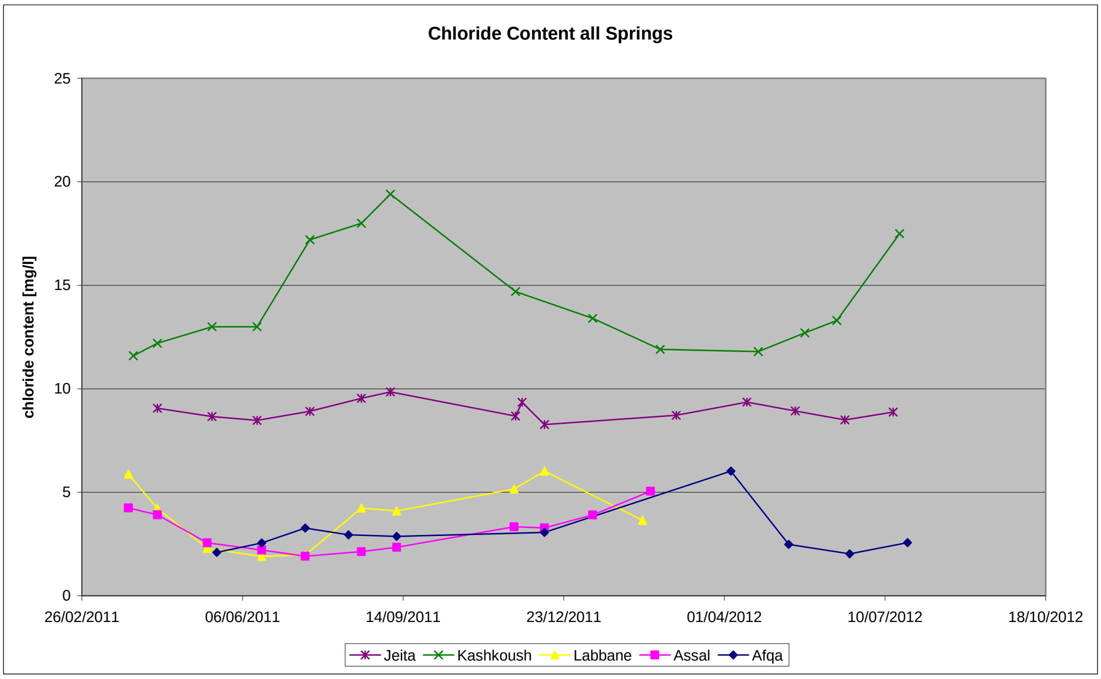


Figure 100: Chloride Content of Snow in the Assal Catchment and of Assal Spring

Labbane Spring

The differences between Assal and Labbane spring were already highlighted in Chapter 3.2.

Labbane spring shows a pronounced daily water level and temperature fluctuation as a response to the significant day/night temperature differences in the snow cover area (Figure 101). These can reach more than 20°C. At night temperatures in most of the catchment usually drop below 0°C at least until mid April. At Labbane spring the daily water level fluctuation (and with this the spring discharge) reaches as much as 10 cm (> 10%). At Assal spring, this daily fluctuation is also observed but much less (max. 3 cm or <5%; Figure 102).

At Labbane spring EC varies between 83 and 180 µS/cm, temperature between 4.8 and 7.2°C (see Figures x, y in Chapter 3.2).

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

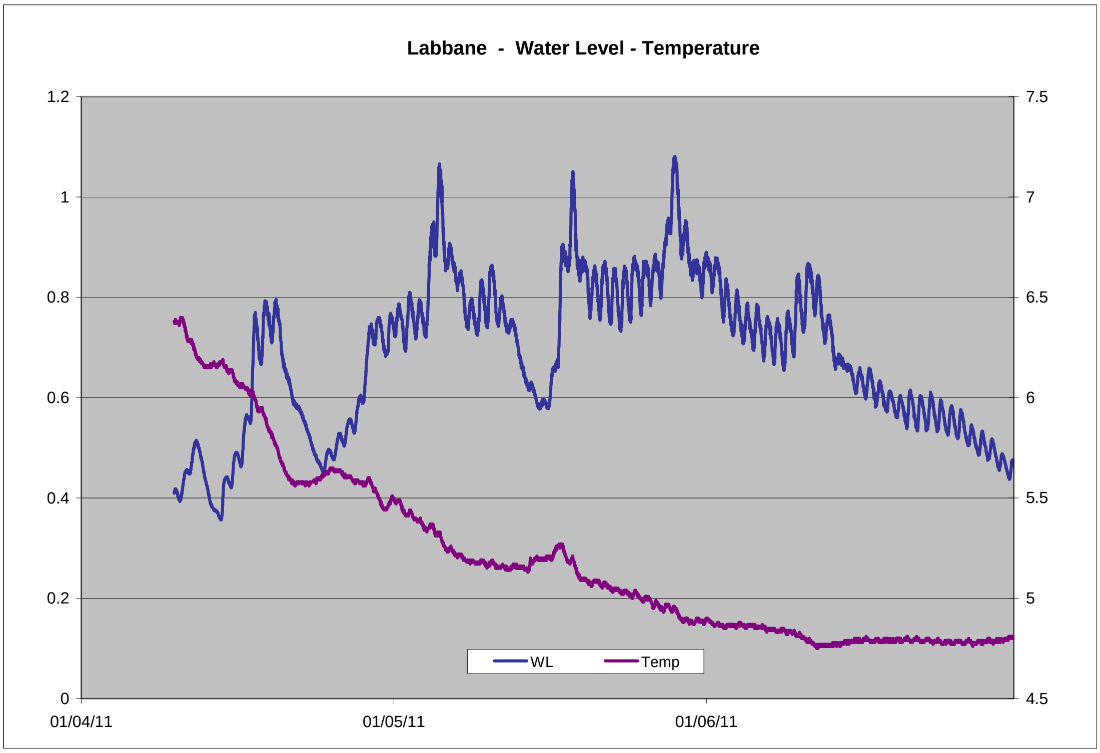


Figure 101: Daily Fluctuation of Water Level during Snowmelt at Labbane Spring

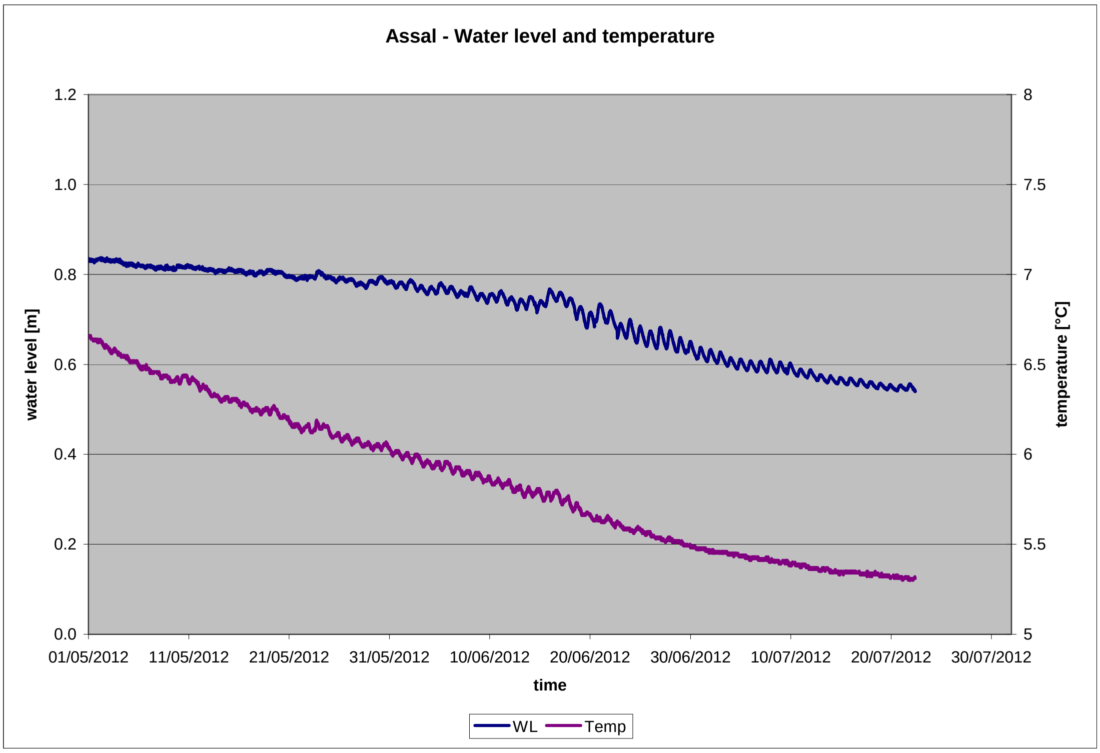


Figure 102: Daily Fluctuation of Water Level during Snowmelt at Assal Spring

Jeita Spring

The comparison of the temperature behavior of Jeita, Assal and Labbane spring shows a significant difference between the discharge from the Upper Aquifer and the discharge from the Lower Aquifer. As already described in Chapter 3.3, the latter is a mixture of two different main flow components, direct and indirect GW recharge. There are four different flow paths of indirect GW recharge and on these individual flow paths it must be differentiated between those parts where flow occurs on large conduits as fast flow component and those where flow occurs on small fractures and voids as slow flow component. The mixing of water from all these different flow paths leads to a significant difference in the temperature and EC signal between the Upper and Lower Aquifer as can be seen in Figures 103 and 104.

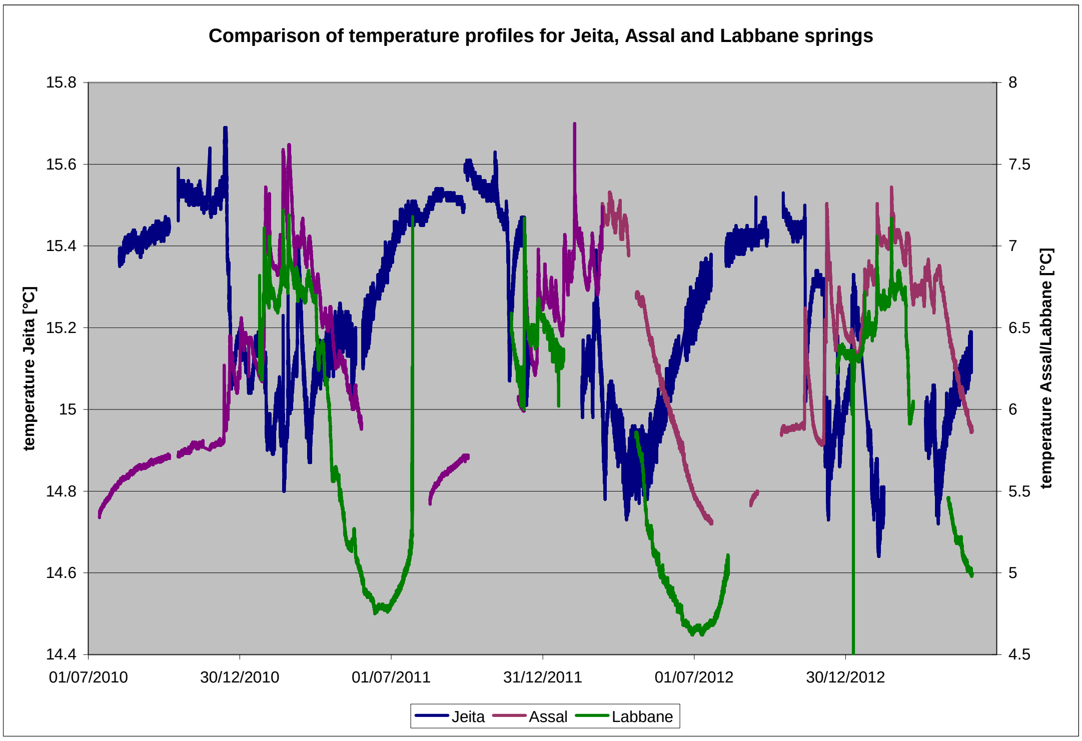


Figure 103: Comparison of temperature profiles at Jeita, Assal and Labbane springs

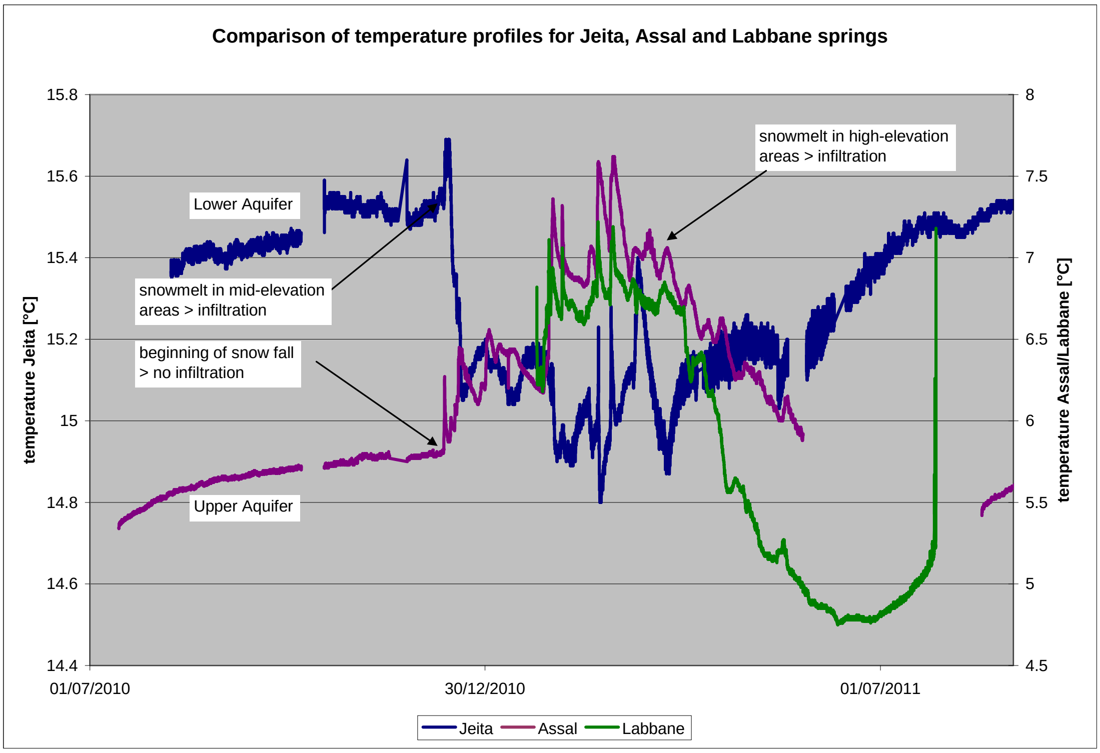


Figure 104: Comparison of temperature profiles at Jeita, Assal and Labbane springs during winter 2010/11

Kashkoush Spring

Kashkoush spring was monitored because at the start of the project the general assumption was that this spring has a common or similar catchment as Jeita spring and that the only reason for their different places of issuance is that Jeita is discharging from the J4, while Kashkoush is discharging from the J6 aquifer. It later turned out that both is not the case. Kashkoush spring has an entirely different catchment from Jeita spring and receives most of its recharge from the much more extensive J4 aquifer.

However, the comparison of physicochemical monitoring data between both, Jeita and Kashkoush, reveals some insight about their catchments.

In general the behavior of the measured parameters is relatively similar for both springs. Especially the temperature and EC curves show almost the same reaction, however, the following differences can be noticed:

- temperature (T) in Kashkoush spring is approx. 1°C higher than in Jeita (Figure 105);
- also electric conductivity (EC) (at least until end of 2011) was significantly higher in Kashkoush compared to Jeita spring (Figure 106);

- the interannual variation of both, T and EC, is much higher in Kashkoush than in Jeita (Figures 105, 106);
- both, T and EC, exhibit a downward trend (Figures 105, 106);
- response time in Jeita (Figure 107) to rainfall events is slightly longer than in Kashkoush (Figure 108).

Rainfall/snow in winter 2010/11 and winter 2012/13 was higher than usual (wet years), while 2011/12 was an average water year. This explains the decrease in T and EC between 2010 and 2013.

Kashkoush has a higher T and EC because its average catchment elevation is lower, as also proven by stable isotope analyses (Chapter 3.11.4). Kashkoush, however, also has a considerable pollution problem so that higher mineralization may be explained by that.

The rapid drops of both, T and EC, in winter 2010/11 (Figures 105, 106): a) first drop around 13.12.2010, b) second drop around 30.01.2011, in Jeita and Kashkoush are related to a) rainfall infiltrating only at mid altitudes (that is why this is not observed in Assal spring), while precipitation was fixed as snow at high altitudes, and b) rainfall falling as rain also at higher altitudes (also observed in Assal spring). the effects of these two distinct rainfall events are noticed in Kashkoush 11 hours sooner than in Jeita spring.

Rainfall event January 2011:

(rainfall Beirut airport: 11.-14.12.2010: 148 mm; 29.-31.01.2011: 61 mm)

Assal:	29.01.11 01:00
Jeita:	30.01.11 13:20
Kashkoush:	30.01.11 02:20

The response time to rainfall events (based on hourly records of the BGR stations) in the Jeita catchment observed at Jeita and Kashkoush springs (20 minute interval records) are shown in Figures 93 and 94. These rainfalls peaking on 14.05.2013, 16:00, and 15.05.2013, 10:00, were preceded and followed by extended dry spells. Rainfall was as follows: Sheile: 6.5 mm, AIS: 7.5 mm, Bakeesh: 15.4 mm, Chabrouh dam: 15.9 mm. Jeita spring monitoring exhibits a small direct response only 4-5 hours after rainfall. This probably comes from the immediate vicinity of Jeita spring and is related to groundwater recharge in the valley descending to Jeita Grotto. The main response follows about 26 hours later but lasts for three days, showing that water flows towards Jeita from this event from a large catchment. The response in Kashkoush to the same two distinct rainfall events is much shorter, lasting only for one day. This shows that the contribution zone must be much smaller and less far reaching. The response time to both rainfall events is 16 hours in Kashkoush spring.

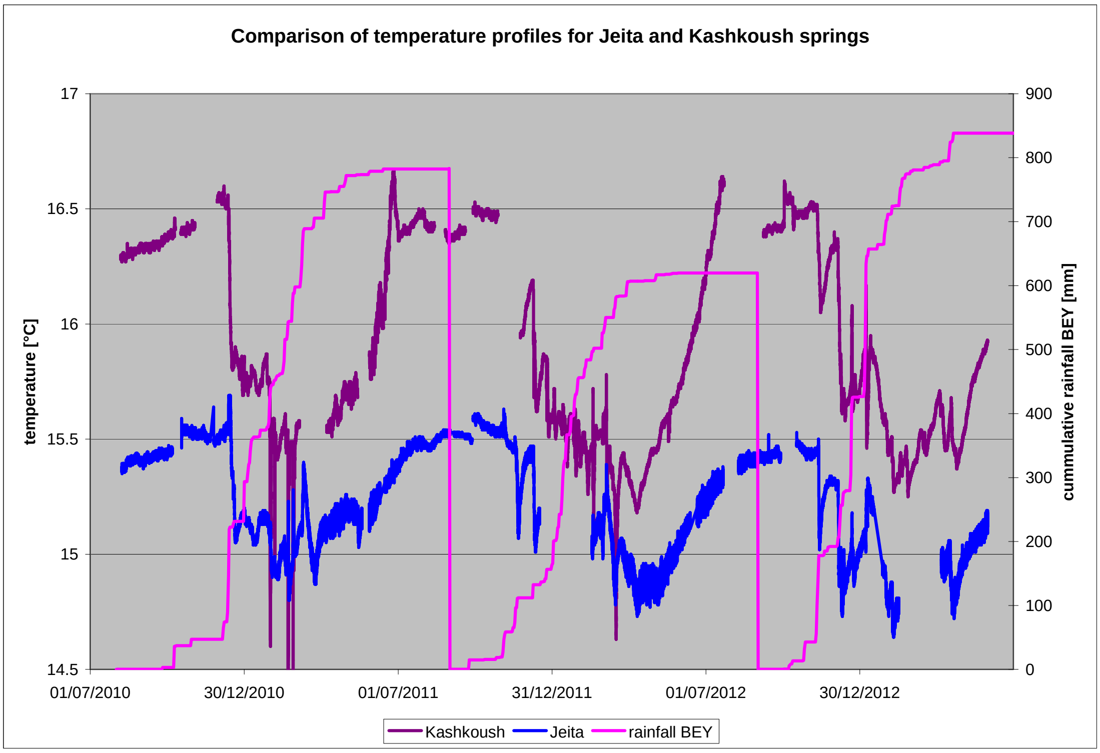


Figure 105: Comparison of temperature profiles for Jeita and Kashkoush springs

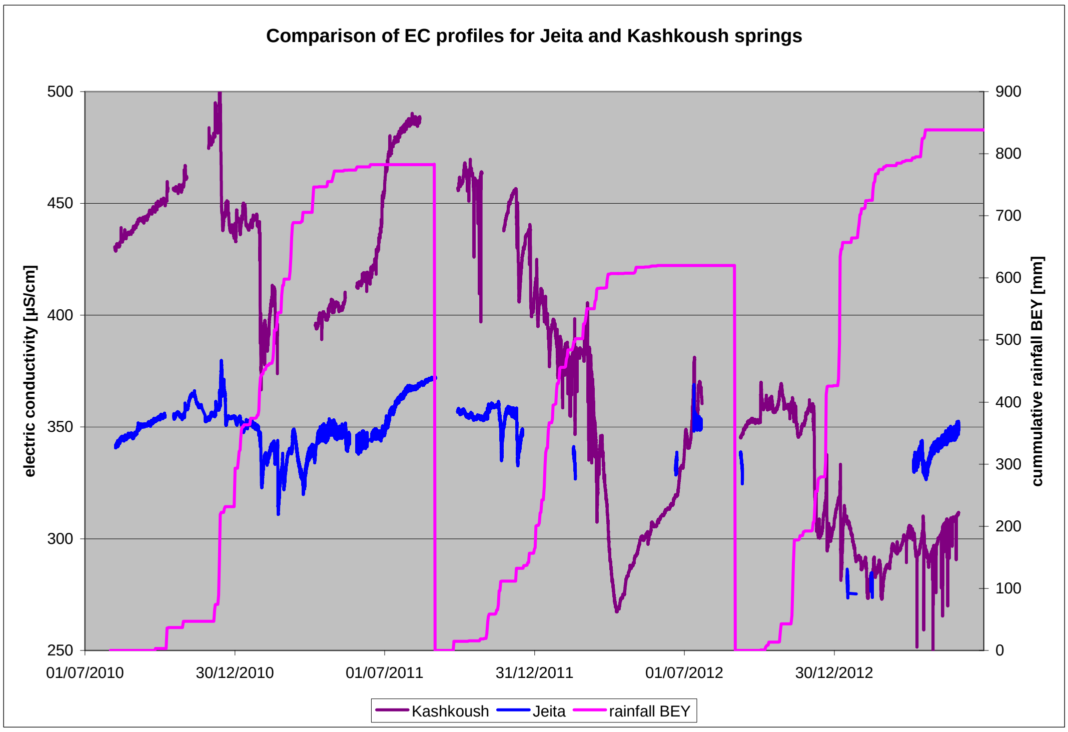


Figure 106: Comparison of electric conductivity profiles for Jeita and Kashkoush springs

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

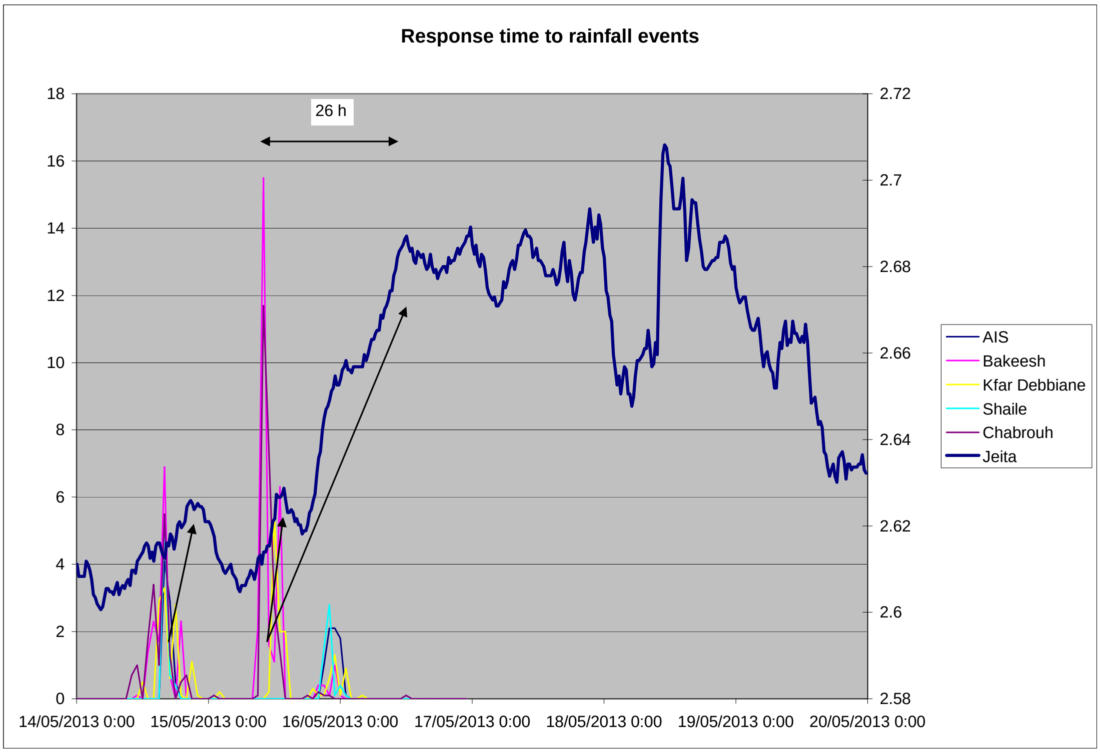


Figure 107: Response Time to Rainfall Events observed at Jeita Spring

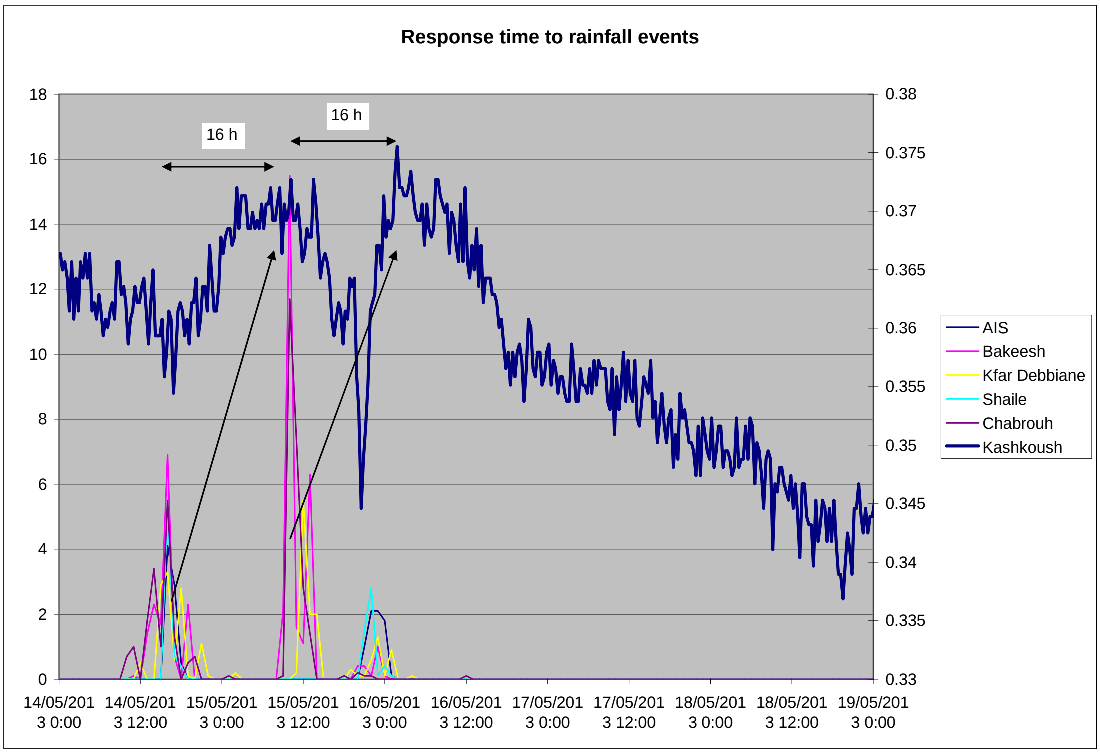


Figure 108: Response Time to Rainfall Events observed at Kashkoush Spring

3.11.2 Water Analyses of WEBML and others

The Water Establishment of Beirut and Mount Lebanon (WEBML) is one of the few governmental water laboratories in Lebanon. Despite attempts to upgrade the laboratory through foreign donor funded projects, the capacity of the laboratory has not much improved. A similar negative assessment was made by CORAIL & ICEA (2005) and CORAIL (2001). The main problems are:

- incomplete or outdated equipment (3 HP (now Agilent) ICP-MS ~ 15 years old, out or order, no maintenance)
- limited space (~ 150 m² for entire lab)
- insufficient staff: only one permanent staff (director), 3-4 temporary technicians/engineers

Pesticides and heavy metals cannot be analyzed by the Dbayeh lab since many years. It was not possible to determine K ions at the lab, so that the project bought a related ion-selective (IS)-probe.

Due to this limited capacity, the laboratory focuses mainly on microbiological analyses. Related raw water samples are taken approximately every 4 days from the main source of water supply, the Jeita-Dbayeh canal (potential sources: Jeita spring, Jeita wells, Kashkoush spring, Kashkoush wells, surface water). At WEBML lab, microbiological analyses comprise: total coliforms, Enterobacter cloaceae, Proteus mirabilis, Salmonella typhimurium, Thermotolerant coliforms, Klebsiella pneumoniae, Escherichia Coli, and Fecal coliforms. Indicators for pollution from animal farming, such as Cryposporidium, but also other frequently occurring bacteria and viruses such as Clostridium perfringens, Giardia lamblia (intestinalis), Pseudomonas aeruginosa, Enterococci are not included.

Because there was no database, the BGR project compiled a database for the existing analysis results covering the past 10 years. The compiled data show that raw water permanently exceeded the limits of the Lebanese drinking water standard for Escherichia Coli (Figure 109; Table 20). Also Salmonella is frequently found in the Jeita/Kashkoush raw water. Therefore high levels of chlorination are needed to treat the water. At times, however, turbidity is very high in the raw water. Treatment can then not be effective as some turbidity will pass the sandbed filters. Such peaks may not even be noticed and analysis results will definitely not be available before the treated water is fed into the supply network. Another risk is that hydrocarbons contained in the raw water, when treated with chlorine gas, will form carcinogenic chlorinated hydrocarbons.

The Dbayeh lab analyses mostly raw water samples at the entry point to the treatment plant, the so-called 'canal', and only very few samples from the source water itself. This would be crucial because the canal is already a mixture of different source waters (see above).

Many raw water analyses, even at times Assal and Afqa springs, show elevated levels of ammonium and nitrite, indicating contamination by wastewater or manure. Both indicators are especially high at Kashkoush spring, which contributes to the water supply of the Greater Beirut Area. This pollution in Kashkoush spring (CHRABIEH & MARGANE, 2012) must be urgently addressed.

Analyses of trace elements like fluoride, bromide, boron, radon, radium, uranium, and others could provide important information concerning the groundwater flow paths. Unfortunately such analyses can mostly not be done in Lebanon. Such more detailed analyses could among others provide insights into the occurrence of hydrothermal waters. It is quite likely that there is some inflow of hydrothermal waters especially near the main E-W fault lines in Nahr es Hardoun (Sannine Fault) and in the Upper Nahr Ibrahim Valley (Afqa Faults), where large intrusions of basalt are found.

A study conducted by Mey Jurdi from Environmental Health Department at AUB, found Cd and Cu in Kashkoush and Jeita springs (presentation at MoEW), however, the number of samples analyzed is not enough to draw conclusions. A further investigation of the occurrence of heavy metals in Jeita and Kashkoush springs is urgently needed.

Also MTBE must be assumed to be present in Jeita and Kashkoush raw water because of the high probability of fuel leakage from old and unprofessionally built underground storage tanks (USTs) of gas stations. Unfortunately a laboratory able to analyze MTBE could not be found in Lebanon. Due to the high risk for public health it is highly recommended to carry out MTBE analyses for all drinking water sources providing water to the Dbayeh drinking water treatment plant.

The establishment of a true water laboratory for all of Lebanon is urgently recommended. The laboratory of the Water Authority of Jordan (WAJ) can be seen as a guiding example in the region, which regularly carries out water analyses of all groundwater and surface water resources in Jordan, wastewater, and the water supply network. This lab is internationally accredited, also for stable isotope analyses, is accommodated in a building larger than the MoEW building in Lebanon and has a permanent staff of around 130 persons (pers. comm.).

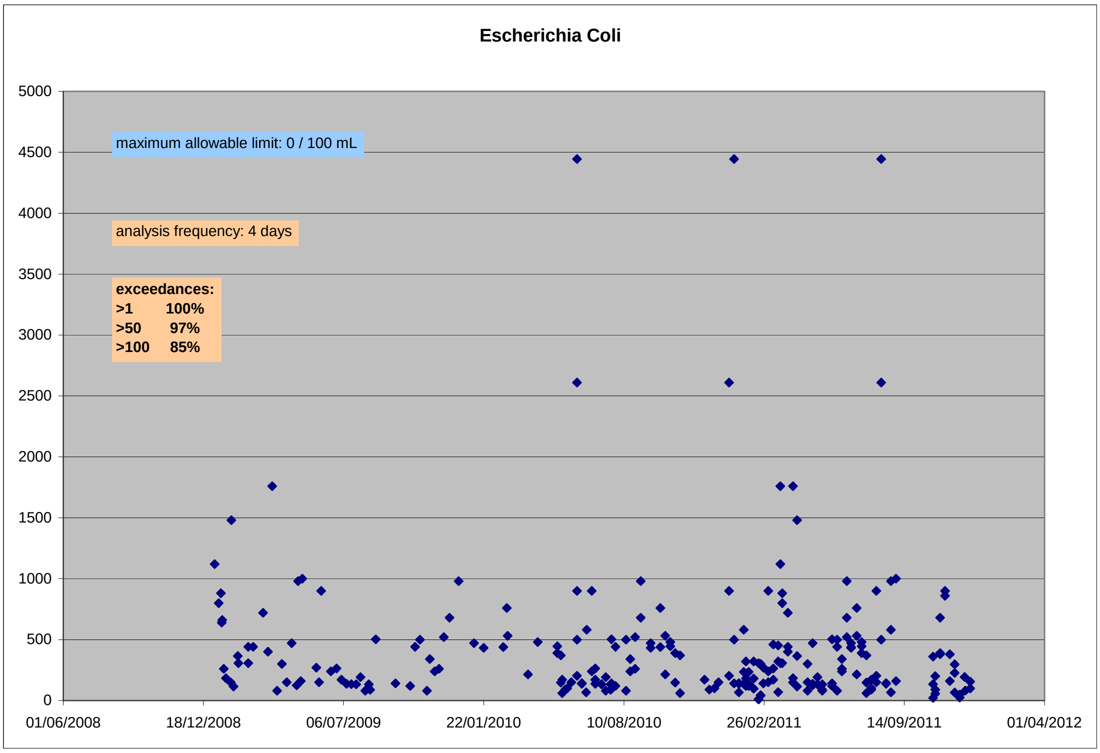


Figure 109: Escherichia Coli Analyses of Raw Water at the Dbayeh Intake (canal)

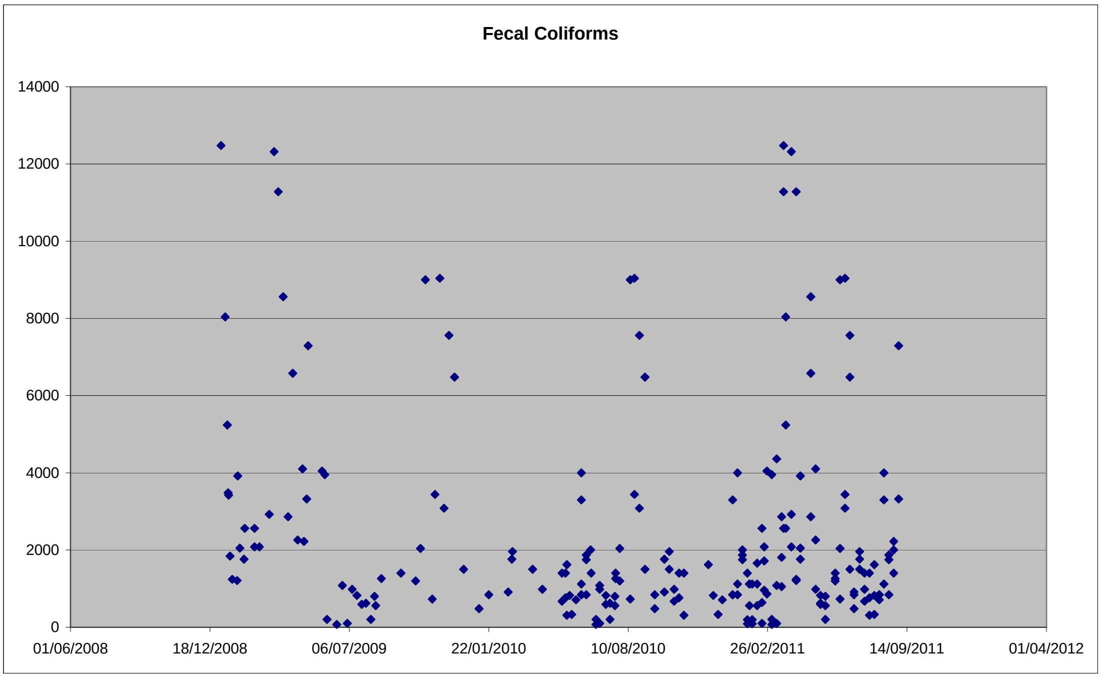


Figure 110: Fecal Coliform Analyses of Raw Water at the Dbayeh Intake

Table 20: Microbiological Analyses

Location	Date	pH	EC [µS/cm]	Total Coli	Fecal Coli	E.Coli
Jeita	23/11/2005		436			
Jeita	21/11/2007			3300		1450
Jeita	15/12/2007	-	381	1000		900
Jeita	01/03/2010	7.38	437	7370	3250	320
Jeita	14/05/2010	7.37	447	11380	8480	680
Jeita	02/12/2010	7.63	484	498	68	30
Jeita	13/12/2010	7.35	470	27010	20000	5000
Jeita	14/12/2010	7.22	443	45560	4200	600
Jeita	04/04/2011	7.31	446	3596	532	148
Jeita	06/09/2011	7.4	444	1101	453	60
Jeita	28/11/2011			1732	120	116
Kashkoush	19/12/2005		545			
Kashkoush	21/11/2007			3650		1750
Kashkoush	15/12/2007			950		750
Kashkoush	01/03/2010	7.47	415	42697	40000	676
Kashkoush	14/05/2010	7.47	502	14800	10880	680
Kashkoush	02/12/2010	7.42	575	726	188	12
Kashkoush	13/12/2010	7.45	591	38310	20000	13160
Kashkoush	14/12/2010	7.08	555	54280	11920	1840
Kashkoush	04/04/2011	7.13	486	17240	8400	1720
Kashkoush	05/09/2011	7.04	565	1013	498	85
Kashkoush	23/11/2011	6.96	575	4544	200	620
Afqa	29/03/2011	8.03	265	266	2	1
Afqa	15/11/2011	7.62	282	1012	3	2
Labbane	28/03/2011	7.71	280	148	19	4
Chabrouh	06/10/2010	7.83	218	1407	1072	0
Chabrouh	28/03/2011	7.96	280	336	22	0
Fawar Antelias	01/07/2010	7.23	517	224	84	42
Fawar Antelias	31/01/2011	7.3	492	33350	11800	2100
Fawar Antelias	28/02/2011	7.38	480	27050	2000	1880
Fawar Antelias	26/05/2011	7.14	380	868	324	26
Fawar Antelias	04/07/2011	7.3	493	179	102	7
Fawar Antelias	11/07/2011	7.27	520	298	163	14
Fawar Antelias	29/07/2011	7.21	515	709	52	34
Fawar Antelias	24/10/2011	7.32	538	271	64	7
Fawar Antelias	10/11/2011	7.29	528	1488	106	186

source: WEBML lab

Table 21: Hydrochemical Analyses

Location	date	Temp	Color	Turb	EC	PH	Total Hardness	Cl	SO4	PO4	P	Fe	NH4	NO2	NO3
		[°C]		NTU	[µS/cm]		CaCO3	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Assal	24/01/2004			0	265		160	5	9		0.04	0.12	0.19	0.016	10.18
Assal	10/05/2004			0	215		100	5	0		0.04	0.01	0.09	0.016	6.64
Assal	20/08/2004			0	190		100	5	1		0.02	0.02	0.09	0.026	6.64
Assal	11/12/2004			1	270		165	5	6		0.04	0.01	0.25	0.018	10.05
Assal	26/02/2005			0	256		135	5	8		0.04	0.02	0.18	0.018	7.96
Assal	09/06/2005			0	290		145	5	1		0.03	0.01	0.14	0.023	5.75
Assal	07/07/2005			0	165		90	2.5	2		0.03	0.01	0.11	0.023	8.41
Assal	06/08/2005			0	376		200	7.5	4		0.08	0.13	0.27	0.029	11.06
Assal	30/09/2005			0	191		110	5	1		0.02	0.01	0.09	0.023	7.59
Assal	15/12/2008			1	226		120	5	6		0.03	0.01	0.11	0.016	8.41
Labbane	11/04/2008	16.1	2	0	232	7.6	140	5	3	0.03	0.04	0.01	0.15	0.021	8.42
Labbane	15/12/2008			0	273		150	7.5	6		0.08	0.01	0.15	0.016	9.29
Afqa	23/05/2003			1	200		140	10	1		0.01	0.04	0.09	0.019	6.21
Afqa	15/05/2004			0	200		110	7.5	2		0.02	0.03	0.11	0.032	6.21
Afqa	07/08/2004			0	245		140	7.5	1		0.02	0.01	0.12	0.026	7.08
Afqa	01/12/2004			8	259		170	7.5	2		0.03	0.01	0.21	0.042	8.41
Afqa	04/12/2004			4	256		170	7.5	3		0.04	0.01	0.17	0.032	8.41
Afqa	29/01/2005			1	257		150	5	1		0.04	0.01	0.16	0.029	7.08
Afqa	16/03/2005			1	256		140	7.5	1		0.03	0.01	0.15	0.029	7.96
Afqa	28/05/2005			0	219		120	2.5	3		0.03	0.01	0.15	0.029	7.52
Afqa	09/07/2005			0	237		150	7.5	2		0.02	0.03	0.08	0.021	11.51
Afqa	22/10/2005			0	273		160	5	8		0.05	0.01	0.11	0.022	8.41
Afqa	04/03/2006			0	289		155	10	4		0.03	0.01	0.09	0.019	10.63
Afqa	21/06/2006			0	233		140	5	3		0.03	0.01	0.11	0.023	7.52

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Location	date	Temp	Color	Turb	EC	PH	Total Hardness	Cl	SO4	PO4	P	Fe	NH4	NO2	NO3
		[°C]		NTU	[µS/cm]		CaCO3	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Afqa	07/09/2007			0	244		150	5	5		0.03	0.01	0.11	0.023	7.52
Afqa	13/02/2008			1	233		150	5	3		0.03	0.01	0.15	0.021	6.65
Afqa	07/04/2008			1	237		120	5	5		0.03	0.01	0.12	0.029	8.42
Afqa	10/06/2008			0	263		140	7.5	7		0.03	0.01	0.11	0.021	4.86
Afqa	30/03/2011	13.2	0	0	265	7.7	150	5	4	0.03	0.04	0.02	0.14	0.026	7.97
Afqa	16/11/2011	14.2	2	0	282	7.6	140	5	8	0.02	0.03	0.01	0.21	0.026	7.95
Kashkoush	20/05/2003	15.8	46	15	466	7.5	240	10	16	0.04	0.06	0.01	0.15	0.026	8.85
Kashkoush	02/10/2004		7	2	552	7.7	270	15	27	0.31	0.71	0.02	0.21	0.036	14.61
Kashkoush	19/11/2004	16.2	30	9	586	7.3	265	27.5	34	0.65	0.85	0.07	0.27	0.389	14.16
Kashkoush	19/03/2005	15.2	24	8	454	7.5	260	15	25	0.07	0.03	0.09	0.21	0.013	11.95
Kashkoush	21/10/2005	19.8	12	4	551	7.7	280	30	38	0.05	0.11	0.02	0.21	0.039	16.82
Kashkoush	27/07/2006	22.1	7	2	514	7.7	270	20	36	0.59	0.79	0.03	0.25	0.042	15.05
Kashkoush	24/01/2007	12.7	4	1	410		220		19				0.28	0.043	8.85
Kashkoush	21/11/2007	18.2	18	2	555	7.5	270	30	46	0.49	0.66	0.35	0.61	1.372	15.49
Kashkoush	10/12/2007	17.3	20	6	491		220		19				0.28	0.043	8.85
Kashkoush	07/04/2008	20.9	3	1	575	7.3	250	20	41	0.22	0.3	0.01	0.15	0.022	12.83
Kashkoush	18/05/2009	24.9	14	4	491	7.2	230	16	29	0.21	0.28	0.05	0.22	0.032	11.95
Kashkoush	03/01/2010	16.8		50.3	415	7.5	235	10	26	0.16	0.22	0.05	0.23	0.033	11.06
Kashkoush	01/03/2010	16.8		50.3	415		220		19				0.28	0.043	8.85
Kashkoush	14/05/2010	18.8	22	6	502	7.1	270	25	42	0.18	0.24	0.21	0.33	0.266	17.71
Kashkoush	02/12/2010	19.4	1	0	575	7.4	275	27.5	38	0.61	0.81	0.07	0.22	0.023	14.17
Kashkoush	04/12/2010	16.5	89	28	555	7.7	310	25	33	0.34	0.79	0.06	0.48	0.052	19.28
Kashkoush	13/12/2010	15.2	214	69	591	7.5	260	18	23	0.11	0.23	0.08	0.29	0.036	11.06
Kashkoush	14/12/2010	16.5	89	28	555	7.1	270	25	42	0.18	0.24	0.21	0.33	0.266	17.71
Kashkoush	04/04/2011	17.9	42	14	486	7.1	270	25	42	0.18	0.24	0.21	0.33	0.266	17.71
Kashkoush	09/06/2011	15.1	7	2	565	7.0	280	22.5	34	0.51	0.68	0.05	0.26	0.036	15.05

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Location	date	Temp	Color	Turb	EC	PH	Total Hardness	Cl	SO4	PO4	P	Fe	NH4	NO2	NO3
		[°C]		NTU	[µS/cm]		CaCO3	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Kashkoush	23/11/2011	17.1	54	13	575	7.0	260	25	40	0.23	0.31	0.09	0.23	0.098	14.61
Jeita	20/05/2003	14.9	8	0	403	7.5	240	10	16	0.04	0.06	0.01	0.15	0.026	8.85
Jeita	29/05/2004			0	522	7.6	220	12.5	18	0.12	0.17	0.11	0.18	0.029	12.39
Jeita	11/09/2004			0	534	7.4	230	12.5	15	0.06	0.03	0.02	0.11	0.013	11.07
Jeita	04/10/2004		0	0	454	7.8	230	10	10	0.07	0.17	0.01	0.11	0.029	8.41
Jeita	23/11/2004	15.3	161	54	444	7.4	230	10	12	0.07	0.18	0.02	0.28	0.026	10.08
Jeita	05/02/2005			1	528	7.4	210	10	12	0.05	0.07	0.07	0.14	0.026	8.85
Jeita	19/03/2005	14.3	97	30	398	7.4	220	15	23	0.19	0.25	0.01	0.17	0.026	11.51
Jeita	28/05/2005			1	517	7.5	180		11				0.23	0.033	7.97
Jeita	23/07/2005			0	536	7.4	210	10	12	0.05	0.07	0.07	0.14	0.026	8.85
Jeita	24/09/2005			0	550	7.4	220	15	23	0.19	0.25	0.01	0.17	0.026	11.51
Jeita	21/10/2005	20.3	18	9	468	7.4	240	15	22	0.03	0.09	0.08	0.25	0.029	13.73
Jeita	25/02/2006			0	518	7.2	230	15	14	0.03	0.04	0.03	0.18	0.026	12.39
Jeita	06/03/2006			0	533	7.5	180		11				0.23	0.033	7.97
Jeita	27/07/2006	23.2	2	0	425	7.8	240	10	18	0.21	0.29	0.02	0.15	0.026	14.16
Jeita	12/08/2006			1	518		260	17.5	19	0.05	0.03	0.01	0.24	0.026	13.28
Jeita	27/09/2006	17.5	4	2	433	7.5	230	12.5	18	0.18	0.25	0.03	0.12	0.029	15.05
Jeita	30/09/2006			2	506		260	20	26	0.06	0.04	0.03	0.27	0.029	9.29
Jeita	24/01/2007	12.7	4	1	410	7.5	240	10	16	0.04	0.06	0.01	0.15	0.026	8.85
Jeita	07/04/2008	19.7	9	3	406	7.4	220	12.5	17	0.07	0.1	0.03	0.11	0.019	10.18
Jeita	18/05/2009	25.8	7	2	445	7.5	210	12.5	15	0.05	0.07	0.03	0.18	0.026	10.18
Jeita	03/01/2010	17.2	592	173	381	7.5	180		11				0.23	0.033	7.97
Jeita	01/03/2010	17.2	592	173	381		245	15	19	0.06	0.04	0.01	0.27	0.032	11.95
Jeita	14/05/2010	21.6	16	4	437	7.4	210	10	12	0.05	0.07	0.07	0.14	0.026	8.85
Jeita	02/12/2010	19.2	1	0	447	7.5	240	10	16	0.04	0.06	0.01	0.15	0.026	8.85
Jeita	13/12/2010	17.4	419	161	484	7.6	240	12.5	29	0.25	0.34	0.16	0.22	0.204	8.85

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Location	date	Temp	Color	Turb	EC	PH	Total Hardness	Cl	SO4	PO4	P	Fe	NH4	NO2	NO3
		[°C]		NTU	[µS/cm]		CaCO3	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Jeita	14/12/2010	16.5	51	16	470	7.4	235	20	24	0.13	0.17	0.03	0.24	0.032	8.85
Jeita	04/04/2011	17.9	5	2	443	7.5	230	12.5	18	0.18	0.25	0.03	0.12	0.029	15.05
Jeita	06/09/2011	14.8	2	0	446	7.3	240	12.5	15	0.09	0.13	0.01	0.17	0.029	12.39
Jeita	28/11/2011	15.4	37	11	444	7.4	235	20	24	0.13	0.17	0.03	0.24	0.032	8.85

source: WEBML lab

3.11.3 Micropollutant Survey

Due to the high number of potential pollution sources of different origin (RAAD & MARGANE, 2013), there is a wide range of contaminants that could potentially be in the raw water, such as pesticides, heavy metals, pharmaceuticals. Most of them can currently not be analyzed by the WEBML lab and would therefore pass unnoticed to the supply network.

As already mentioned above, one of these substances is MTBE, added to unleaded fuel in Lebanon. In regular fuel (95 octane) and super benzene (98 octane) the share of MTBE is 10 %. Many USTs of the 83 gas stations in the GW catchment of Jeita spring are fairly old, consist of single-layer tanks and are commonly not controlled for leakage. Welding of USTs is not professional so that fuel leakage into groundwater must be expected. The fuel components are commonly difficult to trace due to their volatility, except for MTBE. Unfortunately, the BGR project could not find any laboratory in Lebanon being able to analyze water samples for MTBE content.

To potentially locate certain pollution sources a micopollutant study was conducted by the University of Goettingen, Germany (DOUMMAR et al., 2012) as part of a contract for the BGR project. Micropollutants comprise compounds and metabolites of pharmaceuticals, pesticides and industrial production.

Four sampling campaigns were undertaken between September 2010 and January 2012, during which 100 samples from major springs, rivers, and wastewater effluents were taken:

- Campaign 1: A pre-sampling campaign consisted of the sampling of the major springs (6 samples) in the catchment area on the 22nd of September 2010 during low flow periods.
- Campaign 2: A major campaign was undertaken in March 2011 during high flow periods, consisting of the sampling of major springs, river branches (the Dog river), and wastewater effluents (51 samples).
- Campaign 3: This sampling campaign consisted of 16 samples and was undertaken during low flow period in September 2011. Major springs and flowing surface water were mainly sampled. Additionally samples were taken along the cave over the last 1000 m to assess the behavior of the different compounds along the course of the cave under the village of Jeita.
- Campaign 4: The last sampling campaign was performed in intermediate flow periods in December 2011 and January 2012 and consisted of the sampling of various river branches, and major springs. Additionally samples were taken along the cave over the last 1000 m to assess the behavior of the different compounds along the course of the cave under the villages of Daraya and Aajaltoun.

The samples were analyzed for the components listed in Table 22.

Certain pharmaceuticals, such as carbamezapine (used as an anticonvulsant and mood-stabilizing drug used primarily in the treatment of epilepsy and bipolar disorder), Gemfibrozil, Diclofenac, Cetirizine, etc. were found repeatedly in wastewater and Jeita and Kashkoush springs during high and low flow periods. Benzoylecgonite, a cocaine metabolite, was found virtually in all samples of springs (only Lower Aquifer, not in the Upper Aquifer), surface water, wastewater and even tapwater ! Also caffeine was found in nearly every sample. The results show that wastewater discharge into groundwater through open cesspits or wells is common practice in all areas. Only the Upper Aquifer is spared yet from pollution.

Iodinated X- ray contrast media are widely used in hospitals and practical surgery. One of the typical associated products, iopamidol, was found in wastewater Hrajel, Nahr El Salib river and Jeita spring, indicating discharge of contrast media with wastewater from hospitals and small health care centers into open cesspits of wells.

Table 22: Micropollutants analyzed

Group	Substance
Analgesics/Anti-inflammatories	Diclofenac Ibuprofen Naproxen Paracetamol Phenazone
Stimulants/Caffeine metabolites	Caffeine Paraxanthine Theobromine Theophylline 1-Methylxanthine 3-Methylxanthine
Antihypertensive agents	Atenolol Metoprolol Sotalol
Iodinated contrast media	Iohexol Iomeprol Iopamidol Iopromide
Antibiotics	Clarithromycin Erythromycin Roxithromycin Sulfamethoxazole Trimethoprim
Gastric acid regulator	Pantoprazole
Lipid regulators	Bezafibrate Clofibric acid Gemfibrozil

Group	Substance
Antihistamines	Cetirizine Loratadine
Anticonvulsants / Sedatives	Carbamazepine Diazepam Primidone Tetrazepam
Selective serotonin reuptake inhibitors	Citalopram Fluoxetine Sertraline
Herbicides / Herbicide metabolites	Atrazine Desethylatrazine Desisopropylatrazine Diuron Isoproturon Mecoprop Metazachlor
Corrosion inhibitors	1H-Benzotriazole Tolyltriazole
Cocaine metabolite	Benzoylecgonine

3.11.4 Stable Isotope Analyses

Stable isotope analysis can among many other applications be used to (CLARKE & FRITZ, 1997; LERNER et al.,1990; MOOK, 2000):

- study the groundwater recharge mechanism
- study evaporation effects
- determine the mean elevation of a groundwater catchment
- determine the mean residence time of groundwater.

Very few stable isotope studies have been carried out in Lebanon thus far and unlike in many countries of the region, long-term records of stable isotope composition of rainfall are unfortunately not available.

This analysis is based laboratory results of the BGR project obtained until May 2013. The analyses are continuing and might exhibit slightly changing values in later on versions that include the completely analyzed dataset. Stable isotope results allow wide reaching conclusions and the results of this investigation will be of major importance for interpretation of the hydrogeology in the entire country.

Sampling was started by the project in March 2011 and will be conducted until at least December 2013. Analyses are done at the BGR stable isotope laboratory using a Picarro CRDS (cavity ring-down spectroscopy) laser system. Details are contained in Special Report No. 12 of the project reports (KOENIGER & MARGANE, 2013).

The following sampling sites were included in the sampling program:

- Rainfall (every 10-15 days): 6 stable isotope rainfall sampling stations: Jeita Grotto restaurant (92 m), Sheile reservoir (471 m), Aajaltoun AIS (821 m), Raifoun BGR office (1036 m), Kfar Debbiane municipality (1307 m), Chabrouh dam treatment plant (1591 m); 90 samples.
- Snow profiles (10 cm depth intervals) and snow integral samples: approximately 20 sites during 2 sampling campaigns in February 2012 and February 2013; about 80 samples.
- Springs (every 2 weeks): Afqa, Rouaiss, Assal, Labbane, Jeita (daily), Kashkoush; about 650 samples.

Stable Isotope Composition of Rainfall

Based on worldwide monitoring CRAIG (1961) established the global meteoric water line (GMWL; $\delta^2H = 8*\delta^{18}O + 10$), which was later modified by ROZANSKI et al. (1993) ($\delta^2H = 8.2*\delta^{18}O + 11.3$) due to a largely improved data collection of the GNIP (Global Network of Isotopes in Precipitation). In reality meteoric water lines are different for every region, due to local differences resulting from air mass movements, continental effects and many other effects so that commonly for each region a local meteoric water line (LMWL) was established. SAAD et al. (2005) proposed a Lebanese LWML ($\delta^2H = 7.1*\delta^{18}O + 16$), however, data were still scanty. Also due to significant differences between the Lebanon and the Bekaa/Antilebanon regions, it might be better to establish separate LWMLs for the two regions.

AOUAD-RIZK et al. (2005) conducted daily and sequential rainfall sampling in the same area as the BGR project over three years (2001-2003) and compared the results with weather satellite data to identify the provenience of rainfall events (trajectories). The regional data of the GNIP program of IAEA are available on the internet (www-naweb.iaea.org/napc/ih/IHS_ resources_isohis.html; Table 23; Figure 111), containing currently 399 samples from Lebanon, 636 from Syria and 2086 from Israel. Similar to GAT & CARMI (1987), the above mentioned study found that there are 3 main trajectories responsible for rainfall over the Lebanon mountain range (Chapter 1.4; Figure 5). AOUAD-RIZK et al. (2005) found a LWML for the samples from the Mount Lebanon catchment following the equation:

$$\delta^2H = 6.3*\delta^{18}O + 8.2$$

Spatial distribution and seasonal variation of rainfall in Lebanon is conditioned by a) the typical trajectories for air mass movements from Western Europe to the Levant (Figure 5) and b) the topography (Figures 1, 48). These facts result in a very characteristic distribution of stable isotopes in rainfall, snow, surface water and groundwater (springs).

The stable isotope composition of the rainfall samples taken between October and May 2013 from the six BGR stations follows a LWML of (Figures 112):

$$\delta^2H = 6.7*\delta^{18}O + 13.6 \qquad R^2\ 0.97 \quad n=41$$

Average composition, weighted by rainfall amount was -5.87‰, -25.7‰ and 21‰ for $\delta^{18}O$, δ^2H and DE, respectively. The number of samples at this moment is still low (100 individual and 41 monthly weighed samples) but it can already be seen that the intercept value differs from those of AOUAD-RIZK et al. (2005).

Depending on the provenience of the air masses (trajectories; Figure 5), the composition of the rainfall will be different (Figure 114). The correlation of mean $\delta^{18}O$ and δ^2H values with elevation (Figure 113) follow these equations:

$$\delta^{18}O = -0.0015*elevation - 4.5 \qquad \delta^2H = -0.0089*elevation - 17.7$$

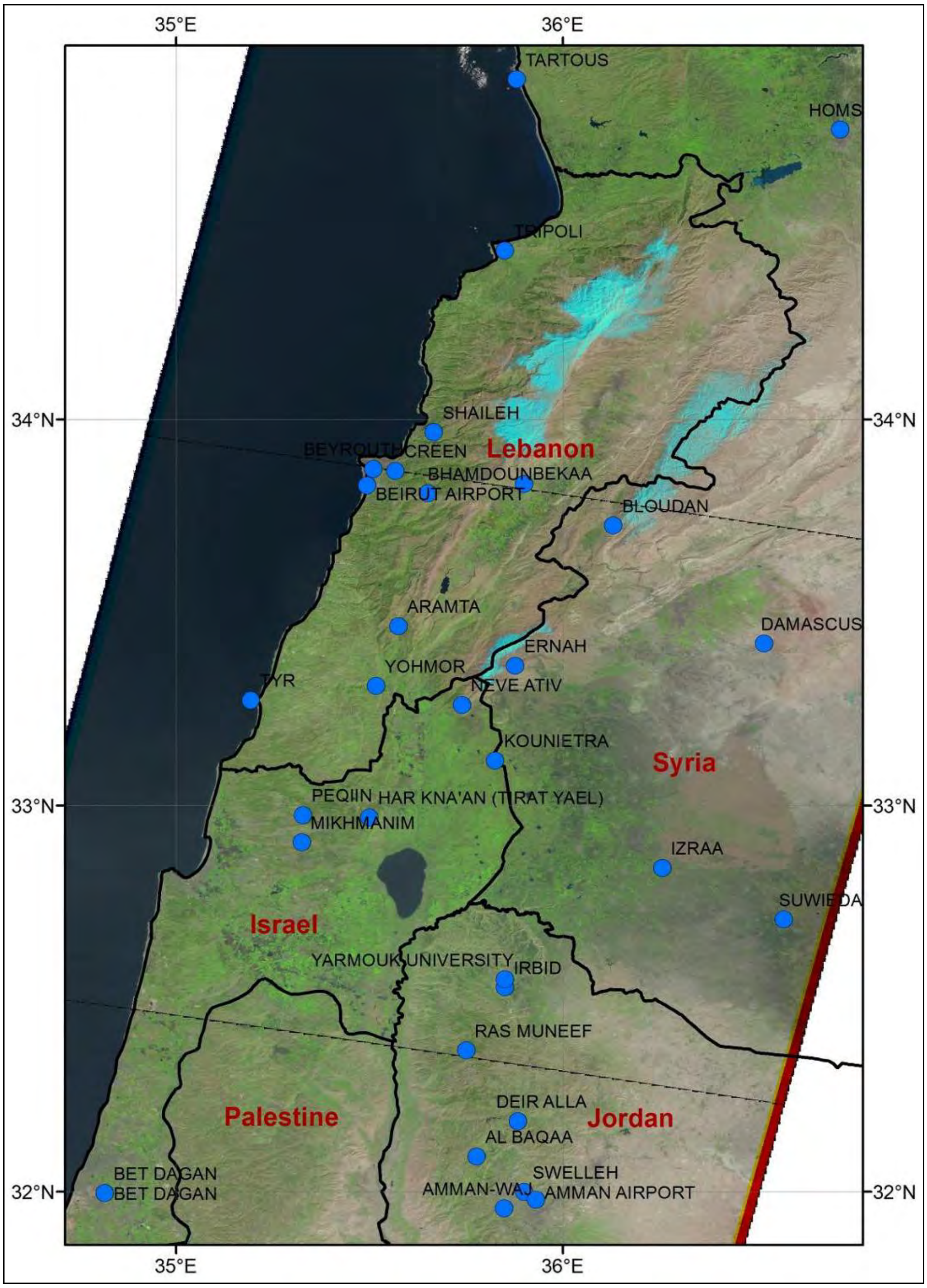


Figure 111: Stations of the GNIP Program

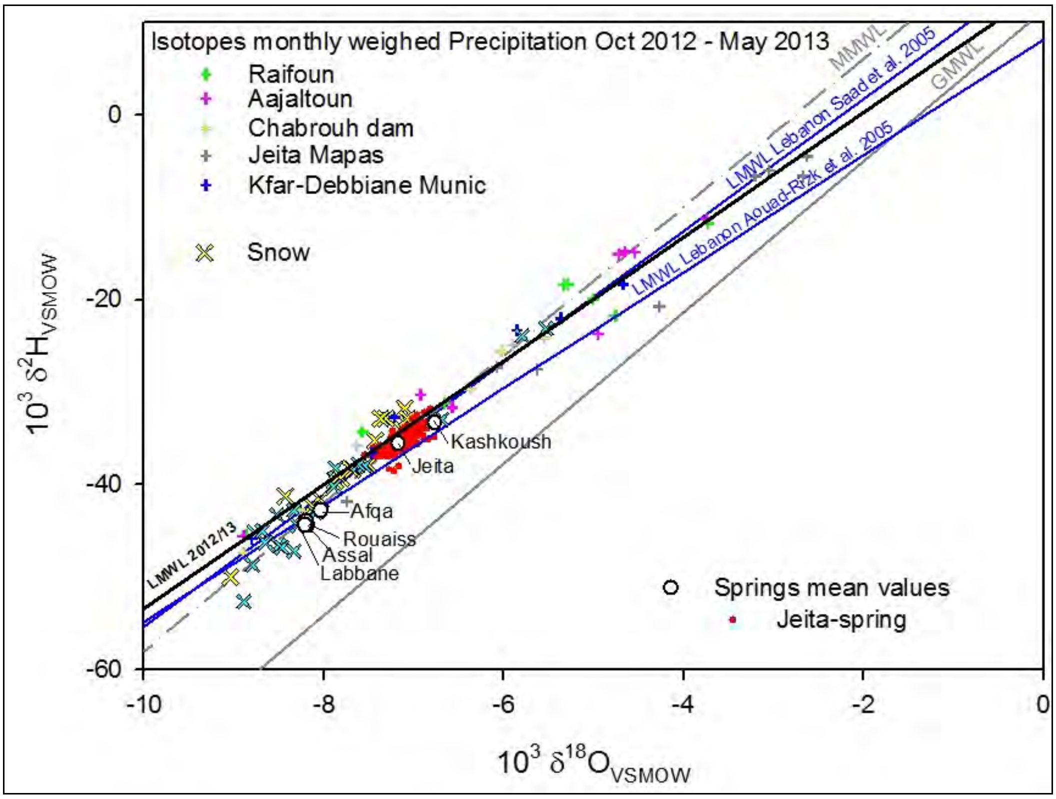


Figure 112: Stable Isotope Composition found in Rainfall and Snow of the Jeita Spring Catchment

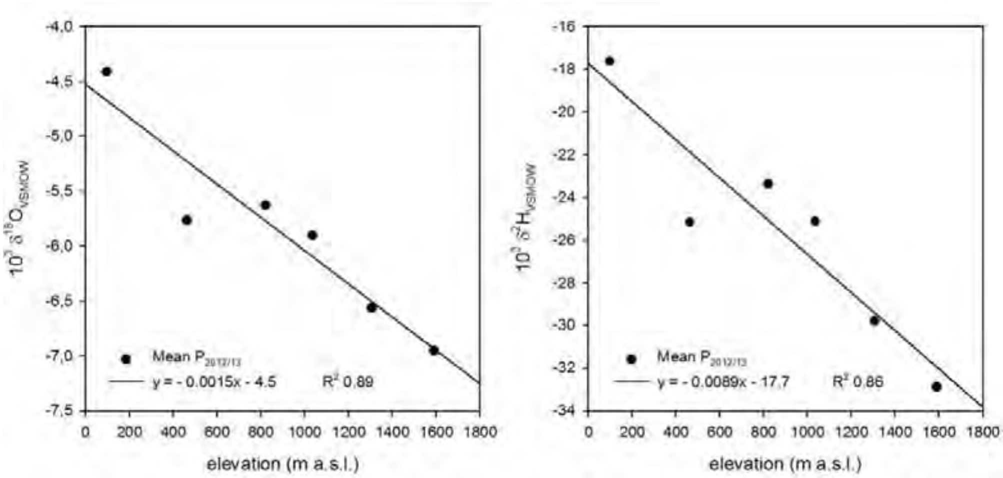


Figure 113: Correlation of Elevation with Mean $\delta^{18}O$ (left) and δ^2H (right) Compositions of Amount Weighted Rainfall Samples from six Stations in the Jeita Spring Catchment

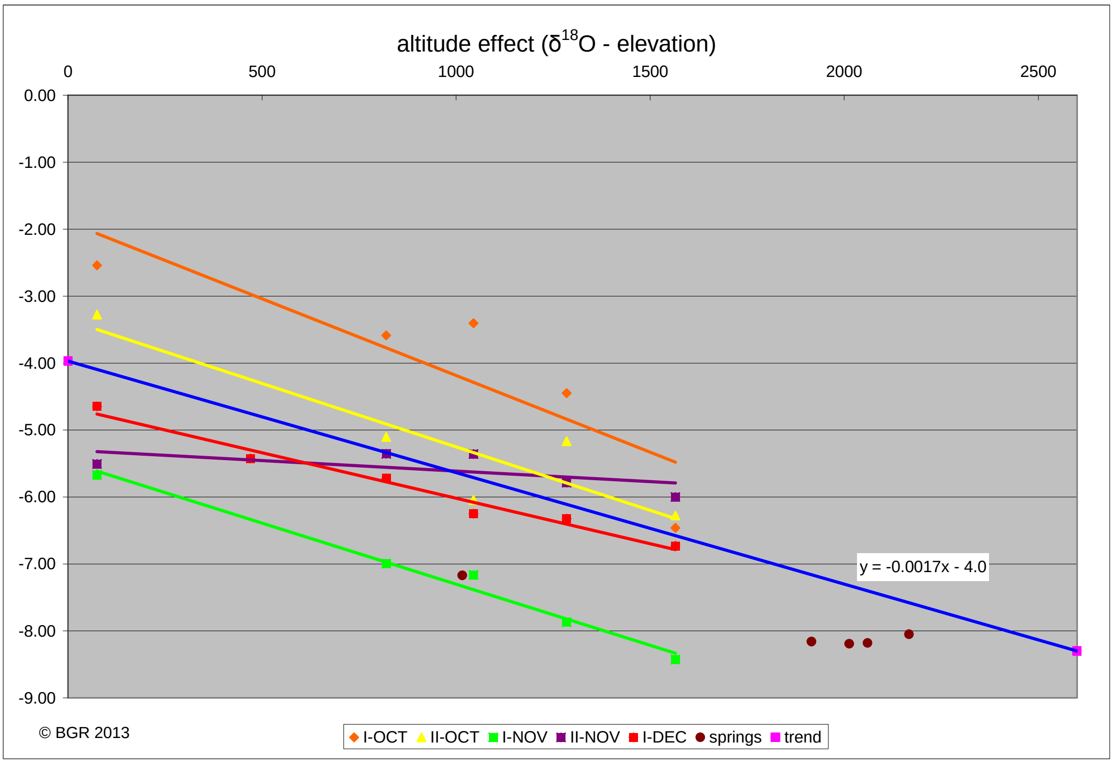


Figure 114: Correlation of Elevation with $\delta^{18}O$ Composition found in Rainfall of the Jeita Spring Catchment for 10-15 Day Intervals

Table 23: Stations of the GNIP Program in the Levant Region

GNIP Code	Country	Station Name	Latitude	Longitude	Altitude [m]	Type	Start	End	Samples total	Samples O18	Samples H2
4000500	Syria	Jarablous	36° 49' 20"	38° 0' 45"	351	Monthly	1991	1993	36	10	10
4000700	Syria	Aleppo	36° 11' 0"	37° 13' 00"	410	Monthly	1989	1992	48	10	10
4001700	Syria	Idleb	35° 56' 21"	36° 36' 24"	451	Monthly	1992	1993	24	6	6
4002201	Syria	Bab-Janet	35° 34' 20"	36° 11' 23"	1100	Monthly	1992	1993	24	5	5
4003900	Syria	Raqqa	35° 53' 50"	39° 20' 30"	246	Monthly	1991	1992	24	5	5
4005000	Syria	Tartous	34° 52' 48"	35° 52' 48"	5	Monthly	1989	1993	60	15	15
4005500	Syria	Homs	34° 45' 00"	36° 43' 00"	490	Monthly	1989	1993	60	14	14
4006100	Syria	Palmyra	34° 33' 0"	38° 18' 0"	400	Monthly	1989	1993	60	14	14
4008000	Syria	Damascus	33° 25' 12"	36° 31' 12"	609	Monthly	1989	1993	60	14	14
4008001	Syria	Bloudan	33° 43' 30"	36° 7' 49"	1540	Monthly	1989	1993	60	15	15
4008002	Syria	Ernah	33° 21' 45"	35° 52' 35"	1400	Monthly	1991	1993	36	10	10
4009501	Syria	Izraa	32° 50' 20"	36° 15' 25"	580	Monthly	1989	1993	60	14	14
4009502	Syria	Suwieda	32° 42' 20"	36° 34' 12"	1020	Monthly	1989	1993	60	14	14
4009503	Syria	Kounietra	33° 7' 00"	35° 49' 30"	930	Monthly	1989	1990	24	5	5
4010000	Lebanon	Beyrouth	33° 52' 19"	35° 30' 35"	19	Monthly	2003	2006	48	11	11
4010000	Lebanon	Beirut Airport	33° 49' 46"	35° 29' 39"	27	Events	2002	2002	10	10	10
4010002	Lebanon	Creen	33° 52' 00"	35° 34' 00"	249	Events	2001	2003	50	50	50
4010003	Lebanon	Shaileh	33° 58' 00"	35° 40' 00"	650	Events	2002	2003	27	27	27
4010101	Lebanon	Bekaa	33° 50' 0"	35° 54' 0"	961	Monthly	2003	2006	48	11	11
4010300	Lebanon	Tripoli	34° 26' 12"	35° 50' 59"	20	Monthly	2003	2006	48	10	10
4010401	Lebanon	Yohmor	33° 18' 37"	35° 31' 01"	514	Monthly	2003	2004	24	5	5
4010402	Lebanon	Aramta	33° 27' 54"	35° 34' 30"	431	Monthly	2003	2006	48	11	11
4010403	Lebanon	Tyr	33° 16' 24"	35° 11' 38"	5	Monthly	2003	2006	48	9	9
4011001	Lebanon	Bhamdoun	33° 48' 30"	35° 39' 04"	1080	Monthly	2003	2006	48	11	11
4015301	Israel	Har Kna'an (Tirat Yael)	32° 58' 12"	35° 30' 00"	964	Monthly	1961	1991	372	93	55
4015301	Israel	Neve Ativ	33° 15' 40"	35° 44' 22"	900	Events	2001	2003	27	27	27
4015302	Israel	Peqiin	32° 58' 33"	35° 19' 43"	545	Events	2001	2003	97	97	94
4015303	Israel	Mikhmanim	32° 54' 20"	35° 19' 31"	504	Events	2001	2003	120	119	115
4017900	Israel	Bet Dagan	31° 59' 50"	34° 48' 58"	39	Monthly	1960	2001	504	247	171
4017900	Israel	Bet Dagan	31° 59' 50"	34° 48' 58"	39	Events	1996	2001	38	27	27
4017901	Israel	Rehovot	31° 54' 0"	34° 39' 0"	50	Events	2000	2003	122	122	98
4017901	Israel	Rehovot	31° 54' 0"	34° 39' 0"	50	Vapour	2001	2003	148	148	118
4018401	Israel	Jerusalem	31° 47' 22"	35° 12' 49"	795	Events	2003	2003	20	18	17
4018402	Israel	Alon	31° 50' 03"	35° 21' 22"	235	Events	2002	2003	66	66	66
4018403	Israel	Soreq	31° 45' 21"	35° 1' 19"	400	Events	1995	2003	307	307	306
4019100	Israel	Beer	31° 13' 48"	34° 46' 48"	270	Monthly	1963	1978	192	8	7

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

GNIP Code	Country	Station Name	Latitude	Longitude	Altitude [m]	Type	Start	End	Samples total	Samples O18	Samples H2
		Sheva									
4019101	Israel	BEER SHEVA (Levin Et Al. 1980)	31° 15' 00"	34° 48' 0"	300	Events	1977	1978	8	8	6
4019102	Israel	KIRYAT SDE BOQER (Levin Et Al. 1980)	30° 52' 12"	34° 47' 24"	500	Events	1977	1978	16	16	13
4019103	Israel	REVIVIM (Levin Et Al. 1980)	31° 2' 24"	34° 43' 12"	300	Events	1977	1978	14	14	8
4019104	Israel	AVDAT (Levin Et Al. 1980)	30° 47' 24"	34° 46' 48"	650	Events	1977	1978	11	11	9
4019105	Israel	MIZPEH-RAMON (Levin Et Al. 1980)	30° 36' 36"	34° 48' 0"	900	Events	1977	1978	10	8	7
4023001	Israel	SADOTH (Dismantled, Levin Et Al. 1980)	31° 16' 48"	34° 10' 12"	2	Events	1977	1978	14	14	12
4025500	Jordan	Irbid	32° 31' 48"	35° 51' 00"	555	Monthly	1965	2002	180	67	67
4025501	Jordan	Yarmouk University	32° 33' 0"	35° 51' 00"	616	Monthly	1989	2003	91	74	49
4025701	Jordan	Deir Alla	32° 11' 0"	35° 53' 0"	-224	Monthly	1989	2003	51	27	24
4025701	Jordan	Deir Alla	32° 11' 0"	35° 53' 0"	-224	Events	1997	2002	20	13	7
4026601	Jordan	Ras Muneef	32° 22' 00"	35° 45' 00"	1150	Monthly	1985	2004	240	95	65
4026901	Jordan	Swelleh	32° 0' 00"	35° 54' 0"	1050	Monthly	2002	2003	24	6	6
4027000	Jordan	Amman Airport	31° 58' 48"	35° 55' 48"	850	Monthly	1965	1968	48	18	18
4027001	Jordan	Amman-Waj	31° 57' 28"	35° 50' 54"	900	Monthly	1985	2003	228	82	42
4027002	Jordan	Al Baqaa	32° 5' 31"	35° 46' 37"	700	Monthly	1990	1998	31	21	10
4027201	Jordan	Queen Alia Airport	31° 40' 00"	35° 59' 0"	715	Monthly	1990	2003	52	24	12
4027901	Jordan	Azraq	31° 51' 00"	36° 49' 00"	533	Monthly	1989	2003	59	38	18
4029401	Jordan	Walla	31° 43' 12"	35° 47' 0"	785	Monthly	1987	2000	47	47	17
4031001	Jordan	Rabba	31° 12' 0"	35° 45' 00"	970	Monthly	1965	2002	76	30	22
4031001	Jordan	Rabba	31° 12' 0"	35° 45' 00"	970	Events	1991	1998	9	9	2
4031002	Jordan	Shoubak	30° 16' 12"	35° 34' 48"	1300	Monthly	1965	2003	60	17	17
4034001	Jordan	Aqaba	29° 33' 00"	34° 54' 0"	2	Monthly	2002	2002	12	1	1

Stable Isotope Composition of Snow

Snow conditions during the winter periods in 2011/12 and 2012/13 were quite different from each other. Snow depths of 0.30 m to 3.10 m where measured during the first campaign and 0.05 m to 1.65 m during the second campaign in altitudes between 1,200 m asl and 2,400 m asl. The stable isotope composition of snow (integral samples) taken end of February 2012 and end of February 2013 are plotted in relation to MWLs in Figure 112. The snow integral samples are more depleted in general than monthly weighed precipitation samples collected during winter 2012/2013. The average composition of the snow integral samples was -7.79‰ and -38.4‰ in 2012 (n=17) and -7.73‰ and -39.4‰ in 2013 (n=21), for $\delta^{18}O$ and $\delta^{2}H$ respectively (Figure 112).

Stable Isotope Composition of springs

Six springs in the Upper Aquifer (C4: Afqa, Rouaiss Assal, Labbane) and Lower Aquifer (J4: Jeita, Kashkoush) were monitored (for further details concerning the subdivision of the groundwater system in the Jeita catchment see: MARGANE et al., 2013). The stable isotope content ($\delta^{2}H$, $\delta^{18}O$) of all above mentioned springs behaves very similar over time (Figure 115), exhibiting a seasonal variation, however, also showing a clear altitude effect (Figure 117; KOENIGER et al., 2012). The isotopic composition of Jeita (60 m asl) and Kashkoush (50 m asl) springs, discharging from the Lower Aquifer, is significantly lower than that of the springs discharging from the Upper Aquifer (C4), the Afqa (spring elevation: 1,280 m asl), Rouaiss (1,336 m asl), Assal (1,540 m asl) and Labbane (1,644 m asl) springs (Figure 116). Rainfall samples also exhibit a clear elevation effect (Figures 113, 114). Stable isotope composition of snow samples taken in the outcrop area of the C4 is very similar to that of the C4 springs. Stable isotope as well as CFC, SF6 and He/^{3}H analyses point to a relatively short mean groundwater residence time of a few years only (Chapters 3.11.6 and 3.11.7).

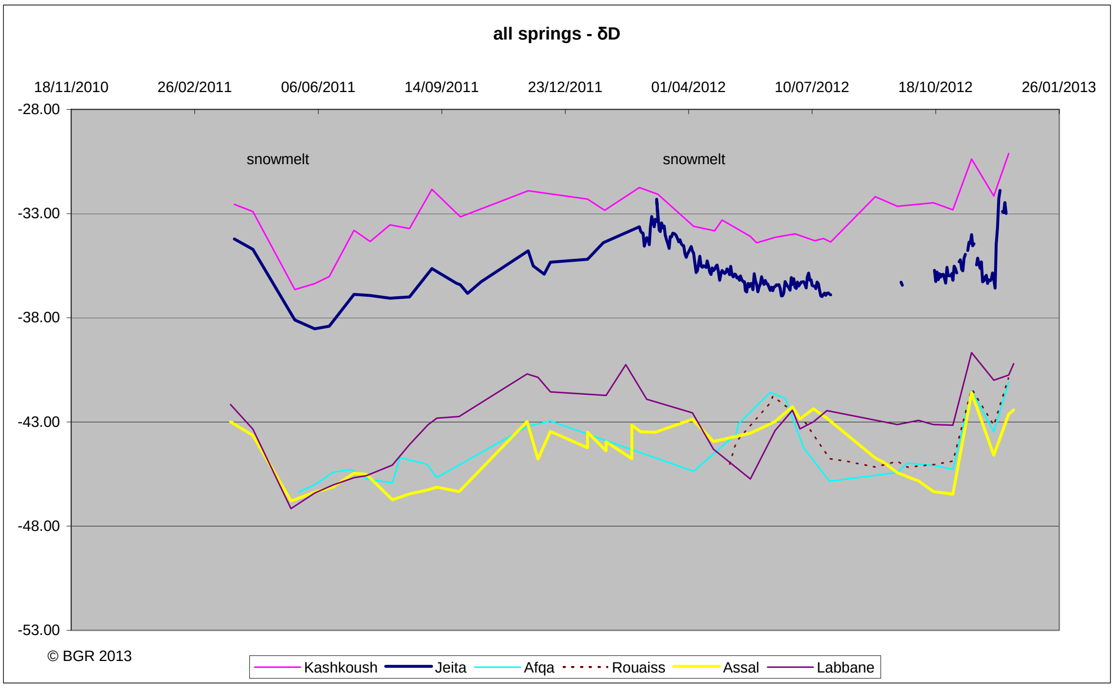


Figure 115: δ^2H Composition found in six Springs of the Jeita Catchment

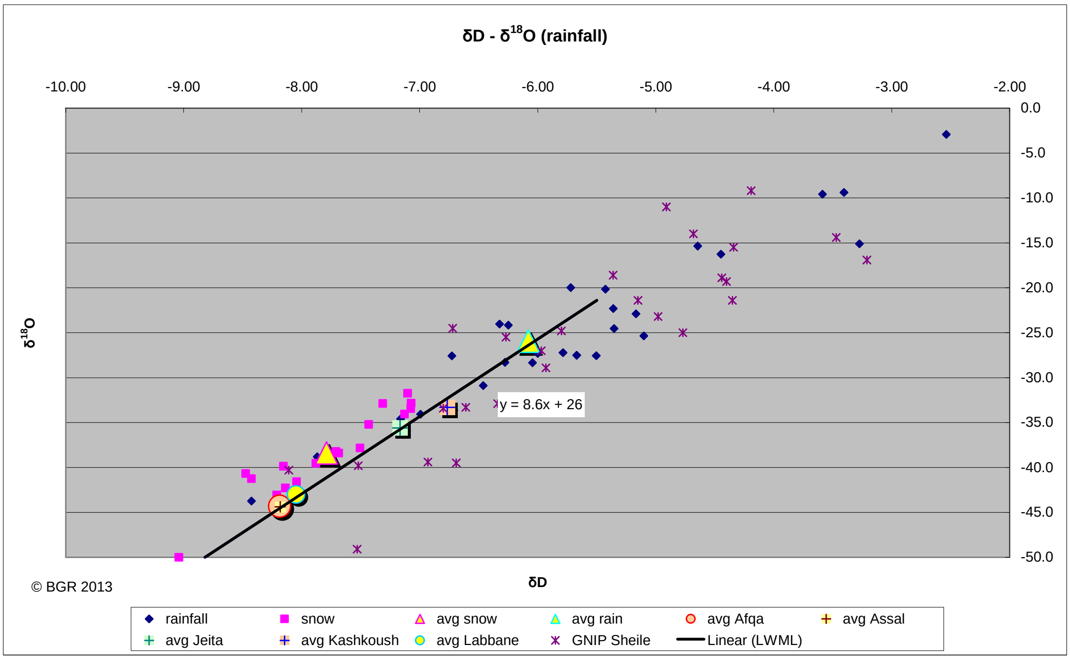


Figure 116: Averages of Rain, Snow and Spring Stable Isotope Composition

The comparison of $\delta^{18}O$ values from springs and from snow/rainfall (Figure 117) shows that the mean catchment elevation of Jeita spring must be higher than 1,400 m asl. However, the J4 outcrop area has a mean elevation of only 1,016 m. Therefore Jeita spring (as Kashkoush spring too) must have a major contribution from groundwater that was recharged at higher elevations, i.e. in the Upper Aquifer (C4). This confirms the assumption of major surface water infiltrations in the outcrop area of the uppermost C4 in Nahr Ibrahim, Nahr es Salib, Nahr es Msann and Nahr es Zirghaya and is in line with other major findings of the BGR project (Chapter 3.4). Based on stable isotope analyses, it is assumed that the share of groundwater coming from the Upper Aquifer must be more than 30 % (based on the WEAP model the C4 contributes 42% to the J4 aquifer through riverbed infiltration; see Chapter 3.9), which confirms previous assumptions based on differential surface water flow measurements (MARGANE, 2012a, 2012b).

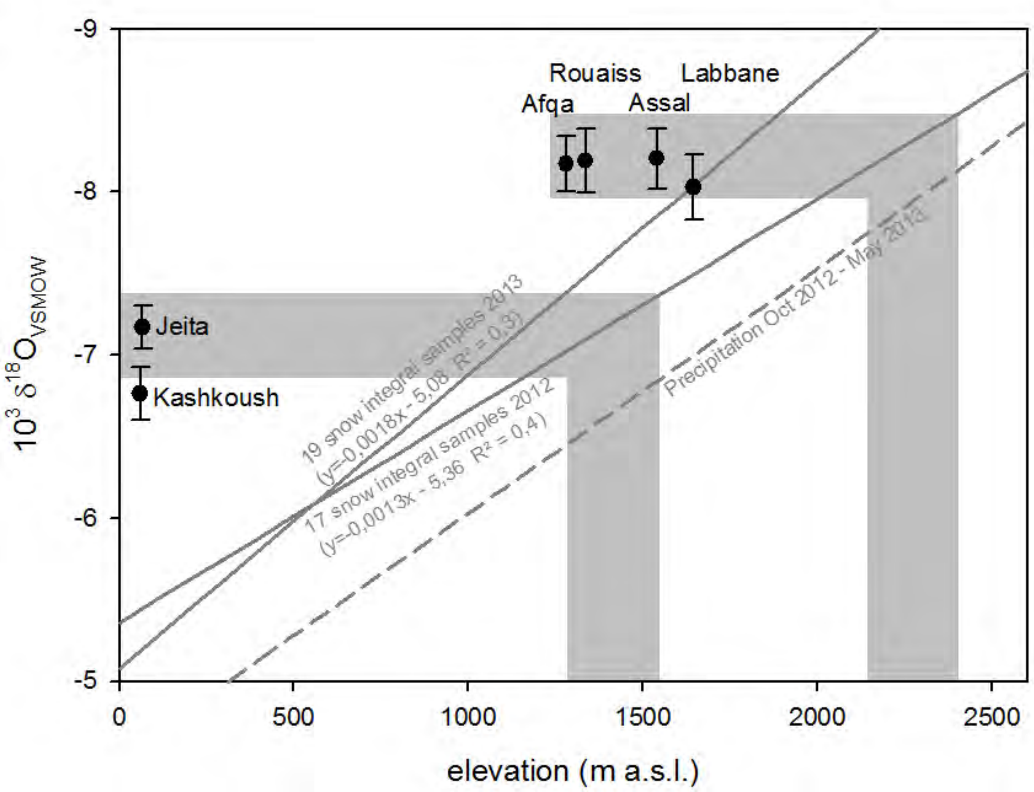


Figure 117: Assumed Mean Elevation of Spring Groundwater CatchmentS based on Isotope Composition of Springs and Snow Sampling in 2012

3.11.5 Rainfall Analyses

As already mentioned in the previous chapter, rainfall samples were taken mainly for stable isotope analysis. However, also rainfall amount (which fits nicely with the more sophisticated measurements at the meteorological stations (Annex 5), done often at the same location; Figure 118), electric conductivity (Figures 120, 121) and chloride content (Figure 122) of rainfall were determined. Sampling started at the beginning of the rainy season 2012/13 (October 2012). A considerable temporal variability in EC and chloride content in rainfall can be observed (Figures 120, 122). However, often high EC and chloride coincide with low amount of rainfall.

In general a decrease of EC with elevation and distance from the coastline can be observed (Figure 123). The reason is the decreasing chloride content in rainfall with increasing elevation and distance from the coast. This fact is observed globally and is often used for groundwater recharge calculations based on chloride content in groundwater and rainfall (chloride mass balance method). Although the level of EC (and with this the chloride content) is different for every rainfall event (in this case a collection of events over 10 to 15 days; Figure 119), the trend seems to be almost the same (Figure 121).

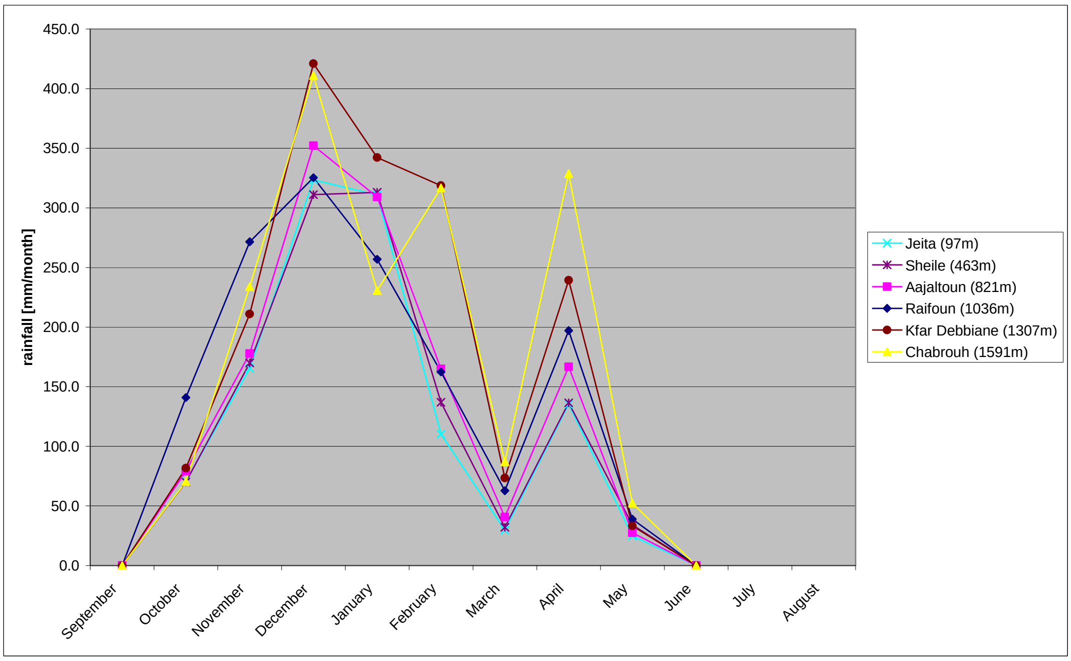


Figure 118: Monthly Rainfall measured using Rainfall Samplers during Water Year 2012/13

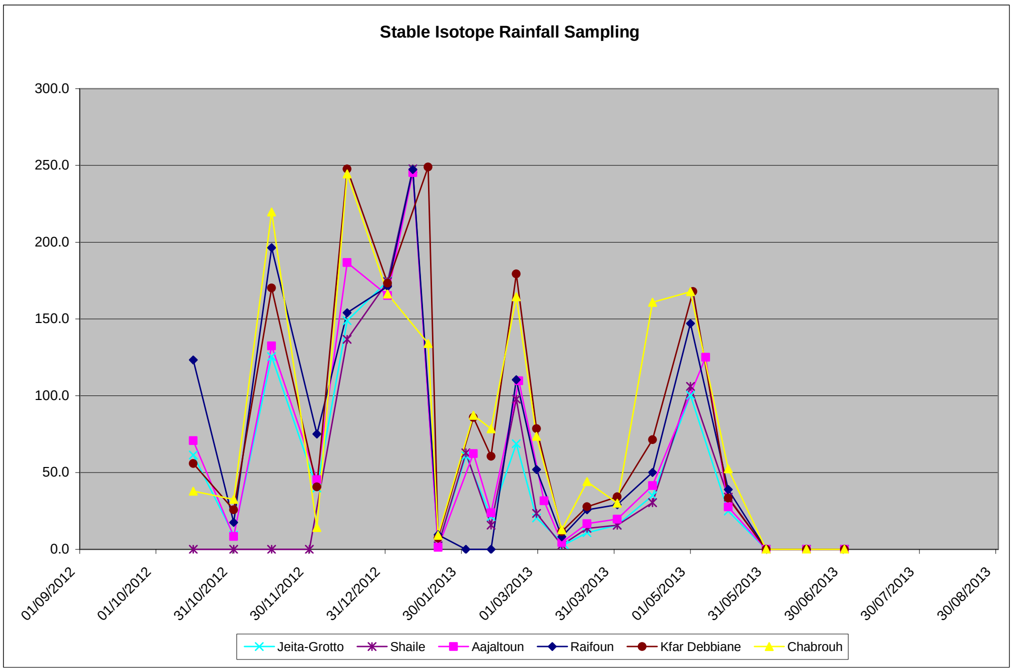


Figure 119: Rainfall Amounts collected using Rainfall Samplers for 10 or 15 Day Intervals during Water Year 2012/13

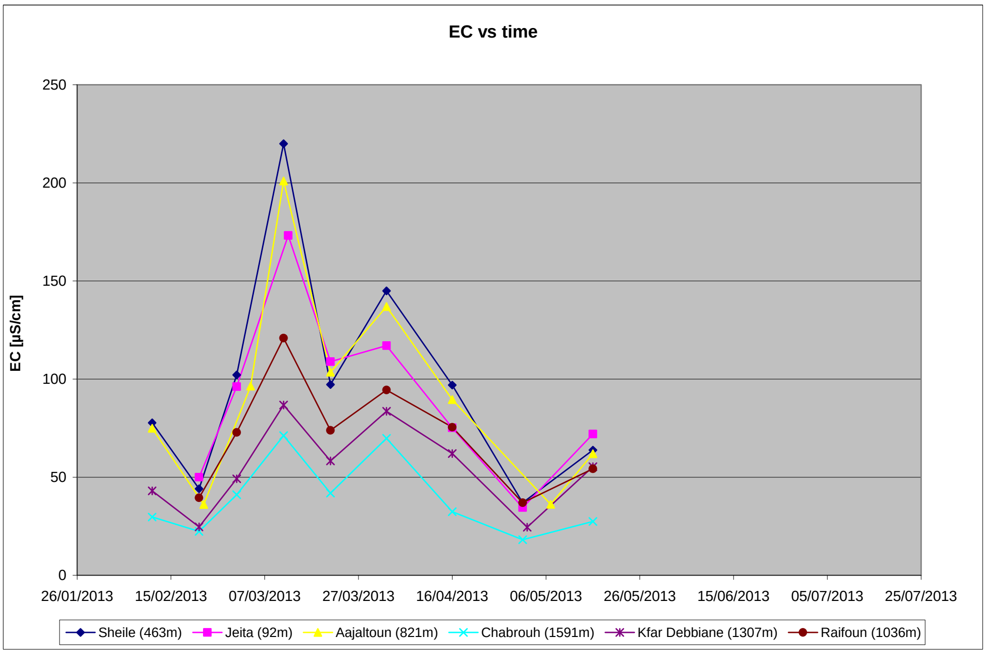


Figure 120: Temporal Variation of Electric Conductivity in Rainfall measured during Water Year 2012/13

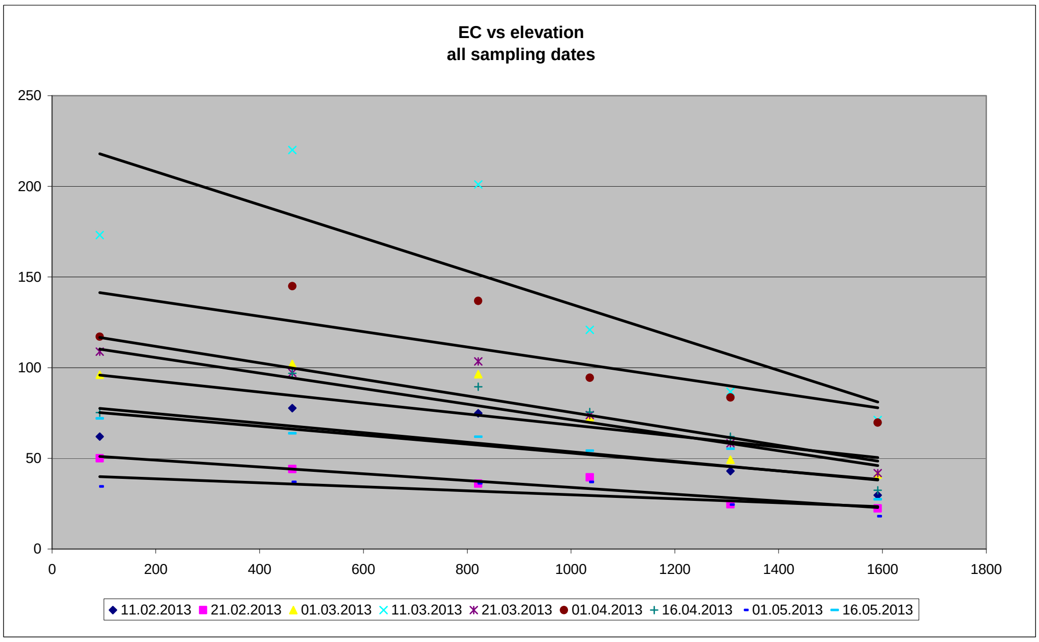


Figure 121: Correlation of Electric Conductivity in Rainfall with Elevation for Sampling Campaigns during Water Year 2012/13

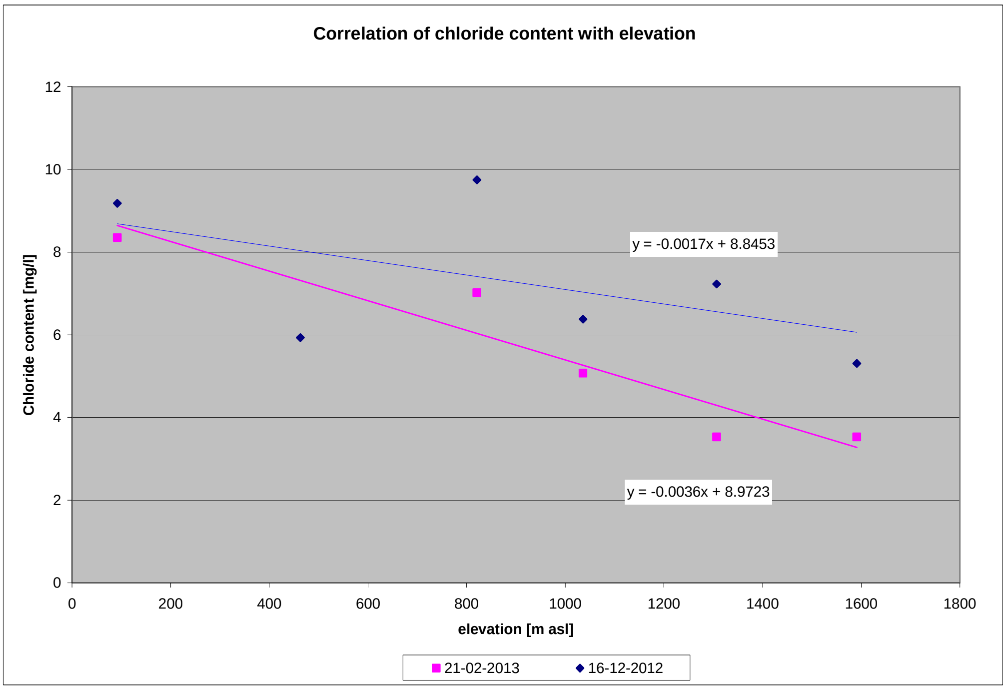
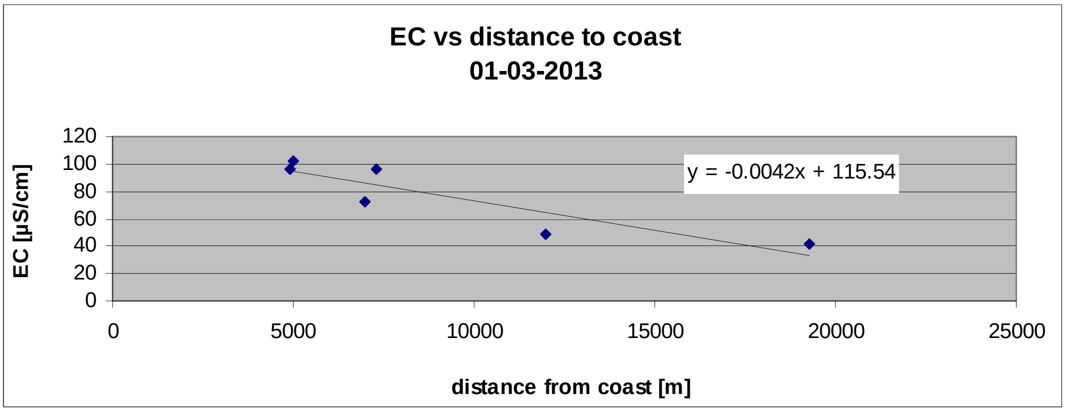


Figure 122: Correlation of Chloride Content of Rainfall with Elevation for two Sampling Campaigns during Water Year 2012/13



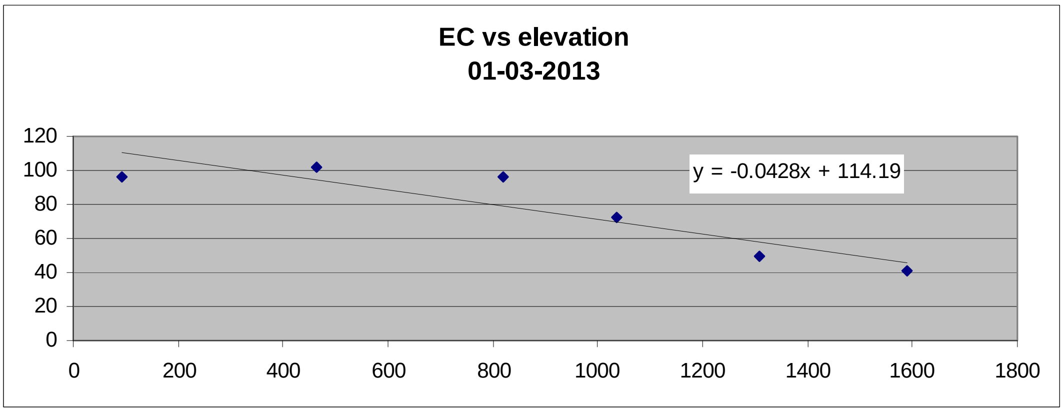


Figure 123: Correlations of Electric Conductivity with Distance from Coast and with Elevation for Sampling Campaigns during Water Year 2012/13

3.11.6 Helium/Tritium, CFC and SF6 Analyses

Helium-tritium, chlorofluorocarbons (CFC) and SF_6 samples were taken from Jeita, Daraya (Jeita siphon terminale), Assal, Labbane and Kashkoush springs, in order to quantify the mean groundwater residence time (GEYER & DOUMMAR, 2013). Groundwater dating with CFC-11 (CCl_3F), CFC-12 (CCl_2F_2) and CFC-113 ($CFCl_2CClF_2$) is possible because their amounts in the atmosphere over the past 50 years have been reconstructed, their solubilities in water are known, and concentrations in air and water can be measured (USGS: pubs.usgs.gov/fs/ FS-134-99/). Age determination requires knowing the concentration of the above mentioned elements in the atmosphere. For this study these were taken from literature resources (USGS: water.usgs.gov/lab/software/ air_curve/). However, there are worldwide too few stations where CFCs and SF6 in the atmosphere is continuously measured (AGAGE - Advanced Global

Atmospheric Gases Experiment: http://agage.eas.gatech.edu/index.htm) and there is a large difference between the recorded data (Figure 124) so that there is some uncertainty related to the intake of CFCs from the atmosphere at a specific location. The method requires also that there is no other source for intake (e.g. atmospheric pollution events or groundwater pollution) of the above mentioned elements and no sink (loss). Moreover, chemical processes (microbial degradation, sorption) also can affect the concentration of CFCs found in groundwater. Due to the numerous pollution sources, there are, however, also other sources for the considered CFCs so that the results of the CFC- SF_6 age determination cannot be considered alone. Also the helium-tritium method can be affected by $^3He/^4He$ loss to the atmosphere, which is facilitated in an open karst system. Therefore the age determinations conducted have to be considered with great care.

The apparent groundwater ages determined based on the considered CFCs and SF_6 were less than 10 years.

Based on the helium-tritium method GEYER & DOUMMAR determined mean groundwater residence times of 0.9 - 1.7 years (Table 24).

For the above mentioned age determinations only 5 samples were taken at one sampling campaign. More such sampling campaigns would have to be conducted in order to improve validity of the obtained result.

Table 24: Age Determination by Helium-Tritium Method for Springs in the Jeita Catchment

Location	Date	Tritium	Helium-3	Helium-4	Helium/ Tritium Age
		TU	ccSTP kg^{-1}	ccSTP kg^{-1}	Years
Jeita	17.09.2010	3,03 ±0,31	6.65E-11	4.85E-05	0,9
Daraya tunnel	17.09.2010	3,00 ±0,18	6.85E-11	4.97E-05	1,6
Labbane	18.09.2010	3,26 ±1,32	5.82E-11	4.20E-05	1,7
Assal	18.09.2010	3,27 ±0,23	5.81E-11	4.24E-05	1,5
Kashkoush	19.09.2010	2,99 ±0,24	6.91E-11	5.03E-05	0,9

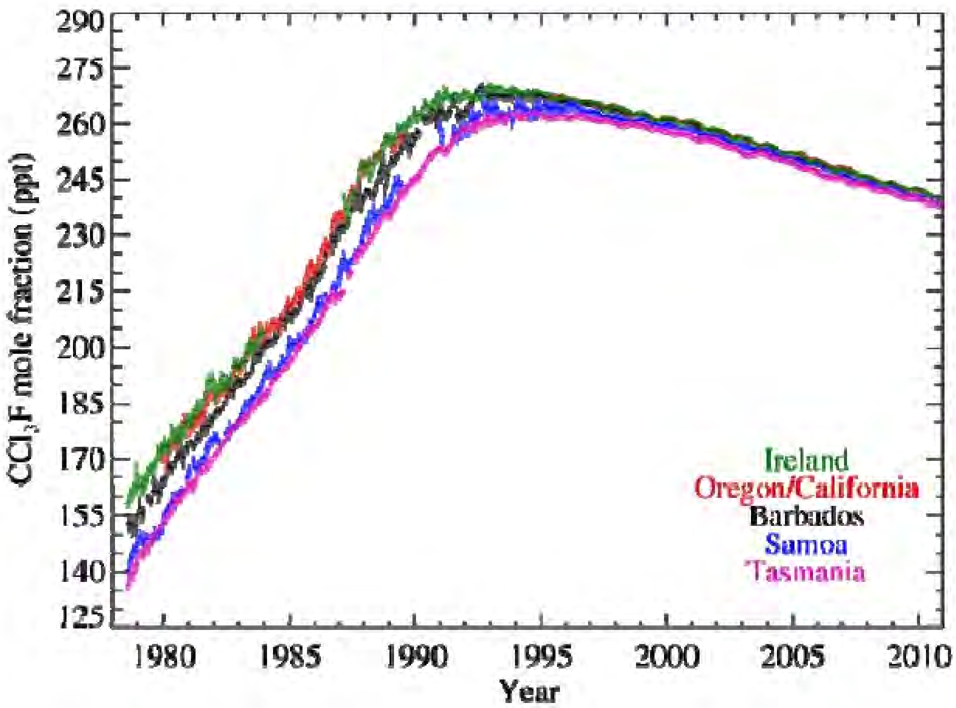


Figure 124: CFC-11 Concentration measured by ASAGE in the World Atmosphere

(source: www.agage.eas.gatech.edu)

4 Groundwater Hazards

Various mappings of hazards to groundwater have been undertaken over the past two decades, mostly mapping hazards in the surface water catchment, not the groundwater catchment:

- Bahzad HAKIM (1993)
- Mark SAADEH (1994)
- Lina ABD EL NOUR (1998)
- AVSI (2009)

However, these assessments did not provide sufficient details concerning the amount and type of substances used in the process, the waste and wastewater management and the specific risk of each site for the groundwater source, i.e. Jeita spring. At the time of assessment, the groundwater catchment of Jeita spring was not yet properly delineated, and was believed being much smaller. Therefore a new and more comprehensive inventory of all existing hazards to Jeita groundwater was compiled by the BGR project through intensive field work. The related pollution risk was assessed based on the quantities and substances used at the sites, the procedures followed concerning storage, handling and disposal of the substances, waste and wastewater management, groundwater vulnerability, and the distance of the site to the source. The environmental problems in the Jeita catchment are not new and the previous assessments have almost come to the same conclusion but the main question remains: why no action was taken to reduce the serious pollution of the country's most important water source?

Following the civil war, a rapid and uncontrolled urban development took place in the Jeita catchment. However, a proper wastewater network is still not installed. Therefore the main pollution hazard in the Jeita catchment still is improper disposal of wastewater in open cesspits, wells or river courses (ACE, 1995). Four large wastewater schemes were proposed to be implemented (Table 25), many of them almost 20 years ago and still for all of these WW schemes, except now for the KfW JSPP project, an implementation is not in sight.

Table 25: Proposed Wastewater Schemes

Donor/area/project	Fund (Mio USD)	Approx. no. of inhabitants	Year of first agreement / signed / start of construction
EIB/AFD Keserwan Water and Wastewater project	110	~ 438,000 Lower Keserwan	1995 / 2009 / -
EIB Metn	75	-	1995/canceled
KfW JSPP	36	~ 85,000	2008 / 2009 / -
Italian Protocol	12	~ 30,000 Faraya-Mairouba-Hrajel-Ayoun es Simane	1995 / -

Based on various sources

This chapter summarizes the findings of a comprehensive field assessment conducted by the BGR project (RAAD & MARGANE, 2013a). The risk of each hazard was assessed based on the groundwater vulnerability map and the groundwater protection zones with related proposed landuse restrictions (MARGANE & SCHULER, 2013). A related report summarizing which consequences result from this risk assessment was prepared (RAAD, 2013) in order to present in brief to decision-makers the required actions. Another report lists upon request of CDR and KfW the 10 most critical groundwater hazards (RAAD & MARGANE, 2013b).

Despite being the most widely spread pollution source, wastewater is not the only major hazard in Jeita catchment. While microbiological contamination is monitored and partly treated by WEBML, hydrocarbons, pesticides, heavy metals, radioactive components, and many other contaminants are neither monitored nor treated at the Dbayeh drinking water treatment plant, providing around 75% of drinking water to the Greater Beirut Area from Jeita spring.

Each contamination source was assessed separately, in order to determine the relevance of the risk it presents to Jeita groundwater.

Identified threats to Jeita spring were divided in two categories:

- Non-point sources: wastewater, agriculture and stormwater,
- Point sources: gas stations, generators and residential heating systems, quarries, industries, feedlots and slaughterhouses, illegal dumpsites, military barracks and maneuvers, cemeteries, in addition to touristic resorts or restaurants.

The field assessment revealed alarming practices and unsuitable infrastructures related to the located hazards. All these coupled with gaps in actuated laws and guidelines, overlapping governmental responsibilities, lack of law enforcement and of monitoring and institutional capacities for enforcement and control.

4.1 Non-Point Sources

4.1.1 Wastewater

To date, institutional management of the wastewater sector in Lebanon is ineffective. The roles and responsibilities are dispersed between ministries and many other authorities making it difficult to discern clear responsibilities.

Despite the existence of clear actuated and quite developed guidelines for wastewater treatment and discharge limits, unsound practices are ruling the sector, in complete absence of any kind of control and law enforcement.

In the Jeita catchment, as elsewhere in Lebanon, it is still common practice to discharge wastewater into open cesspits, abandoned wells, into river courses, water canals, and elsewhere to the environment. Even if wastewater collectors were haphazardly built by the municipalities, the sole purpose was to divert untreated wastewater out of the village boundaries. Mostly these 'collector lines' were found heavily leaking and discharge wastewater into river courses (such as at Baskenta, Marj Baskenta, Hrajel, Kfardebiane, Beit Chebab, Mar Boutros, etc.) or into sinkholes (e.g. Mayrouba). Due to this diffuse contamination, wastewater must be considered a non-point source. The above mentioned disposal practices adopted by the population as a response to the lack of government action, requires to be addressed urgently due to the severe impact on Jeita spring.

Figure 125: Tanker dumping wastewater in Nahr el Salib near Deir Chamra

Figure 126: Sewage canal discharging into Nahr el Salib at Hrajel

The monitoring of Jeita raw waters carried out by WEBML reveals continuous presence of E. coli and Fecal coliforms in concentrations far exceeding US EPA allowable limits in water resources used for drinking water supply. This fact in combination with the often high turbidity renders Jeita spring waters unsafe for drinking water supply. Chlorination and physical water treatments adopted by WEBML are unable to efficiently treat viruses and other contaminants generated by such huge WW contamination. The latter is becoming a threat to public health in the areas fed by Jeita spring waters. Enteroviruses (usually generated by WW contamination) have been subject to analysis in several Metn schools (fed by Jeita and Kaskoush waters) in 2013), noting a significant microbiological contamination of the supplied drinking water.

Actions required

- Establish sewage networks covering the entire catchment area and connect it to wastewater treatment plants (WWTPs) to protect the Jeita spring drinking water source. From the perspective of groundwater resources protection, a centralized approach with WWTPs at the coast is recommended under current conditions (high deficits in electricity coverage, lacking control and enforcement, lacking institutional capacity). Decentralized small wastewater treatment plants may be established in small villages, in relevant touristic resorts and in army barracks.
- Raise public awareness related to the contamination generated by unsound wastewater disposal in the nature and leakage to groundwater
- Enforce laws and apply penalties related to unsound disposal of untreated wastewater.
- A harmonization of the legal framework and establishment of an enforcement agency (environmental police) are urgently required.

4.1.2 Agriculture

Around 32 ha (7.8%) are used for agricultural land cultivation in the Jeita catchment. Irrigation water sources are either: local springs, groundwater pumping from wells (drilled within the properties) or irrigation ponds.

Produced crops are mainly fruit trees (apples, peaches) in addition to tomatoes, cucumber, beans and lettuces.

As emphasized in Figure 127, 28.0% of agricultural activity takes place on vulnerable groundwater, while 60.7 % of agricultural areas are located on very low vulnerable groundwater. However, the noted anarchic practices (in this sector and its relevant contamination risk mainly due to the presence of irrigation wells within agricultural lands (facilitating direct groundwater contamination) added to illegal disposal of agricultural wastes increase the related risk of GW contamination.

Furthermore, as conducted on shallow soils and fractured limestone, agricultural practices might easily contaminate Jeita groundwater with different kinds of toxic contaminants (pesticides, nitrates, etc.) and many kinds of hazardous wastes.

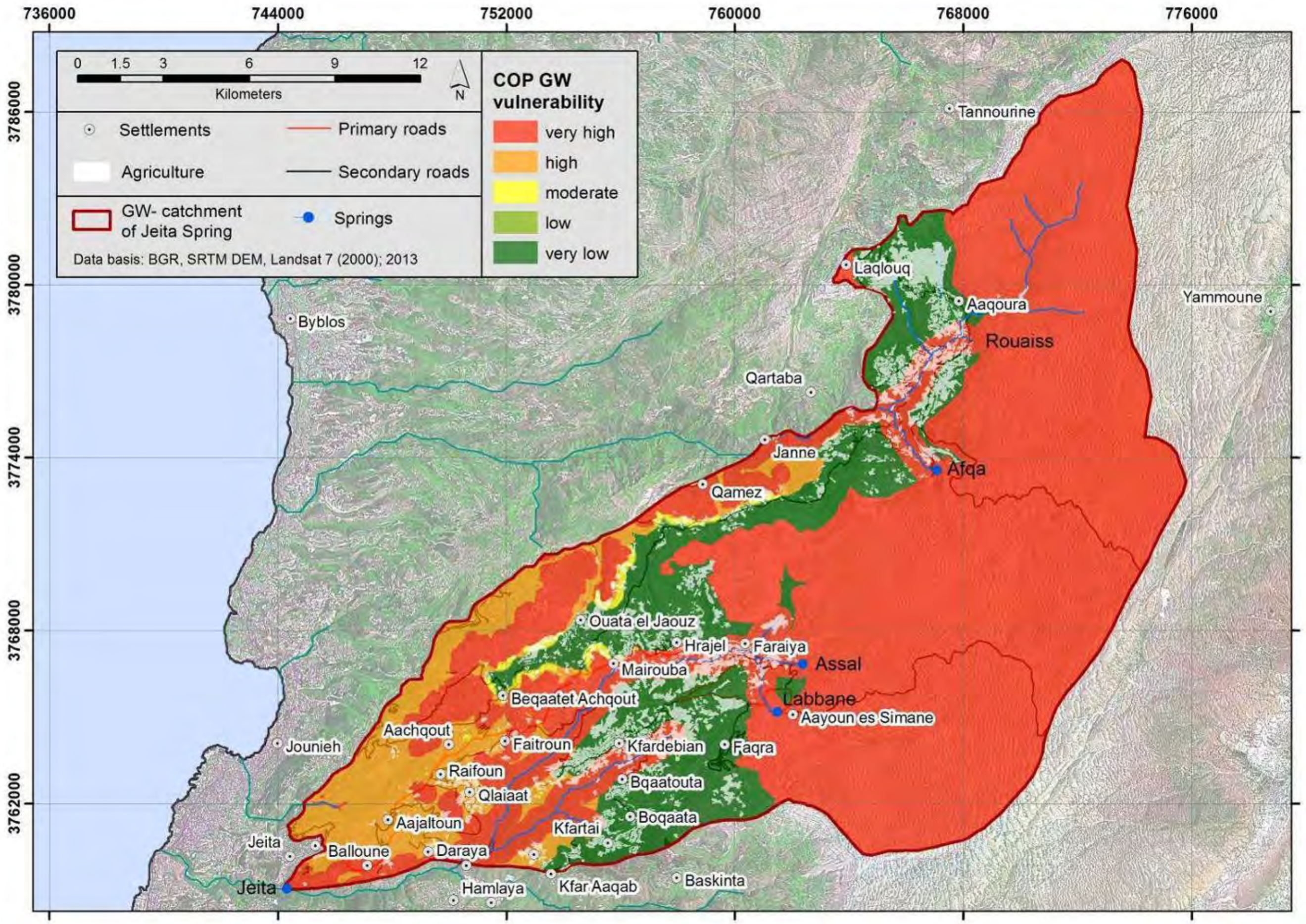


Figure 127: Distribution of Agricultural Landuse Activity (crop production) and Groundwater Vulnerability

However, WEBML is unable to monitor or treat such contamination. **Related monitoring is vital, considering analysis related to the components of the main used pesticides and fertilizers in the study area**.

4.1.2.1 Pesticides

Given the lack of environmental awareness and of public agriculture extension services, the available pesticides in the Lebanese market (many of these are of very bad quality or banned however still available and imported under false labelling) and the disposal of pesticides containers in the nature (Figure 128), the danger generated by crop production activity in the Jeita catchment must be given more attention.

In complete absence of adequate facilities able to receive, recycle and/or dispose empty pesticides containers and unused or expired pesticides, farmers are disposing them in the environment near or at their properties, in sinkholes, near water courses or in their wastewater network or cesspits. This generates a high risk on groundwater quality.

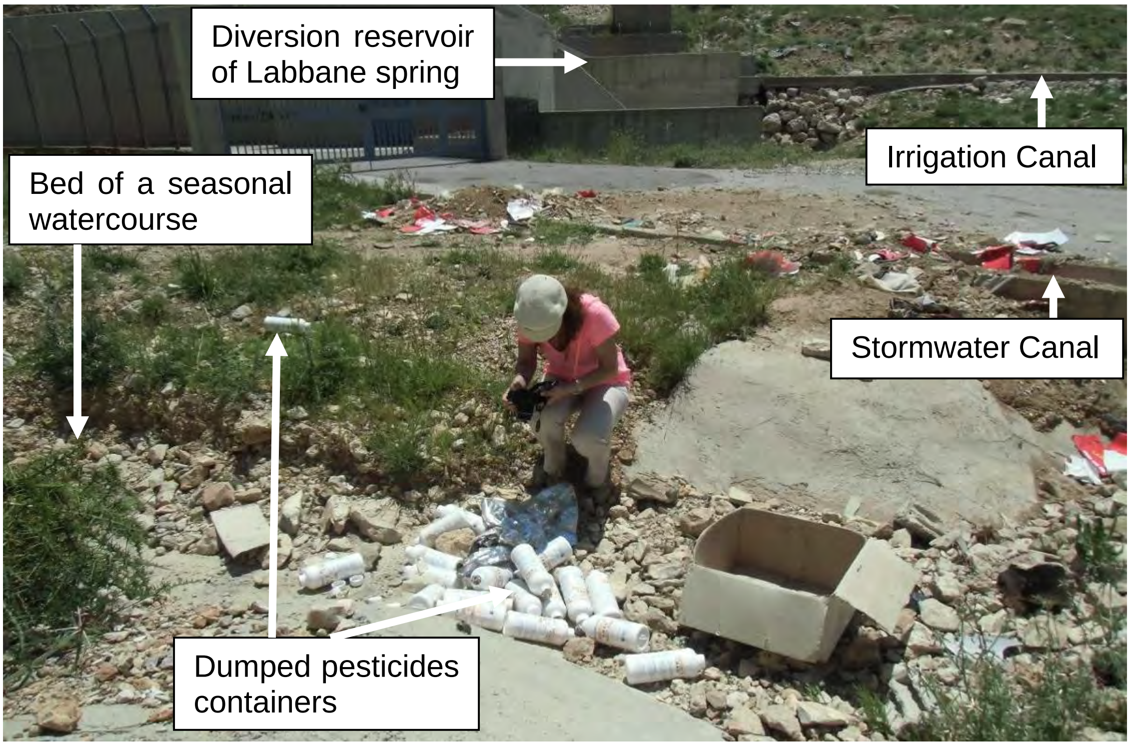


Figure 128: Dumping of empty Pesticide Containers at Labbane Spring.

4.1.2.2 Fertilizers

Considering the unsound fertilization practices common in the Jeita catchment, the contamination risk by fertilizers is also not to be neglected.

Organic fertilizers

When untreated and unfermented, the use of manure can generate a high risk of groundwater contamination by microbiological constituents in addition to nitrates and dioxins. The field assessment revealed that many farmers use untreated, unfermented manure which contributes to groundwater contamination.

The monitored NO_3 contents in Jeita spring raw water vary between 8 and 15 mg/l, those of NH_4 range between 0.1 and 0.3 mg/l. In all samples the detection limit of 0.025 mg/l NH_4 was exceeded. WHO (2011) set an allowable limit of 50 mg/L NO_3 and 3 mg/L NO_2 in groundwater due to the risk of methemoglobinemia.

Inorganic (chemical) fertilizers

The absence of serious control of the local market for fertilizers and an efficient agricultural extension service, high application rates of chemical fertilizers and widespread use of ammonium nitrate and incorrect labeling of the fertilizers contribute to bad fertilizer management and pave the way for agricultural pollution.

Main fertilizer components related to hazardous contaminants presenting major risk on human health are: nitrate, nitrite, barium, beryllium, cadmium, chromium (total), copper, cyanide, fluoride, lead, mercury. Fluoride and arsenic are among the most serious inorganic contaminants in drinking water worldwide. Both are not analyzed by WEBML.

Radioactive elements uranium and polonium-210 are contained in phosphate fertilizers (e.g. DAP). Both were never measured by WEBML.

Fertilizers management, through careful observation of soil characteristics and crops requirement must be implemented to mitigate the effects of excess fertilization and subsequent leaching to groundwater. Chemical fertilizers must be banned in groundwater protection zone 2 and the use of slow release fertilizers and treated organic fertilizers are to be recommended in protection zone 3.

4.1.2.3 Solid Wastes from Agricultural Activities

Agricultural activities produce many hazardous solid wastes (ashes and sludge, plastic wraps and containers, PE pipes & fittings and greenhouses' cladding material, green wastes). These are commonly disposed of near the farms in the nature, in sinkholes and sometimes at riverbanks: During the field assessment fertilizers bags and pesticides containers (sometimes half full) were frequently found dumped in the nature, sometimes inside or on the borders of water courses (Figure 129) or inside sinkholes.

Figure 129: Chemical Fertilizer Bag dumped on a Riverside in Kfar Debbiane

Contaminated pre-harvest crops are often disposed of by plowing the crop into the soil, thereby creating the potential for aflatoxin contamination of groundwater.

Such contamination would be expected to occur in shallow sandy soils such as in Qehmez, Ain el Tannour and Hayata. (RAAD & MARGANE 2013).

Despite being banned in Lebanon, agricultural wastes incineration is a common practice among rural society in the Jeita catchment. It presents a high risk to groundwater quality. It may lead to accumulation of significant amounts of toxic substances, such as lead, cadmium, chromium, dioxin and furan compounds in soils and subsequent flushing to groundwater. Dioxin (2,3,7,8-TCDD), resulting from waste incineration at temperatures < 1,200°C, leads to reproductive difficulties and increased risk of cancer.

Actions to be taken

It is important to reach an effective and tangible commitment by the authorities to environmentally sound practices in agriculture. The following actions are to be undertaken to reach a proper protection of GW resources:

- Limit agricultural production to protection zone 3 and enforce applying best crop management practices. Restrict crop production to organic agriculture in protection zone 2.
- Set standards for maximum allowable limits of pesticide in drinking water.
- Design and put into practice a national long-term plan that includes the necessary control and management mechanisms for water resources.
- Introduce, implement and enforce legislation related to agricultural practices. Law enforcement must insure that groundwater protection requirements as proposed for the groundwater protection zones (MARGANE & SCHULER, 2013) are considered in the agricultural sector.
- Provide a composting facility for collecting all organic waste from animal farms, agricultural farms and slaughterhouses that can be used to produce treated organic fertilizer (site should be near demand and production sites and on GW protection zone 3, e.g. in Wata el Jaouz).
- Provide a collection and temporary storage facility for solid and liquid hazardous waste at a central location in GW protection zone 3 (e.g. Wata el Jaouz, on J5 geological unit) that is designed and managed based on international accepted practices. The site must be well protected against leakage to groundwater. From there hazardous waste must be transported to a designated site for permanent storage, once officially declared.

Responsible agencies (WEBML) must monitor this potential type of contamination in vulnerable areas.

4.1.3 Stormwater

In the Jeita catchment strongly contaminated stormwater by sewages, roads runoff, agriculture, etc. presents a threat to groundwater as much of the untreated stormwater with all its constituents (e.g. viruses, bacteria, salmonella, and many toxicants: hydrocarbons, pesticides, heavy metals) will ultimately end up in groundwater. The stormwater network must be upgraded to be able to accommodate most of the stormwater and clearly separated from the wastewater network, which is currently not the case. Measures must be taken to mitigate its contamination and to reduce the infiltration of contaminants from stormwater into Jeita groundwater.

4.2 Point Sources

4.2.1 Gas Stations

Any leak from underground storage tanks (UST) for fuel as small as one drop per second will release about 1515 L of gasoline in one year. The contamination can spread over long distances (tens of km) and would be extremely difficult and costly to remediate.

Petroleum fuels contain a number of potentially toxic compounds, including common solvents such as benzene, toluene and xylene, and additives such as Methyl tert-butyl ether (MTBE), ethylene dibromide (EDB) and carbon-based lead compounds. EDB and benzene are carcinogenic. There is worldwide concern about MTBE in drinking-water sources.

Dbaye treatment plant is not equipped to remedy petroleum contamination and such contamination is not even monitored yet. **To date there are still no substantial investigations in Lebanon concerning the extent of contamination from petroleum, petroleum by-products and waste oil, even for drinking water supplies**.

In consideration to the important threat to public health that petroleum contamination can generate, BGR project has conducted a study detailing the practices, ruling legislations and guidelines, the permitting process and the related stakeholders. An attempt to assess MTBE contamination was hindered by the absence of laboratories in Lebanon able to carry out related analyses.

The field survey found 84 gas stations in the Jeita catchment (Figure 130 and Table 26). The extremely high number and dense spacing of gas stations in the lower part of the Jeita catchment is in complete disregard of water resources protection requirements and the importance for water supply.

Table 26: Distribution of the operating gas stations in the Jeita catchment in correspondence to groundwater vulnerability at their locations.

Protection zone	Number of gas stations	Groundwater vulnerability at the location
2a	22	J4/(J5 dolinas) within stream buffer above aquitard, travel times < 10 days
2b	23	High vulnerability J4/(J5 dolinas), travel times < 10 days
3a	1	and high vulnerability J4 with, travel times > 10 days
3b	13	very low vulnerability, Aquitard, no streams

The field assessment has revealed many serious concerns such as:

Many gas stations are operating without permits and even those who held permits are not abiding actuated laws and guidelines especially concerning carwash water pretreatment prior to disposal, fuel storage limits, leakage prevention infrastructure, and drainage systems.

The fuel storage facilities (USTs) are single layered, lacking of alarm systems and containment devices able to contain any leakage. Leakage is not properly monitored in most cases. Waste oil management and storage is also probably generating groundwater contamination (bad storage, frequent spills and unsound disposal of empty containers).

More than half of the assessed gas stations have USTs older than 15 years. These present a high risk of leakage, especially that most tanks are not professionally welded. It is recommended to seriously monitor leakage at these sites and replace them by double-layered tanks, especially those located in protection zone 2.

While gas stations must be completely banned in protection zones 1, 2 and 3a, the permitting in zone 3 must be based on an environmental impact assessment including groundwater, hydrological and geotechnical studies in order to exclude contamination risks. Such study must be made obligatory for new permits and renewal of existing ones.

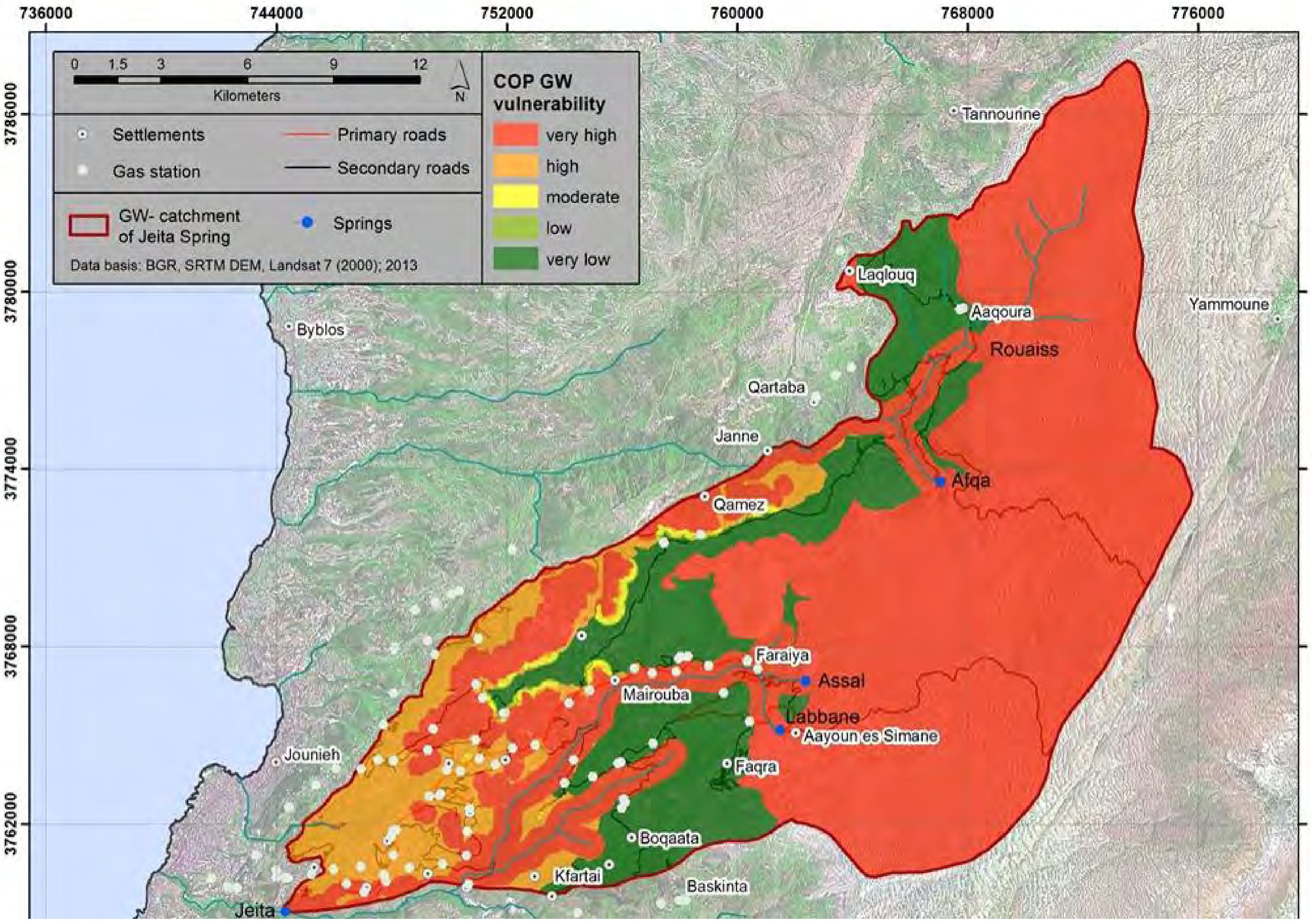


Figure 130: Distribution of Gas Stations and Groundwater Vulnerability

4.2.2 Generators

Diesel generators are a major source of petroleum pollution in Lebanon and they are growing in capacity and number every year especially in the absence of a continuous provision of electricity by the Lebanese government.

According to the assessment of the practices in the Jeita spring catchment, residences are furnished with small private generator in order to ensure a continuous energy supply in the villages where there are no large generators for private electricity supply. Operating generators of important size requires a permit following environmental guidelines set by the Ministry of Environment. However, these guidelines attributed little consideration to monitor the related diesel storage and to impose penalties on operators who discharge or spill their used oils in the nature, which unfortunately is often observed. An update to these guidelines is therefore required to protect the water resources.

There is an urgent need to control these practices, and to limit the number of operating generators. This can be carried out by the municipality police (until the proposed environmental police would be created and enforced in Lebanon) or by any entity able to efficiently apply laws and regulations in this field.

4.2.3 Residential Heating Systems

Residential heating oil storage tanks have been installed and widely used in Lebanon especially in the last 15 years in the mountainous areas.

Underground diesel storage tanks must be banned in protection zone 1 and 2 of Jeita, Afqa, Assal, Labbane and Rouaiss spring catchments and there is an urgent need for assessing and controlling the existing leaking heating systems.

To date, no control of leaking pipes or oil reservoirs is carried out by any authority in Lebanon. Municipalities are called to be active in controlling such leakages, especially in protection zones 1 and 2 of springs used for drinking water supply purposes. Awareness raising is needed mainly at the level of the population living in the highly vulnerable areas.

4.2.4 Car Repair Workshops

Often operating without permits, these workshops present a risk of groundwater contamination mainly due to spills of used oil, solvents, acids, grease, anarchic disposal of solid wastes (empty containers, spare parts, etc).

Vehicle repairs should be done outside protection zones 1 and 2 of Jeita, Afqa, Assal, Labbane and Rouaiss spring catchments, and in the remaining part of the

Jeita catchment, they must be forced to adopt best management practices preventing anarchic disposal of liquid and solid wastes and ensuring proper storage of used oils and old batteries that are to be sent to certified entities for recycling. Used spare parts should be brought to a collection point to be specified by the municipality. From there they should be transferred to a specialized scrap yard.

4.2.5 Healthcare Establishments

Lebanon is still considered as one of the countries that lack adequate and well-operated infrastructure for management and disposal of healthcare wastes. As a result, unresolved environmental problems have been accumulating for years now, which lead to major issues such as: 1) Increased air pollution due to indiscriminate burning of medical waste; and 2) water and soil pollution due to inappropriate disposal of health care effluents and wastes (SWEEP-NET, 2010).

Major sources of healthcare waste in the Jeita catchment are: Saint George hospital (Aajaltoun), two operated public dispensaries (Hrajel and Mayrouba). While minor sources are the other 12 public dispensaries, physician’s office, dental clinics, pharmacies, and an elderly nursing home (Sheile).

Fortunately, following the Ministry of Environment’s efforts and by the assistance of a European grant, Potentially Infectious Medical Waste (PIMW) is collected from Aajaltoun hospital and from Hrajel public medical center (public dispensary) and safely treated by Arc En Ciel (NGO). But the problem of disposal of untreated laboratory and other liquid wastes, in addition to the problem of radioactive wastes remain to be addressed at these locations.

The healthcare wastes that are <u>not</u> collected or treated by Arc en Ciel are :

- **Chemicals and laboratory solutions** (mercury, formaldehyde, lead, genotoxic, cytotoxic and radioactive components, etc.)
- Mercury thermometers (disposed of with the municipal wastes)
- Cytotoxic and expired medicines
- **Radioactive waste** (pretended being kept at the hospital premised in dedicated closed space)
- Recognizable organs (probably incinerated onsite)
- Batteries, accumulators (probably disposed of at the municipal wastes
- Oils, fats (disposed of within the wastewater system without prior treatment) and of course all the assimilated waste to household waste.
- **Pharmaceuticals**

Major attention must be paid to the wastes management practices at dispensaries including x-rays, dental clinics and conducting operations (even minor ones) such as the dispensaries of Hrajel, Mayrouba, Kfar Debbiane, Ballouneh, Raifoun, and Faitroun.

An alarming presence of benzoylecgonine in surface water and Jeita groundwater was observed in 2010 and 2011. According to DOUMMAR et al. (2012) benzoylecgonine (cocaine metabolite) is introduced in surface water (Nahr El Salib) at the level of Hrajel village.
Iodinated X-ray contrast media (widely used in practical surgery) and one of the typical associated products, iopamidol, was found in wastewater of Hrajel, in Nahr El Salib river and in Jeita spring, indicating discharge of contrast media with wastewater from healthcare establishments (most probable being generated at Hrajel and Mayrouba healthcare centers and by Aajaltoun hospital).

We note that wastewater contaminated by hazardous healthcare wastes requires specific treatment that goes far beyond the secondary treatment planned to be adopted in KfW wastewater scheme to which Aajaltoun hospital would be connected.

A detailed assessment of the environmental impact of operating healthcare facilities is urgently required in the Jeita spring catchment. All healthcare facilities must be forced to cooperate with MoE and provide a waste and wastewater management plan. An active mitigation plan of environmental impact related to existing healthcare institutions is vital for avoidance of Jeita spring contamination. Permitting for new hospitals, dentists clinics, pharmacies, medical clinics and elderly nursing homes must be limited to proposed GW protection zone 3 of Jeita spring. Environmental awareness must be raised at the level of public healthcare establishments' operators and managers.

A solution for the radioactive wastes disposal must be created at the national level in Lebanon and an enforced control and monitoring of best waste management practices must be applied mainly in groundwater protection zones.

4.2.6 Feedlots and Slaughterhouses

Figure 131 shows the locations of assessed feedlots and slaughterhouses in the catchment. These include small and medium size ovine/bovine/caprine and swine farms in addition to small, medium and large-scale poultry farms (RAAD & MARGANE 2013).

Because of the high density of animals and lack of proper infrastructure common to feedlots in the Jeita catchment, these establishments probably contaminate water resources with animal dung and other waste related to the raising of animals (dead animals, pharmaceutics (particularly antibiotics) pesticides, contaminated fodder). Poultry feed may contain arsenic to promote growth. Poultry and other animal farms transfer many bacteria and viruses, such as Escherichia coli, Salmonella typhimurium, Campylobacter jejuni, Staphylococcus aureus, etc., which may be found not only in the feedlots' wastes but also in groundwater.

The compilation of the WEBML data related to water monitoring, covering the past 10 years reveals that raw water frequently showed occurrence of Salmonella in the Jeita/Kashkoush raw water, which is most likely related to the huge amount of feedlots and slaughtering wastes dumped in the environment.

All assessed feedlots and slaughterhouses in the Jeita spring catchment present a very bad waste management (Figure 132). Solid wastes (viscera, Specific Risk Materials, manure, etc.), highly contaminating liquid effluents and wastewater are illegally discharged into the nature without any prior treatment. Additional contamination load reaching Greater Beirut drinking water supply is due to the disposal of wastes generated by feedlots and slaughterhouses neighboring the Jeita catchment (mainly in Beit Chebab and Baskinta).

In absence of any facility able to valorize the huge generated amount of feedlots wastes, unfermented manure is commonly dumped in the nature. Tens of manure trucks and litters are disposed of in the nature every week from the feedlots and poultry farms in the Jeita catchment. Most of the feedlots are built in disregard with actuated landuse regulations, often only a few meters away from river courses, or within residential areas.

In general, poultry slaughtering is conducted outside Jeita catchment. Bovine, ovine, caprine and swine slaughtering is carried out mainly by: 2 slaughterhouses and by numerous butchers spread all over the catchment.

The two slaughterhouses located in the Jeita catchment were both identified as presenting a high risk of GW contamination. Situated in locations presenting high GW vulnerability (protection zone 2b; travel time <10 days), they reveal very poor infrastructures, lack of liquid effluent treatment and major illegal dumping of liquid and solid wastes. In both slaughterhouses liquids from intestines and viscera are emptied into the wastewater system (open cesspits) and the solid viscera are then disposed of in the nature with the rest of the slaughtering wastes, in absence of any control.

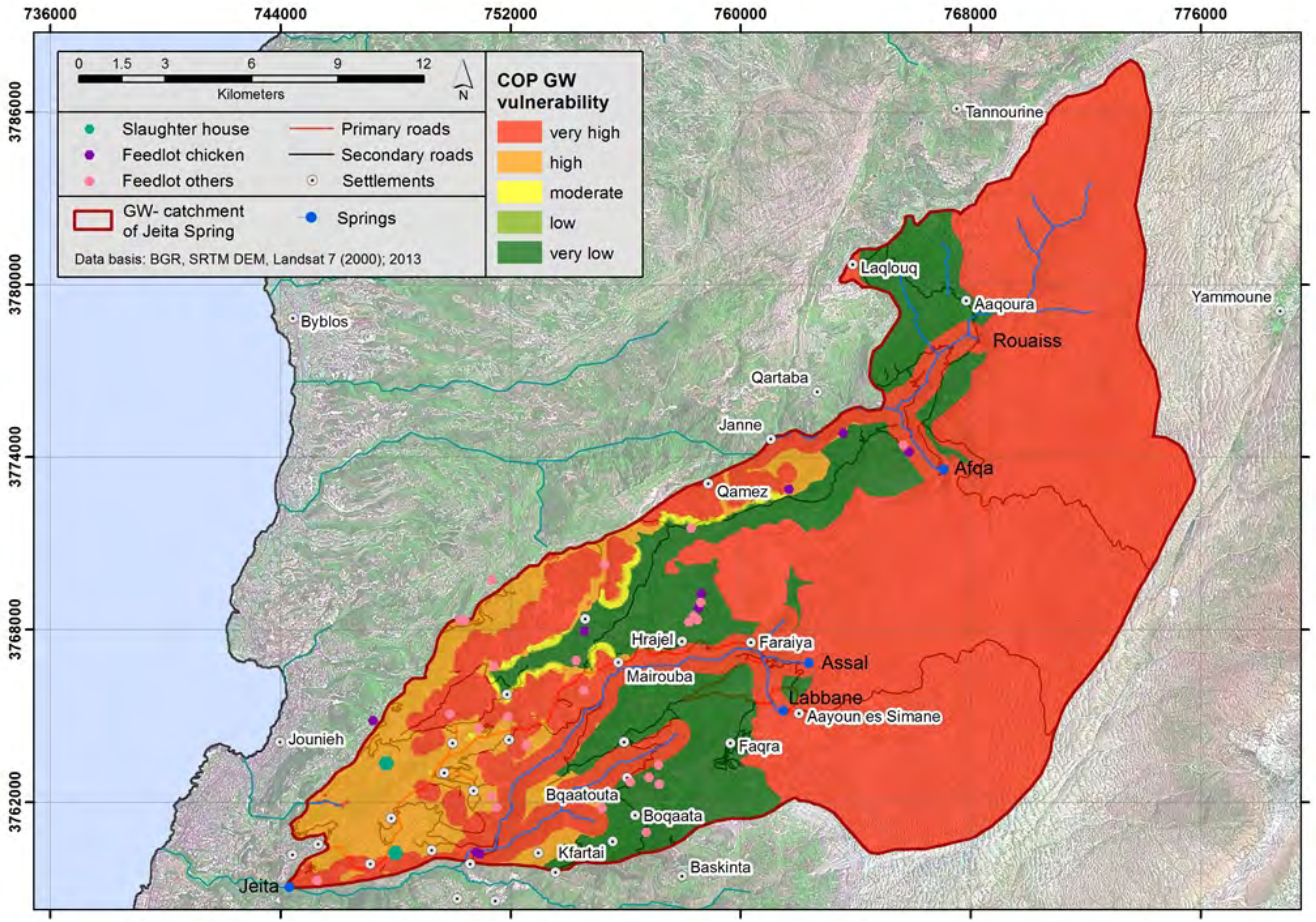


Figure 131: Distribution of Feedlots (bovine, ovine, caprine and swine) and Poultry Farms and Groundwater Vulnerability

The main issue here is the absence of a properly designed composting facility able to valorize these wastes and prevent such high contamination risks. Nevertheless, a successful experience in composting slaughtering waste was noted at Beirut slaughterhouse. It is recommended to follow this example in the Jeita catchment (RAAD & MARGANE, 2013).

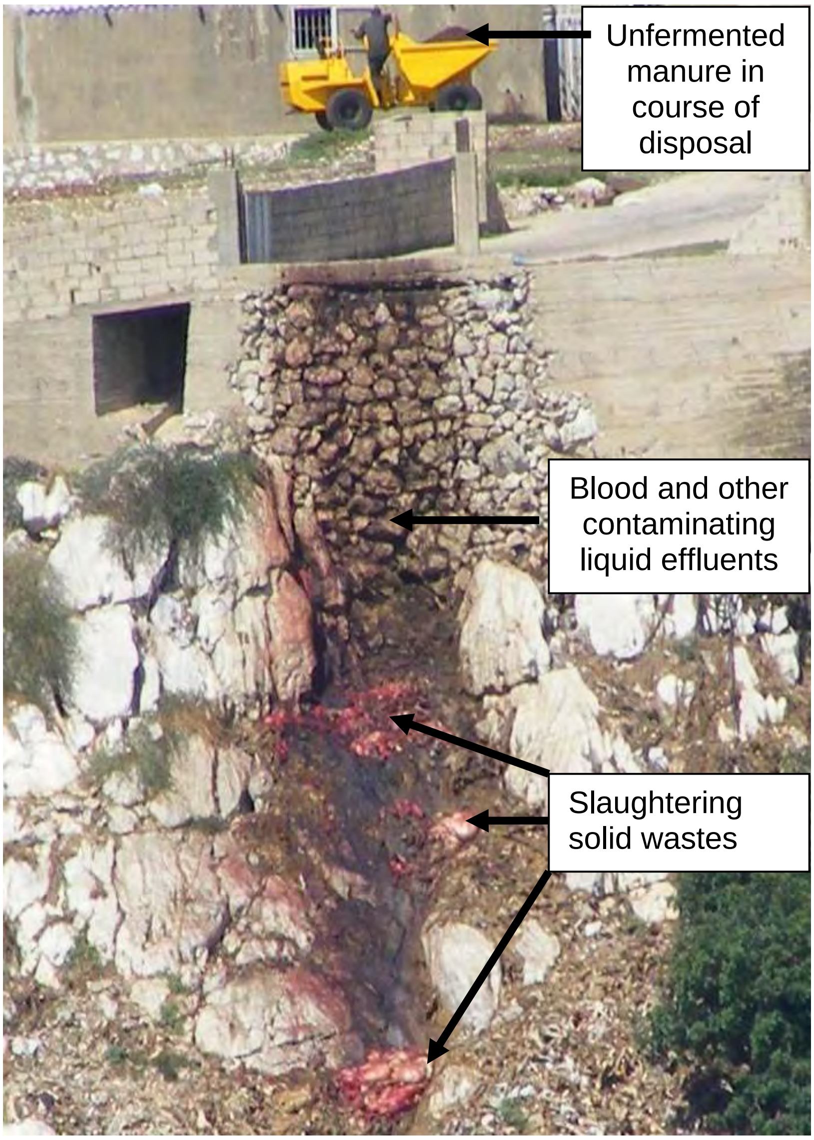


Figure 132 Waste Disposal at Chbeir Slaughterhouse at Ghosta

Actions to be taken:

At both sites, proper infrastructure able to treat the liquid effluents generated by the two feedlots and slaughterhouses must be installed. The quality of the effluents discharged from these two establishments must be regularly monitored, collected, and be transferred to a liquid waste disposal. It should not be mixed with wastewater.

A facility able to treat the slaughtering wastes and the manure must be established in the Jeita catchment in order to provide an acceptable solution instead of the illegal dumping of these contaminating wastes.

4.2.7 Quarries

Quarries and the pressure they exert on natural areas as well as on the quality of life constitute a major challenge to the environment and especially to groundwater.

28 quarries operating inside Jeita catchment or near it and discharging their wastes in the Jeita catchment are affecting Jeita water quality. They mainly extract limestone and sand, and are spread over the entire catchment as displayed in Figure 133.

In correspondence to the existing kinds of permits, 4 main categories can be distinguished:

- Dimension rocks (where very limited quantity of explosives is used)
- Decoration rocks (building stones)
- Aggregates (crashed stone) (including major use of explosives)
- Sand (no use of explosives).

The challenge of quarries is to be examined considering water resources protection criteria, and differentiating between the 4 major categories of materials extracted in Jeita Spring catchment: The blasting techniques used in crushed stone operations are significantly different from those used in dimension stone quarrying. Whereas large amounts of explosives are used in crushed stone operations to produce appropriate-sized rocks, the dimension stone industry uses only small amounts of explosives to loosen large blocks of stone.

Considering the hydrogeological context, the location of the existing operating quarries and the practices assessed in the catchment, relevant threats to Jeita spring groundwater are noted, especially from storage and handling of oil and fuel used for operation and maintenance of machinery.

Despite major efforts to control the quarries sector, to date Lebanon did not succeed in adequately managing this issue. Many of the assessed quarries (the majority of them) are unlicensed, and most of them, even the authorized ones, do not respect legal requirements in terms of material extraction and site rehabilitation.

In addition to the municipalities, the National Council of Quarries is by law the main stakeholder of the quarry sector. However, this council, where too many stakeholders are represented, has been so far unable to assert control of the quarrying sector, and the opinion of the municipalities is not taken in consideration.

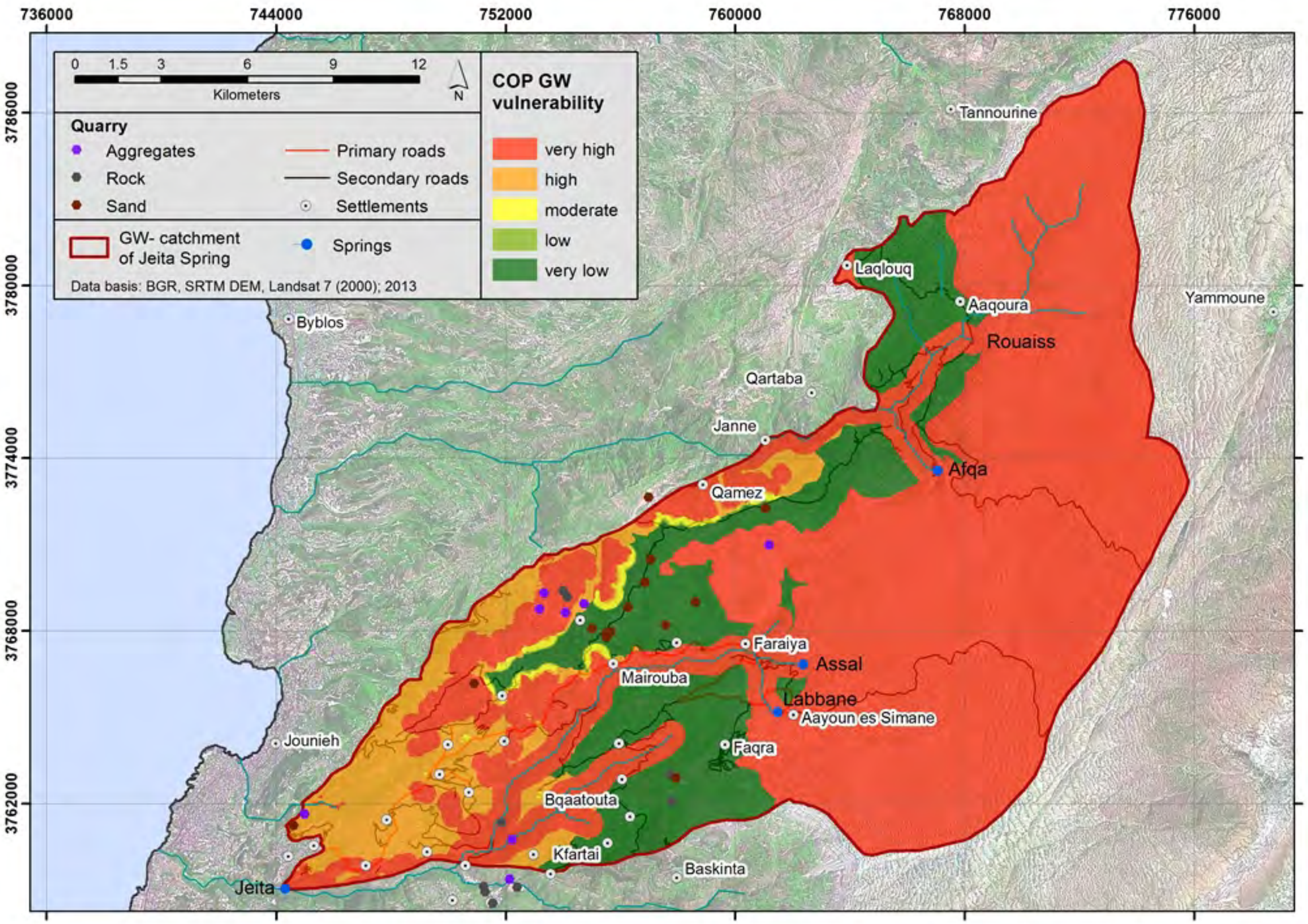


Figure 133: Distribution of Quarries and Groundwater Vulnerability

Actions to be taken

- The hope to limit quarrying activities relies now on the EIA decree, promulgated in August 2012. However, if this decree acts on new quarries only, a solution must be found to mitigate the impact of the operating quarries that impose high risks to Jeita groundwater. An urgent solution must be found for those located in protection zone 2.
- Waste dumping in quarries must be carefully controlled especially in proposed protection zones 2 a. 2b and 3a, as construction waste may also be mixed with other waste.
- A strict control of the engineering operations should be conducted in all quarries. Proper planning schemes and management are necessary to ensure meeting the criteria of the environmental sustainability and safety of quarrying. The planning must be based on both the geomechanical behavior of the material and the vulnerability and potential impact on groundwater from the exploited sites. The groundwater vulnerability maps prepared by BGR project can be used as a basis for such evaluation.
- Taking into consideration the steep topography of Lebanon and the high rate of urbanization and groundwater protection criteria, a rigorous management policy is required to control the quarrying activities. The demand for natural raw material is ever increasing but at the cost of landscape destruction it strongly affects the local livelihood and touristic sector. If the entire required volume is to be provided from local production, the impact of quarries would be very significant, also the impact on groundwater resources.
- Raise public awareness on the environmental hazards generated by quarries.

4.2.8 Industries

Despite the existence of actuated national guidelines related to the allowed limits of pollutants in the liquid effluents, there is a complete absence of control and of an enforcement concerning industrial pollution. None of the factories has a proper wastewater treatment facility as required by law.

The field assessment conducted by BGR in 2012-2013 located 38 factories in the Jeita catchment and its close neighborhood (Abou Mizane). The distribution of these establishments is displayed in Figure 134. A detailed assessment of the potential impact on Jeita groundwater was conducted. 14 classified industrial establishments of different categories are located in protection zone 2a, and 13 in protection zone 2b. Principally industrial activities should not be permitted in both areas.

The field assessment revealed a very poor solid waste management. All kinds of related solid wastes (including empty chemicals and oils containers) were found illegally dumped near the factories locations. Also, they all evacuate their liquid effluents without prior treatment, mainly within their wastewater system. Some dispose them in open cesspits, others in boreholes and many directly in their neighborhood.

A dangerous practice that needs to be immediately banned is open air waste incineration. Liquid and solid waste management must be enforced at all industrial facilities. Raising the environmental awareness of the owners and staff at the industrial establishments is of major importance.

Waste generated could be valorized; for example dried sludge generated by rock saws (and quarrying) could be sold as filler e.g. for tiling. However, it is widely illegally discharged in the environment leading to a high turbidity in surface and groundwater which causes severe problems for treatment of raw water (MARGANE & CHRABIEH, 2012). Construction wastes generated by such industries can be profitably used in land leveling, MAR dam construction, etc. A national plan organizing the process of construction wastes reuse is urgently needed and would significantly reduce contamination and landscape destruction.

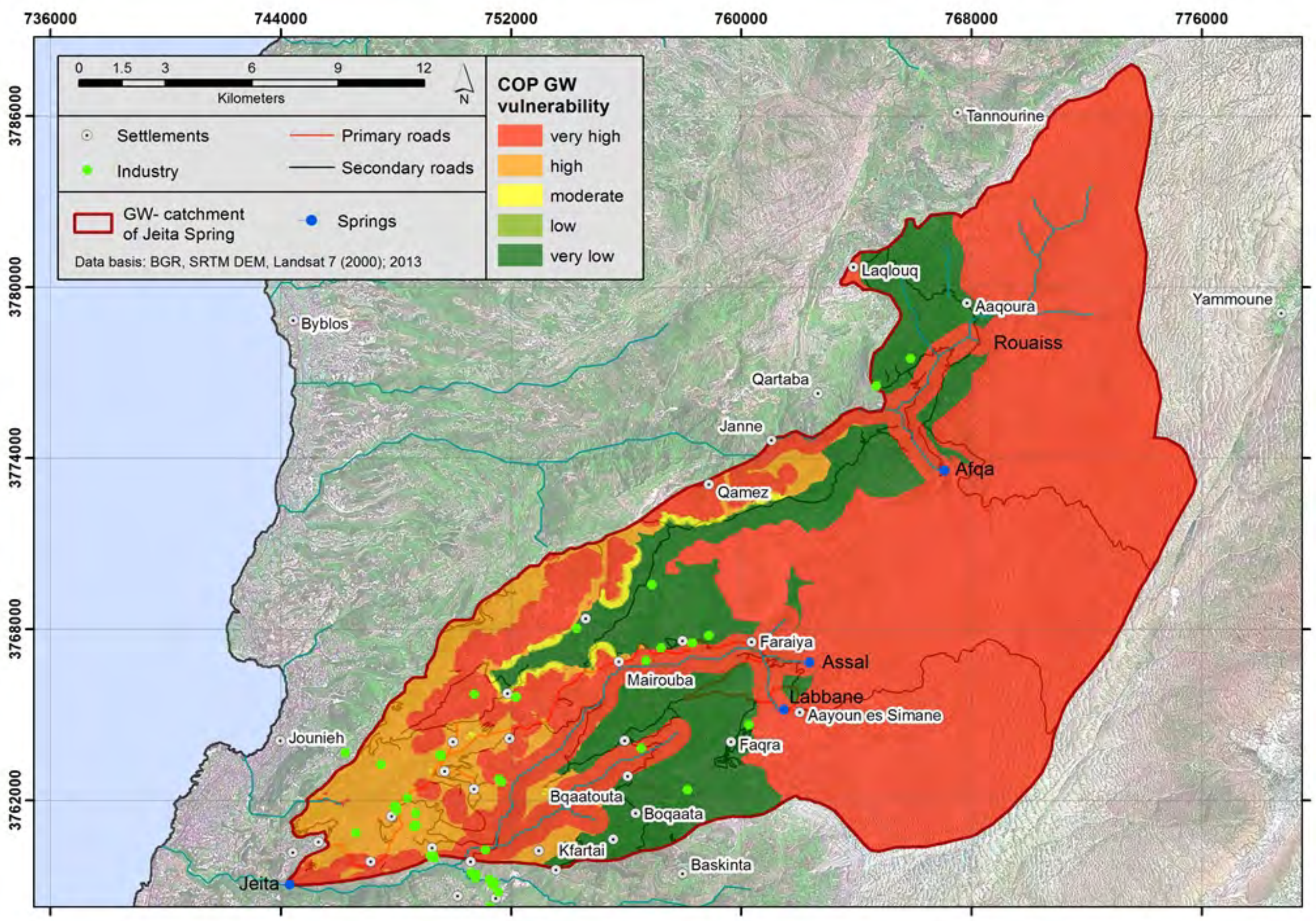


Figure 134: Location of the Factories and Groundwater Vulnerability

Solvent using industries (SUI) among others, are expanding in Jeita catchment without adequate waste management. Currently, used solvents are commonly disposed of in the environment, degrading quality of related water bodies. Printing and packaging, car paint shops, and dry cleaners have been identified as main actors in Jeita spring catchment in this respect. VOCs are used in dry cleaning, manufacture of foam, paint removal/stripping, metal cleaning and degreasing. Unfortunately these are not analyzed by WEBML. The main elements to be checked in groundwater are: methylene chloride, PCE (perchloroethene), TCE [trichloroethene], and TCA [1,1,1-trichloroethane].

To protect the groundwater from hazardous solvents solvent recycling should be introduced as a concept of “cleaner production”. Restrictions for use of hazardous solvents are to be enforced in groundwater protection zones (MARGABNE & SCHULER, 2013).

As far as the bakeries (2 in the catchment) are concerned, the main related issue is their fuel storage (for electricity generation), the disposal of used oils, in addition to the chemicals, pesticides and rodenticides frequently used.

Actions to be taken:

- Enforce construction of WWTPs for all industries, where required by law.
- Conduct specific analysis of discharged wastewater to ensure that industries are respecting the related maximum allowable limits for industrial wastewater discharge.
- Enforce, control and monitor application of environmentally sound practices in all industrial establishments located in the Jeita catchment, especially those located in protection zone 2. Apply severe penalties in case of violation of law.
- New permits for industrial activities should not be given in groundwater protection zones 2.
- Raise awareness related to water resources protection and cleaner production. Unfortunately, only bad practices are adopted in the catchment in complete lack of environmental awareness and governmental control.
- Establish a sludge collection and reuse program in Jeita catchment.
- Organize the reuse of the construction wastes in Land reclamation mainly in old quarrying sites. Major attention should be given to the content of the construction wastes.

4.2.9 Touristic Resorts and Restaurants

In the touristic resorts, such as Satellity and Irani in Faitroun, Sun City in Aajaltoun, Faqra Club in Faqra, Mzaar in Ouyoun El Simane, Intercontinental resort, etc., in general diesel reservoirs of significant size are located and unsound sewage management, with absence of a collection network and wastewater treatment system is found. Especially in the protection zones 2 of Afqa, Rouaiss, Assal and Labbane springs no further touristic development should take place as these water resources are much more pristine than Jeita spring and have a great potential, especially for future water resources development.

Another relevant high-risk contamination source is the restaurants located in the “Roumieh” area of Qleyyat. The main concern generated from these is their fuel storage, their disposal of cooking oils and their wastewater disposal practices. For the moment these restaurants dispose of their liquid wastes within their wastewater which is discharged in open cesspits infiltrating directly to Jeita spring as these are located in groundwater protection zone 2a, very close to the underground river of Jeita.

4.2.10 Army Operations

Army barracks and facilities present as any other human activity many risks of contamination to the groundwater. Of these we mention:

- Petroleum contamination generated by diesel and fuel storage, environmentally unsound operations using petroleum products, electricity generators, etc.,
- Wastewater
- Healthcare waste
- Equipment and vehicle maintenance waste and spills
- Ammunitions: Mainly destruction of expired or damaged ammunition, currently frequently conducted in highly vulnerable areas of Kfar Debbiane (dolines in C4 geological unit) of the Jeita catchment.

The project had contacts with the army headquarters on how to reduce contamination risks from army operations. Due to the very positive response the project is optimistic that the Lebanese army will address related issues shortly. The army showed full collaboration and is ready to act upon proper practical related recommendations. High ranking officers showed being open to any possible collaboration with international entities able to provide assistance in improving environmental status at barracks, other facilities and routine operations related to waste separation and recycling, wastewater infrastructure, improving fuel storage infrastructure, etc.

Also, through exemplary application of environmental laws, the army can promote their use and therefore play a crucial role in protecting Jeita spring.

4.2.11 Dumpsites and Municipal Wastes

Each previously mentioned groundwater contamination source generates solid wastes. Responsibility for waste management is assigned to municipalities by local laws. However, municipalities face: lack of funds, weak technical know-how, absence of sufficient sanitary landfills or recycling facilities and a low income from taxes.

Population growth and urbanization in absence of waste separation and related recycling facilities, added to a severe lack of environmental awareness are worsening the problem of waste management in Lebanon in general and in the Jeita catchment in particular.

Waste collection fees paid to SUKLEEN are imposed on the municipalities and automatically deduced from their annual budget. Waste collection fees can reach 80% of the allocated annual municipal budget. Lacking adequate financial capacities, many municipalities of the Jeita catchment are not served by SUKLEEN. This leads to uncontrolled waste dumping in those municipalities which cannot afford to pay for this service.

Despite the fact that the municipalities are by law responsible for damages caused by illegally dumped waste, many municipalities still dump hazardous wastes illegally in their own areas (Aajaltoun, Lassa, Daraya, Ballouneh, Boquaatet Ashquout, etc). They also regularly conduct open air waste incineration (Figure 135), which is banned by national laws, or burry the wastes (without prior treatment) by covering them with a soil layer (Figure 136). Both practices generate a high risk of groundwater contamination.

The BGR project found 74 dumpsites spread all over the catchment area.

- 48 were found within areas where Jeita spring is highly vulnerable to contamination.
- 26 dumpsites are located in low and very low vulnerable areas.

These dumpsites include mainly: construction waste, household waste including: batteries, pharmaceutics, plastics, chemicals, etc., and hazardous waste e.g.: pesticides containers, pharmaceuticals, slaughtering wastes, animal carcasses, etc.

Figure 134: Incineration of Waste at Ballouneh

Figure 135 : Kfar Debbiane Dumpsite on riverside, before Waste was covered

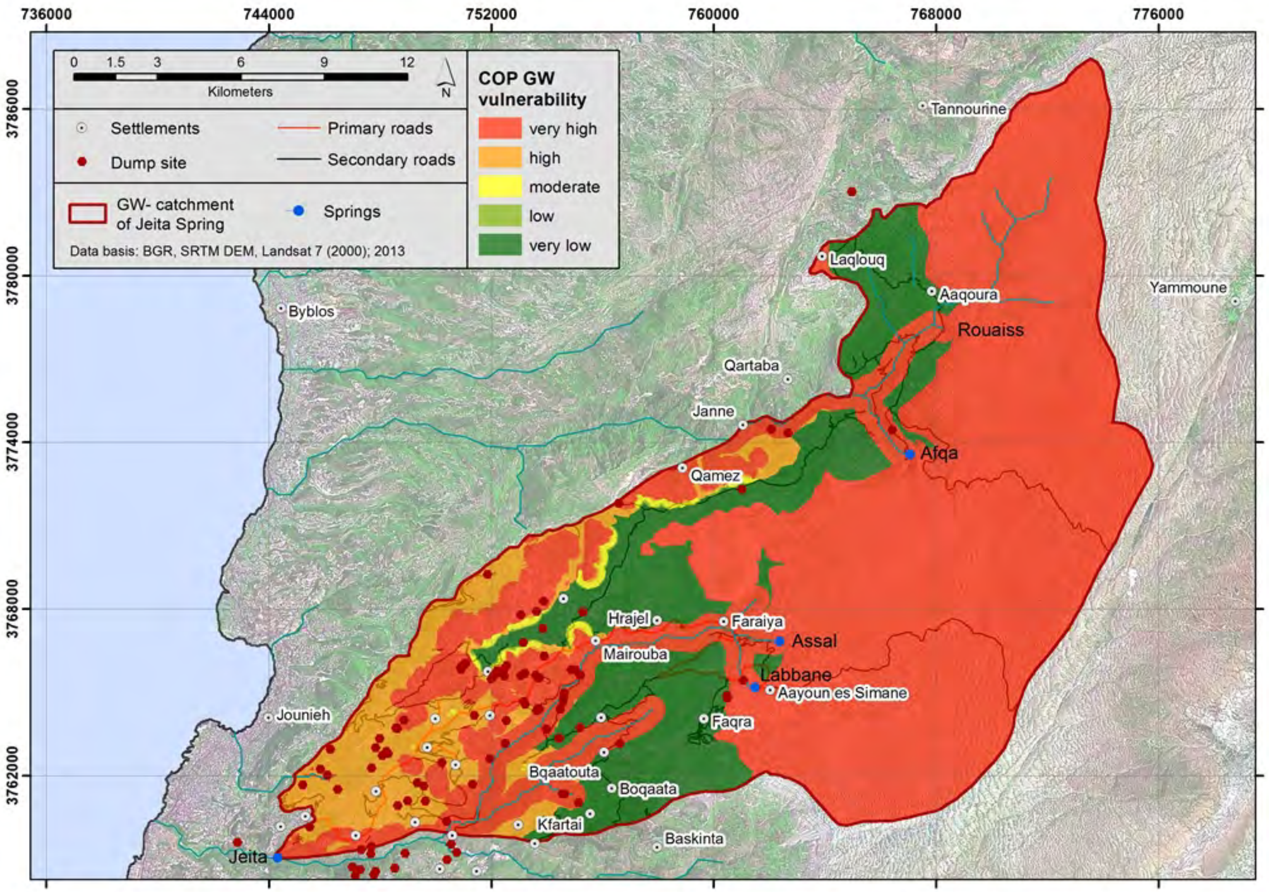


Figure 136 Distribution of Dumpsites and Groundwater Vulnerability

Actions to be taken

- Establish a sound solid waste management strategy in the Jeita catchment.
- Reform of municipal waste collection system.
- Establish waste separation facilities at low vulnerability locations, managed by the municipality, by the Union of Municipalities, or by a private entity (in collaboration with the municipality).
- Municipality must ensure environment cleanliness (control illegal disposal of untreated liquid effluents, solid waste and hazardous waste)
- Implement awareness campaigns for the local populations related waste avoidance, waste separation and recycling/reuse of waste.
- Enforce control measures at the municipality level.
- Enforce the application of the polluter-pays principal.
- Improve temporary waste storage (more and larger waste containers) so that no risk for the environment results.
- Undertake existing dumpsite urgent cleanup process following:
    - Site remedial investigation
    - Feasibility study
    - Define site cleanup options : waste removal, containment of the waste, or waste treatment

5 Groundwater Vulnerability

A groundwater vulnerability map was prepared for the entire groundwater catchment of Jeita spring, based on the COP method (VIAS et al., 2002, 2006). This method was developed in the framework of the EU COST620 project with the aim to establish a method which could be used in all of Europe in all geological conditions. It therefore specifically addresses infiltration processes in karst. To be applicable in all of Lebanon, the method was slightly modified by BGR (MARGANE & SCHULER, 2013). The resulting map is shown in Figure 137. Due to the intensive karstification, a large share of the catchment falls into the categories of high and very high vulnerability. This underlines the urgent need to protect the groundwater resources of Jeita spring.

Table 27: Absolute and Relative Coverage of the Groundwater Vulnerability Classes within the Jeita Catchment

Vulnerability	Area [km²]	Percentage
very high	288	70.9
high	39	9.5
moderate	3	0.7
low	1	0.2
very low	76	18.8

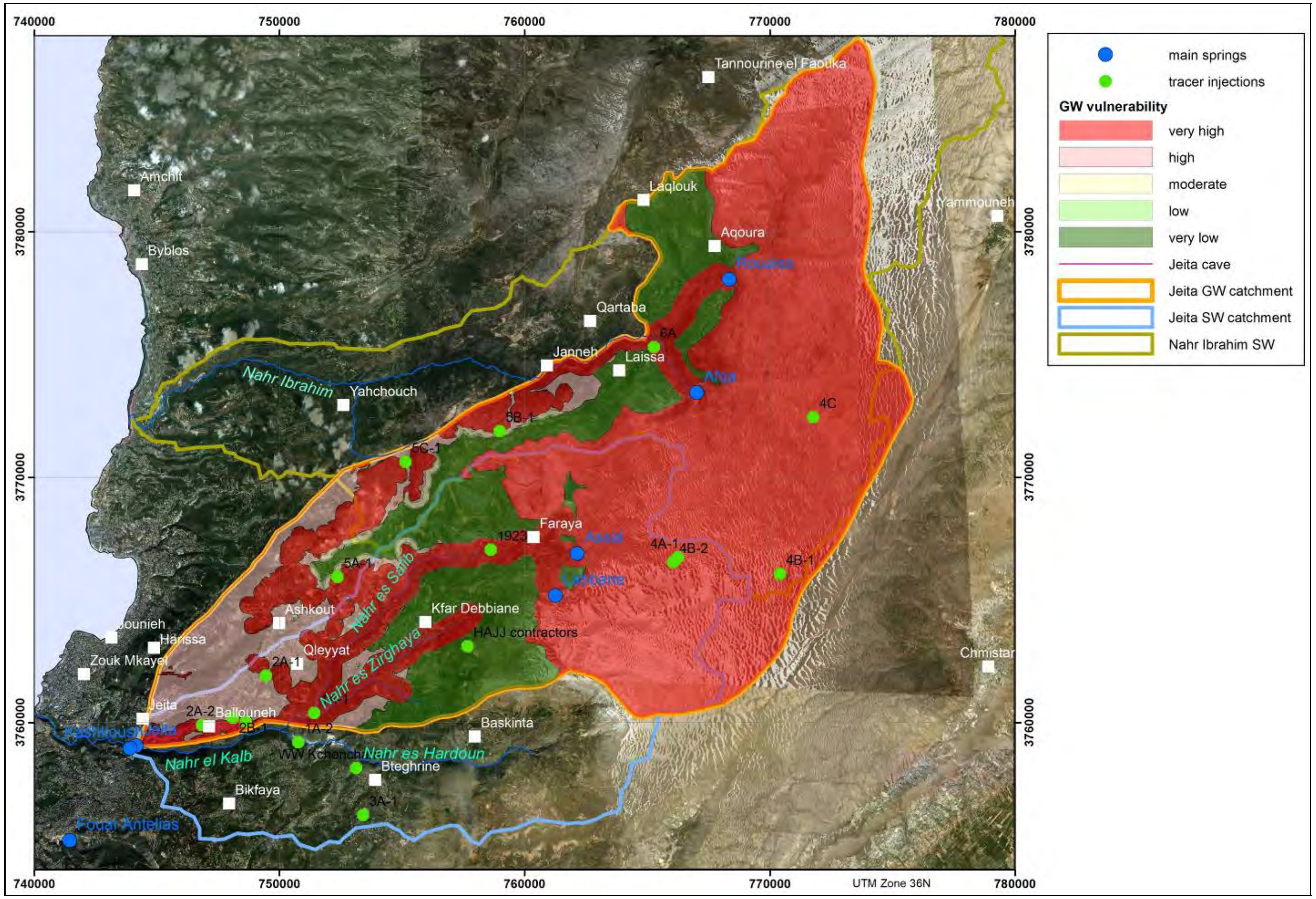


Figure 137: Groundwater Vulnerability Map of the Jeita Groundwater Catchment

6 Groundwater Protection

Based on the above mentioned groundwater vulnerability map and the determined flow velocities in the groundwater system, groundwater protection zones were determined for Jeita spring and all other major springs in the Jeita catchment, i.e. Afqa, Rouaiss, Assal and Labbane spring (MARGANE & SCHULER, 2013). Groundwater protection zones were classified into:

- zone 1: immediate protection zone
  protects groundwater from direct contamination risk > access only for authorized staff
- zone 2: inner protection zone
  protects groundwater more particularly from contamination by pathogenic microbiological constituents such as bacteria, viruses, parasites and worm eggs and from other contamination which may be hazardous.
- zone 3: outer protection zone
  protects groundwater from contamination affecting water over long distances such as contamination by radioactive substances or chemicals which are non- or hardly degradable.

Zone 2 reaches to a groundwater travel time of 10 days. Zone 2 is subdivided into zone 2A (very high groundwater vulnerability) and 2B (high groundwater vulnerability).

Zone 3 is subdivided into zone 3A and 3B, based on groundwater vulnerability. In zone 3A groundwater travel time is > 10 days, and groundwater vulnerability is very high. Zone 3B comprises all other parts of the groundwater catchment.

Protection zone 1 covers all parts of water resources, which are directly accessible, until reaching the drinking water treatment plant. This comprises:

- the entire Jeita cave (approx. 5.8 km long), i.e. the touristic part of Jeita grotto: both parts, the upper gallery and lower grotto (because there is a direct connection between them) and that part of the cave, which can be reached on foot, either from the touristic entrance or from the so-called Daraya tunnel;
- the water conveyor (canal and tunnel) from Jeita spring to the Dbayeh drinking water treatment plant.

Protection zone 1 also encompasses the area over Jeita cave where the overlying rock thickness is less than 100 m or where faults can lead to a rapid infiltration (Figure 138). Construction in the area with reduced rock cover over the cave may lead to cave collapse (Figure 139).

The resulting classification of protection zones is depicted in Figure 140.

A comprehensive list of landuse restrictions is proposed for all groundwater protection zones. This list must now be agreed on with all Lebanese stakeholders. The same landuse restrictions and criteria for delineating groundwater protection zones should be followed in all of Lebanon.

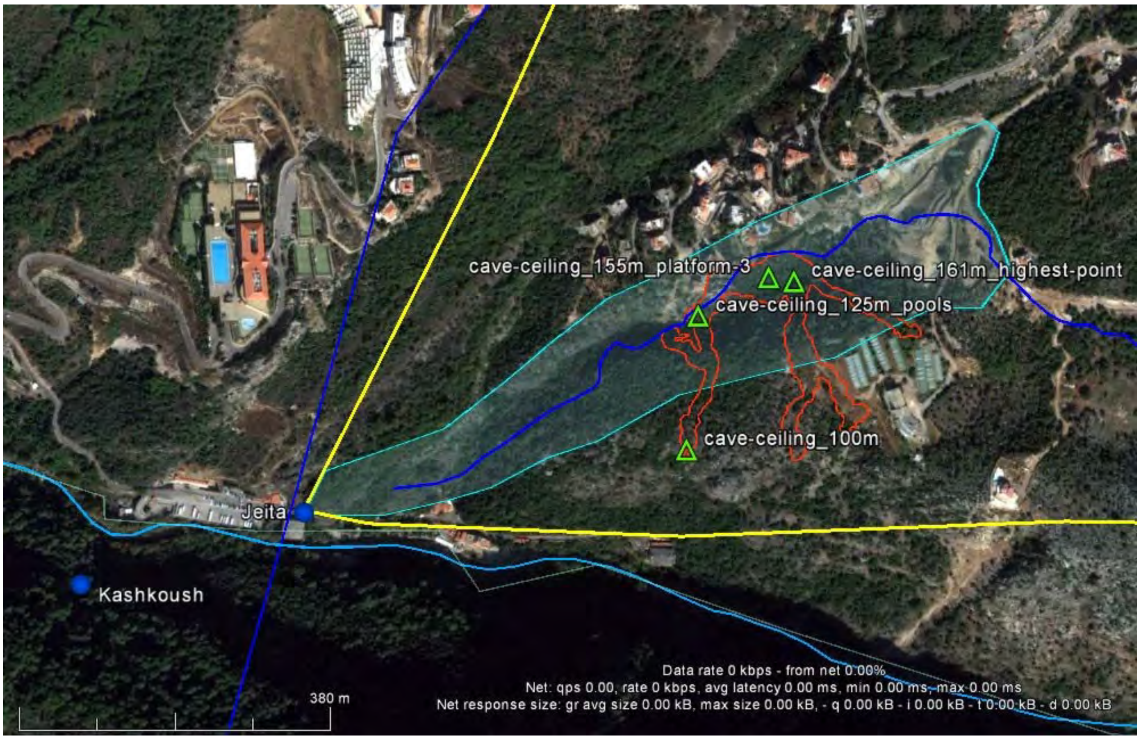


Figure 138: Groundwater protection zone 1 in the area over Jeita cave

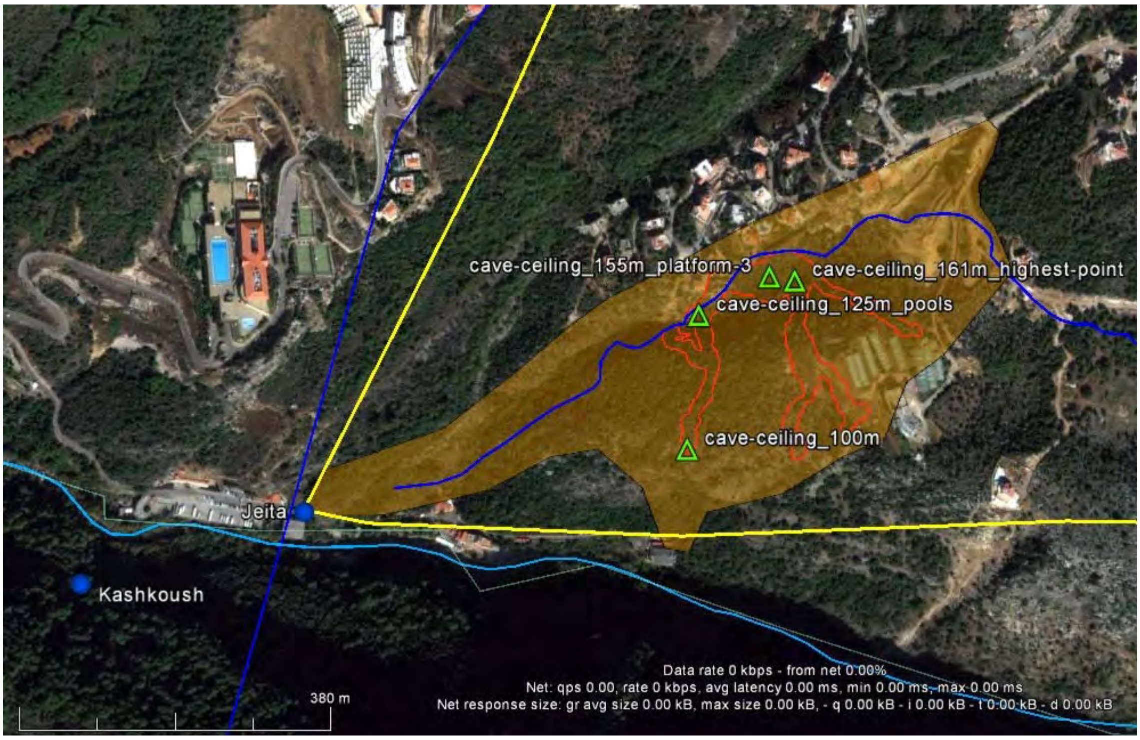


Figure 139: Critical zone (brown marked area) where an immediate construction ban over Jeita Grotto is advised

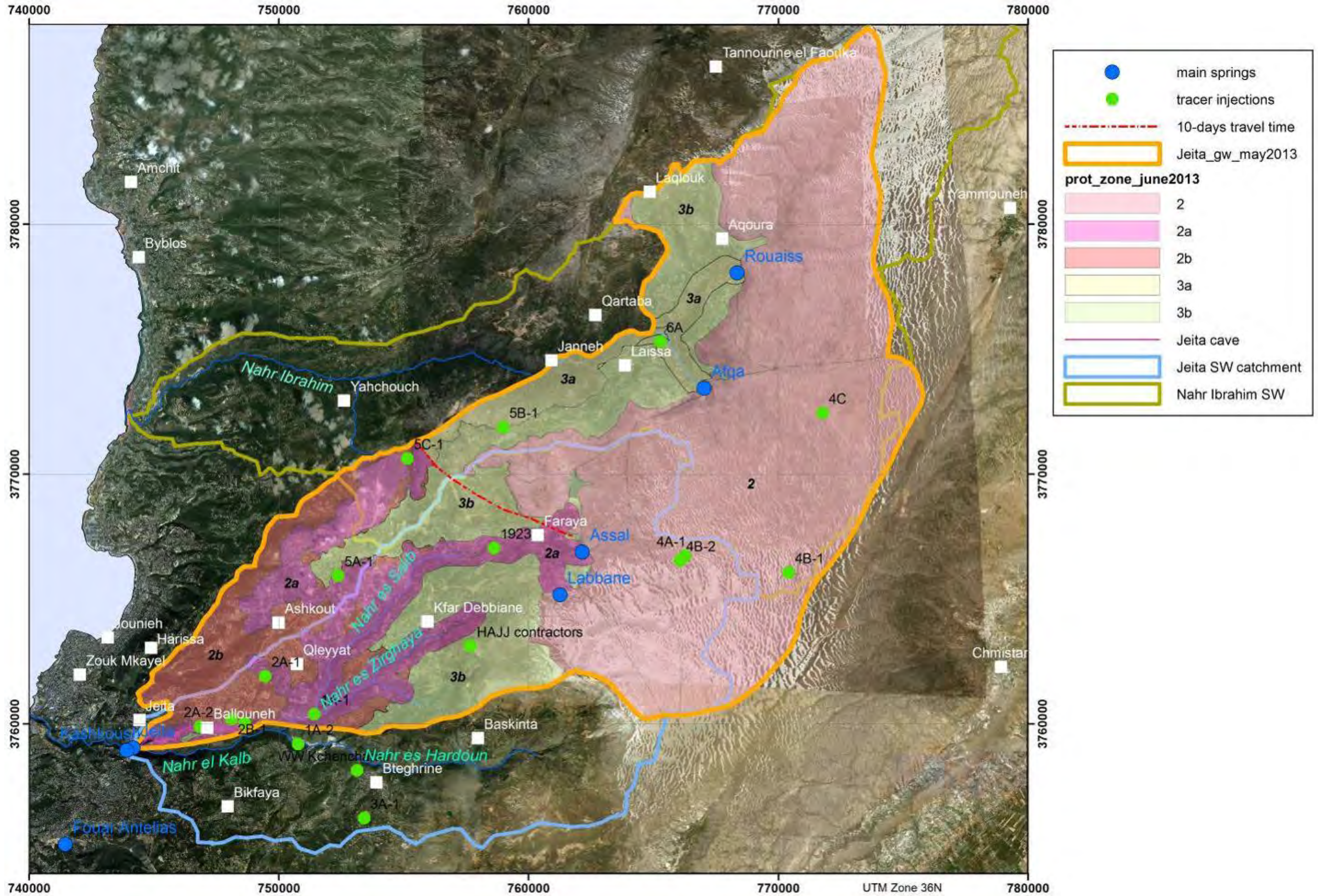


Figure 140: Proposed Groundwater Protection Zones for the Jeita Groundwater Catchment

7 Risk Assessment and Mitigation Proposals

A list of the most critical pollution sources (Table 28; Figure 141) was prepared by the BGR project in order to prioritize interventions (RAAD & MARGANE, 2013). It ranks the existing hazards based on the groundwater vulnerability at the location (equivalent to the GW protection zone), their distance to Jeita spring and their impact on groundwater resources (amount and type of substances discharged). All respective high-risk pollution sources are located in GW protection zones 2. Detailed recommendations concerning the mitigation of pollution risks were given in the above mentioned report.

Table 28: List of most critical Pollution Sources

Site Name	Located in Protection Zone	Scale of Assumed Impact on Water Resources (1 - very low, 10 - very high)	Distance from Jeita spring [m]
Site 1: MEDCO Gas Station Ballouneh	2A	10	2640
Site 3: Murr Slaughterhouse Aajaltoun (Spiridon Trading & Maritime S.A.R.L)	2B	10	4000
Site 7: Saint George Hospital Aajaltoun	2B	10	4600
Site 2: Total Gas Station Ballouneh	2A	8	2960
Site 4: Chbeir Slaughterhouse Ghosta	2B	8	5500
Site 8: George Matta Furniture Factory Aajaltoun	2B	8	5000
Site 10: Roumieh restaurants	2A	6	7200
Site 5: Hunting Rifle Cartridge Factory Daraya (National Ammunition Co.)	2A	5	5130
Site 6: Polyethylene Pipes Factory Building Daraya	2A	5	5240
Site 9: Carosserie Assad Saliba Ballouneh	2B	5	3600

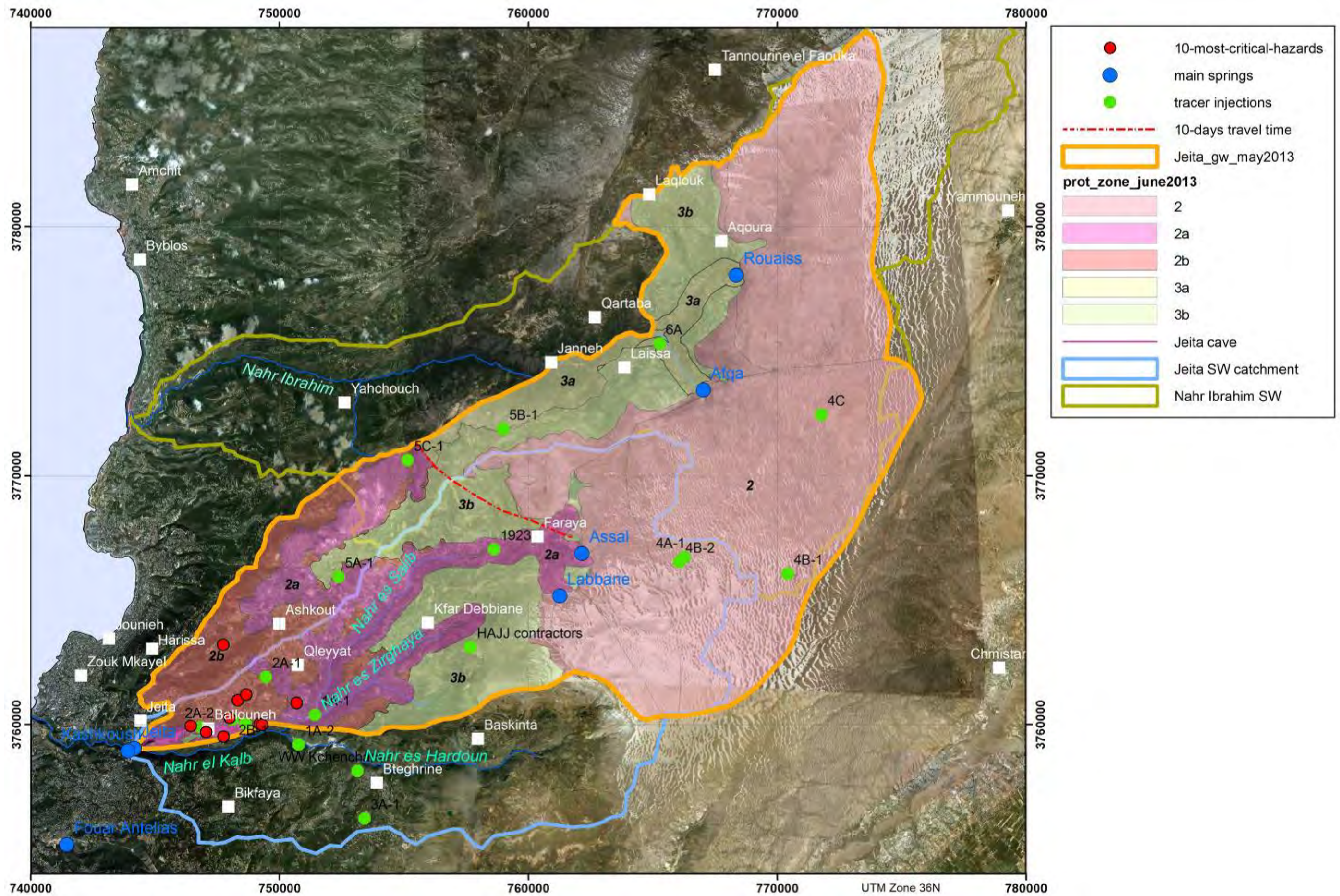


Figure 141: Locations of most critical Pollution Sources

In general the following mitigation actions are required in the proposed GW protection zones (further details are contained in MARGANE & SCHULER, 2013):

Protection Zones for the Upper Aquifer (C4)

(Afqa, Rouaiss, Assal and Labbane springs)

Due to the limited development the water resources in these catchments is still of good quality. Microbiological contamination occurs but is much less than in Jeita or Kashkoush springs. Afqa and Rouaiss springs have a relatively high discharge but usage is still limited to the local areas near the springs. The uncontrolled development in the Assal and Labbane catchment cannot continue. **It is highly recommended not to allow any residential development in the Afqa, Rouaiss, Assal and Labbane spring catchments** in order to preserve groundwater quality in a good status.

Zones 1

Only the staff responsible for operation of the water supply from the source should be given access to GW protection zones 1. Access to the public should be banned.

Fences need to be established around the water source (50 m upstream, 15 m to each side, 10 m downstream of the spring and 10 m to each side of related water infrastructure, e.g. conveyor line, reservoir, etc. until entry into the actual water supply infrastructure (pipeline)). The ownership of the land plots should be with the government.

Signposts need to be erected at the boundary of GW protection zones 1 and inform the public about the aim of the protection zones, what is forbidden to do in these zones and whom to call in case of violations.

Stormwater runoff to the springs or conveyors must be avoided by constructional means.

Zones 2

The following activities shall not be allowed :

- Gas stations,
- Industrial sites,
- Commercial businesses (e.g. repair shops) using or storing hazardous substances,
- Storage of hazardous substances,
- Quarries, rock cutting facilities, brick factories,

- Dumping of waste (including construction waste),
- Animal farms,
- Agricultural farms,
- Slaughterhouses,
- Application of pesticides and chemical fertilizers.

Actions required

Signposts need to be erected at the boundary of GW protection zones 2 and inform the public about the aim of the protection zones, what is forbidden to do in these zones and whom to call in case of violations.

Wastewater:

- The collection of wastewater at Aayoun es Simane must have highest priority. Therefore an urgent implementation of Italian Protocol WW projects and enforcement of connection to the new wastewater network is recommended.
- In all houses the existing drainage must be diverted to the new collection system and the existing cesspits must be closed so that infiltration of WW into underground cannot occur.
- The new network in protection zone 2A must be constructed in such a way that leakage of untreated wastewater into groundwater is not possible.

Hotels: the building of new or extensions of exiting hotels with more than 20 rooms should not be allowed in zone 2. They can be allowed downstream of the springs.

Restaurants: new restaurants should not be allowed unless they are connected to the new wastewater collection system.

Ski lift stations: It is recommended not to allow building new or extensions of exiting ski lift stations unless environmental impact assessments (EIAs) have been prepared proving that negative impacts on water resources (groundwater and surface water) cannot occur. The gas station at the ski lift must be removed or equipped with a double-layer tank and leakage detection and alarm system.

Skidoo and quad bike rentals: No new or extensions of existing skidoo and quad bike rentals should be allowed. The existing skidoo and quad bike rentals should not be allowed to store fuel or undertake repairs on their premises.

Skidoo/quad bike users: Clear signs at the skidoo rentals and at several places inside the catchment must instruct skidoo users about the risk of groundwater contamination by fuel and oil leakages. Related signposts must be erected by the skidoo and quad bike rentals. Skidoos might also enter from the Afqa, Assal or Rouaiss catchment to the Labbane catchment. Therefore, the information must be provided in the entire area of groundwater protection zones 2 for the Afqa, Assal, Labbane and Rouaiss springs.

Army: The army check points at Wardeh and near Afqa have to consider environmental-friendly operation. Fuel should not be stored here.

Protection Zones for the Lower Aquifer (J4)

(Jeita spring)

Zones 1

Only the staff responsible for operation of the water supply from the source should be given access to GW protection zone 1. Access to the public should be banned.

Fences need to be established around the water source (50 m upstream, 15 m to each side, 10 m downstream of the spring and 10 m to each side of related water infrastructure, e.g. conveyor line, reservoir, etc. until entry into the actual water supply infrastructure (Dbayeh treatment plant)). The ownership of the land plots should be with the government. Zone 1 includes the area over Jeita cave and underground river with a rock cover of less than 100 m (MARGANE, 2013).

Signposts need to be erected at the boundary of GW protection zones 1 and inform the public about the aim of the protection zones, what is forbidden to do in these zones and whom to call in case of violations.

Stormwater runoff to the springs or conveyors must be avoided by constructional means.

Actions required

- A fence must be erected along the canal at 10 m distance from the canal.
- Houses and commercial businesses at the canal must be removed (10 m distance).
- Construction ban in the critical zone (risk of cave collapse)

Zones 2

The following activities shall not be allowed :

- Gas stations,

- Industrial sites,
- Commercial businesses (e.g. repair shops) using or storing hazardous substances,
- Storage of hazardous substances,
- Quarries, rock cutting facilities, brick factories,
- Dumping of waste (including construction waste),
- Animal farms,
- Agricultural farms,
- Slaughterhouses,
- Application of pesticides and chemical fertilizers.

Actions required

Wastewater collection in zone 2A must be of highest priority. The new network in protection zone 2A must be constructed in such a way that leakage of wastewater into groundwater is not possible. The main collector lines should be built as line-in-line system. New residential buildings should not be allowed to be built downgradient of the new wastewater collector line (escarpment collector). No new commercial businesses should be allowed to be established. Infiltration of fuel and oil from gas stations and car repair workshops poses a high risk. Relocation of existing gas stations in zone 2A should be considered. If this is not feasible, at least adequate environmental standards must be enforced, i.e. all gas stations must be equipped with double-layer tanks, drainage collection of water from car wash facilities, etc. (RAAD et al., 2012).

All existing illegal waste dumps should be removed. Deposition of construction waste should not be allowed in protection zones 2A and 2B.

The slaughterhouses located in zone 2, in Aajaltoun (Murr) and Ghosta should be closed. If not feasible they at least require a strict implementation and control of environmental friendly practices.

[The animal farms in the Beit Chebab, Mar Boutros, Safilee and Hemlaya area pose a high risk to Kashkoush spring (MARGANE & CHRABIEH, 2013). Water from Kashkoush spring is fed into the Jeita-Dbayeh water conveyor some 500 m downstream of Jeita spring. The capture of and conveyance system from Kashkoush spring has been upgraded by CDR in 2003. However, due to high pollution loads, the water from Kashkoush spring can most of the time not be used.]

8 Conclusions and Recommendations

The study conducted by the BGR project increased the understanding about the groundwater flow characteristics in the Jeita catchment and about groundwater systems in the Lebanon mountain range in general. The Lebanon and Anti-Lebanon mountain ranges are characterized by the predominance of karstified limestone. Using a large number of tracer tests, tests already conducted before and information gathered for pollution events, and other hydrogeological investigations, the groundwater catchment of Jeita spring could be delineated. It was proven that the Jeita surface water catchment is very different from its groundwater catchment. The reason for this is the karstic nature of the aquifer system. This is expected to be similar for all groundwater catchments of the Lebanon and Anti-Lebanon mountain ranges and constitutes a basic fact that must be considered in all water related planning in the country. The interaction between groundwater and surface water plays a major role. It could be proven that in many areas a large share of surface water infiltrates into groundwater as indirect groundwater recharge due to the presence of an extended karst network under the riverbeds. Riverbed infiltration is most extensive in all areas where the uppermost part of the J4 geological unit is highly karstified, i.e. in the Upper Nahr Ibrahim Valley, the Upper Nahr es Salib Valley, Nahr es Msann and Nahr es Zirghaya. This was proven by differential measurements of surface water flow (MARGANE, 2012a, 2012b) and by investigation of recurring pollution events (MARGANE et al., 2012).

The groundwater system was subdivided into three main hydrogeological units:

- Upper Aquifer: C4 geological unit (highly karstified limestone), assumed thickness up to 1,050 m;
- Aquitard: J5 to C3 geological units, assumed thickness: 500 to 800 m;
- Lower Aquifer: J4 geological unit (highly karstified limestone), assumed thickness up to 1,070 m.

Due to the high thickness of the aquitard, downward leakage is believed to be negligible. This was also proven by a tracer test (DOUMMAR et al., 2011a).

For the first time in Lebanon, a comprehensive groundwater balance was prepared for a groundwater catchment. The groundwater balance for Jeita spring is based on existing and new data acquired from monitoring stations of the project (SCHULER & MARGANE, 2013). The result shows that groundwater recharge to the Upper Aquifer is around 81 %, while it reaches only 58 % in the Lower Aquifer. A considerable proportion of surface water infiltrates into groundwater (~22-23 %) through riverbed infiltration. It is estimated that around 80 MCM (32 %) of Jeita spring discharge originate from riverbed infiltration, mainly from the C4. Most of this surface water comes from spring discharge from the C4 aquifer.

Not surprisingly for a highly karstified area, the study also showed that the boundaries of surface and groundwater are considerably different and that surface water – groundwater interaction plays a significant role. These processes have not yet been studied anywhere else but will be quite relevant in all of the Mount Lebanon and Antilebanon mountain ranges. These facts need to be taken into consideration in the planning process of water and wastewater projects, which is currently not the case.

A comprehensive stable isotope study of rainfall, snow and spring waters (KOENIGER & MARGANE, 2013) showed that there is a clearly identifiable interannual variation of stable isotope composition in all springs. This variation is similar in all monitored six springs: Jeita, Kashkoush, Assal, Labbane, Afqa and Rouaiss. There is a rapid response to snowmelt. All rainfall events show a clear correlation with elevation and distance from the sea. Heavy isotopes decrease with elevation and distance from the sea. This is also the case for the chloride composition. The correlation of the water samples taken from the C4 springs (average catchment elevations between 1950 and 2200 m asl) with the integral snow samples taken before snowmelt reflect well the average elevation of the corresponding catchments. The correlation of Jeita spring with the same data, however, shows that the catchment elevation must be higher than 1,400 m asl, indicating a much higher mean elevation than the average J4 outcrop area (1019 m asl), from which Jeita spring discharges. This is another proof that there must be a fairly large contribution of water from the C4 springs through riverbed infiltration into the Lower Aquifer and flowing towards Jeita spring. The highest inflow contribution comes from a riverbed infiltration zone in the Upper Nahr Ibrahim where around 66 MCM/a infiltrate (SCHULER & MARGANE, 2013; MARGANE, 2012a, 2012b).

Dilution tests conducted in the explored part of the underground river of Jeita showed that travel time varied between 220 (dry season) and 1900 m/h (wet season). During peak flow, flow velocity will even exceed 2,000 m/h. The profile in which these flow measurements were done is highly irregular but often has a width of 5 m and more. Until now the underground river is only explored over a distance of 5800 m, where it disappears in a siphon (siphon terminale), close to Nahr es Salib. A minor contribution (approx. 15%) to Jeita spring discharge from a northern branch of Jeita Grotto (approx. 800 m upstream of the boat mooring) was proven through differential discharge measurements.

The vulnerability of the groundwater resources in the Jeita catchment was evaluated using the EPIK and COP methods (DOUMMAR et al., 2012; MARGANE & SCHULER, 2013). Both methods show a very high vulnerability in more than 70% of the catchment. The COP method (VIAS et al., 2002, 2006) was slightly modified to be applicable in all of Lebanon and to reflect the partly strong surface water – groundwater interaction. The groundwater vulnerability map was used in combination with mean groundwater travel times, found by tracer tests, to determine the boundaries of groundwater protection zones. **Groundwater protection zones were proposed for Jeita spring and other major springs in the Jeita catchment** (MARGANE & SCHULER, 2013). Protection zones 2 cover a large part of the Jeita groundwater catchment (71 %). To ensure that GW protection could be effective, a list of required landuse restrictions was proposed to the Lebanese Government. Implementation of these landuse restrictions will be crucial and require tough decisions and amendments of the related laws and regulations. Therefore it is expected that implementation will take time but there is no alternative – otherwise these important GW resources may be lost forever due to massive pollution. The results of the micropollutant study (DOUMMAR et al., 2012) confirm the groundwater vulnerability and show the extensive impact of landuse activities on Jeita spring quality. The impact of the agricultural activity, which mainly occurs on the aquitard, on GW quality, however, is until now relatively low.

The groundwater hazards existing in the Jeita catchment were investigated together with the current legal framework governing landuse licensing decisions (RAAD et al., 2012, RAAD & MARGANE, 2013). **The main hazards found were: wastewater disposal in rivers, wells and open cesspits, gas stations (84 stations in the catchment), slaughterhouses, hospitals, quarries, animal farms, and illegal dumping of waste.** The comparison of the existing groundwater hazards with the vulnerability of the aquifers and the proposed groundwater protection zones show that there are many serious pollution sources inside groundwater protection zone 2. Some of these should be abandoned. Improvement of groundwater resources protection and implementation of the above mentioned protection zones often requires a modification of related regulations concerning the existing hazards to groundwater. Also existing control measures are highly insufficient. In order to come to be better quality of water resources an agency with policing power needs to be established otherwise clandestine landuse practices will continue. In this context it is urged to truly implement the proposed **Environmental Police** under the Ministry of Environment. Also the Lebanese army could play a major role in the enforcement of the application of water protection laws and guidelines as this falls under the protection of the public from major health threats.

The assessment of pollutants by the BGR project revealed that there is an urgent need for the establishment of an appropriate governmental water laboratory with adequate capacities for water quality monitoring of all relevant parameters. The monitoring program needs to be adapted to the existing contamination sources. Currently the pollution of raw water at Jeita does not have any consequences, neither for the polluters nor for the consumers, and no action is taken in case of pollution.

Among others the following components are currently not analyzed by the existing WEBML laboratory but need to be included in a comprehensive water quality monitoring program: pesticides, MTBE and other fuel components, heavy metals, hydrocarbons, pharmaceutics. Currently these can also not be treated at the Dbayeh drinking water treatment plant. Also certain microbiological components, resulting from animal farming are not included in the current WEBML monitoring (e.g. Cryptosporidium). The microbiological monitoring program needs to be adapted to the existing agricultural and domestic contamination sources.

A major project component was to provide geoscientific advice to CDR concerning the site searching for the CDR/KfW wastewater treatment plant (WWTP) of the Jeita Spring Protection Project (JSPP), related collector lines and the effluent discharge location. The preexisting planning was revised based on a BGR proposal, developed subsequent to the first tracer test of the BGR project (MARGANE, 2011), a wastewater master plan for the most sensitive part of the Jeita catchment was then jointly developed (GITEC, LIBANCONSULT & BGR, 2011) and an environmental impact assessment (EIA) was submitted to CDR and Ministry of Environment (BGR & LIBANCONSULT, 2013). The EIA was based on a related guideline prepared by the BGR project (MARGANE & ABI RIZK, 2011b). An improved spring capture and water conveyance to the Dbayeh drinking water plant was recommended (GITEC & BGR, 2011) to increase water supply to Beirut and to ensure that in case of damage of one conveyor line the second one could still provide drinking water. This is currently not the case, with the consequence that the population in the Greater Beirut Area may be without water for an extended period in case of a damage of the existing old and leaky system.

As a general recommendation the BGR project advises, because of the tremendous negative impact on the water quality of Jeita spring, and due to the high degree of karstification and the high flow velocities, to **urgently collect all wastewater, with highest priority in the most sensitive, i.e. highly vulnerable parts of the catchment, and convey it for treatment to a point downstream of Jeita spring** (i.e. outside of the groundwater catchment). This centralized wastewater treatment approach provides that the drinking water source cannot be contaminated by non or incompletely treated wastewater. **It is recommended to follow a centralized concept for the planning of wastewater facilities in all of the Mount Lebanon mountain range** because any treatment within the hydrogeological boundaries imposes an inacceptable risk on drinking water sources. The reason why the previously proposed WWTP location was relocated was that a tracer test, conducted by the project at the proposed effluent discharge location, showed that this effluent would arrive in Jeita after very short time, making the situation even worse than before. In this context **the project recommends**

conducting tracer tests at the proposed effluent discharge locations of all wastewater schemes in karst areas at the beginning of the planning process during the dry season and monitor tracer arrival at all relevant downstream water sources.

More hydrogeological studies such as those conducted by the BGR project are needed in order to come to a better understanding of the groundwater recharge processes, the flow mechanisms in the groundwater system and the resources actually available. Until now a **comprehensive (ground)water resources assessment** of Lebanon has not been done due to lack of basedata but would be urgently needed. Such an assessment cannot be established before (ground)water resources in all catchments have been quantified through adequate monitoring data. Not having such (ground)water resources assessments at hand would inadvertently result in **failed investments**. Currently planning of water projects is commonly done without conducting adeqate hydrogeological investigations.

Due to a general lack of geologists and more specifically hydrogeologists in Lebanon, the current institutions working in the water sector are not able to conduct such studies, to monitor the water resources of the country and to provide adequate protection for the drinking water sources. It is therefore highly recommended to create a **National Water Resources Management Agency**, which would countrywide be responsible for

- water resources monitoring (quality and quantity of groundwater and surface water);
- water resources assessments for all groundwater catchments;
- water resources management (assessment of demand and allocation);
- proposal of related water infrastructure projects.

Lebanon is one of the few countries worldwide affording not to have a geological survey. There is a large gap of geological information and the existing one is outdated or not detailed enough. The creation of a **Geological Survey** is therefore highly recommended. One of its tasks would be to assist the National Water Resources Management Agency by preparing updated geological maps, conduct geophysical investigations, establish structure contour maps (top/base of geological units) and prepare tectonic maps.

Because the deeper underground is virtually unknown, a **groundwater exploration program** should be undertaken using geophysical measurements (seismics, TEM) and deep boreholes to investigate the groundwater system (geological structure, base of Sannine Fm., base of Keserwan Fm.) in all of the country. Concerning this, the objectives of groundwater and oil exploration should be combined into one single exploration program, meeting both purposes.

In order to decide where potentially hazardous landuse activities, such as waste disposal sites, treated wastewater reuse, treated wastewater discharge, industrial sites/zones could be established, commonly groundwater vulnerability maps are used. **Groundwater vulnerability maps** should therefore be established **for the entire country** to help in the related site selection process.

Already many springs in Lebanon are affected by pollution. This puts the health of the population at considerable risk. Groundwater protection zones provide the only means to safeguard drinking water supply. **The delineation of groundwater protection zones for all important drinking water sources (springs) in the country must therefore be a national duty.**

The monitoring of spring discharge and the collection of meteorological data done by the project should be continued. Long-term monitoring is the only means to make informed decisions concerning water usage. In this regard an **upgrading of the existing surface water monitoring stations** and the installation of new surface water monitoring stations at locations where the construction of dams is planned will be important. Currently most dams are planned under wrong assumptions concerning water resources availability because the differences between ground and surface water catchments and the interactions between both, i.e. the knowledge about where surface water is influent and where it is effluent, are not taken into consideration at all.

Currently no groundwater monitoring wells exist so that there is no adequate information about the seasonal and long-term behavior of the groundwater system. **Climate change** is expected to have a tremendous impact on Lebanon. If temperatures were to rise, as forecast, there would be a **significant upward orographic shift of snow lines**. Due to a then less extensive snow cover and shorter period of snow fall, there would be an **extended period of water shortage**. Groundwater monitoring wells would be very useful to propose mitigation actions for climate change impacts. Groundwater monitoring wells are also the only means to calibrate groundwater models. Without them groundwater models cannot be established. A large number of monitoring wells is needed to investigate the long-term behavior in the groundwater system concerning water level and water quality (physico-chemical parameters) in all of the country.

A large number of violations by landusers against current legal provisions were observed. This pertains especially to illegal dumping of commercial, agricultural, domestic, hazardous and construction waste. Control of environmental practices must be enforced and penalties applied to effectively reduce pollution risks.

Out of three wastewater projects, only the CDR/KfW project is currently on track. The EIB/AFD/EU wastewater project in the lower Keserwan district and the Italian protocol project in the Hrajel/Faraya area are delayed since a very long time. Implementation of wastewater collection and treatment systems is urgently needed to reduce pollution from wastewater in all sensitive areas of the Jeita catchment. A better coordination between all projects in a catchment would be desirable since the main aim of wastewater projects generally is to protect the water resources. **The comprehensive integration of geoscientific expertise in all steps of a wastewater project (planning and EIA), as fruitfully practiced in the JSPP project of KfW and CDR, is of utmost importance to the success of these projects**. This experience should be transferred to all foreign donor funded projects, otherwise many of them will fail to meet their objectives.

The experiences gained during the preparation of the EIA of the JSPP project showed that large infrastructure projects such as WWTPs, water conveyors, dams, roads, tunnels, etc., are often affected by geo-risks (MARGANE, 2013). In many projects these risks are not investigated; many EIAs do not even look at the potential impact on water resources. The plannings of such projects urgently need to consider a more comprehensive integration of geoscientific expertise to recognize these risks and mitigate them.

Landuse planning in Lebanon follows an antiquated process inherited from the French rule. Despite always underlining the matter in its decision, landuse planning does not at all integrate water resources protection needs. A change of landuse planning practices is urgently needed. Landuses potentially negatively impacting on water resources must be allowed only in areas with low and very low groundwater vulnerability with no drainage towards areas of high groundwater vulnerability. **Groundwater vulnerability maps should be used for all landuse licensing decisions related to: industrial sites, slaughterhouses, quarries, gas stations, liquid, solid and hazardous waste disposal sites, wastewater treatment plants, areas proposed for treated wastewater reuse, power plants, refineries, army posts, etc.** All major proposed landuses which may have a potentially negative impact on water resources should require the preparation of an EIA with specific consideration of the impact an water resources.

In this respect, **an updated regional landuse management plan must be elaborated, based on the vulnerability mapping in the catchment of Jeita spring and the proposed groundwater protection zones**. EIAs related to proposed landuse activities in the area must consider the proposed GW protection zones.

Considering the high pollution risk by the existing illegal dumpsites in the catchment, solid wastes management has become a serious issue. There is an urgent necessity to establish facilities able to absorb and recycle slaughtering and feedlots wastes, pesticides containers, etc. A link needs to be established between waste producers and waste recycling entities. As far as municipal waste is concerned, the promotion of waste separation at source can be a good start in this respect. A related awareness campaign is necessary.

A real control of the pesticides market, import and relabeling practices and the development of an efficient agricultural extension service would be required.

The existing regulations concerning liquid and hazardous waste management (temporary storage and disposal) must be enforced for the only existing hospital, St. George Aajaltoun, and the industrial sites in the area. This pertains e.g. to liquid and radioactive waste from the hospital laboratory and x-ray instruments. Many industrial sites did not construct industrial wastewater treatment systems as they must by law. Strict control measures need to be applied concerning the design, implementation and operation of industrial wastewater treatment systems.

The existing gas stations constitute a high contamination risk because of assumed leakage to groundwater (RAAD et al., 2012). **All gas stations should be scrutinized and be submitted to an urgent environmental auditing by the Ministry of Environment.** Most of them will require replacement of underground storage tanks (USTs) by double-layer tanks and installation of drainage systems, oil separators, etc. In this context it is highly recommended to revise the existing guidelines and make the installation of double-layer tanks obligatory, as well as the installing of automated leakage detection systems and of leakage containment devices.

Oil leakage and spillages from generators and residential heating systems constitute another major contamination risk. Related guidelines must be improved with respect to water resources protection and an annual inspection should be enforced.

All the above require public awareness raising campaigns including academia, universities, municipalities, private sector, NGO, but also decision makers (local administration, ministries).

The comprehensive assessment of the existing hazards to groundwater as done by the project can be used to draft GW quality monitoring program in order to assess the impacts of the hazards on the drinking water sources. In this context, the micropollutants study conducted by the project can only be seen as a starting point.

Considering the importance of Jeita spring as the main source of drinking water supply for the Greater Beirut Area, a continuous monitoring of contamination risks and their impacts on raw water is vital to the protection of public health.

The existing water laboratory of WEBML is much too small and its equipment is inadequate and outdated to deal with the required number and type of analyses for the monitoring of source water quality (springs, wells) and the monitoring of raw and treated water quality (in/outflow of the Dbayeh treatment plant). This lab cannot analyze wastewater, pesticides, heavy metals, hydrocarbons as well as many other substances. **There is an urgent need to establish a real governmental Water Laboratory** in an adequate building and with adequate staff and equipment. A comprehensive **Water Quality Monitoring Program** needs to be implemented to adequately address the issues of public health and environmental pollution control.

The Dbayeh drinking water treatment plant is at the limit of its capacity and cannot remove many of the contaminants detrimental to human health and encountered in the raw water. Chlorination of hydrocarbons leads to the formation of carcinogenic chlorinated hydrocarbons. Treatment capacity must be increased and treatment methods be improved to cover also removal of heavy metals, pesticides, hydrocarbons and pharmaceuticals.

Irrigation of vegetables by untreated contaminated water, as largely practiced, especially in the lower parts of the catchment constitutes a health risk. Here irrigation should only be allowed for fruit trees and not for vegetables.

9 References

ABI RIZK, J. (2013): Meteorological Stations installed by the BGR Project. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 18; Ballouneh/Lebanon.

ABI RIZK, J. & MARGANE, A. (2011): Mapping of Surface Karst Features in the Jeita Spring Catchment. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 7, 59 p.; Ballouneh/Lebanon.

ABI RIZK, J. & MARGANE, A. (2011): Surface Karst Features Mapping for the Groundwater Catchment Area of Jeita Spring. – Conference Proceedings "Hydrogeology of Arid Environments" March 2012, Hannover, p. 190; Stuttgart (Borntraeger).

ACE (1988): Nahr el Kalb – Dbaye water conveyor – avant projet sommaire. – Report prepared for CDR, 256 p.; Beirut.

ACE (1995): Water and wastewater feasibility studies for Kesrouan drainage zone. – Report prepared for CDR, 125 p; Beirut.

AKHRASS, C. (2009): Rectification des coordonnees des gouffres au plateau d'Afqa et du plateau de Jabal Kesrouane. – Speleorient, 5, pp. 5-54; Beirut.

AOUAD-RIZK, A., JOB, J.-O., KHALIL, S., TOUMA, T., BITAR, C., BOQCUILLON, C. & NAJEM, W. (2005): Snow in Lebanon: A preliminary study of snow cover over Mount Lebanon and a simple snowmelt model. – Hydrol.Sci.Journal, 50, 3, pp. 555-569; London (Taylor & Francis)

AOUAD-RIZK, A., JOB, J.L., NAJEM, W., TRAVI, Y., BLAVOUX, B & GOURCY, L. (2005): Oxygen-18 and Deuterium Contents over Mount Lebanon Related to Air Mass Trajectories and Local Parameters. – IAEA-TECDOC-1453, pp. 75-82; Vienna.

AVSI (2009):The Study of Nahr el Kalb – Results. – Final Project Report, 148 p; Beirut.

BAR, O., GVIRTZMAN, Z., FEINSTEIN, S. & ZILBERMAN, E. (2011): Late Tertiary subsidence of the Levant margin: Distinction between sedimentary load and tectonics. – Report prep. by GSI for Min.Infrastruct., GSI/20/2011, 33 p.; Jerusalem.

BAR-MATTHEWS, M., AYALON, A., KAUFMAN, A., WASSERBURG, G.J. (1999): The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel. – Earth and Planetary Science Letters 166, pp. 85–95. (Elsevier)

BCT (2008): JEITA Spring Protection Project - Project Preparatory Report. – Prepared for KfW, 42 p.; Neu-Isenburg.

BEERLING, D.J., LOMAX, B.H., ROYER, D.L., UPCHURCH, G.L. & KUMP, L.R. (2002): An atmospheric pCO2 reconstruction across the Cretaceous-Tertiary boundary from leaf megafossils. ─ Proceedings of the National Academy of Sciences, 99, 12: 7836-7840, Washington.

BEN-AVRAHAM, Z. & TEN BRINK, U. (1989): Transverse faults and segmentation of basins within the Dead Sea Rift. - Journal of African Earth Sciences, 8 (2/3/4), pp.603-616. (Pergamon Press)

BLANCKENHORN, M.L.P. (1891): Grundzüge der Geologie und Physischen Geographie von Nordsyrien. – 101 p.; Berlin. (Friedlaender & Sohn)

BOU JAOUDE, I., KARANOUH, R., MOMJIAN, N. & HUSSEIN, S.C. (2010): Understanding the Leaks in Chabrouh Dam Through Detailed Hydrogeological Analysis of the Qana Plateau (Lebanon). – In: ANDREO et al. (Eds.): Advances in Research in Karst Media, pp.407-413. (Springer)

BREW, G.E. (2001): Tectonic Evolution Of Syria Interpreted From Integrated Geophysical And Geological Analysis. - PhD thesis, Cornell University, 298 p.; Ithaca/NY/USA.

BREW, G. E., BARAZANGI, M., AL-MALEH, K., AND SAWAF, T. (2001): Tectonic map and evolution of Syria. – GeoArabia, 6, 4, pp. 573-616.

BUTLER, R.W.H., SPENCER, S. & GRIFFITH, H.M. (1998): The structural response to evolving plate kinematics during transpression: evolution of the Lebanese restraining bend of the Dead Sea Transform. - Spec. Publs.Geol.Soc.London, 135, 81-106; London.

CHRABIEH, M. & MARGANE, A. (2012): Locating the Pollution Source of Kashkoush Spring. – Technical Cooperation Project ‘Protection of Jeita Spring’, Advisory Service Document No. 3, 18 p.; Raifoun.

CLARKE, I. & FRITZ, P. (1997): Environmental isotopes in hydrogeology. ─ 328 p. Boca Raton (CRC Press/Lewis Publishers).

CORAIL (2001): Appui au renforcement des capacités du laboratoire d’analyse de la qualité des eaux de l’Office des Eaux de Beyrouth - Projet ARCLAB. - Report prepared for OEB, 38 p.; Beirut.

CORAIL & ICEA (2005): Securiser la Ressource, L’adduction et la Production d’eau Potable a partir de la Ressource de - Jeïta – Quashqouch - Risques et Priorites. - Report prepared for CDR and AFD, 53 p.; Beirut.

CRAIG, H. (1961): Isotopic variations in meteoric waters. ─ Science, 133 (3465), pp. 1702–1703.

DIENER, C. (1886): Libanon. Grundlinien der Physischen Geographie und Geologie von Mittel-Syrien. – 412 p.; Vienna (Hoelder).

DAERON, M., BENEDETTI, L., TAPPONNIER, P. , SURSOCK, A. & FINKEL, R. (2004): Constraints on the post 25-ka slip rate of the Yammouneh fault (Lebanon) using in situ cosmogenic 36Cl dating of offset limestone-clast fans. – Earth and Planetary Science Letters, 227, pp. 105–119.

DAERON, M. (2005): Role, cinematique et comportement sismique a long terme de la faille de Yammouneh, principale branche d´ecrochante du coude transpressif libanais (faille du Levant). – PhD thesis, Institut De Physique Du Globe De Paris, 178 p.; Paris.

DAVIES, G.R. & SMITH, L.B. (2006): Structurally controlled hydrothermal dolomite reservoir facies: an overview. – AAPG Bulletin, 90, 11, pp. 1641-1690; Boulder/CA/USA.

DOUMMAR, J., MARGANE, A., JIN, Y., GEYER, T. & SAUTER, M. (2010a): Protection of Jeita Spring – Artificial Tracer Tests (Tests 1A and 1B) – April 2010. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 1, 33 p.; Ballouneh/Lebanon & Goettingen/Germany.

DOUMMAR, J., MARGANE, A., GEYER, T. & SAUTER, M. (2010b): Protection of Jeita Spring – Artificial Tracer Tests (Tests 2) – August 2010. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 2, 27 p.; Ballouneh/Lebanon & Goettingen/Germany.

DOUMMAR, J., MARGANE, A., GEYER, T. & SAUTER, M. (2012a): Protection of Jeita Spring – Artificial Tracer Tests (Tests 4A and 4B) – May 2011. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 5, 17 p.; Ballouneh/Lebanon & Goettingen/Germany.

DOUMMAR, J., MARGANE, A., GEYER, T. & SAUTER, M. (2012b): Protection of Jeita Spring – Artificial Tracer Tests (Test 5A) – June 2011. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 6, 15 p.; Raifoun/Lebanon & Goettingen/Germany.

DOUMMAR, J., MARGANE, A., GEYER, T. & SAUTER, M. (2012c): Protection of Jeita Spring – Artificial Tracer Tests (Test 5C) – September 2011. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 11, 16 p.; Raifoun/Lebanon & Goettingen/Germany.

DOUMMAR, J., MARGANE, A., GEYER, T. & SAUTER, M. (2012d): Vulnerability Mapping using the COP and EPIK Methods. – Technical Cooperation Project Protection of Jeita Spring, Technical Report No. 7b, 43 p.; Goettingen.

DOUMMAR, J., NOEDLER, K., GEYER, T. & SAUTER, M. (2012): assessment and analysis of micropollutants (2010-2011). – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 13, 15 p.; Raifoun/Lebanon & Goettingen/Germany.

DUBERTRET, L. (1951): Carte geologique au 50.000^{e}, feuille de Beyrouth. – Map with explanatory note, 66p.; Beirut.

DUBERTRET, L. (1955): Carte geologique du Liban au 200.000^{e}. – Map with explanatory note, 74 p.; Beirut.

EL- FADEL, M .(2002): Workshop on the issues of water in Lebanon. - Presentation for Parliament of Lebanon. Beirut.

ENZEL, Y., AMIT, R., DAYAN, U., CROUVI, O., KAHANA, R., ZIV, B. & SHARON, D. (2008): The climatic and physiographic controls of the eastern Mediterranean over the late Pleistocene climates in the southern Levant and its neighboring deserts. – Global and Planetary Change, 60, pp. 165-192. (Elsevier)

FLEXER, A., YELLIN-DROR, A., KRONFELD, J., ROSENTHAL, E., BEN-AVRAHAM, Z., ARTSZTEIN, P. & DAVIDSON, L. (2000): A Neogene salt body as the primary source of salinity in Lake Kinneret. – Arch.Hydrobiol.Spec.Issues Advanc. Limn., 55, pp. 69-85.

GARDOSH, M., DRUCKMANN, Y., BUCHBINDER, B & RYBAKOV, M. (2008): The Levant Basin Offshore Israel: Stratigraphy, Structure, Tectonic Eveolution and Implications for Hydrocarbon Exploration. – Report prep. by GSI for Min.Infrastruct., GSI/4/2008, GII 429/328/08, 118 p.; Jerusalem.

GARFUNKEL, Z. (1981): Internal Structure of the Dead Sea Leaky Transform (Rift) in Relation to Plate Kinematics. – Tectonophysics, 80, pp. 81-108. (Elsevier)

GARFUNKEL, Z., ZAK, I. & FREUND, R. (1981): Active Faulting in the Dead Sea Rift. – Tectonophysics, 80, pp. 1-26. (Elsevier)

GAT, J.R. & CARMI, I. (1987): Effect of climate changes on the precipitation patterns and isotopic composition of water in a climate transition zone: Case of the Eastern Mediterranean Sea area. – IAHS Publ. no. 168, pp. 513-523.

GAUTIER, F., CLAUZON, G., SUC, J.P., CRAVATTE, J. y VIOLANTI, D. (1994): Age and Duration of the Messinian Salinity Crisis. - C.R.Acad.Sci.Ser.Ii, 318, pp 1103-1109; Paris.

GEYER, T. & DOUMMAR, J. (2013): Bestimmung der mittleren Verweilzeit des Grundwassers im Einzugsgebiet der Jeita Quelle, Libanon. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 15, 10 p., Goettingen and Beirut.

GIRDLER, R.W. (1990): The Dead Sea transform fault system. – Tectonophysics, 180, pp. 1–13. (Elsevier)

GITEC, LIBANCONSULT & BGR (2011): Regional Sewage Plan. – Technical report prepared for CDR, 140 p.; Ballouneh, Beirut.

GITEC & BGR (2011): Feasibility Study Rehabilitation of Transmission Channel Jeita Spring Intake – Dbaye WTP. – Technical report prepared for CDR, 118 p.; Ballouneh.

GOLDREICH, Y. (1994): The Spatial Distribution of Annual Rainfall in Israel-A Review. – Theor.Appl.Climatol., 50, pp. 45-59; Vienna/AT (Springer).

GOLDREICH, Y. (2003): The Climate of Israel - Observation, Research and Application. – 270 p.; New York (Kluwer).

GOMEZ, F., NEMER, T., TABET, C., KHAWLIE, M., MEGHRAOUI, M. & BARAZANGI, M. (2007): Strain partitioning of active transpression within the Lebanese restraining bend of the Dead Sea Fault (Lebanon and SW Syria). – Geol.Soc.London, Special Pub., 290, p. 285-303; London.

HAHNE, K. (2011): Geological Map, Tectonics and Karstification in the Groundwater Contribution Zone of Jeita Spring supported by Remote Sensing. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Technical Report No. 4; Raifoun/Lebanon.

HAKIM, B. (1993): Etude des pointes de pollution dans les bassins du Nahr el Kalb et du Faouar Antelias. – Report prepared for Water Establishment of Beirut and Mount Lebanon; 72 p; Beirut.

HAKIM, B., KARKABI, S. & LOISELET, J. (1988): Colorations de la riviere souterraine de Jiita etz de la perte superficielle du ouadi Nahr es Salib (Caza du Kesrouane) 1961-1971. – Al Ouat-Ouate, 3, pp. 3-19; Beirut.

HOMBERG, C. & BACHMANN, M. (2010): Evolution of the Levant Margin and Western Arabia Platform. – Geol.Soc.London, Special Publication 341, 329 p.; London.

HUGHES, P. D., & WOODWARD, J. C. (2008): Timing of glaciation in the Mediterranean mountains during the last cold stage. – J.Quat.Sci., 23 (6-7), pp. 575-588. (Wiley).

HUGHES, P.D., WOODWARD, J.C. & GIBBARD, P.L. (2006): Quaternary glacial history of the Mediterranean mountains. – Progr.Phys.Geogr., 30, 3, pp. 334-364; London (Edward Arnold Pub.).

HUIJER, C., HARAJLI, M. & SADEK, S. (2011): Upgrading the Seismic Hazard of Lebanon in Light of the Recent Discovery of the Offshore Thrust Fault System. - Lebanese Science Journal, Vol. 12, No. 2, 2011, 67-82; Beirut.

HURWITZ, S., GARFUNKEL, Z., BEN-GAI, Y., REZNIKOV, M., ROTSTEIN, Y. & GVIRTZMAN, H. (2002): The tectonic framework of a complex pull-apart basin: seismic reflection observations in the Sea of Galilee, Dead Sea transform. – Tectonophysics, 359, pp. 289-306. (Elsevier)

INBAR, N., FLEXER, A., SCHULMAN, H. & YELLIN-DROR, H. (2010): The Role of Solid Salt in Groundwater Salination Process, Kinnarot Basin, Israel. – European Water, 29, pp. 31-38.

JICA (2003): The Study on the Water Resources Management Master Plan in the Republic of Lebanon - Main Report. – 298 p.; Tokyo/Japan.

LERNER, D., ISSAR, A. & SIMMERS, I. (1990): Groundwater recharge - a guide to understanding and estimating natural recharge. ─ 345 p; Hannover (Heise).

LIBANCONSULT & BGR (2013): Environmental Impact Assessment for the Mokhada Wastewater Treatment Plant and related Collector Lines. – Technical report prepared for CDR, xx p; Beirut & Raifoun.

LIBANCONSULT & HYDRATEC (2010): Etude de faisabilité pour la collecte et le traitement des eaux uses Jounieh – Keserouan casa. – Report prepared for EIB/AFD/CDR, 142 p.; Beirut.

KARKABI (2009): Les premieres tracages a l'uranine au Liban. – Al Ouat-Ouate (Speleo Club du Liban), 15, pp. 13-21; Beirut.

KHAIR, K. (2001): Geomorphology and seismicity of the Roum fault as one of the active branches of the Dead Sea fault system in Lebanon. - Journ.Geophys.Research, 106, B3, pp. 4233-4245. (Wiley)

KHAIR, K., TSOKAS, G.N. & SAWAF, T. (1997): Crustal strcuture of the northern Levant region: multiple source Werner deconvolution estimates for Bouguer gravity anomalies. – Geophy.Journ.Int., 128, pp. 605-616; Oxford/UK (Oxford University Press).

KOENIGER,, P., MARGANE, A. & HIMMELSBACH, T. (2012): Stable isotope studies on altitude effect and karst groundwater catchment delineation of the Jeita spring in Lebanon. – IAH 2012 Congress, proceedings, p. 227; Niagara Falls/CDN.

KOENIGER, P. & MARGANE, A. (2013): Stable Isotope Investigations in the Jeita Groundwater Catchment. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 12; xx p.; Raifoun/Lebanon.

KOENIGER,, P., MARGANE, A. & HIMMELSBACH, T. (2012): Isotopenuntersuchungen im Einzugsgebiet der Jeita Quelle, Libanon [Stable isotope studies in the catchment of the Jeita spring, Lebanon]. – Presentation at BGR Colloquium 2012, 23 slides; Hannover. [download from: www.bgr.bund.de/jeita]

LABAKY, W. N. (1998): A Hydrogeological and environmental assessment of the Faouar Antelias catchment. – MSc thesis, American University of Beirut, 132 p.; Beirut.

LIBANCOSULT & HYDRATEC (2010): Etude de faisabilité pour la collecte et le traitement des eaux uses Jounieh – Keserouan casa. – Report prepared for EIB/AFD/CDR, 142 p. ; Beirut.

LUCIC, D., IVKOVIC, Z., TAKIC, D., BUBNIC, J. & KOCH, G. (2010): Depositional sequences and palynology of Triassic carbonate-evaporite platform deposits in the Palmyrides, Syria. – In: VanBUCHEM, F.S.P., GERDES, K.D. & ESTEBAN, M. (Eds.): Mesozoic and Cenozoic Carbonate Systems of the Mediterranean and the Middle East: Stratigraphic and Diagenetic Reference Models, Geol.Soc. London, Spec. Pubs., 329, pp. 43-63.

MAJDALANI, M. (1977): Geology and Hydrogeology of the Faraya-Afqa Area. – MSc thesis, American Univ. of Beirut, 143 p.; Beirut.

MAKHLOUF, I.M. (2002):

MAKHLOUF, I.M. & EL-HADDAD, A.A. (2006): Depositional environments and facies of the Late Triassic Abu Ruweis Formation, Jordan. – Journ. Asian Earth Sciences, 28, pp. 372–384.

MARGANE, A. & SUNNA, N. (2002): Proposal for a National Guideline for the Delineation of Groundwater Protection Zones. – Technical Cooperation Project ‘Groundwater Resources Management’, Technical Report No. 1, prepared by BGR & MWI, BGR archive no. 0125645, 161 p.; Amman.

MARGANE, A. (2003a): Guideline for the Delineation of Groundwater Protection Zones. – Technical Cooperation Project ‘Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region’, Technical Reports Vol. 5, prepared by BGR & ACSAD, BGR archive no. 122917:5, 329 p., 1 CD; Damascus. [download from www.acsad-bgr.org or www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/Acsad/Vol_5_fb_pdf.pdf]

MARGANE, A. (2003b): Guideline for Groundwater Vulnerability Mapping and Risk Assessment for the Susceptibility of Groundwater Resources to Contamination. – Technical Cooperation Project ‘Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region’, Technical Reports Vol. 4, prepared by BGR & ACSAD, BGR archive no. 122917:4, 177 p., 1 CD; Damascus. [download from: www.acsad-bgr.org or www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/Acsad/Vol_4_fb_pdf.pdf]

MARGANE, A. (2011): Site Selection for Wastewater Facilities in The Nahr el Kalb Catchment. General Recommendations from the Perspective of Groundwater Resources Protection. – German-Lebanese Technical

Cooperation Project Protection of Jeita Spring, Technical Report No. 1, 155 p., Ballouneh, Lebanon.

MARGANE, A. (2012a): Quantification of Infiltration into the Lower Aquifer (J4) in the Upper Nahr Ibrahim Valley. – Technical Cooperation Project ‘Protection of Jeita Spring’, Advisory Service Document No. 1-1, 62 p.; Raifoun.

MARGANE, A. (2012b): Quantification of Infiltration into the Lower Aquifer (J4) in the Upper Nahr Ibrahim Valley – Addendum No. 1. – Technical Cooperation Project ‘Protection of Jeita Spring’, Advisory Service Document No. 1-1, 42 p.; Raifoun.

MARGANE, A. (2012c): Locating the Source of Turbidity Peaks occurring in April – June 2012 in the Dbayeh Drinking Water Treatment Plant. – Technical Cooperation Project ‘Protection of Jeita Spring’, Advisory Service Document No. 3, 22 p.; Raifoun.

MARGANE, A., CHRABIEH, M. & SOUAID, P. (2012): Locating the Source of Turbidity Peaks occurring in April – June 2012 in the Dbayeh Drinking Water Treatment Plant. – Technical Cooperation Project ‘Protection of Jeita Spring’, Advisory Service Document No. 2, 22 p.; Raifoun.

MARGANE, A. & DOUMMAR, J. (2012): Delineation of the Groundwater Contribution Zone for Jeita Spring, Lebanon, using Tracer Tests in a Karst Aquifer System. – IAH 2012 Congress, proceedings, p. 81; Niagara Falls/CDN. [download presentation from: www.bgr.bund.de/jeita]

MARGANE, A. & MAKKI (2012): Water Resources Protection for the Water Supply of Beirut. – In: RAUSCH, R., SCHUETH, C. & HIMMELSBACH, T.: Hydrogeology of Arid Environments, p. 89-91; Hannover (Borntraeger).

MARGANE, A. & MAKKI, I. (2012): Hydrogeological Investigations in a Karst Aquifer for Investments in the Wastewater Sector to Protect the Drinking Water Resources of Beirut. – IAH 2012 Congress, proceedings, p. 228; Niagara Falls/CDN. [download presentation from: www.bgr.bund.de/jeita]

MARGANE, A. & ABI RIZK, J. (2011a): Practice Guide for Tracer Tests. - German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 3, 45 p.; Raifoun/Lebanon.

MARGANE, A. & ABI RIZK, J. (2011b): Guideline for Environmental Impact Assessments for Wastewater Facilities in Lebanon. - German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Technical Report No. 3, 26 p.; Raifoun/Lebanon.

MARGANE, A. & MAKKI, I. (2012): Water Resources Protection for the Water Supply of Beirut. – Conference Proceedings “Hydrogeology of Arid

Environments" March 2012, Hannover, pp. 89-91; Stuttgart (Borntraeger).

MARGANE, A. & MAKKI, I. (2011): Safeguarding the Drinking Water Supply of the Cities of Beirut and Damascus by Water Resources Protection in Karstic Environments. - World Water Week 2011, Abstract Volume, pp. 28-29, Stockholm.

MARGANE, A. & SCHULER, P. (2013): Groundwater Vulnerability in the Groundwater Catchment of Jeita Spring and Delineation of Groundwater Protection Zones Using the COP Method. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Technical Report No. 7, 133 p.; Raifoun/Lebanon.

MARGANE & STEINEL (2011): Proposed National Standard for Treated Domestic Wastewater Reuse for Irrigation. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 4, 42 p.; Ballouneh/Lebanon.

MARGANE, A. & STOECKL, L. (2013): Monitoring of Spring Discharge and Surface Water Runoff in the Groundwater Contribution Zone of Jeita Spring. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 8, 97 p.; Raifoun/Lebanon.

MARGANE, A. & ZUHDY, Z. (1995): Rainfall in Jordan, – German-Jordanian Technical Cooperation Project Groundwater Resources of Northern Jordan, Vol. 1, Part 1, 186 p; Amman.

MoE & UNDP (2011): Vulnerability and Adaptation of the Water Sector. – Lebanon's Second National Communication (Chapter 4), 94 p.; Beirut.

MoE & UNDP (2011): State and Trends of the Environment 2010. – 353 p.; Beirut.

MOOK, W.G. (2000): Environmental isotopes in the hydrological cycle. – UNESCO IHP-V & IAEA, Technical Documents in Hydrology, 39, 6 volumes. [download from: http://www.hydrology.nl/ihppublications/149-environmental-isotopes-in-the-hydrological-cycle-principles-and-applications.html]

MORAN, M. (2005): Occurrence and Implications of Selected Chlorinated Solvents in Ground Water and Source Water in the United States and in Drinking Water in 12 Northeast and Mid-Atlantic States, 1993–2002. - USGS Scientific Investigations Report 2005–5268- National Water-Quality Assessment Program-National Synthesis on Volatile Organic Compounds; Denver.

MOULIN, A., BENEDETTI, L., VAN DER WOERD, J., ELIAS, A., BLARD, P.-H., FINKEL, R., BRAUCHER, R., LAVÉ, J., BOURLES, D., DAERON, M. & TAPPONNIER, P. (2011): LGM glaciers on Mount Lebanon? New insights from 36Cl exposure dating of moraine boulders. – Geophysical Research Abstracts Vol. 13, EGU2011-11465.

NADER, F. & SWENNEN, R. (2004): Petroleum Prospects of Lebanon: some remarks from sedimentological and diagenetic studies of Jurassic carbonates. – Mar.Petr.Geol., 21, pp. 421-441. (Elsevier)

NADER, F., SWENNEN, R. & ELLAM, R.M. (2006): Petrographic and geochemical study of Jurassic dolostones from Lebanon: Evidence for superimposed diagenetic events. – Journ.Geochem.Explor., 89, pp. 288-292. (Elsevier)

NMS (1977): Atlas Climatique du Liban. – 2nd edition, 4 volumes; Beirut.

ODEH, Y. (2011): Wind power potential in Palestine/Israel. - An investigation study for the potential of wind power in Palestine/Israel, with emphasis on the political obstacles. – MSc. study, Gotland University, 45 p.; Visby/SE.

QUENNEL, (1959): Tectonics of the Dead Sea Rift. – Congreso Geologico Internacional, 20th session, 1956, Asociacion de Servicios Geologicos Africanos, pp. 385-405; Mexico City.

RAAD, R., MARGANE, A. & SAADEH, E. (2012): Environmental Risk Assessment of the Fuel Stations in the Jeita Spring Catchment. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 14, 126 p.; Raifoun/Lebanon.

RAAD, R. & MARGANE, A. (2013): Hazards to Groundwater and Assessment of Pollution Risk in the Jeita Spring Catchment. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Special Report No. 16, 97 p.; Raifoun/Lebanon.

REILINGER, R., McCLUSKY, S., VERNANT, P., LAWRENCE, S., ERGINTAV, S., CAKMAK, R., OZENER, H., KADIROV, F., GULIEV, I., STEPANYAN, R., NADARIYA, M., HAHUBIA, G., MAHMOUD, S., SAKR, K., ArRAJEHI, A., PARADISSIS, D., AL-AYDRUS, A., PRILEPIN, M., GUSEVA, T., EVREN, E., DMITROTSA, A., FILIKOV, S.V., GOMEZ, F., AL-GHAZZI, R., KARAM, G. (2006): GPS constraints on continental deformation in the Africa–Arabia–Eurasia continental collision zone and implications for the dynamics of plate interactions. – J. Geophys. Res.- Solid Earth 111 (B5), pp. .

RENOUARD, C.. (1955): Oil prospects of Lebanon. – Bull Amer.Assoc.Petrol. Geol., 39, 2125-2169.

ROBERTSON, H.F. (1998): Mesozoic–Tertiary Tectonic Evolution Of The Easternmost Mediterranean Area: Integration Of Marine And Land Evidence. – In: Robertson, A.H.F., EMEIS, K.-C., RICHTER, C. & CAMERLENGHI, A. (Eds.): Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 160.

ROZANSKI, K., ARAGUAS-ARAGUAS, L. & GONFIANTINI, R. (1993): Isotopic patterns in modern global precipitation. Climate Change in Continental Isotopic Records. – Am. Geophys. Union, Geophys. Monogr. 78, pp. 1–36.

SAAD, Z., KAZPARD, V., EL SAMRANI, A.G., SLIM, K. (2005): Chemical and isotopic composition of rainwater in coastal and highland regions in Lebanon. – Journal of Environmental Hydrology, 13, 29, 11 p. [download from: www.hydroweb.com]

SAADEH, M. (1994): Jeita and Kashkoush Springs: Hydrogeological correlation and pollution of the ground water. – PhD thesis, American University of Beirut, 105 p.; Beirut.

SADOONI, F.N. & ALSHARHAN, A.S. (2004): Stratigraphy, lithofacies distribution, and petroleum potential of the Triassic strata of the northern Arabian plate. – AAPG Bulletin, 88, 4, pp. 515–538.

SALIBA, J. (1977): Projet d'adduction gravitaire des eaux du courant souterrain de Jeita – adducteur principal Jeita 140. – Report prepared for OEB, 28 p.; Beirut.

SARIKAYA, M.A., CINER, A. & ZREDA, M. (2011): Quaternary Glaciations of Turkey. – In: EHLERS, J., GIBBARD, P.L. & HUGES, P.D. (Eds.): Quaternary Glaciations – Extent and Chronology. – Developments in Quaternary Science, 15, pp 393-403; London (Elsevier).

SCHULER, P. (2011): Hydrological Balance of the Jeita Spring. - MSc thesis, Univ. Cologne & Univ. Jordan, 117 p.; Ballouneh/Lebanon.

SCHULER, P. & MARGANE, A. (2013): A Water Balance Model of the Jeita Groundwater Catchment using WEAP. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Technical Report No. 6, xx p.; Raifoun/Lebanon.

SEBER, D., VALLVE, M., SANDVOL, E. , STEER, D. & BARAZANGI, M.. (1997): Middle East Tectonics: Applications of Geographic Information Systems (GIS). – Geol.Soc.America Today, 7, 2; Boulder/CA/USA [download from http://atlas.geo.cornell.edu/htmls/ gsa_today.html]

STEINEL, A. & MARGANE, A. (2011): Best Management Practice Guideline for Wastewater Facilities in Karstic Areas of Lebanon – with special emphasis on the protection of ground- and surface waters. – German-Lebanese Technical Cooperation Project Protection of Jeita Spring, Technical Report No. 2, 147 p.; Ballouneh.

TAYMAZ, T., YILMAZ, Y. & DILEK, Y. (2013): The geodynamics of the Aegean and Anatolia: introduction. – Geol.Soc.London, Spec.Pub., 291, pp. 1-16; London.

TRIPATI, A. & ELDERFIELD, H. (2005): Deep-Sea Temperature and Circulation Changes at the Paleocene-Eocene Thermal Maximum. - Science, 308, pp 1894-1998; New York.

UNDP (1970): Liban - Etude des Eaux Souterraines. – 185 p.; New York.

UNDP (1972): Jeita – the famous karst spring of Lebanon – a hydrologic - hydrogeological study. – Report prepared for MHER, 413 p.; Beirut

UNDP & FAO (1973): Pluviometric map of Lebanon (1939-1970). – Map prepared for LRA, 1 map; Beirut.

UNICEF (2010): Water, Sanitation and Hygiene sector review. – 9 p.; Geneva/CH.

USGS (2010): Assessment of undiscovered oil and gas resources of the Levant Basin Province, Eastern Mediterranean. – Fact Sheet 2010-3014, 4 p; Denver/CO/USA.

VERHEYDEN, S., NADER, F., CHENG, H.J., EDWARDS, L.R. & SWENNEN, R. (2008): Paleoclimate reconstruction in the Levant region from the geochemistry of a Holocene stalagmite from the Jeita cave, Lebanon. - Quaternary Research, 70, pp. 368-381; Maryland Heights/USA.

WALLEY, C.D. (1998): The Geology of Lebanon. [download from: http://ddc.aub.edu.lb/projects/geology/geology-of-lebanon/]

WALLEY, C.D. (1997): The Lithostratigraphy of Lebanon – a review. – Lebanese Science Bulletin, 10:1, 20 p. [download from: http://svt-liban.com/IMG/pdf/lithostrat_of_Lebanon_cle4975d6.pdf].

WALLEY, C.D. (1998): Some outstanding issues in the geology of Lebanon and their importance in the tectonic evolution of the Levantine Region. – Tectonophysics, 298 (1-3), pp. 37-62; (Elsevier).

WALLEY, C.D. (2001): The Lebanon passive margin and the evolution of the Levantine Neo-Tethys. – In: ZIEGLER, P.A., CAVAZZA, W., ROBERTSON, A.H.F. & CRASQUIN-SOLEAU, S. (Eds.): Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins, Mem.Mus.Hist.Nat, 186, pp. 407-439; Paris.

WHO (2011): Guidelines for Drinking-water Quality, 4th Edition. - 541 p; Geneva.

WOODWARD, J.C. & HUGES, P.D. (2011): Glaciation in Greece: A New Record of Cold Stage Environments in the Mediterranean. – In: EHLERS, J., GIBBARD, P.L. & HUGES, P.D. (Eds.): Quaternary Glaciations – Extent and Chronology. – Developments in Quaternary Science, 15, pp. 175-198; London (Elsevier).

WOLFART, R. (1966): Zur Geologie und Hydrogeologie von Syrien unter besonderer Berücksichtigung der süd- und nordwestlichen Landesteile.

– Beih. Geol. Jahrbuch, 68, 129 p.; Hannover/Germany. (Schweizerbart)

WOLFART, R. (1967): Syrien und Libanon. – Beiträge zur Regionalen Geologie der Erde, 6, 326 p.; Berlin/Germany (Borntraeger).

WORLD BANK (2004): Cost of Environmental Degradation: The Case of Lebanon and Tunisia. – Environmental Economics Series, paper no. 97, ; 105 p; Washington.

ZIV, B., DAYAN, U., KUSHNIR, Y., ROTH, C. & ENZEL, Y. (2006): Regional and global atmospheric patterns governing rainfall in the southern Levant. – Int.Journ.Climatol., 26, pp. 55-73; London (Wiley).

ZREDA, M., ZWECK, C., SARIKAYA, M. A. (2006): Early Holocene glaciation in Turkey: large magnitude, fast deglaciation and possible NAO connection. - American Geophysical Union, Fall Meeting 2006; .

ANNEX 1: Geological Map of the Jeita Groundwater Catchment

on enclosed DVD

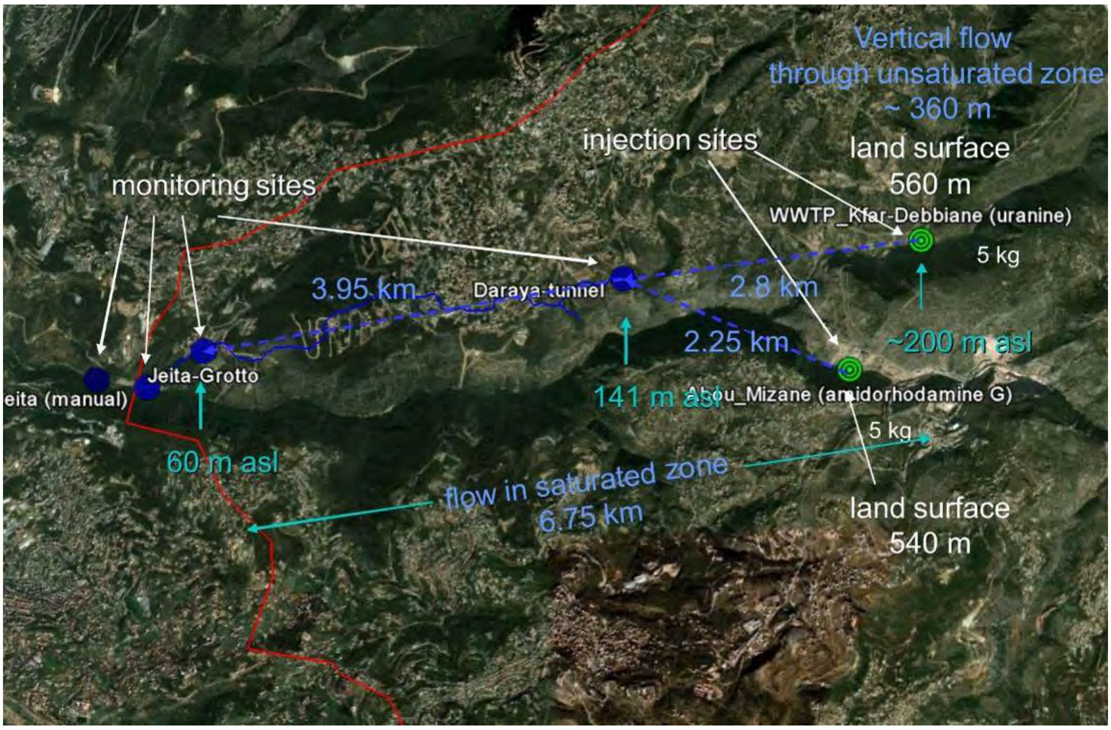
ANNEX 2: Tracer Tests for the Delineation of the Groundwater Catchment of Jeita Spring

Tracer Test 1A-1 – 'gold digger's' pit at the proposed WWTP Kfar Debbiane

Injection date and time: 19.04.2010, 12:11

Injected tracer(s) and amount(s): uranine MKT, 5000 g

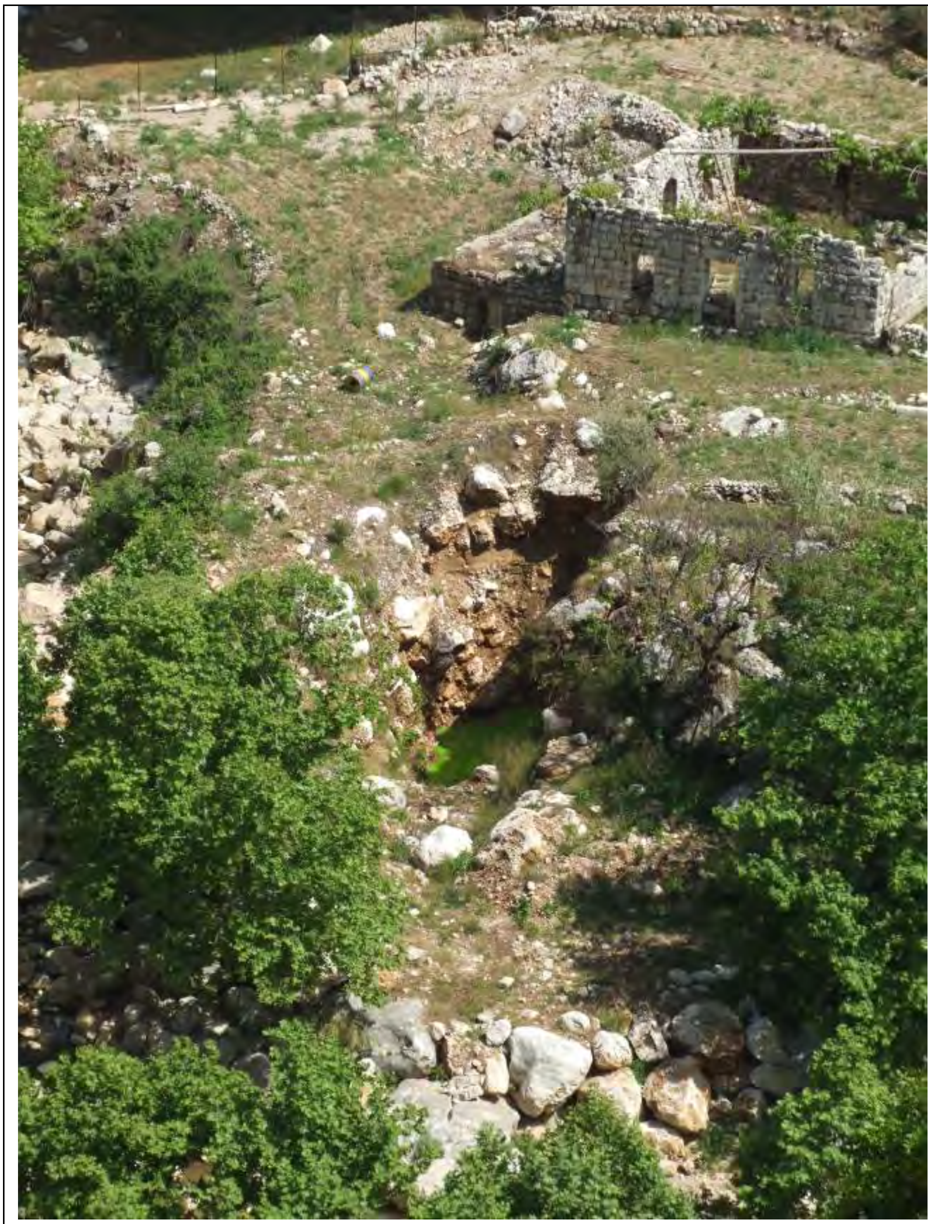
Location map: injection and monitoring sites

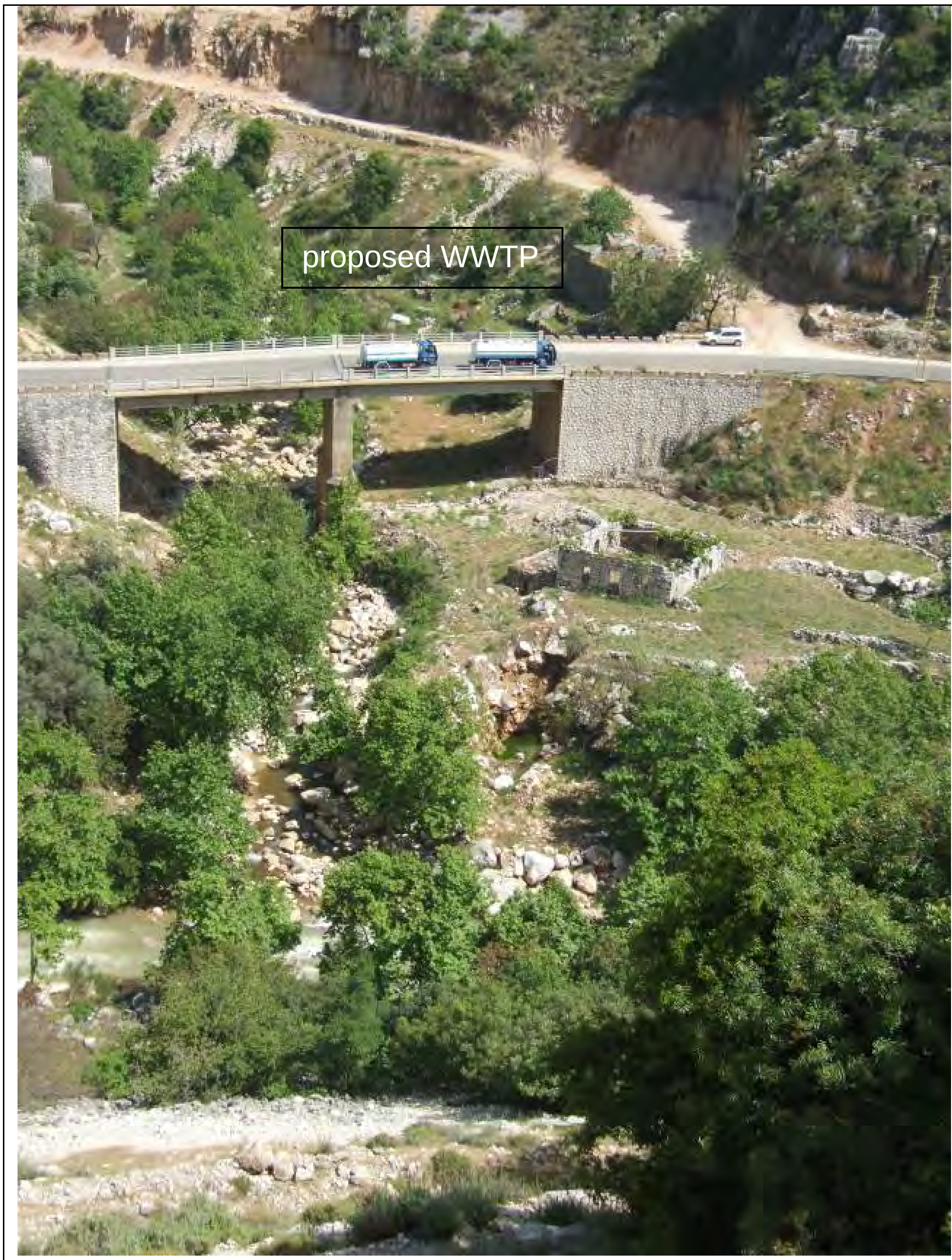


Results: Tracer arrival in Daraya tunnel (siphon terminal) and Jeita

Reference: Special Report No. 1, DOUMMAR et al. (2010a)

Remarks: The injection site represents the proposed effluent discharge site of the proposed WWTP Kfar Debbiane. Based on this test the planning for the proposed site was abandoned and a centralized wastewater treatment concept was adopted as documented in MARGANE, 2011).


injection pit

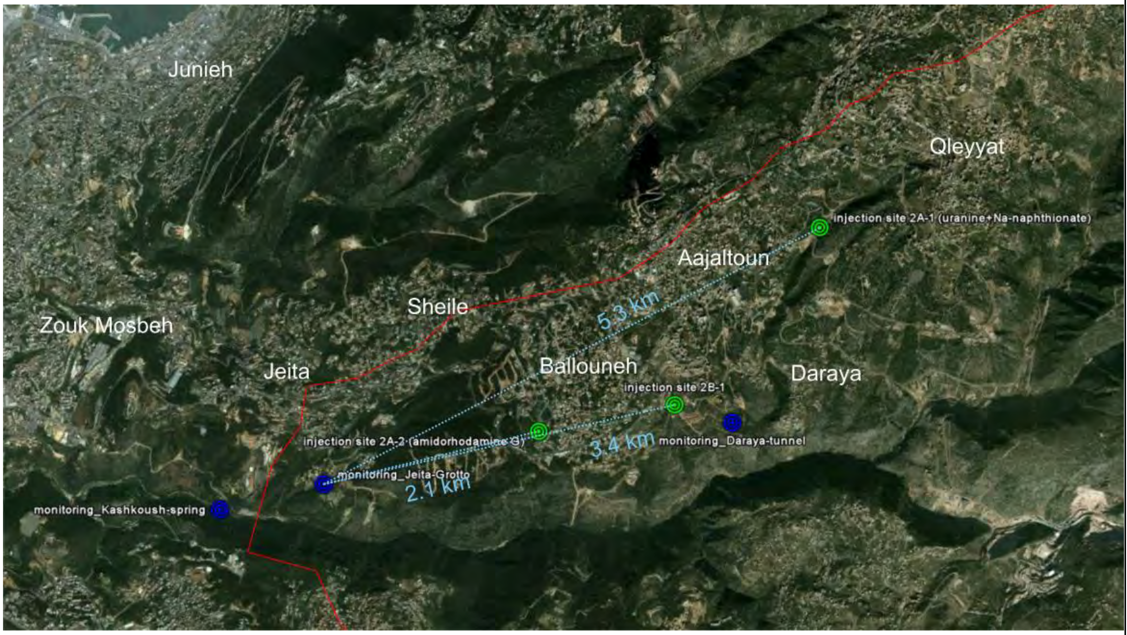


flushing from bridge

Tracer Test 1A-2 – excavated pit near Nahr es Hardoun, Abou Mizaine
Injection date and time: 22.04.2010, 15:59
Injected tracer(s) and amount(s): Amidorhodamine G, 5000 g
Location map: injection and monitoring sites: (see 1A-1)  Excavated pit is located approx. 5 m from river course
Results: no retrieval of tracer substance in any monitoring station (Daraya tunnel, Jeita grotto, Kashkoush, Nahr el Kalb at Jeita grotto) Geological structure (cross section) suggests flow towards Nahr Beirut.
Reference: Special Report No. 1, DOUMMAR et al. (2010a)
Remarks:

Tracer Test 1B-1 – underground river of Jeita (siphon terminale to Jeita boat mooring)
Injection date and time: 28.04.2010, 11:42
Injected tracer(s) and amount(s): uranine MKT, 500 g
Location map: injection and monitoring sites: see 1A-1 
Results:
Reference: Special Report No. 1, DOUMMAR et al. (2010a)
Remarks: Test repeated several times (MARGANE, 2011)

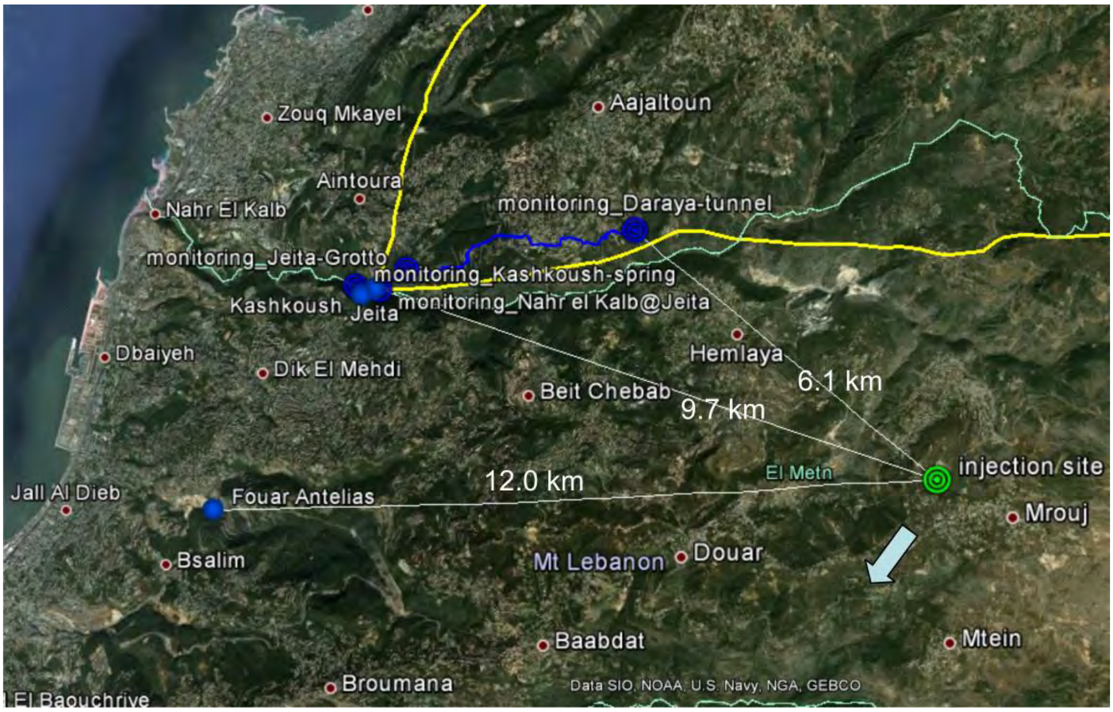
Tracer Test 2A-1 – Fault near George Matta factory, Aajaltoun
Injection date and time: 02.08.2010, 12:50
Injected tracer(s) and amount(s): uranine ORCO, 9233.3 g & Na-Naphthionate, 9084.1 g
Location map: injection and monitoring sites



Results: no retrieval of tracer substance in any monitoring station (Daraya tunnel, Jeita grotto, Kashkoush)
Reference: -
Remarks:

Tracer Test 2A-2 – cesspit of Joseph Nassar building (under construction)
Injection date and time: 02.08.2010, 14:40
Injected tracer(s) and amount(s): Amidorhodamine G, 5749.1 g
Location map: injection and monitoring sites: (see 2A-1) 
Results: no retrieval of tracer substance in any monitoring station (Daraya tunnel, Jeita grotto, Kashkoush)
Reference: -
Remarks:

Tracer Test 2B-1 – Astar sinkhole near Aajaltoun Valley housing project
Injection date and time: 20.08.2010, 11:40
Injected tracer(s) and amount(s): Amidorhodamine G, 5000 g & Na-Naphthionate, 5000 g
Location map: injection and monitoring sites: (see 2A-1) 
Results: arrival in Jeita in 2 peaks (due to flushing pattern)
Reference: Special Report No. 2, DOUMMAR et al. (2010b)
Remarks:

Tracer Test 3A-1 – Chenchara sinkhole
Injection date and time: 13.11.2010, 10:57
Injected tracer(s) and amount(s): uranine ORCO, 10001.1 g & Na-Naphthionate, 15010.8 g
Location map: injection and monitoring sites 
Results: No tracer recovery in Jeita, Kashkoush, Faouar Antelias. Geological structure (cross section) suggests flow towards Nahr Beirut.
Reference: -
Remarks:

Sinkhole next to gas filling station

Tracer injection and flushing through barrel

Tracer Test 4A-1 – sinkhole on central Wardeh plateau near La Cabane
Injection date and time: 16.03.2011, 11:30
Injected tracer(s) and amount(s): uranine ORCO, 5002.2 g
Location map: injection and monitoring sites 
Results: No arrival at any monitoring station (Assal, Labbane, Jeita, Daraya (siphon terminale), Nahr el Kalb at Jeita Grotto) No fluorometer in Afqa installed !
Reference: Special Report No. 5, DOUMMAR et al. (2011a)
Remarks:

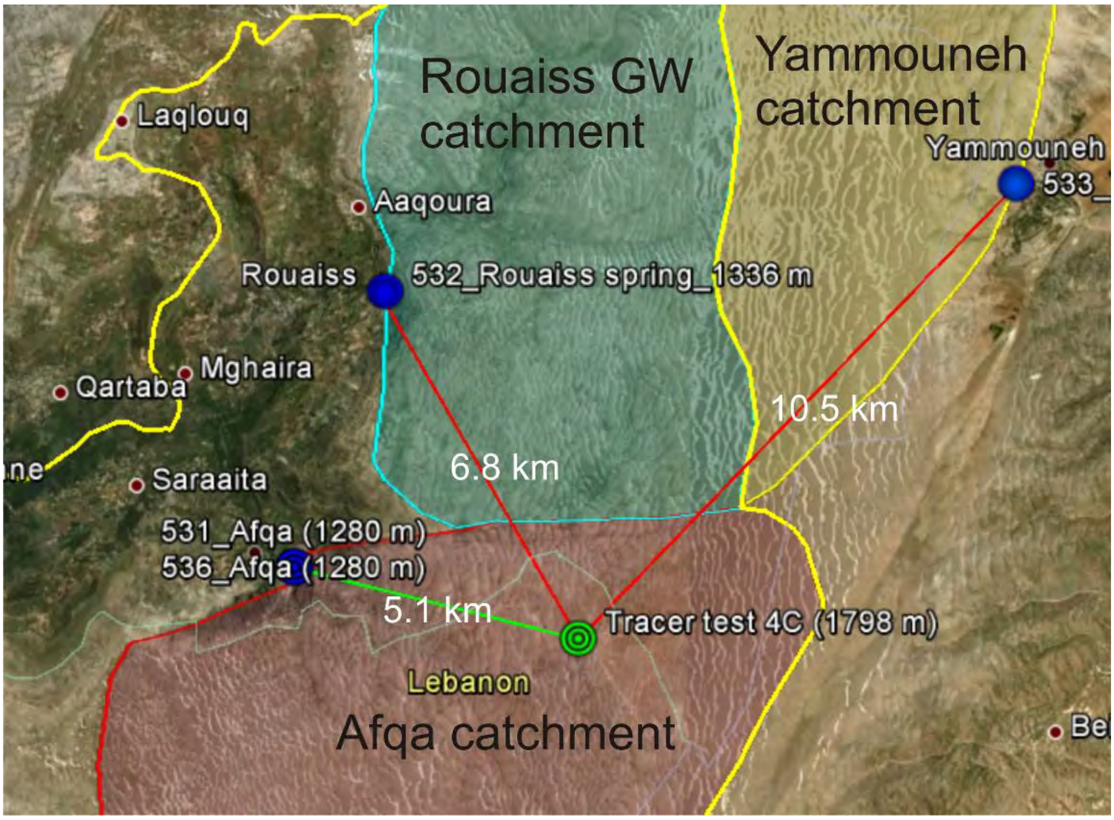
Tracer Test 4B-1 – doline on eastern Wardeh plateau at road to Baalbek
Injection date and time: 18.05.2011, 10:35
Injected tracer(s) and amount(s): eosin ORCO, 10000 g
Location map: injection and monitoring sites

Results: arrival in Afqa only
Reference: Special Report No. 5, DOUMMAR et al. (2011a)
Remarks:

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Tracer Test 4B-2 – sinkhole on central Wardeh plateau near La Cabane
Injection date and time: 18.05.2011, 13:35
Injected tracer(s) and amount(s): uranine ORCO, 5000 g & Na-Naphthionate, 10000 g
Location map: injection and monitoring sites: see 4B-1
Results: arrival in Afqa only
Reference: Special Report No. 5, DOUMMAR et al. (2011a)
Remarks:

Tracer Test 4C-1
Injection date and time: 04.05.2012, 12:00
Injected tracer(s) and amount(s): uranine ORCO, 9000 g
Location map: injection and monitoring sites



Results: arrival in Afqa only
Reference: Special Report No. 17, DOUMMAR et al. (2013)
Remarks:

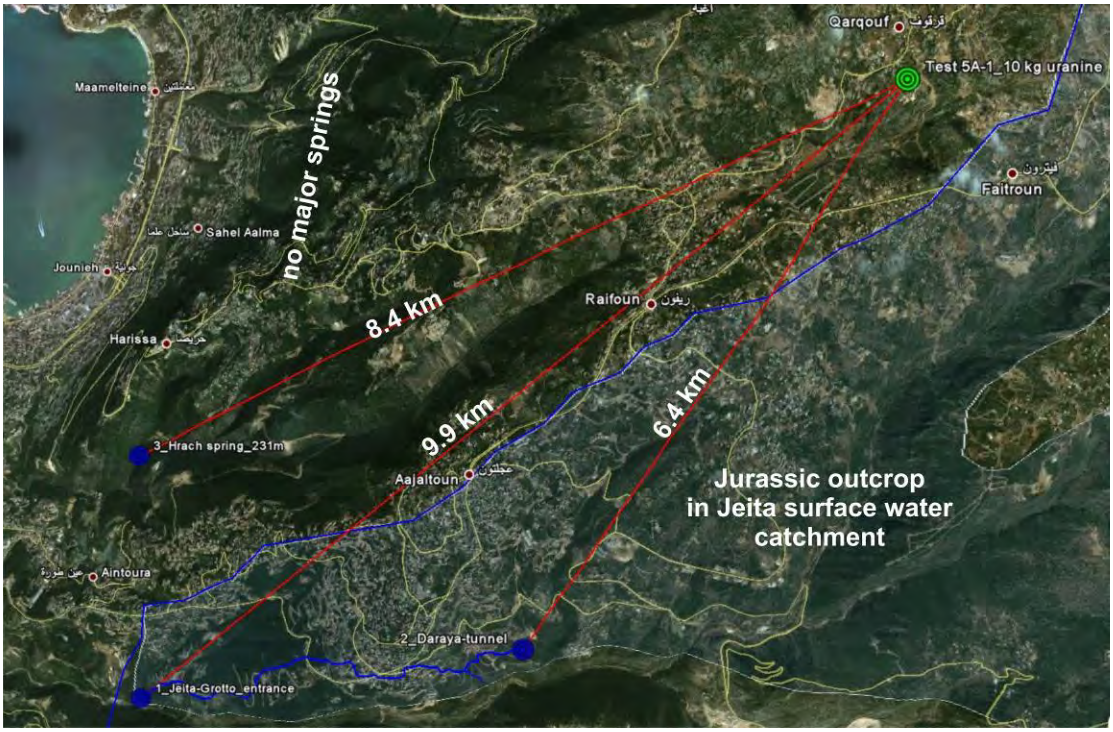

SUZUKI

Tracer Test 5A-1 – sinkhole in Boqaata Ashkout (Rizk family)

Injection date and time: 23.06.2011, 13:00

Injected tracer(s) and amount(s): uranine ORCO, 9373 g

Location map: injection and monitoring sites

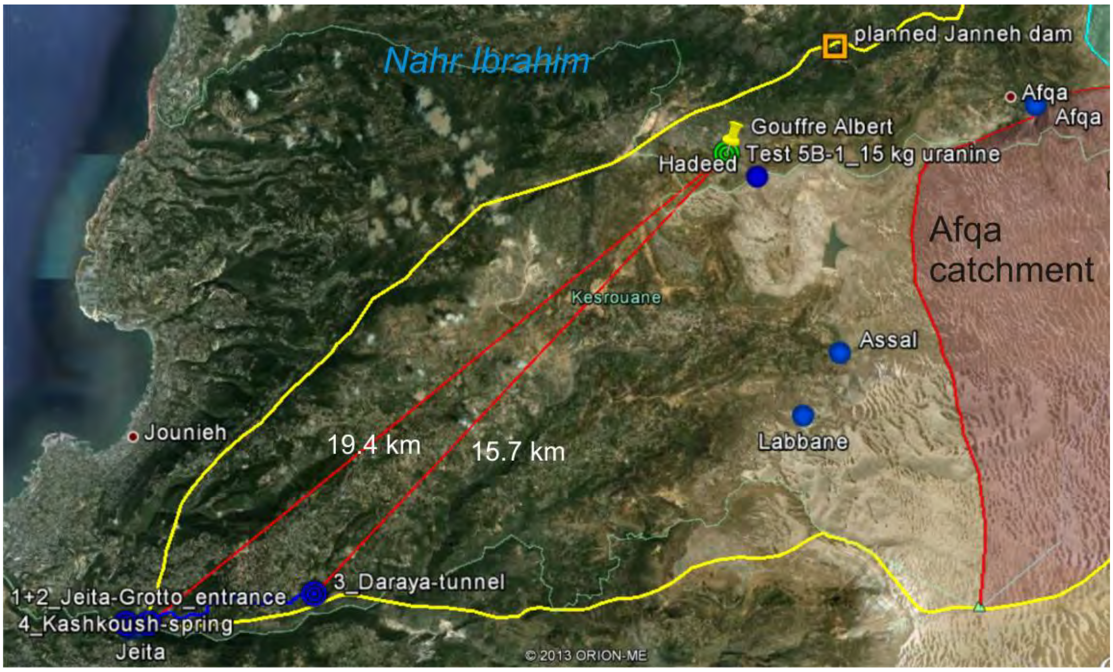


Results: arrival in Jeita only

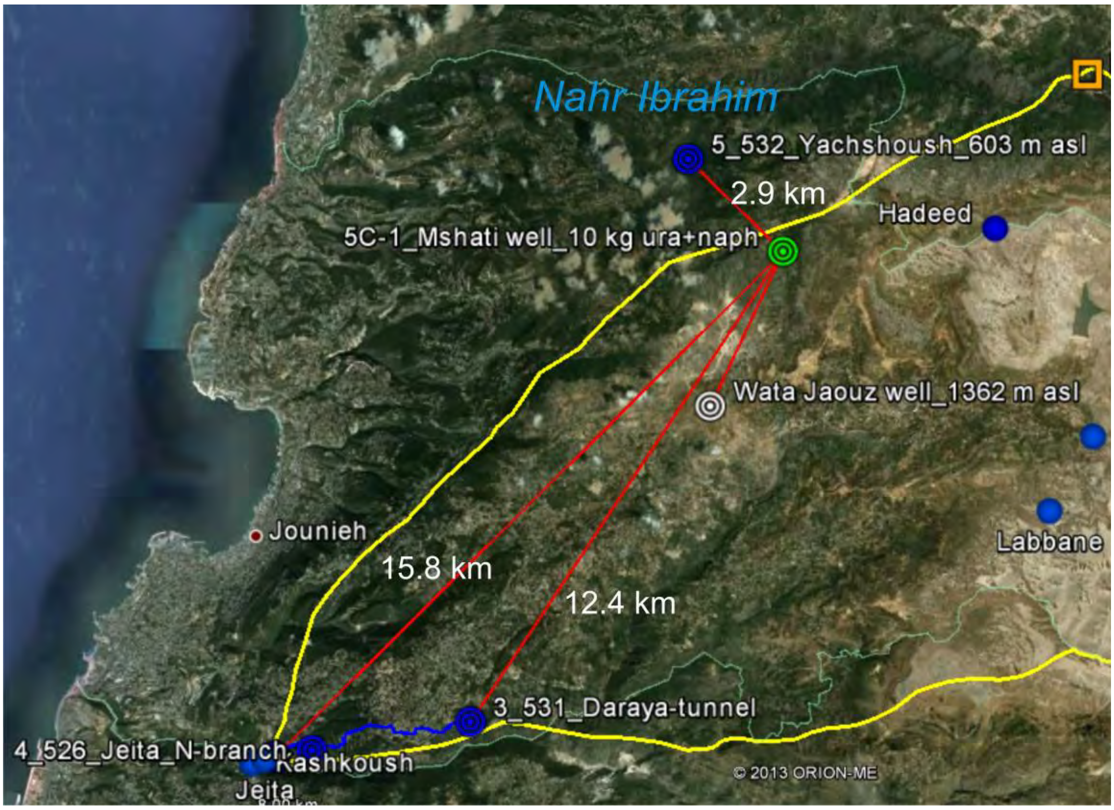
Reference: Special Report No. 6, DOUMMAR et al. (2011b)

Remarks:


SAYAH

Tracer Test 5B-1 – Gouffre Albert near Laissa road (Albert Massaad)
Injection date and time: 11.08.2011, 09:04
Injected tracer(s) and amount(s): uranine ORCO, 14140 g
Location map: injection and monitoring sites 
Results: no tracer retrieval in any monitoring station (Daraya tunnel, Jeita, Kashkoush)
Reference: -
Remarks:

Tracer Test 5C-1 – Msheti well no. 1
Injection date and time: 16.09.2011, 09:52
Injected tracer(s) and amount(s): uranine ORCO, 10000 g, Na-naphthionate, 10000 g
Location map: injection and monitoring sites



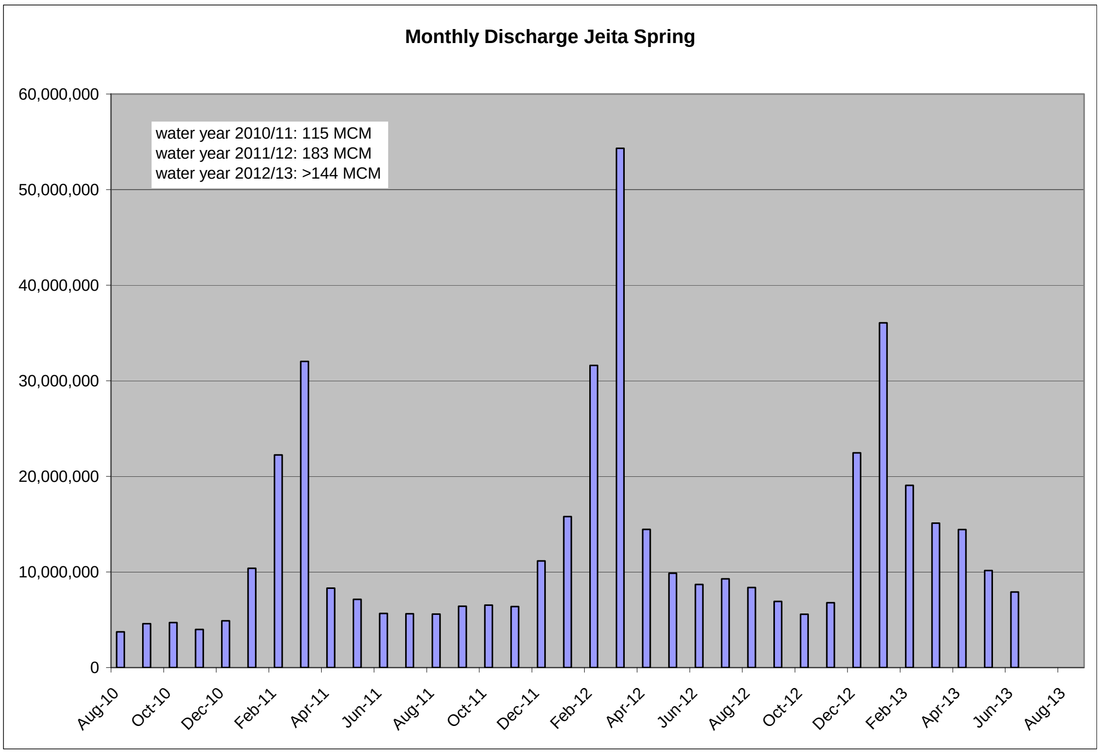
Results: arrival in Daraya tunnel and Jeita only
Reference: Special Report No. 11, DOUMMAR et al. (2012a)
Remarks:

ANNEX 3: Spring Discharge Monitoring

(for further details refer to MARGANE & STOECKL, 2013, where methods and data collected until 01.06.2013 were documented)

Annex 3.1: Jeita Spring

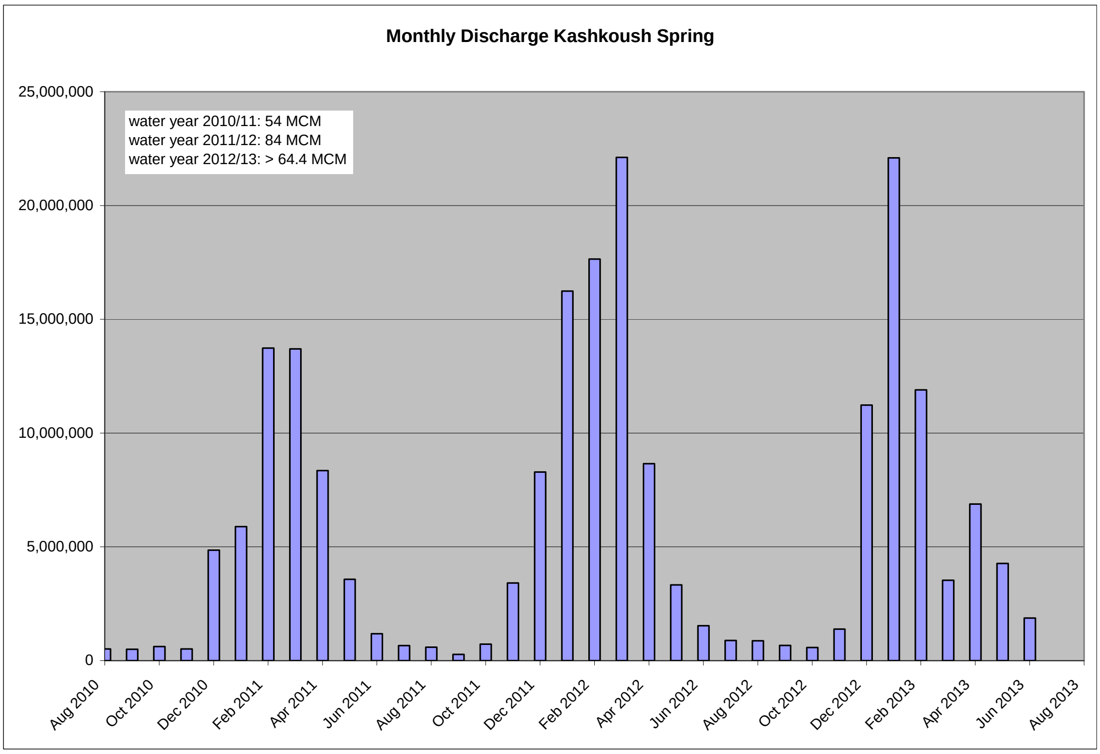
Annex 3.1.1: Spring Discharge of Jeita Spring measured using Multiparameter Probe and Stage-Flow Rating-Curve



Annex 3.1.2: Groundwater discharge at Jeita spring (status 03.07.2013)

Annex 3.2: Kashkoush Spring

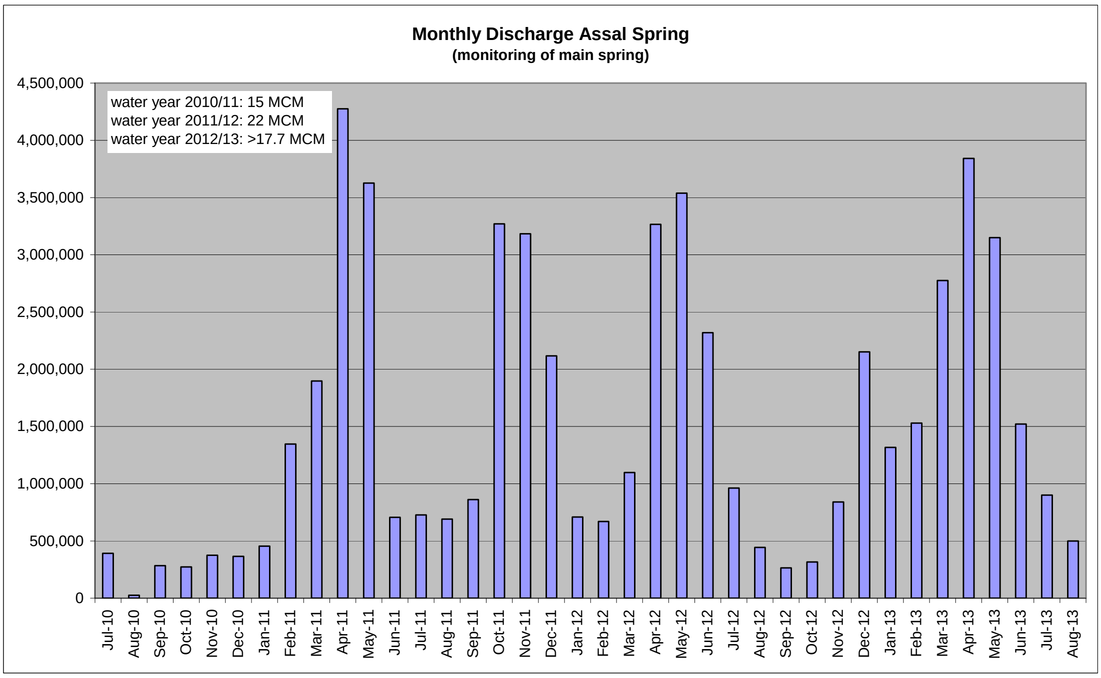
Annex 3.2.1: Spring Discharge of Kashkoush Spring measured using Multiparameter Probe and Stage-Flow Rating-Curve



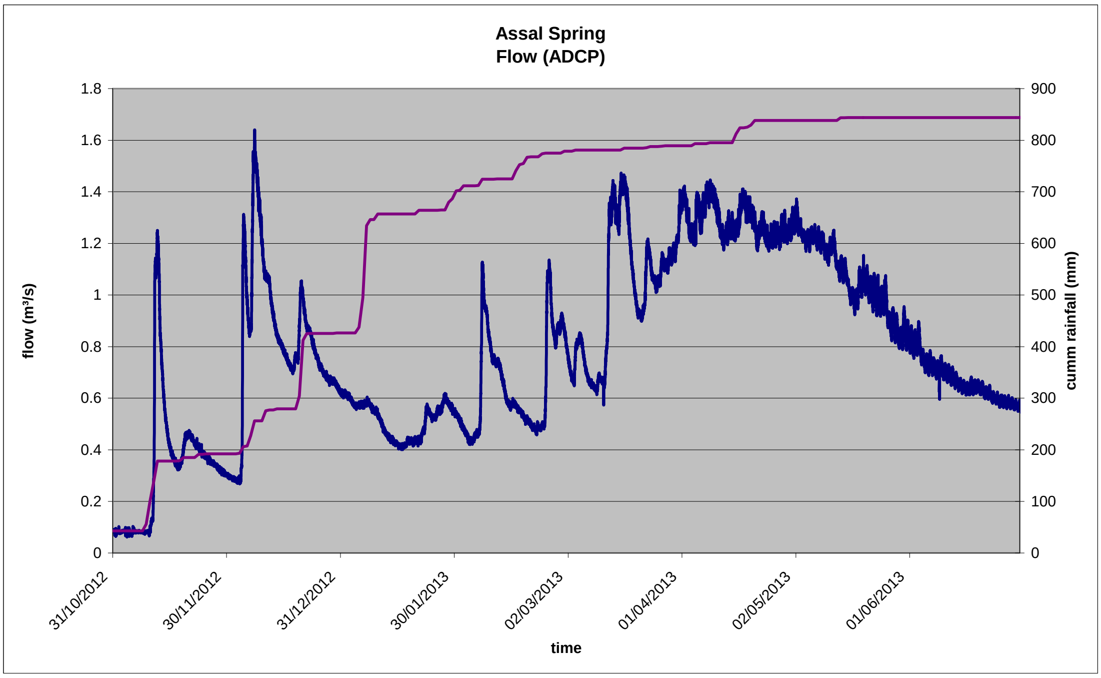
Annex 3.2.2: Groundwater Discharge at Kashkoush Spring (status 03.07.2013)

Annex 3.3: Assal Spring

Annex 3.3.1: Spring Discharge of Assal Spring measured using Multiparameter Probe and Stage-Flow Rating-Curve



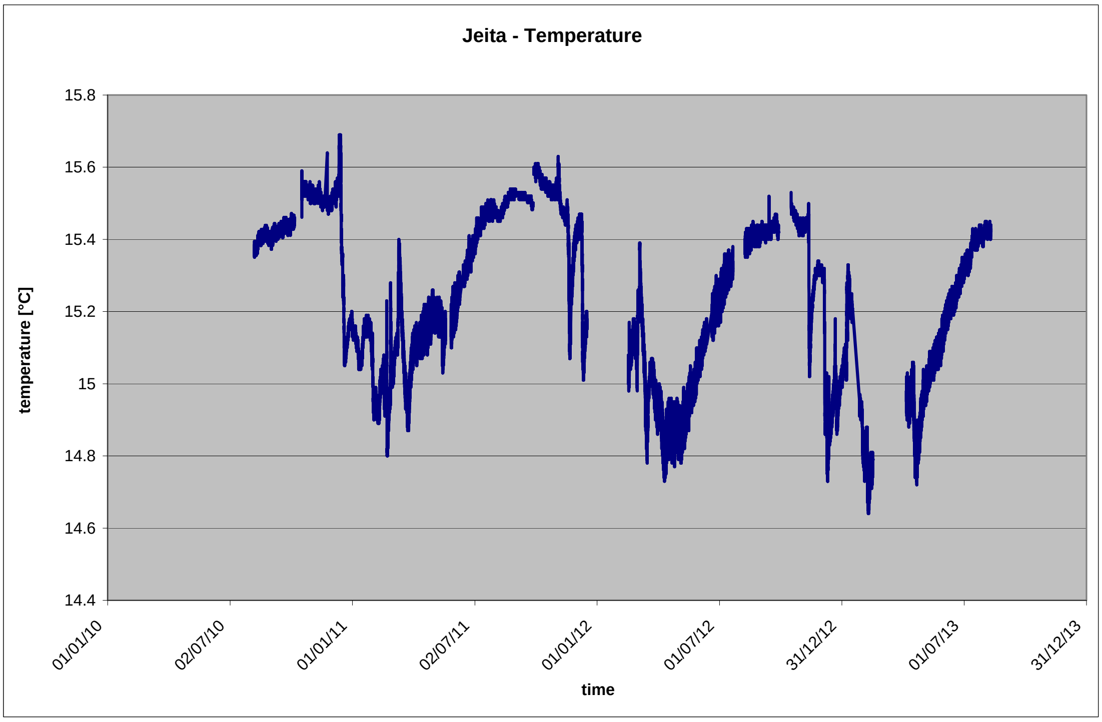
Annex 3.3.2: Groundwater discharge at Assal spring using multiparameter probe (status 03.07.2013)



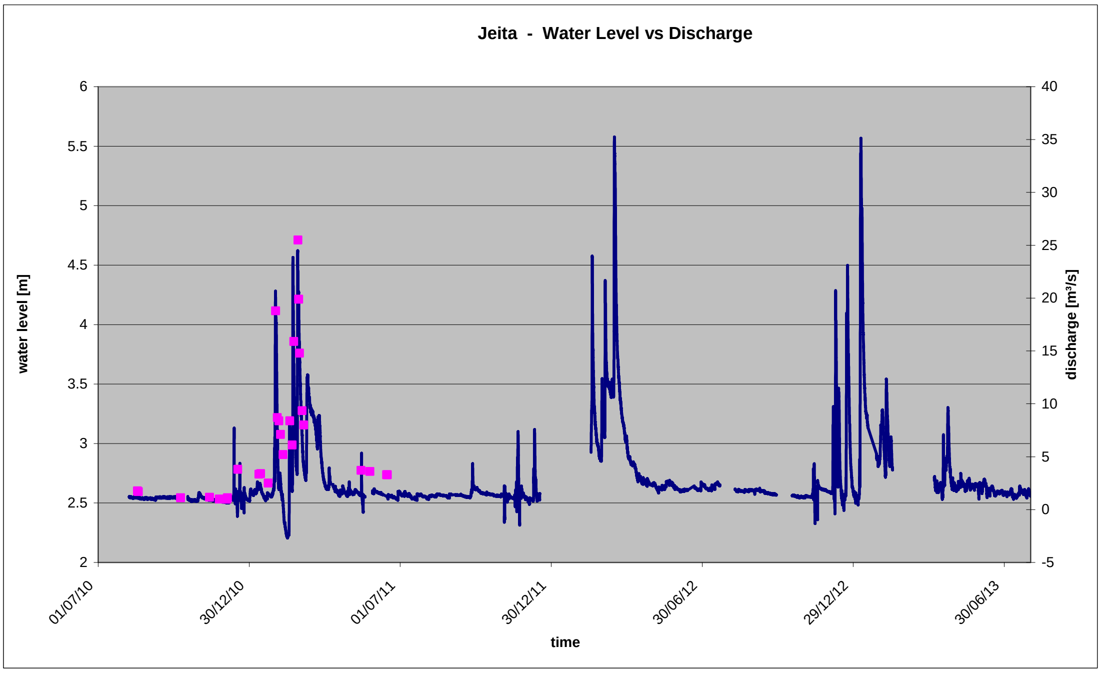
Annex 3.3.3: Spring Discharge of Assal Spring using ADCP direct Flow Measurements (status 03.07.2013)

ANNEX 4: Physico-Chemical Monitoring of Springs

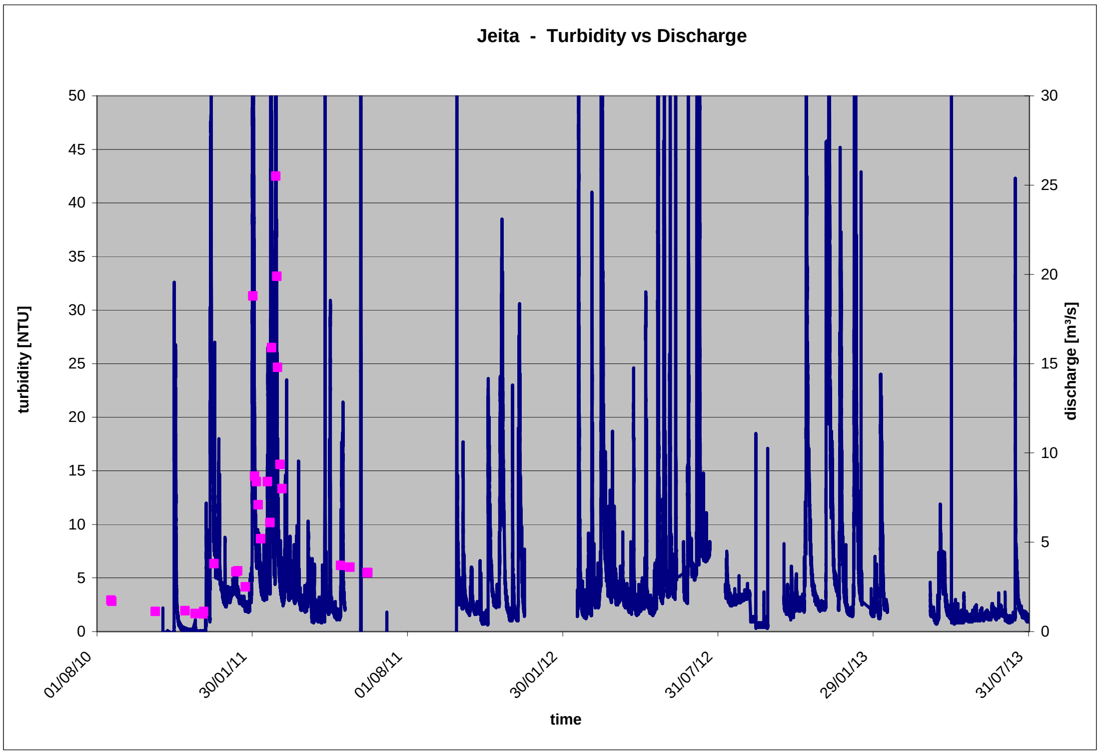
A4.1 Jeita Spring



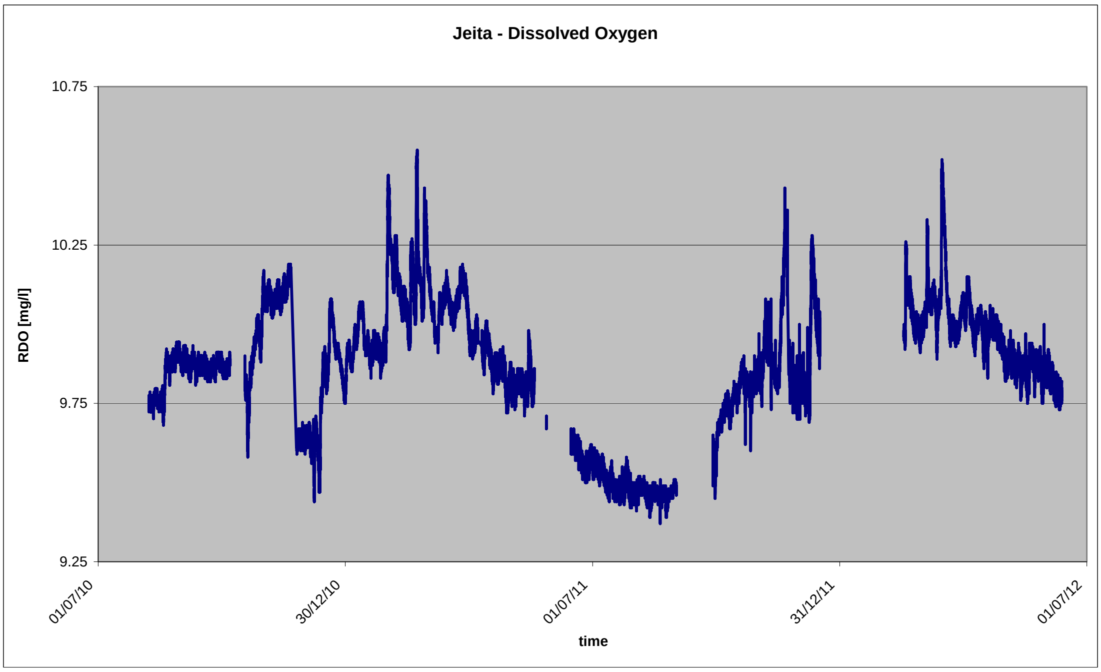
Annex 4.1.1: Monitoring of Temperature in Jeita Spring



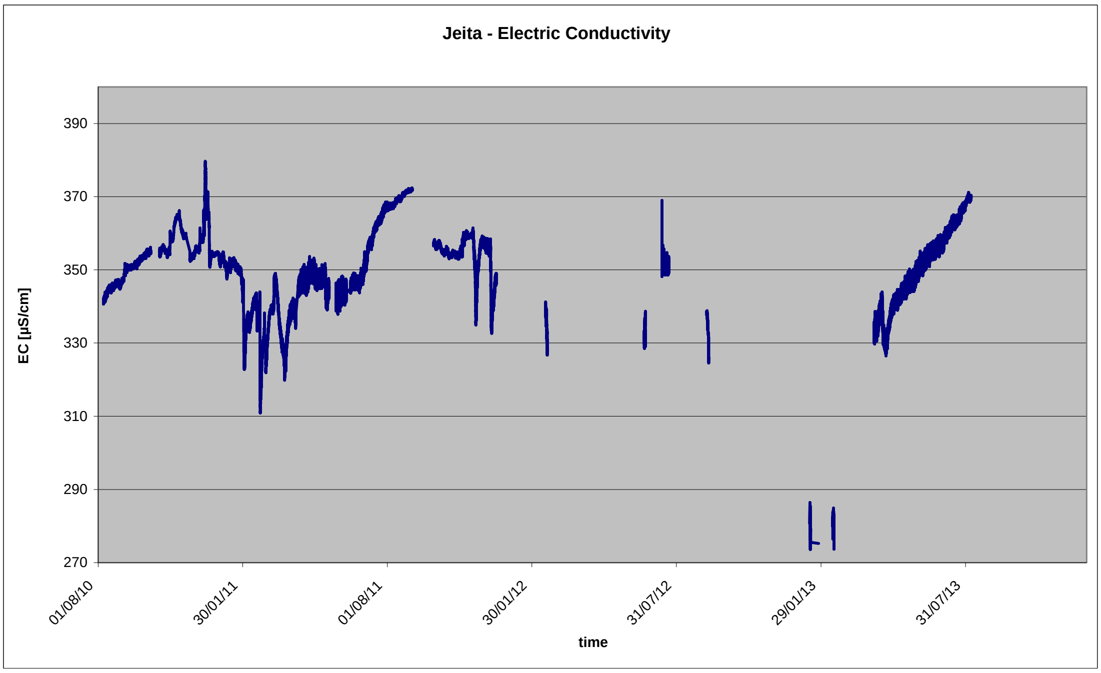
Annex 4.1.2: Monitoring of Water Level in Jeita Spring



Annex 4.1.3: Monitoring of Turbidity in Jeita Spring

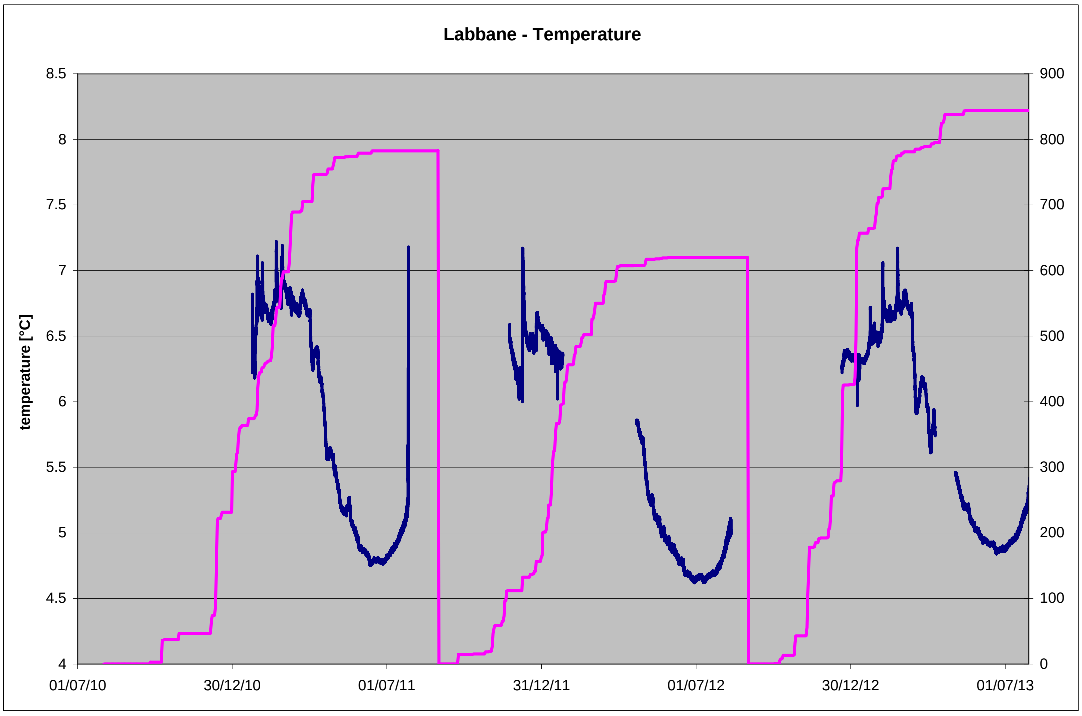


Annex 4.1.4: Monitoring of Dissolved Oxygen Content in Jeita Spring

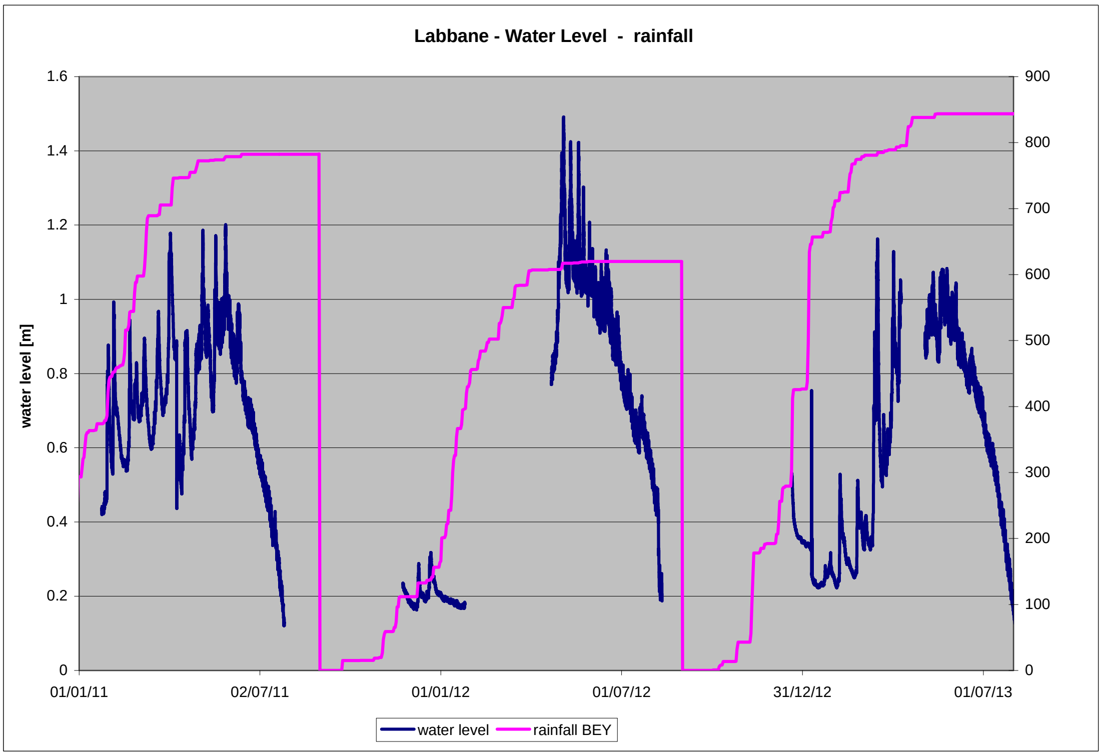


Annex 4.1.5: Monitoring of Electric Conductivity in Jeita Spring

A4.2 Labbane Spring

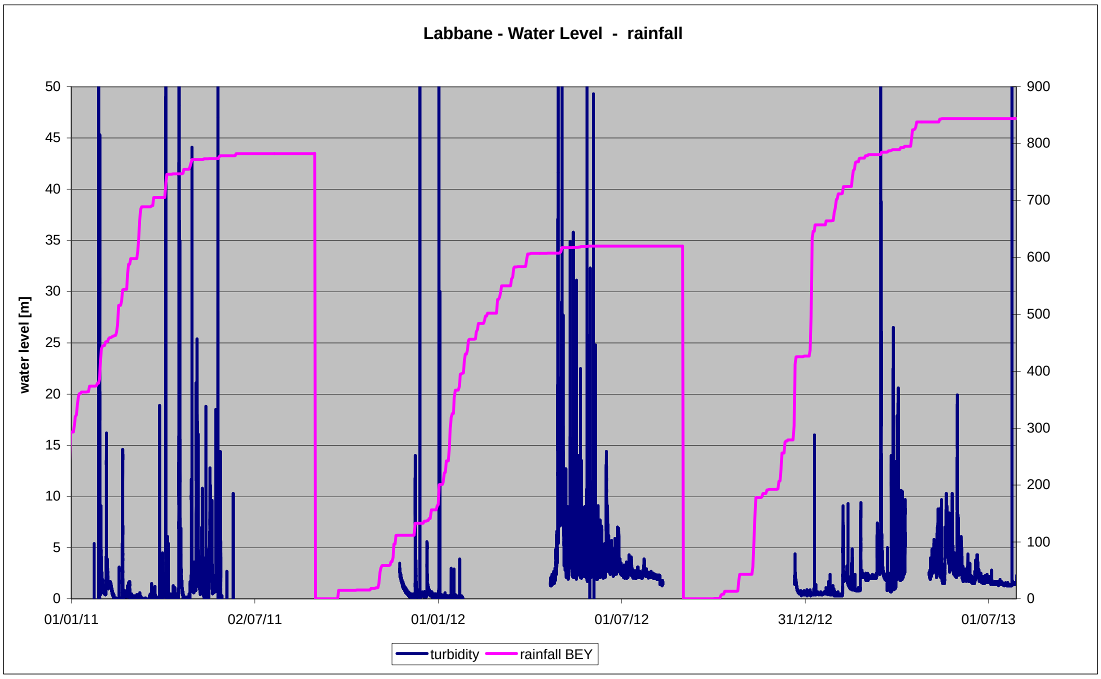


Annex 4.2.1: Monitoring of Temperature in Labbane Spring

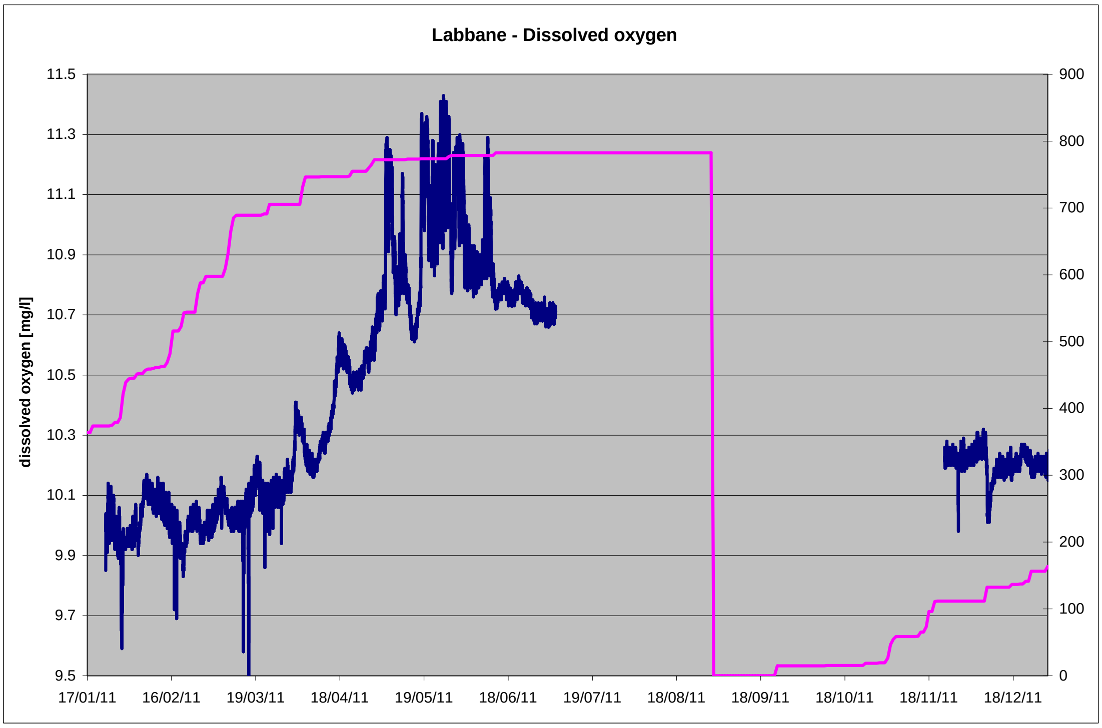


Annex 4.2.2: Monitoring of Water Level in Labbane Spring

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

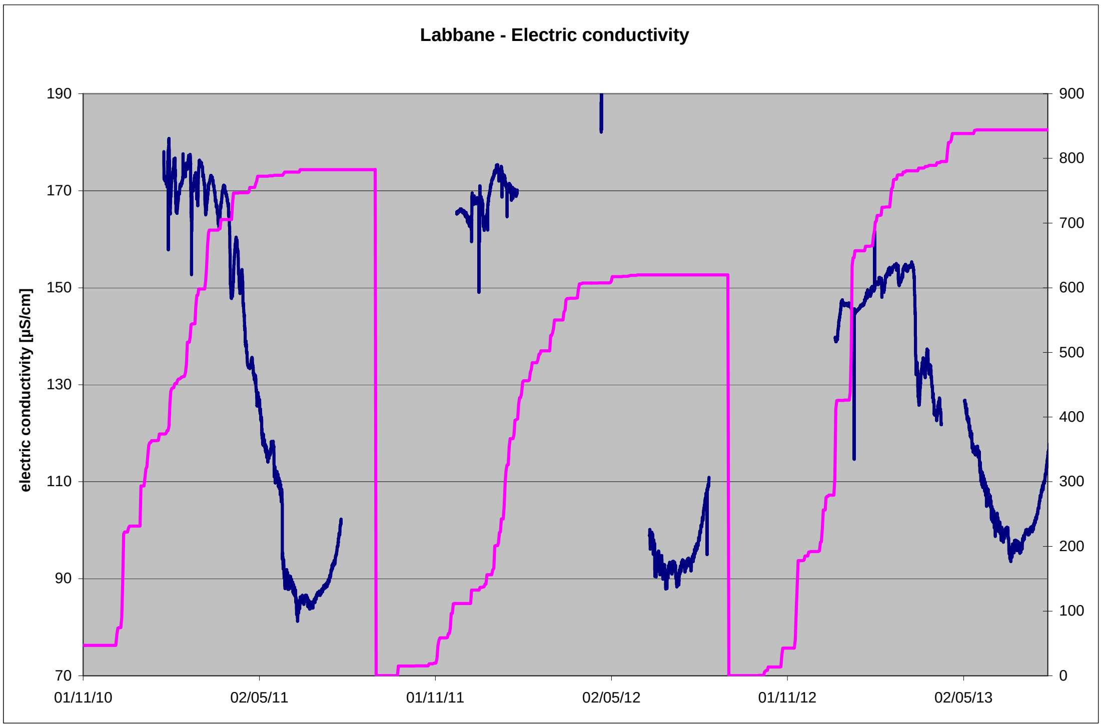


Annex 4.2.3: Monitoring of Turbidity in Labbane Spring



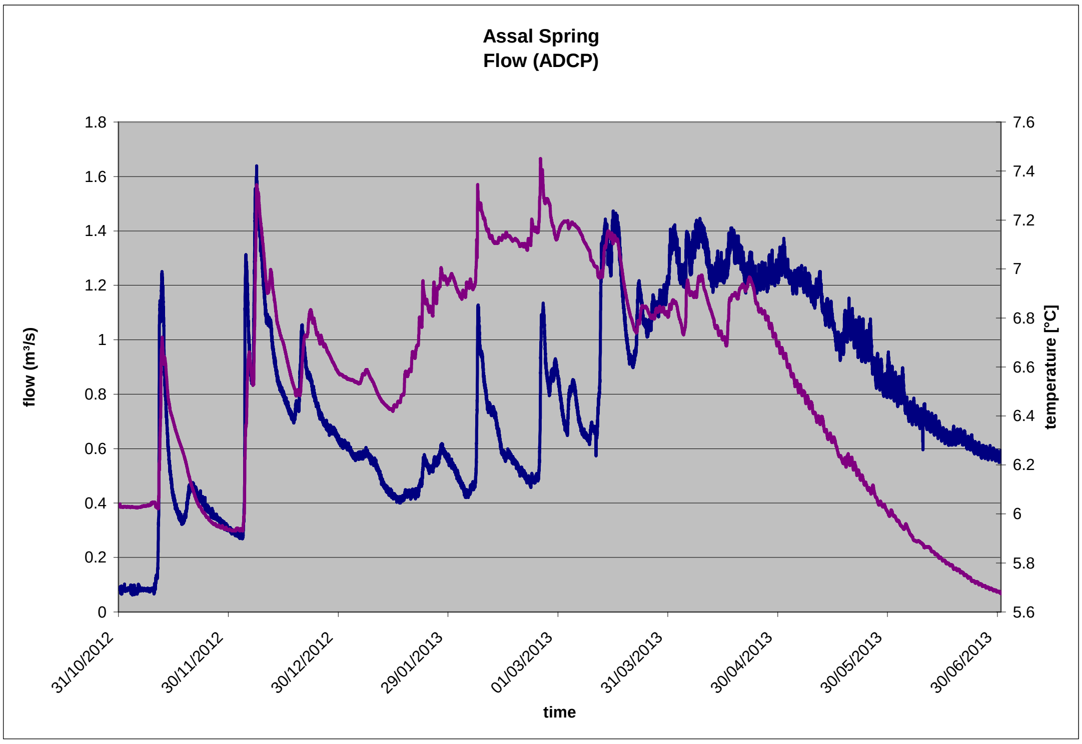
Annex 4.2.4: Monitoring of Dissolved Oxygen Content in Labbane Spring

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

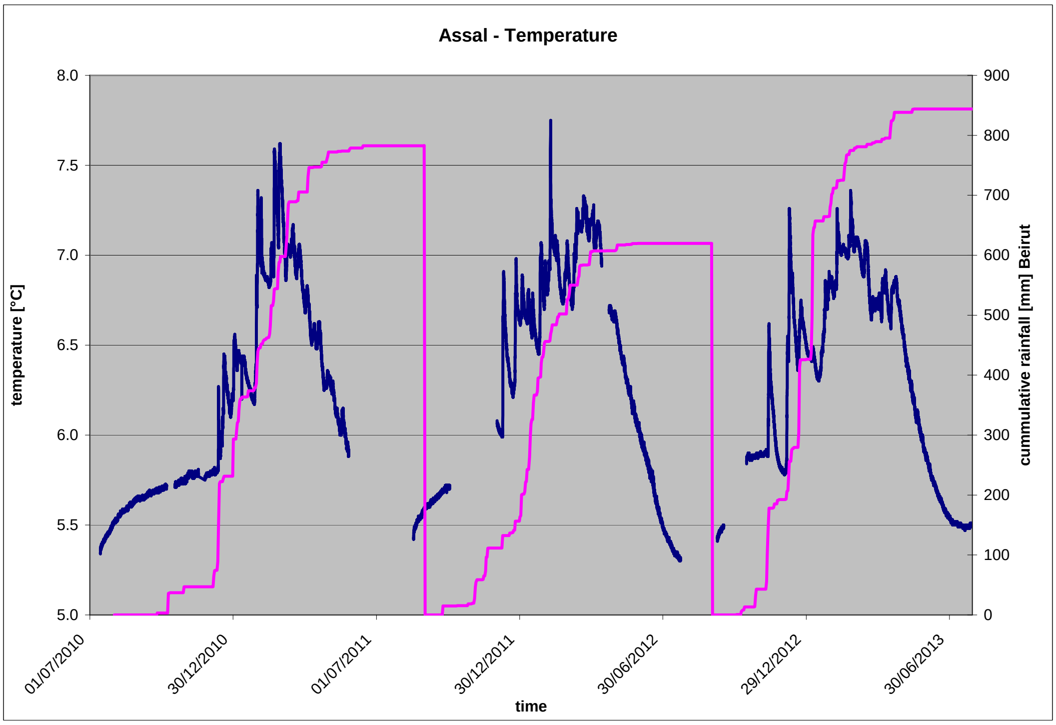


Annex 4.2.5: Monitoring of Electric Conductivity in Labbane Spring

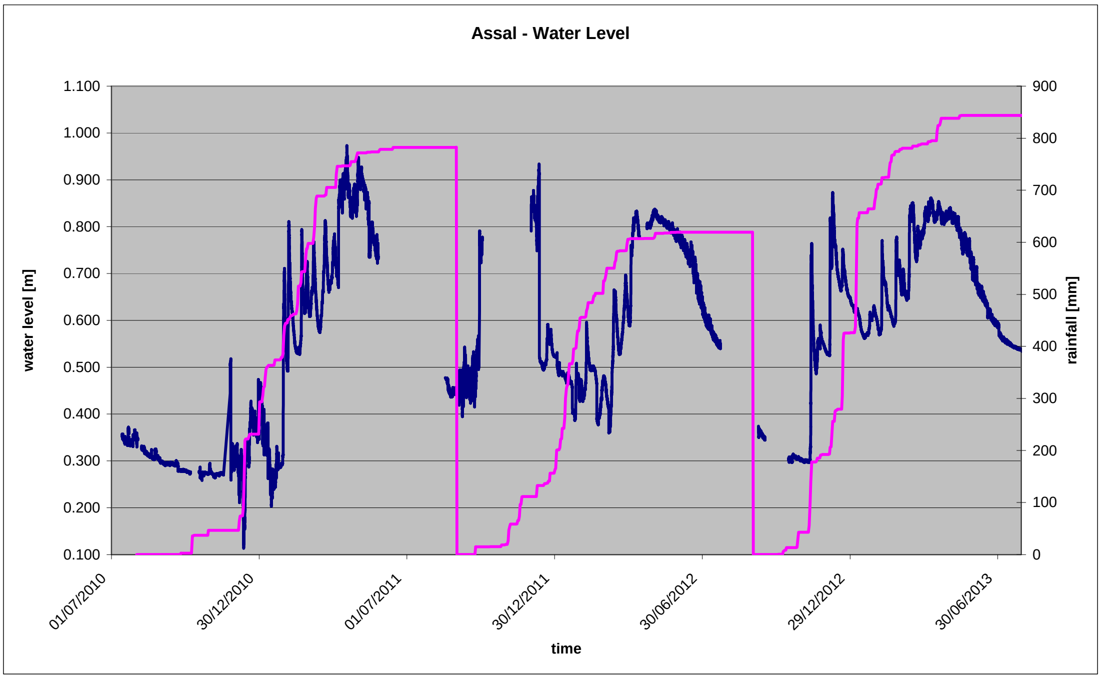
A4.3 Assal Spring



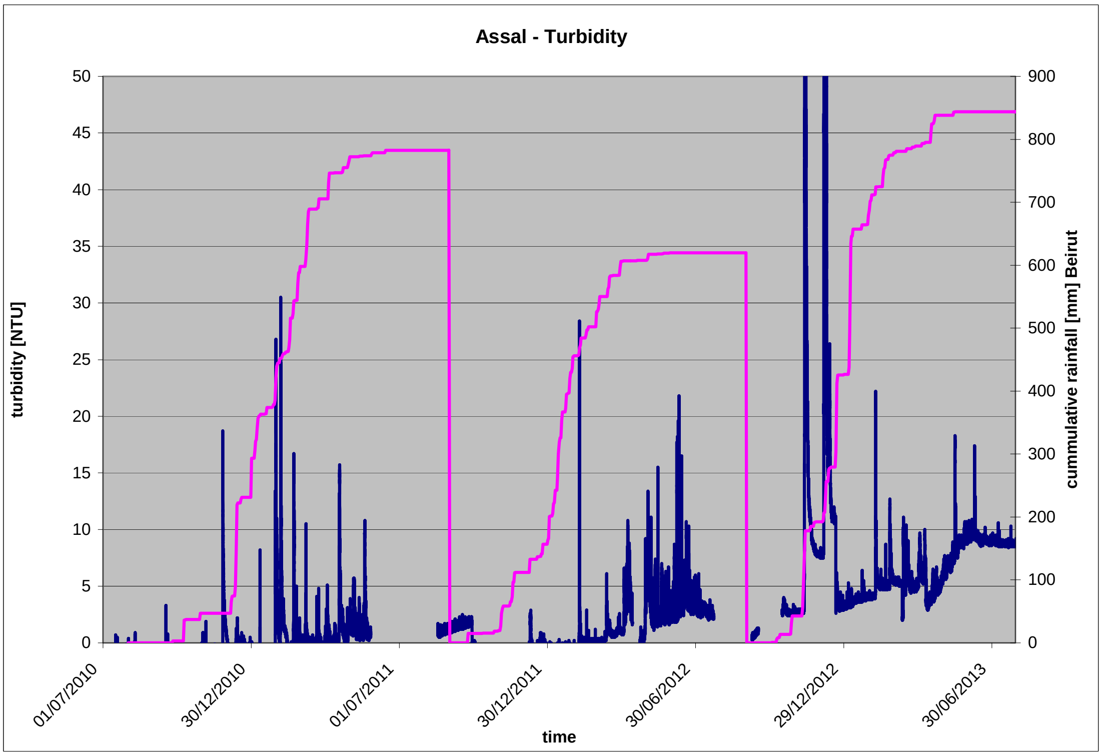
Annex 4.3.1: Flow - Temperature Correlation using ADCP



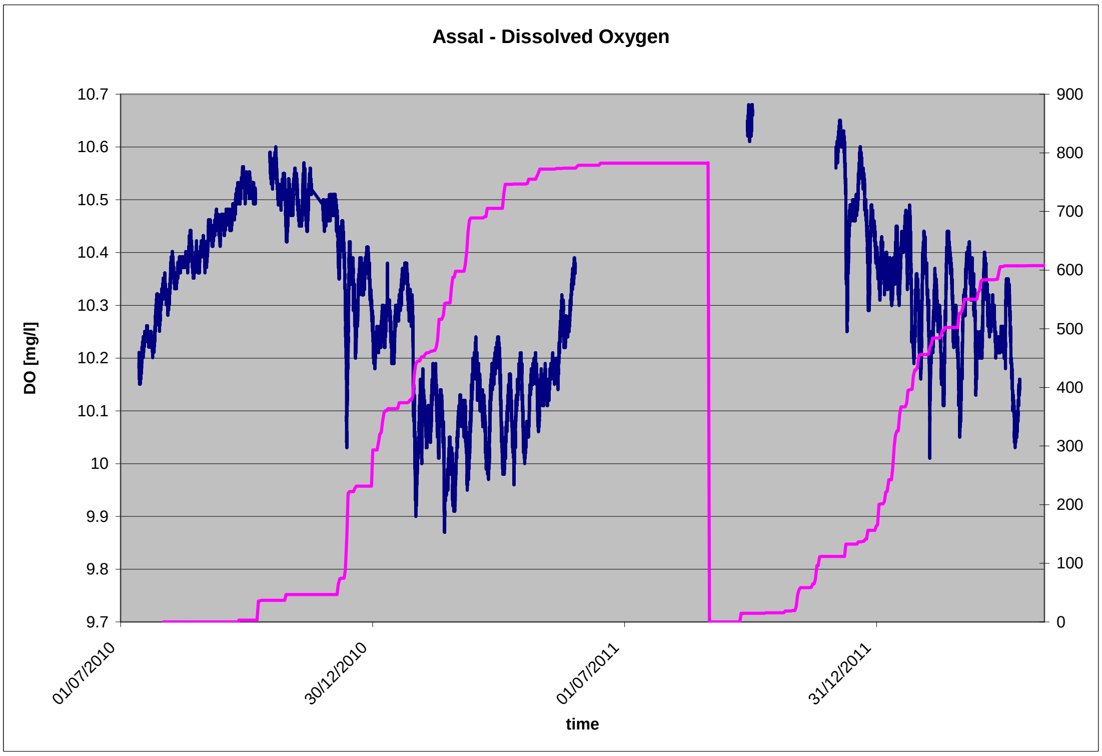
Annex 4.3.2: Monitoring of Temperature in Assal Spring



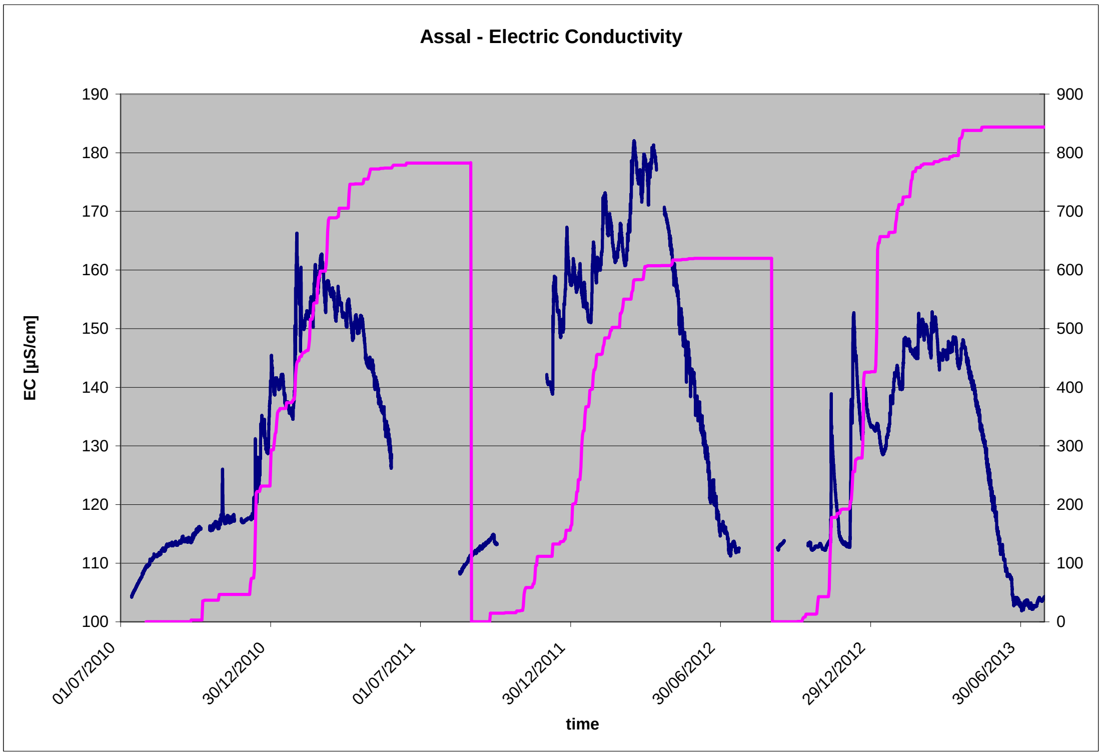
Annex 4.3.3: Monitoring of Water Level in Assal Spring



Annex 4.3.4: Monitoring of Turbidity in Assal Spring

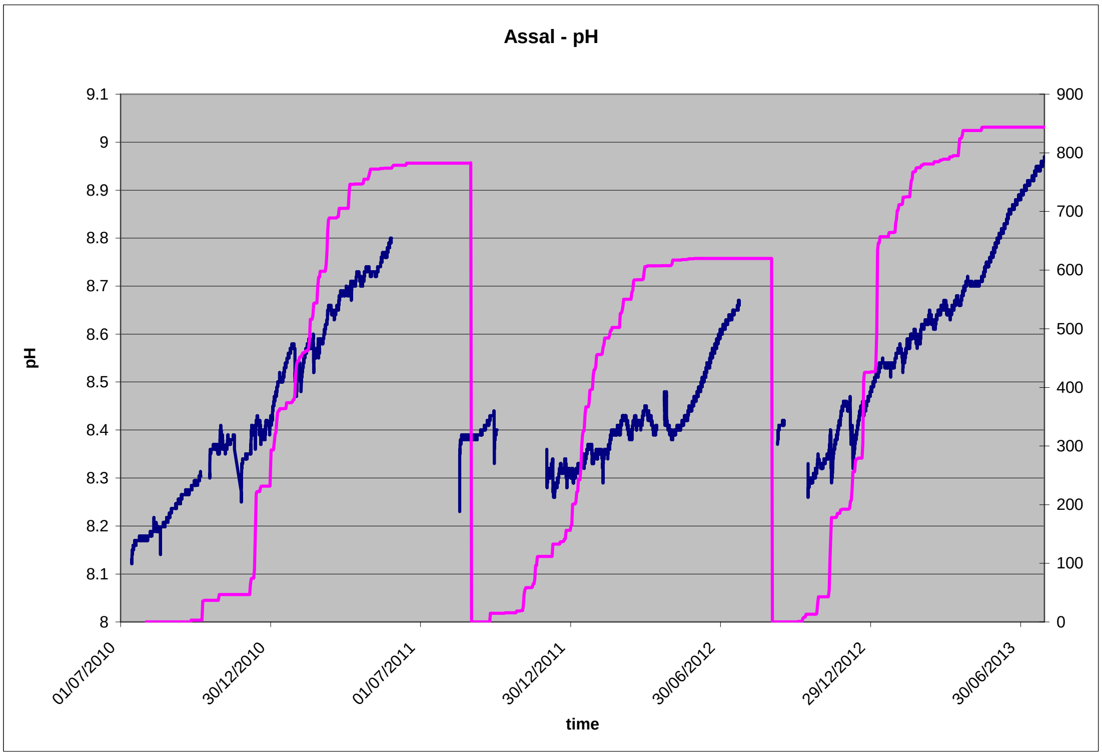


Annex 4.3.5: Monitoring of Dissolved Oxygen Content in Assal Spring



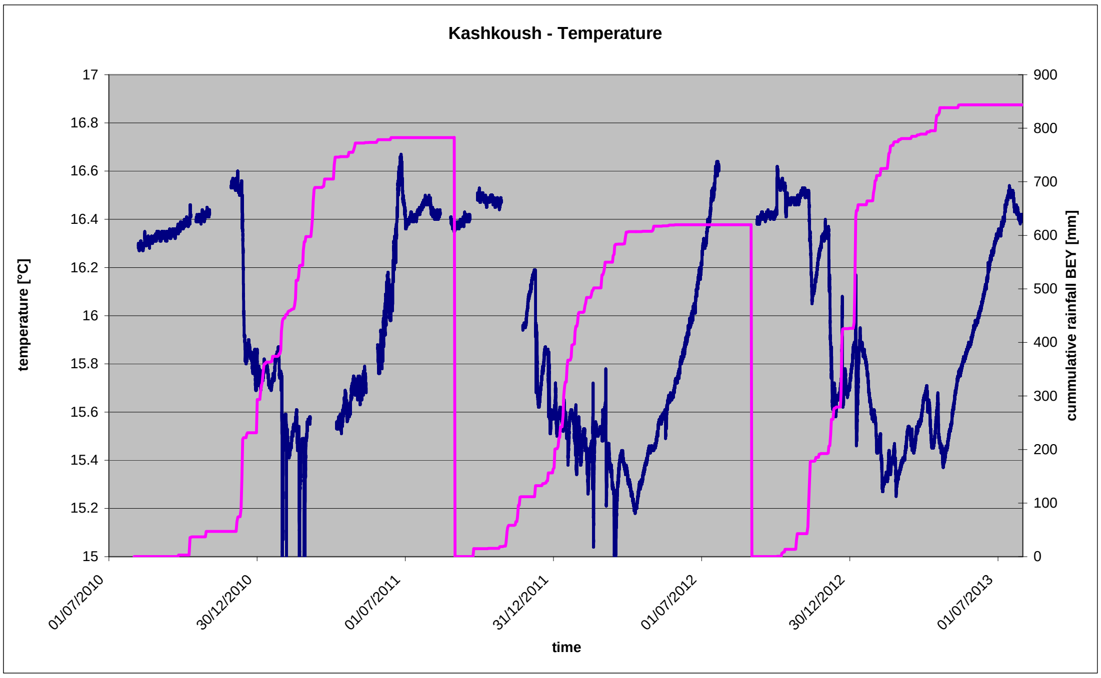
Annex 4.3.6: Monitoring of Electric Conductivity in Assal Spring

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

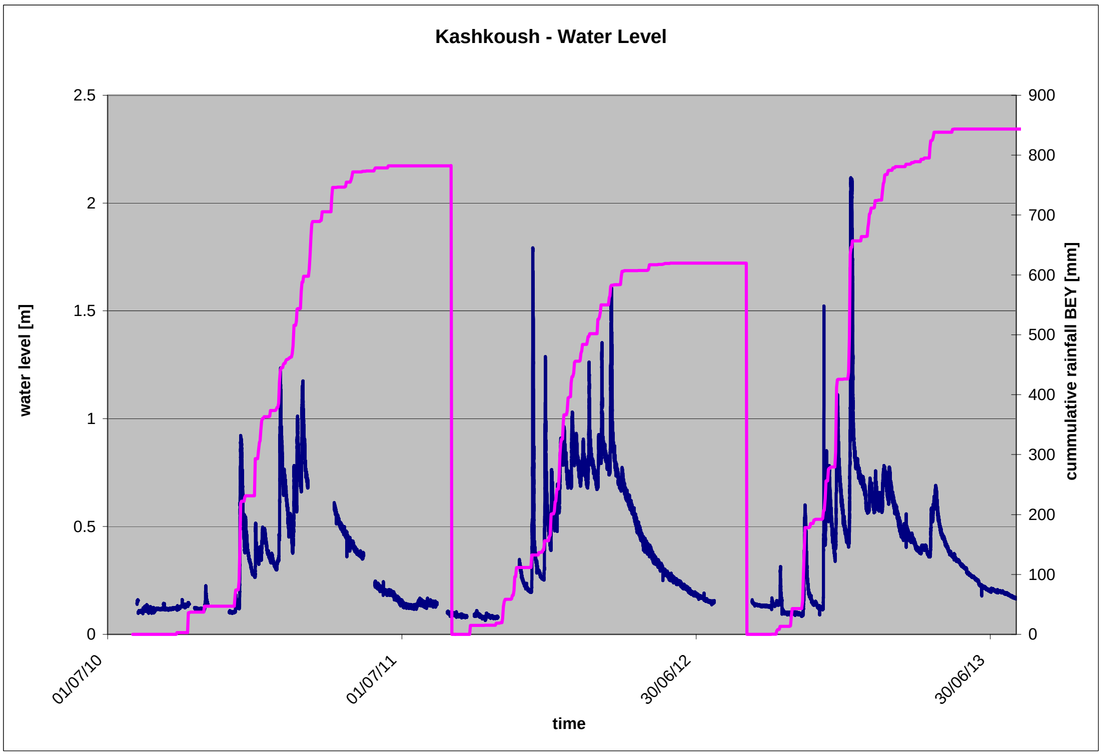


Annex 4.1.7: Monitoring of pH in Assal Spring

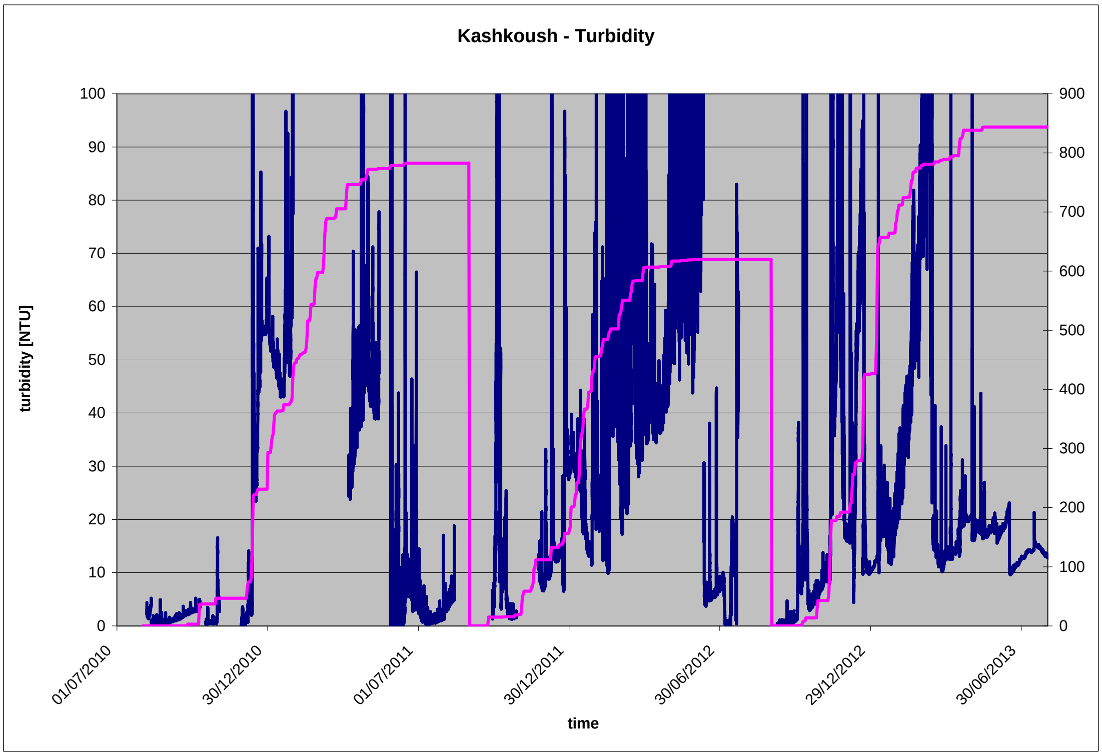
A4.4 Kashkoush Spring



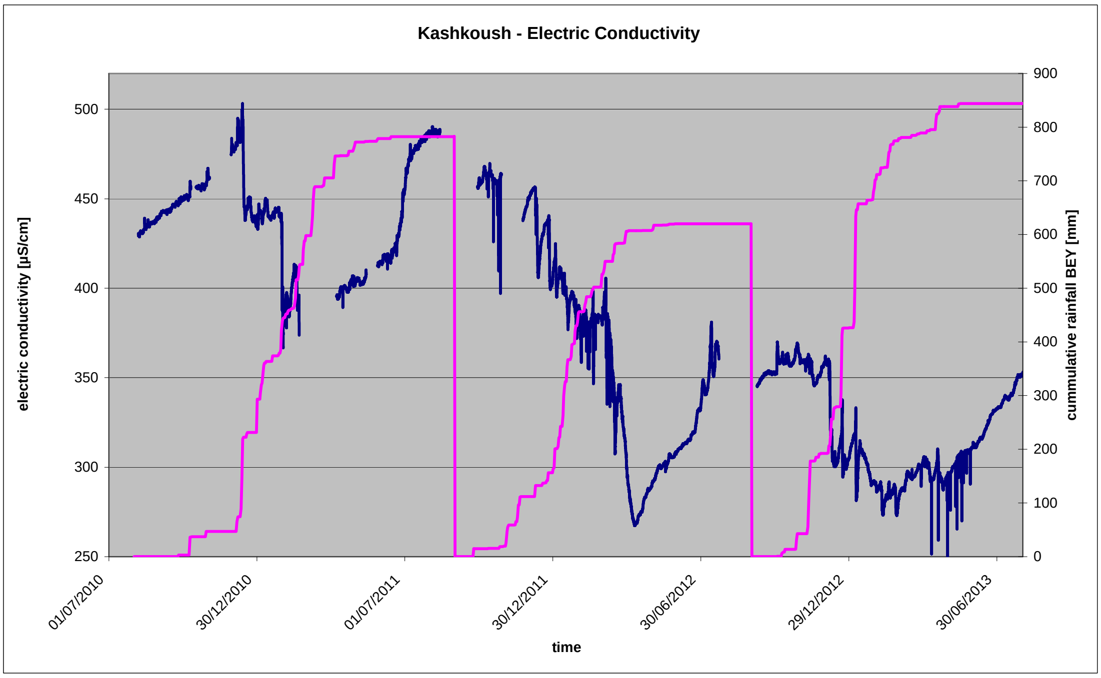
Annex 4.4.1: Monitoring of Temperature in Kashkoush Spring



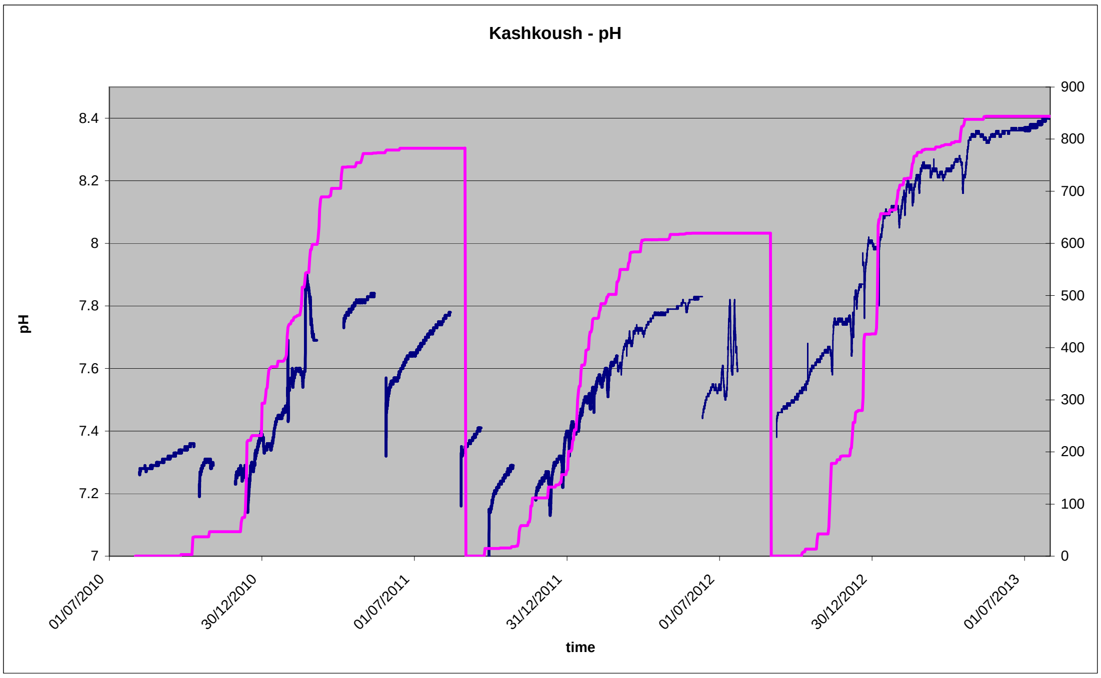
Annex 4.4.2: Monitoring of Water Level in Kashkoush Spring



Annex 4.4.3: Monitoring of Turbidity in Kashkoush Spring



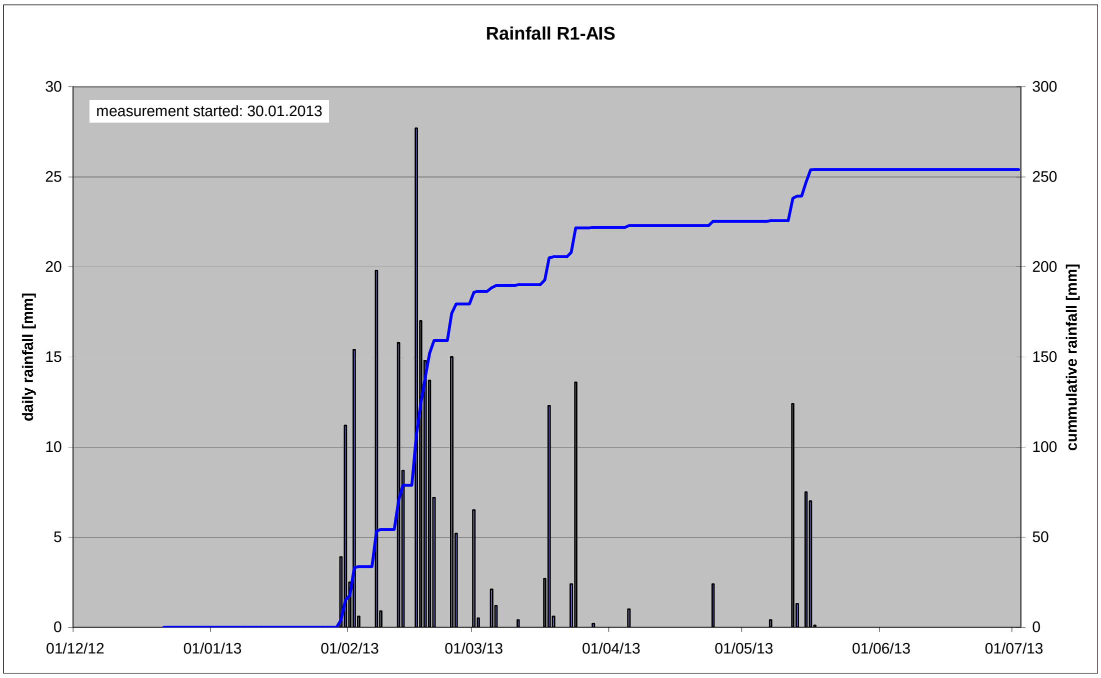
Annex 4.4.4: Monitoring of Electric Conductivity in Kashkoush Spring



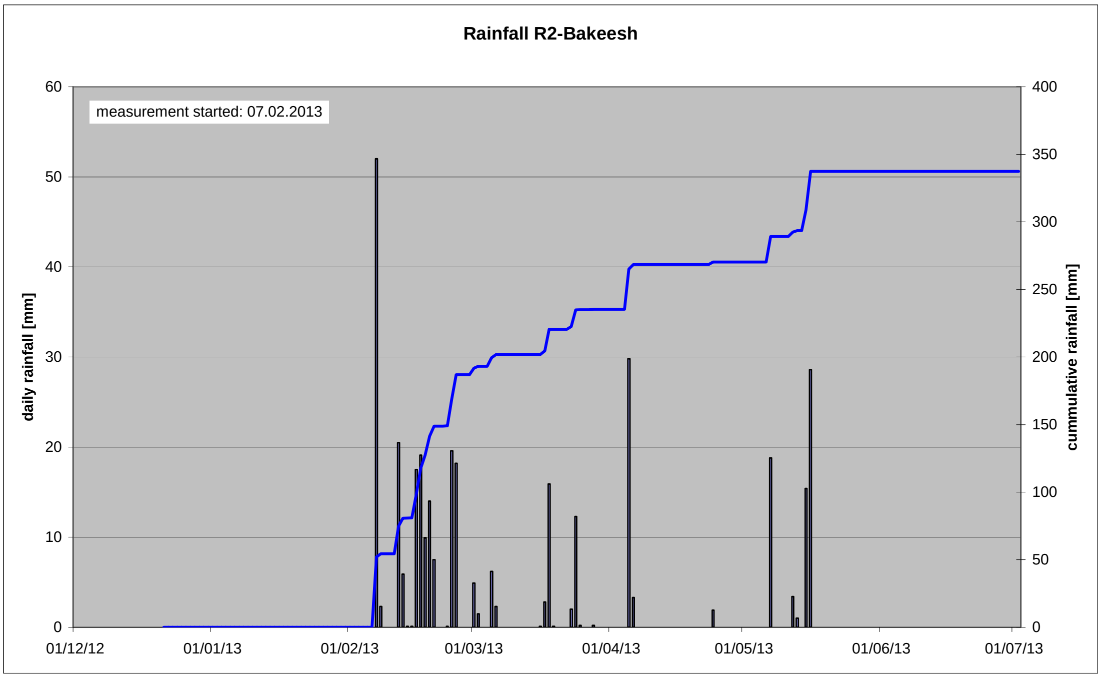
Annex 4.4.5: Monitoring of pH in Kashkoush Spring

ANNEX 5: Meteorological Data collected from the Project Stations

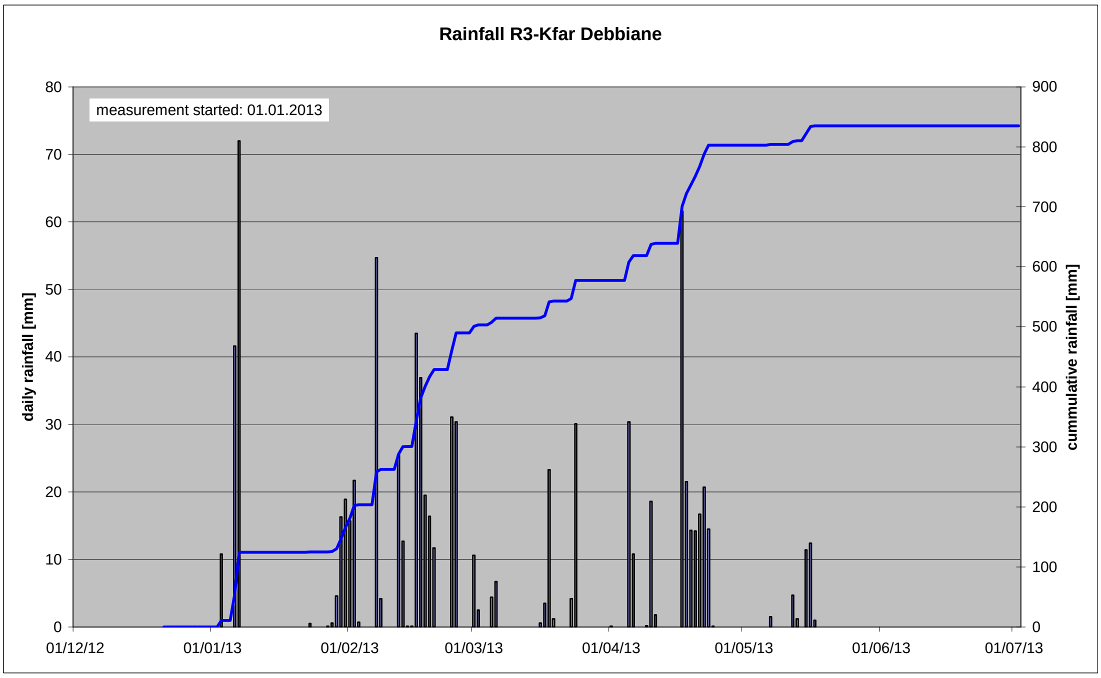
Rainfall - Meteorological Stations installed by BGR



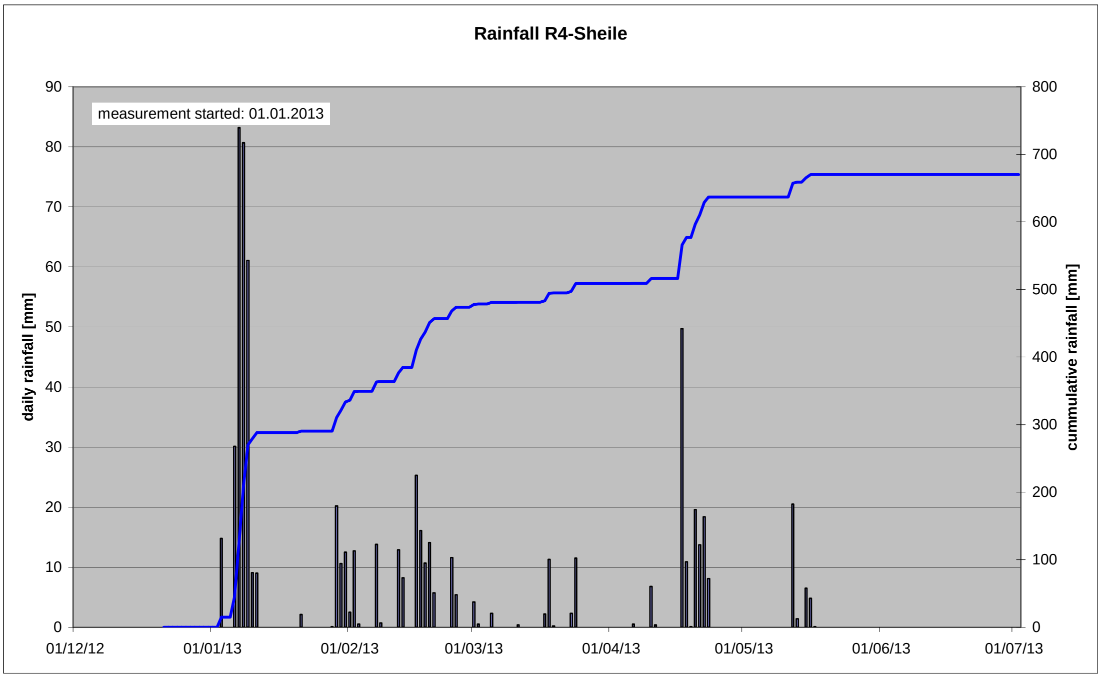
Annex 5.1: Rainfall measured at BGR meteo station R1-AIS (Antonine International School)



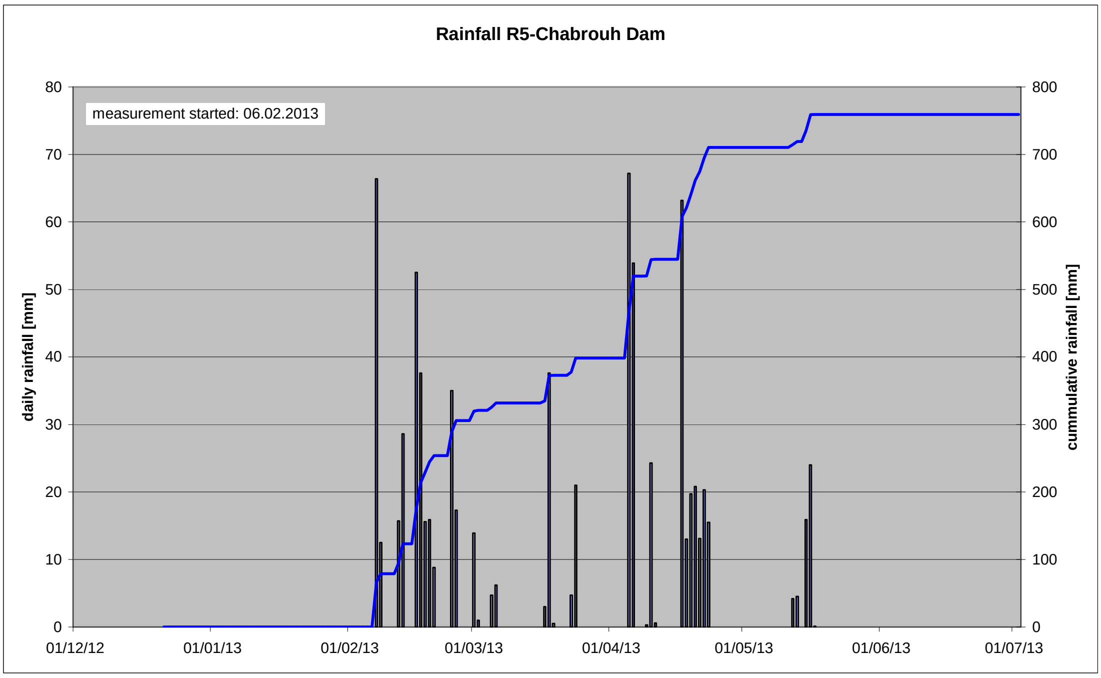
Annex 5.2: Rainfall measured at BGR meteo station R2-Bakeesh (reservoir)



Annex 5.3: Rainfall measured at BGR meteo station R3-Kfar Debbiane (municipality)



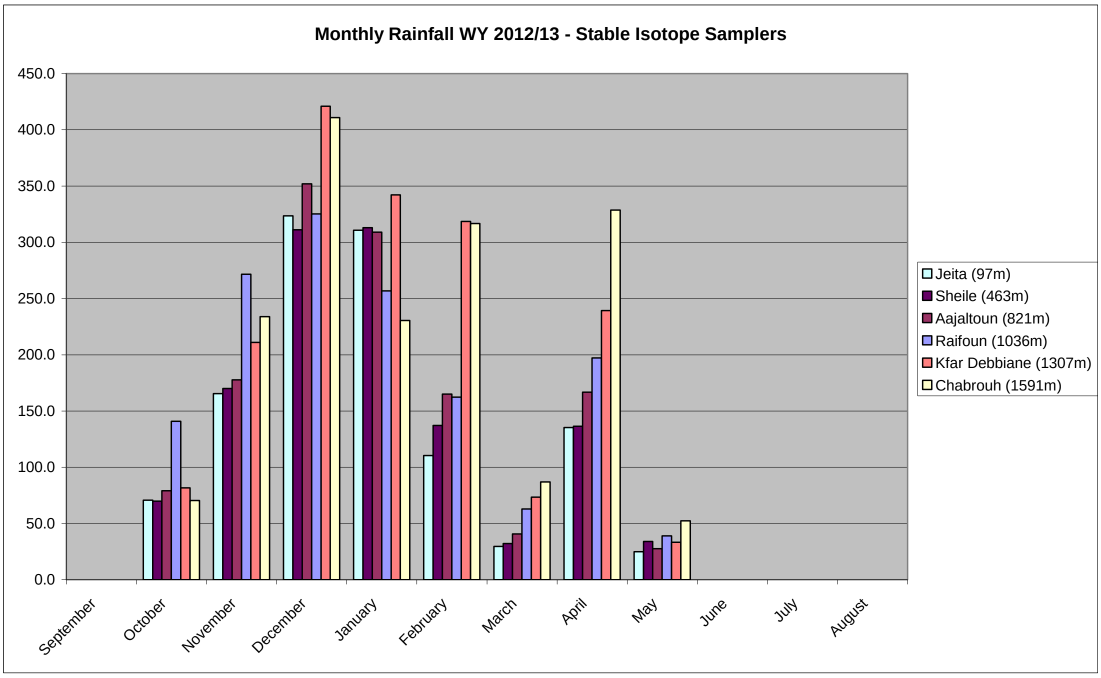
Annex 5.4: Rainfall measured at BGR meteo station R4-Sheile (reservoir)



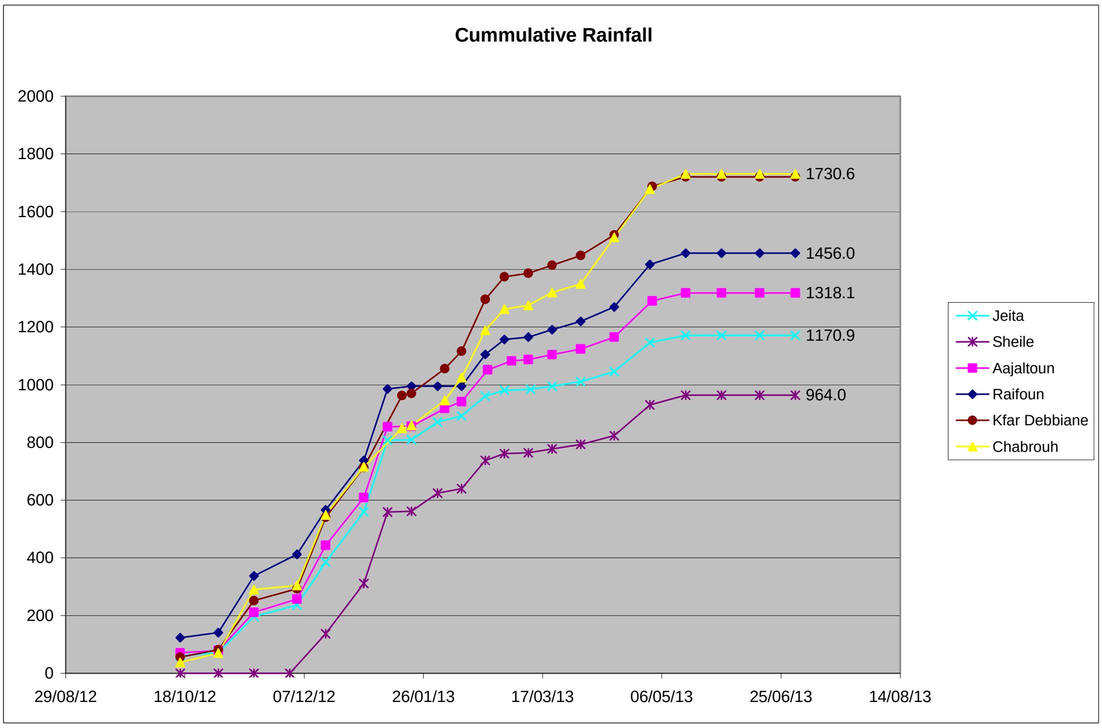
Annex 5.5: Rainfall measured at BGR meteo station R5-Chabrouh dam (treatment plant)

Hydrogeology of the Groundwater Contribution Zone of Jeita Spring

Rainfall - Stable Isotope Samplers

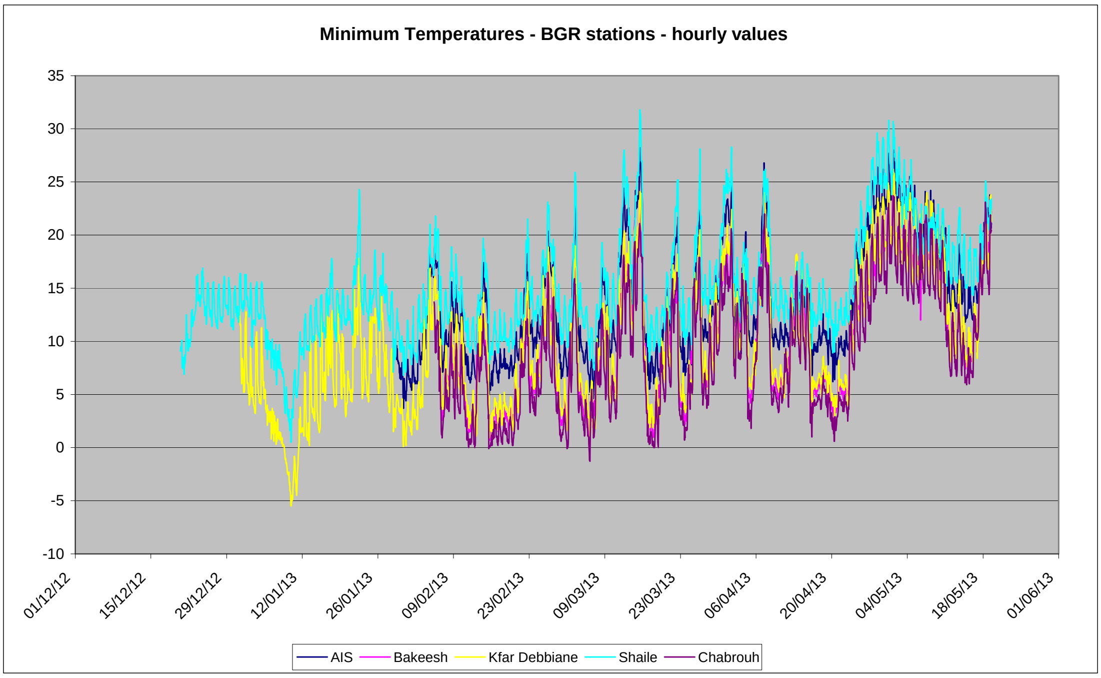


Annex 5.6: Rainfall measured at BGR stable isotope samplers (interpolated for Sheile; started 01.12.2012)

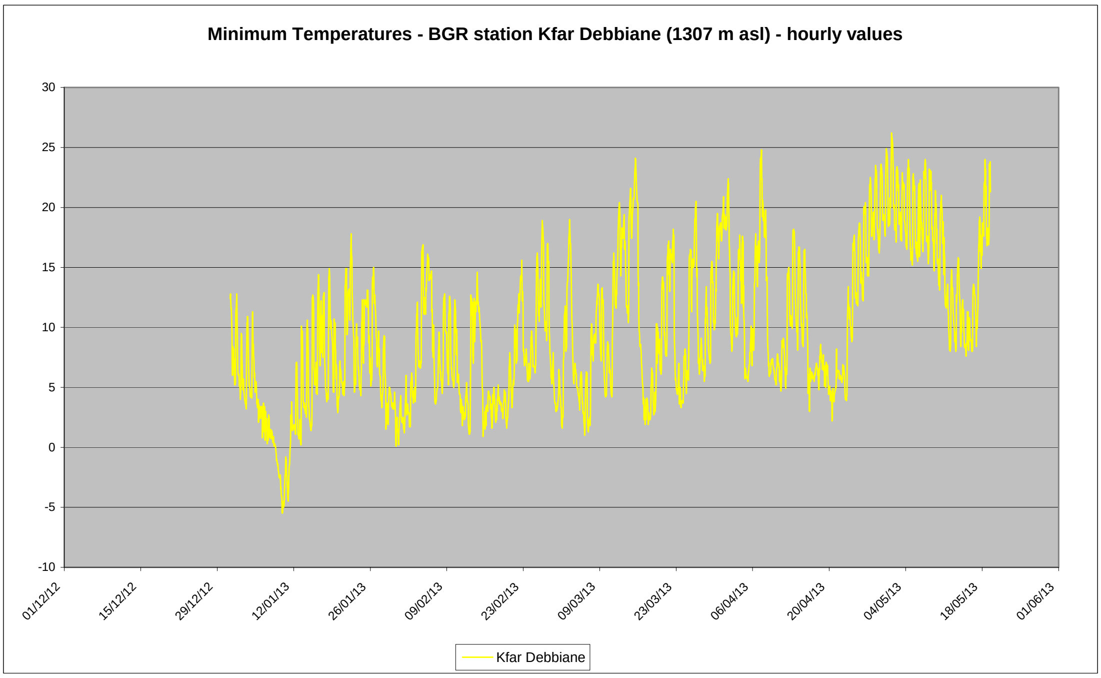


Annex 5.7: Cumulative rainfall measured at BGR stable isotope samplers

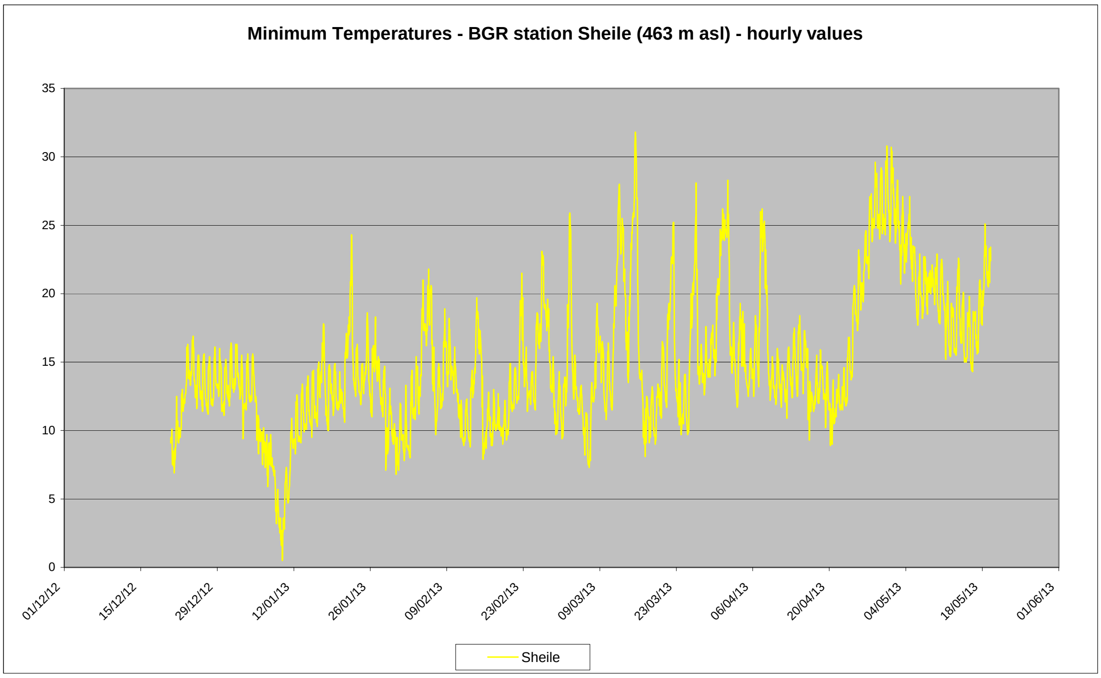
Temperature - Meteorological Stations installed by BGR



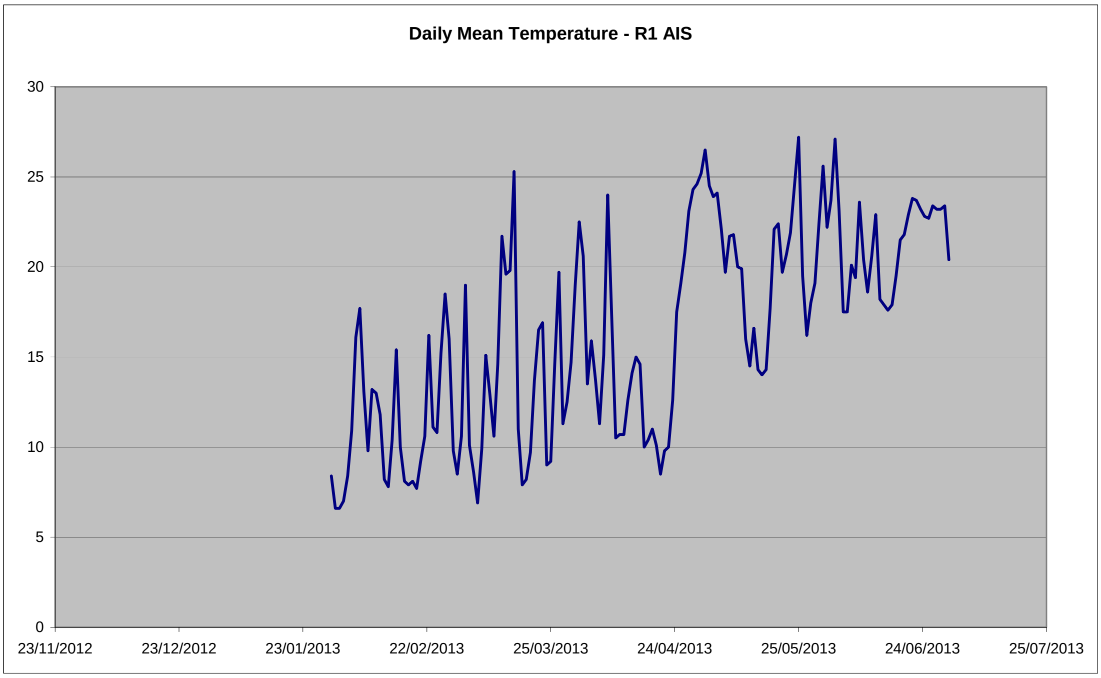
Annex 5.8: Minimum temperatures measured at BGR meteo stations R1 - R5 based on hourly values



Annex 5.9: Minimum temperatures measured at BGR meteo station R3 Kfar Debbiane (municiaplity) based on hourly values

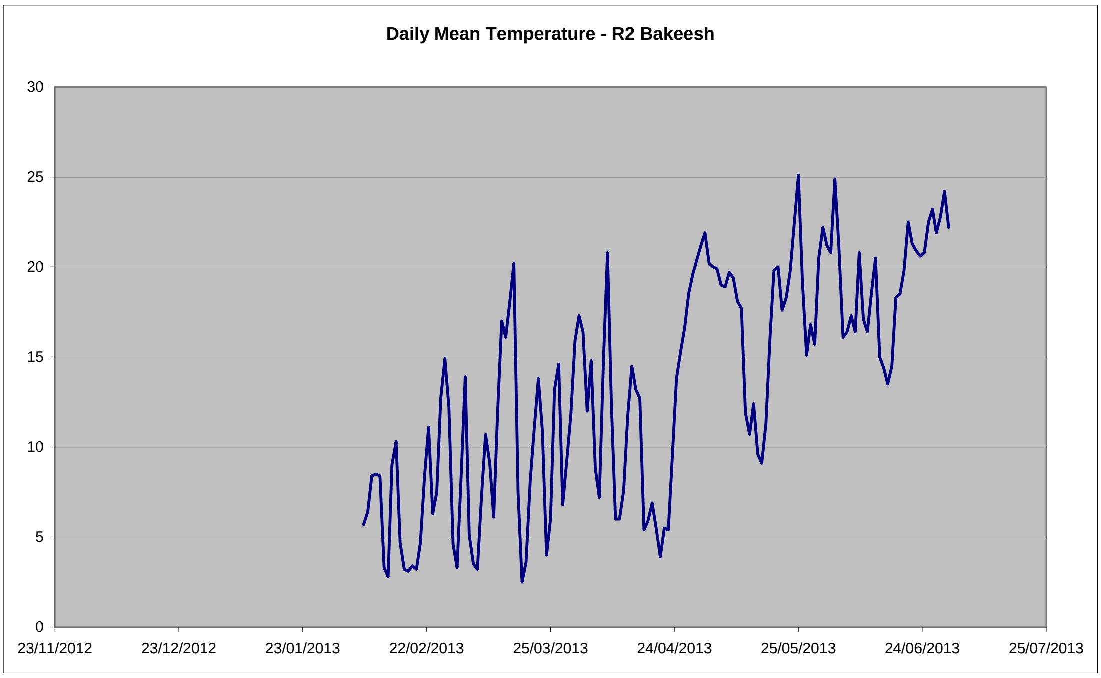


Annex 5.10: Minimum temperatures measured at BGR meteo station R4 Sheile (reservoir) based on hourly values

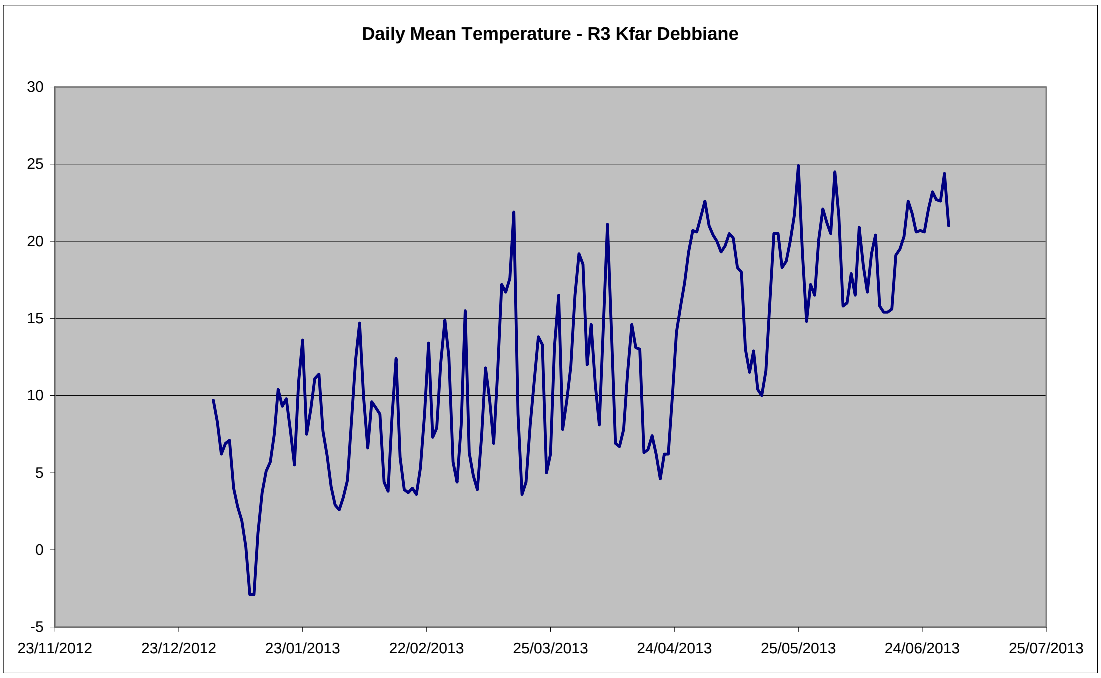


Annex 5.11: Daily mean temperatures measured at BGR meteo station R1 AIS (Antonine International School)

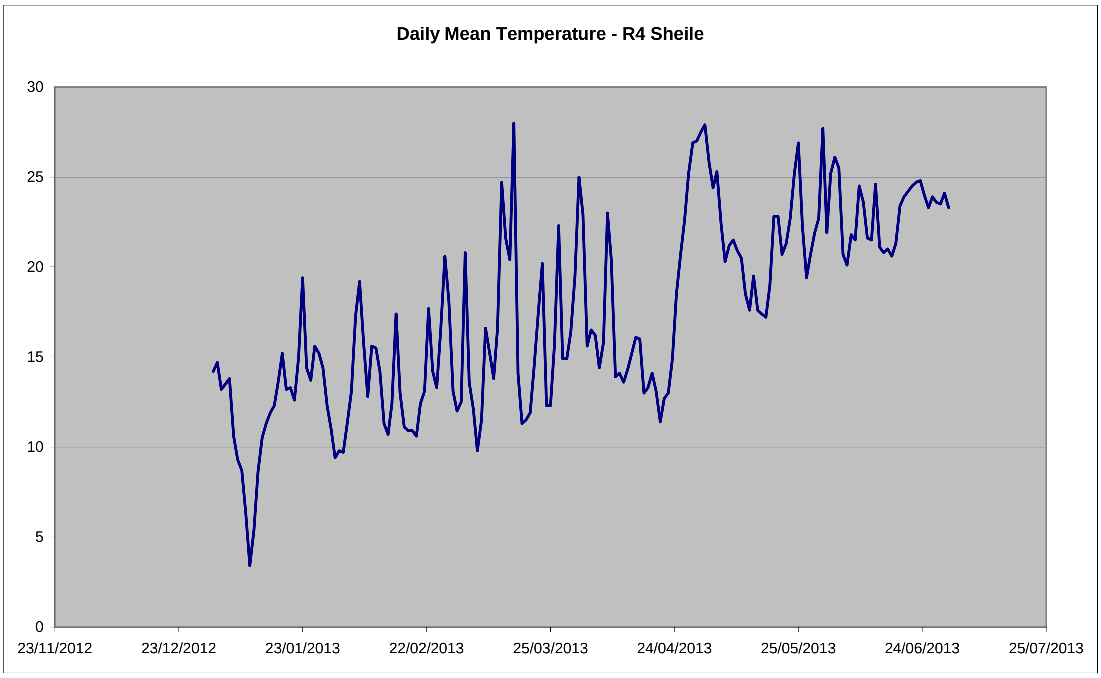
Hydrogeology of the Groundwater Contribution Zone of Jeita Spring



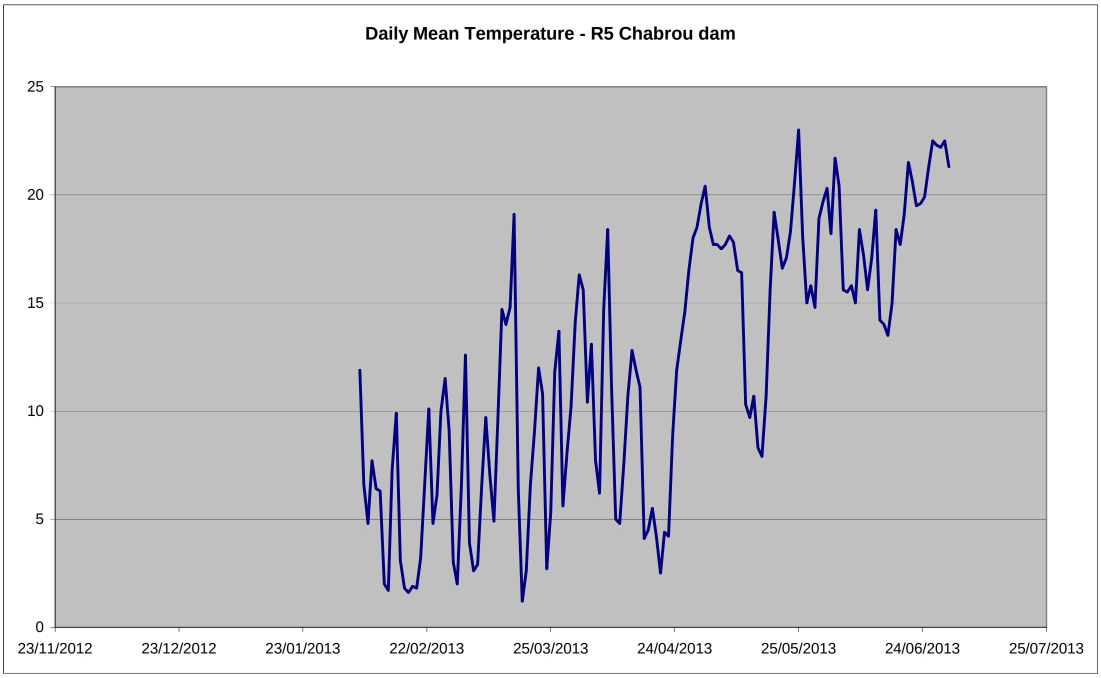
Annex 5.12: Daily mean temperatures measured at BGR meteo station R2 Bakeesh (reservoir)



Annex 5.13: Daily mean temperatures measured at BGR meteo station R3 Kfar Debbiane (municipality)

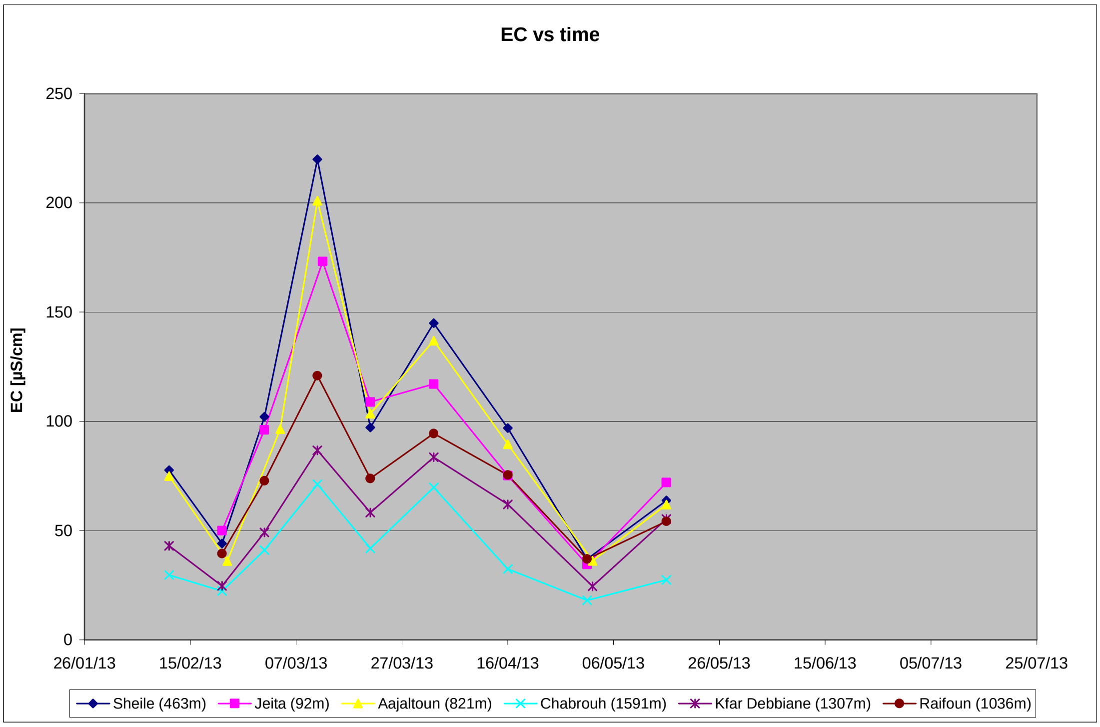


Annex 5.14: Daily mean temperatures measured at BGR meteo station R4 Sheile (reservoir)

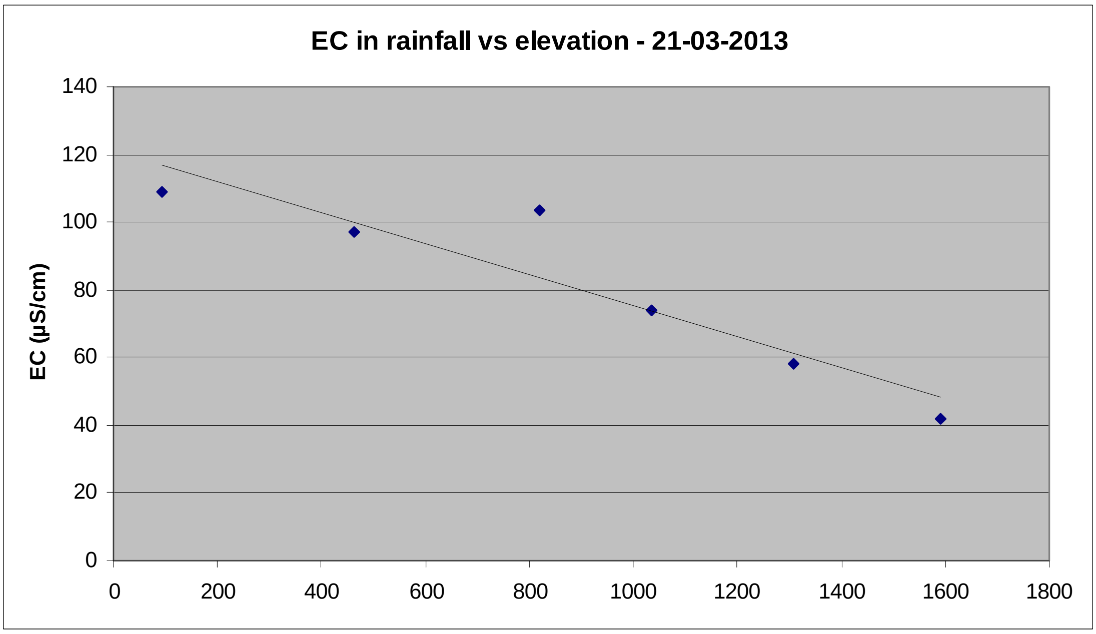


Annex 5.15: Daily mean temperatures measured at BGR meteo station R5 Chabrouh dam (treatment plant)

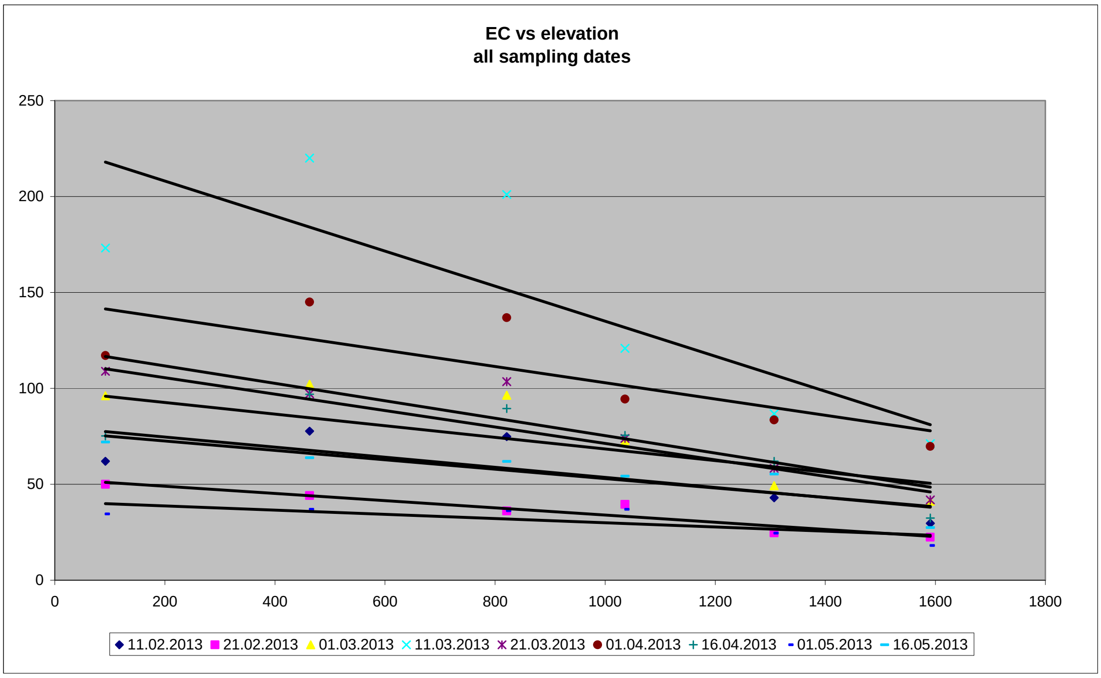
Rainfall - Electric Conductivity measured in Stable Isotope Samplers



Annex 5.16: Electric conductivity of rainfall measured at BGR stable isotope samplers

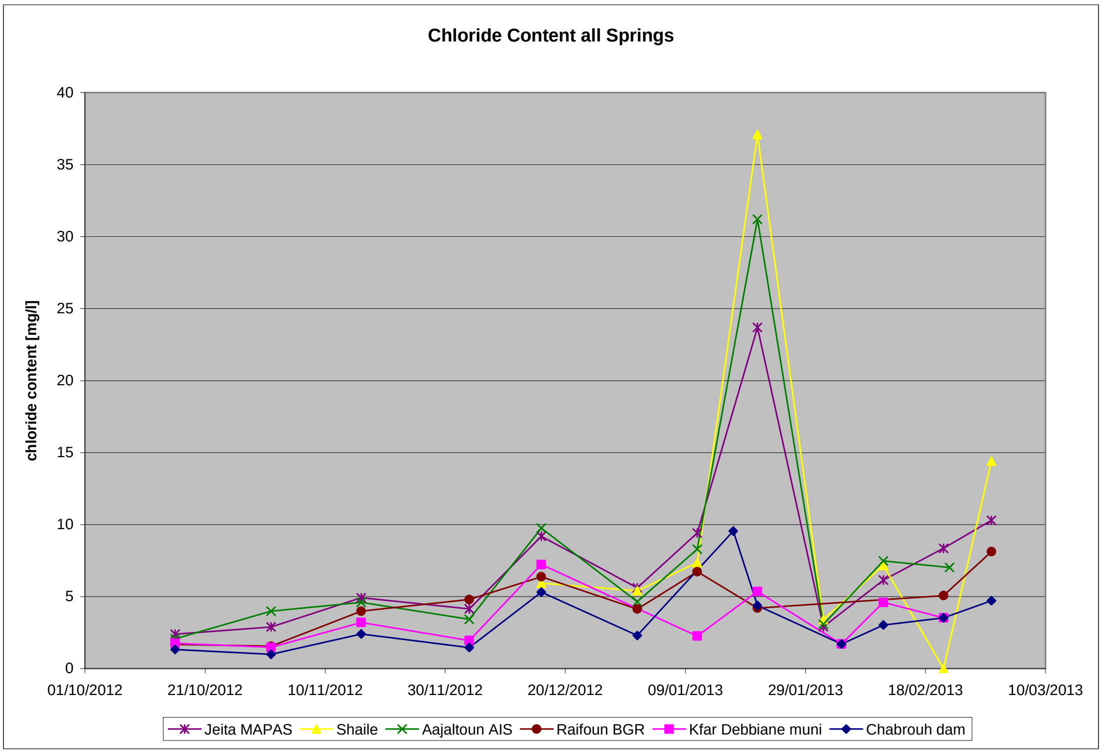


Annex 5.17: Electric conductivity of rainfall (time period 11.03.-21.03.2013) measured at BGR stable isotope samplers correlated with elevation

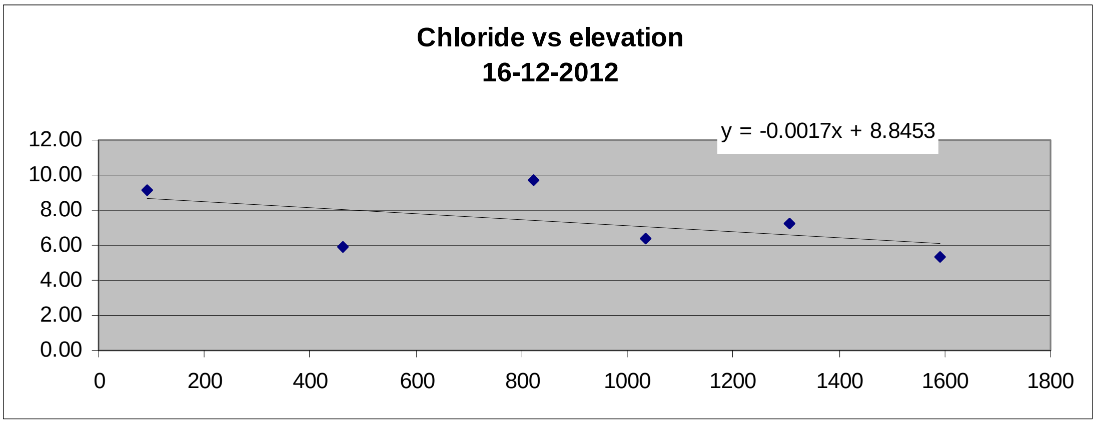


Annex 5.18: Electric conductivity of rainfall (10-15 day time periods) measured at BGR stable isotope samplers correlated with elevation

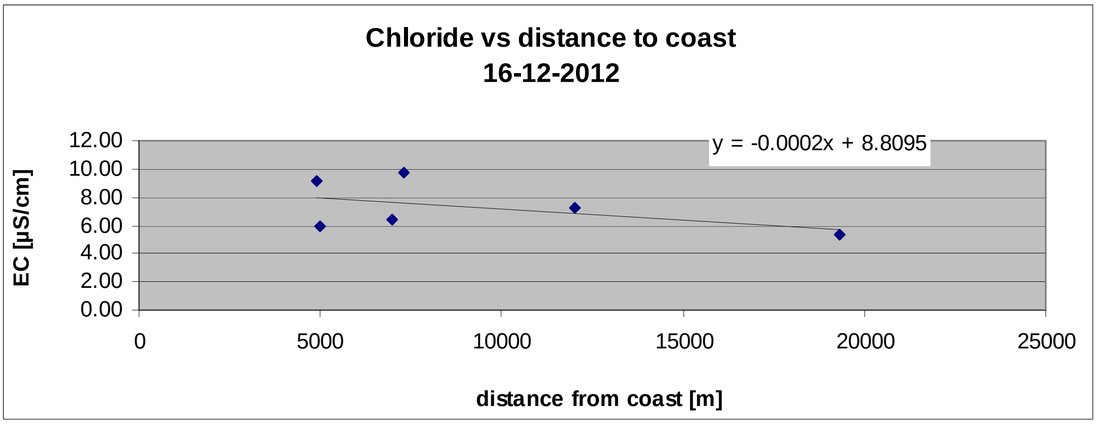
(date when sample was taken)



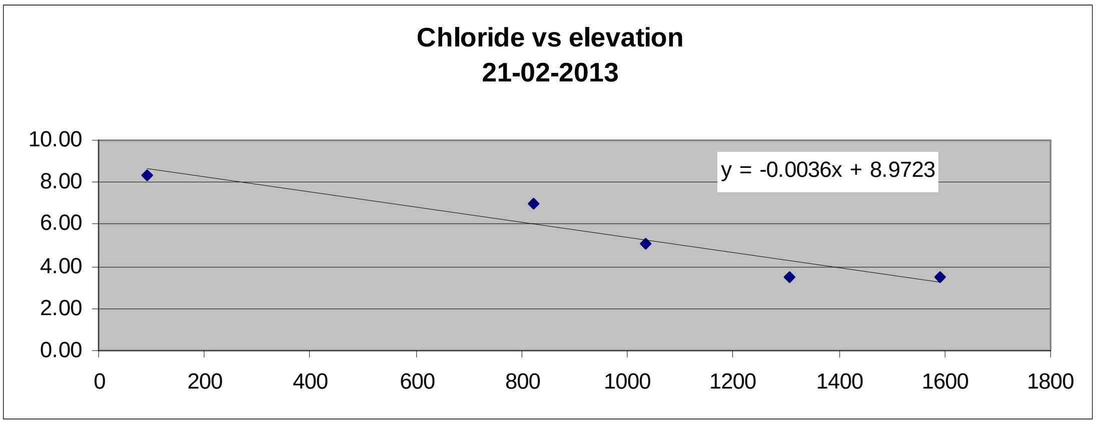
Annex 5.19: Variation of chloride content in rainfall collected from stable isotope samplers



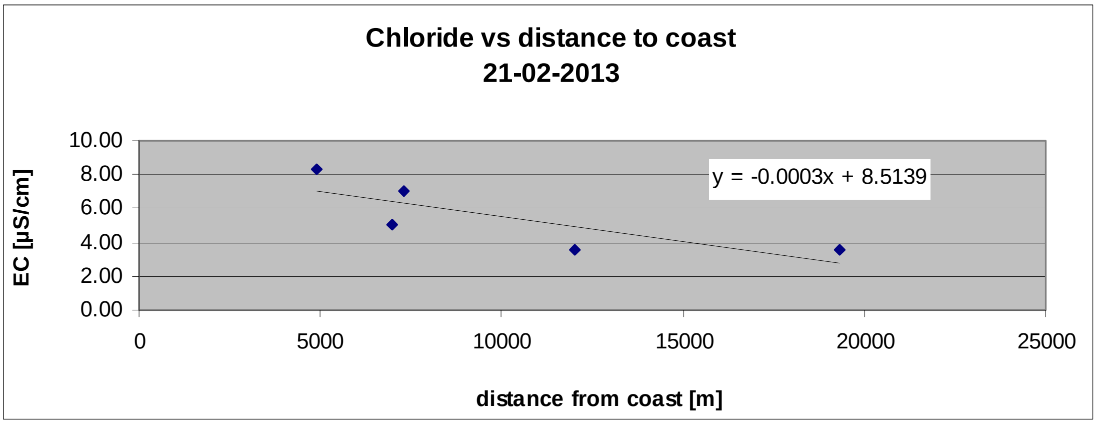
Annex 5.20: Correlation of chloride content in rainfall with elevation collected from stable isotope samplers on 16-12-2012



Annex 5.21: Correlation of chloride content in rainfall with distance from coastline collected from stable isotope samplers on 16-12-2012

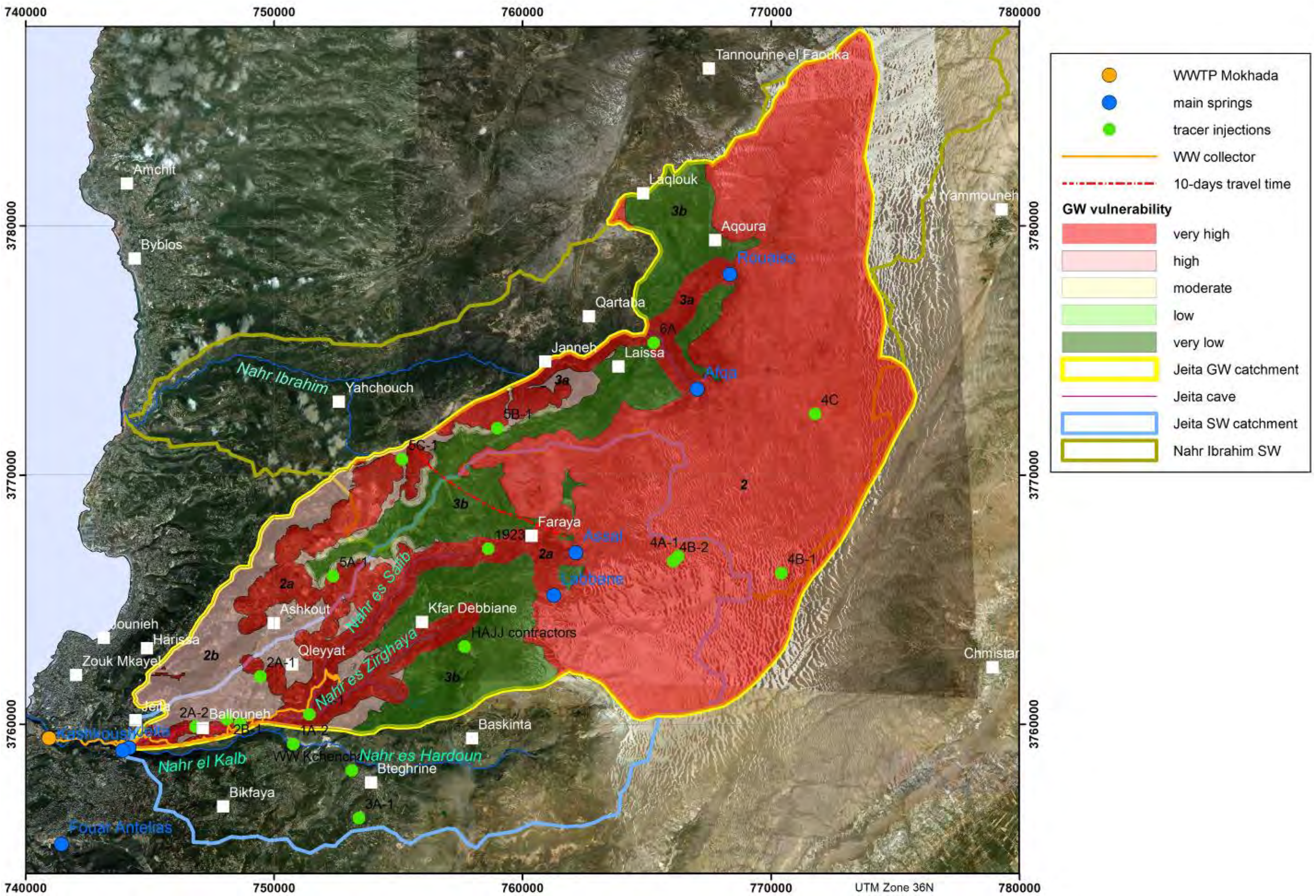


Annex 5.22: Correlation of chloride content in rainfall with elevation collected from stable isotope samplers on 21-02-2013

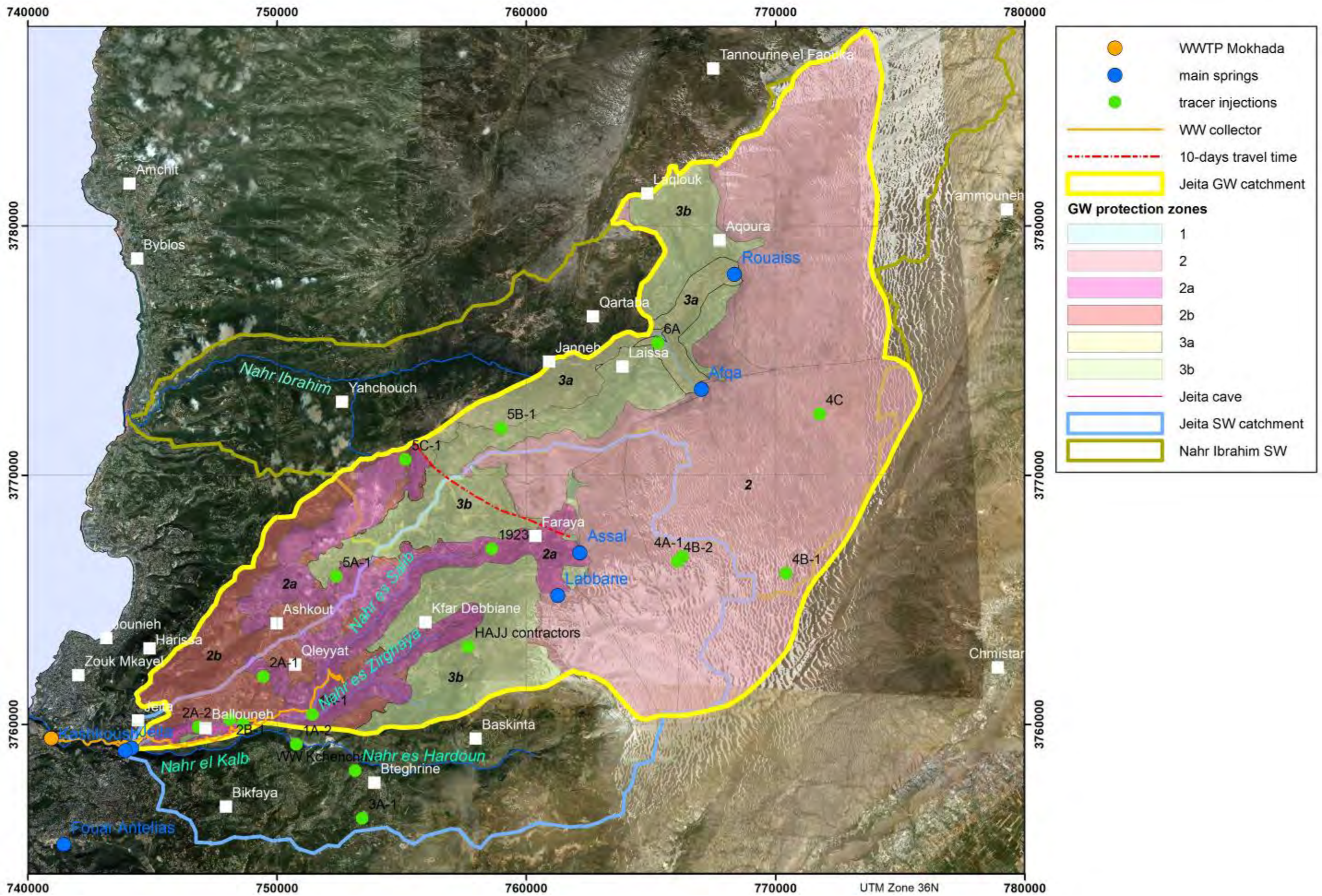


Annex 5.23: Correlation of chloride content in rainfall with distance from coastline collected from stable isotope samplers on 21-02-2013

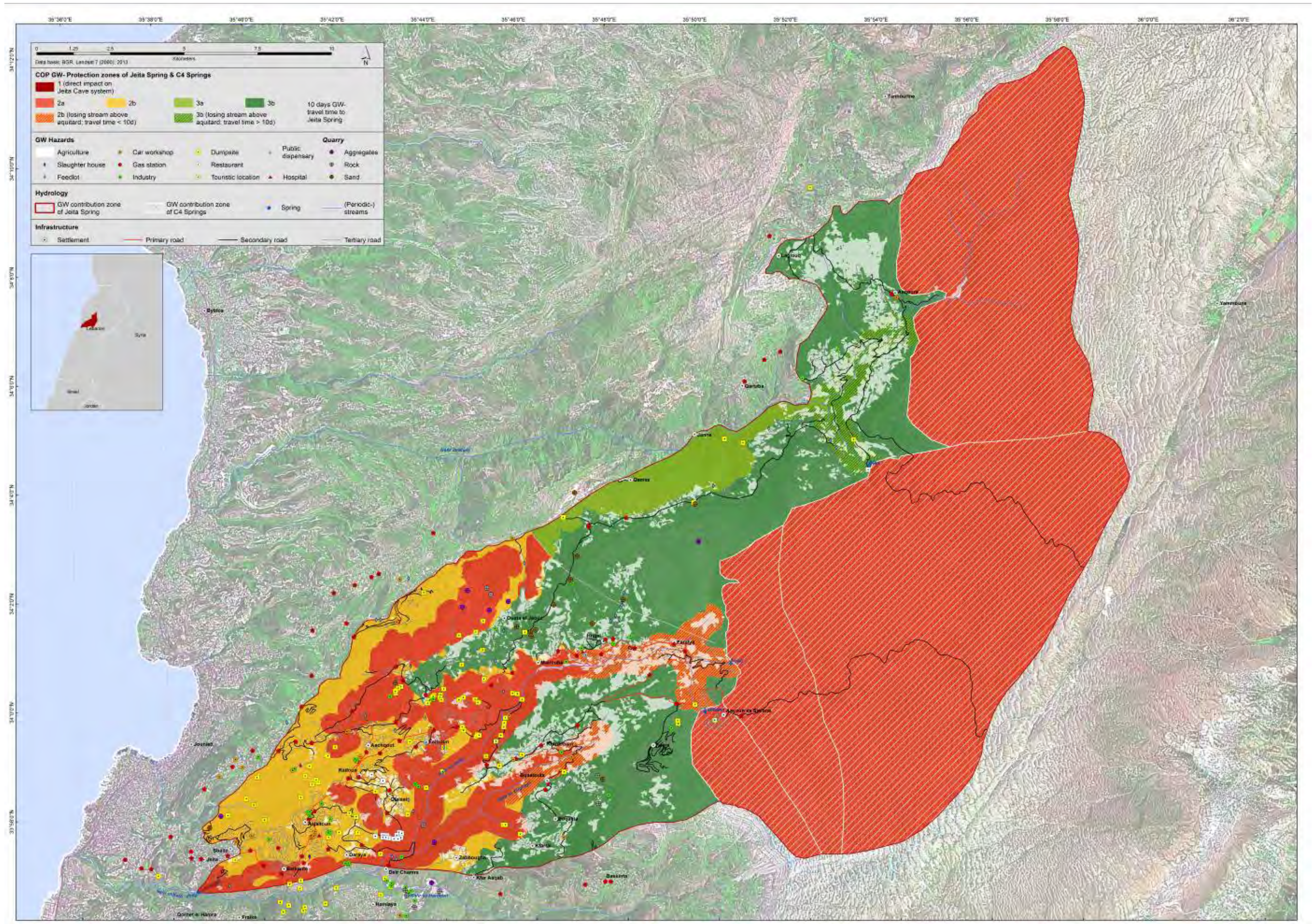
ANNEX 6: Groundwater Vulnerability - Groundwater Hazards and Groundwater Protection Zones



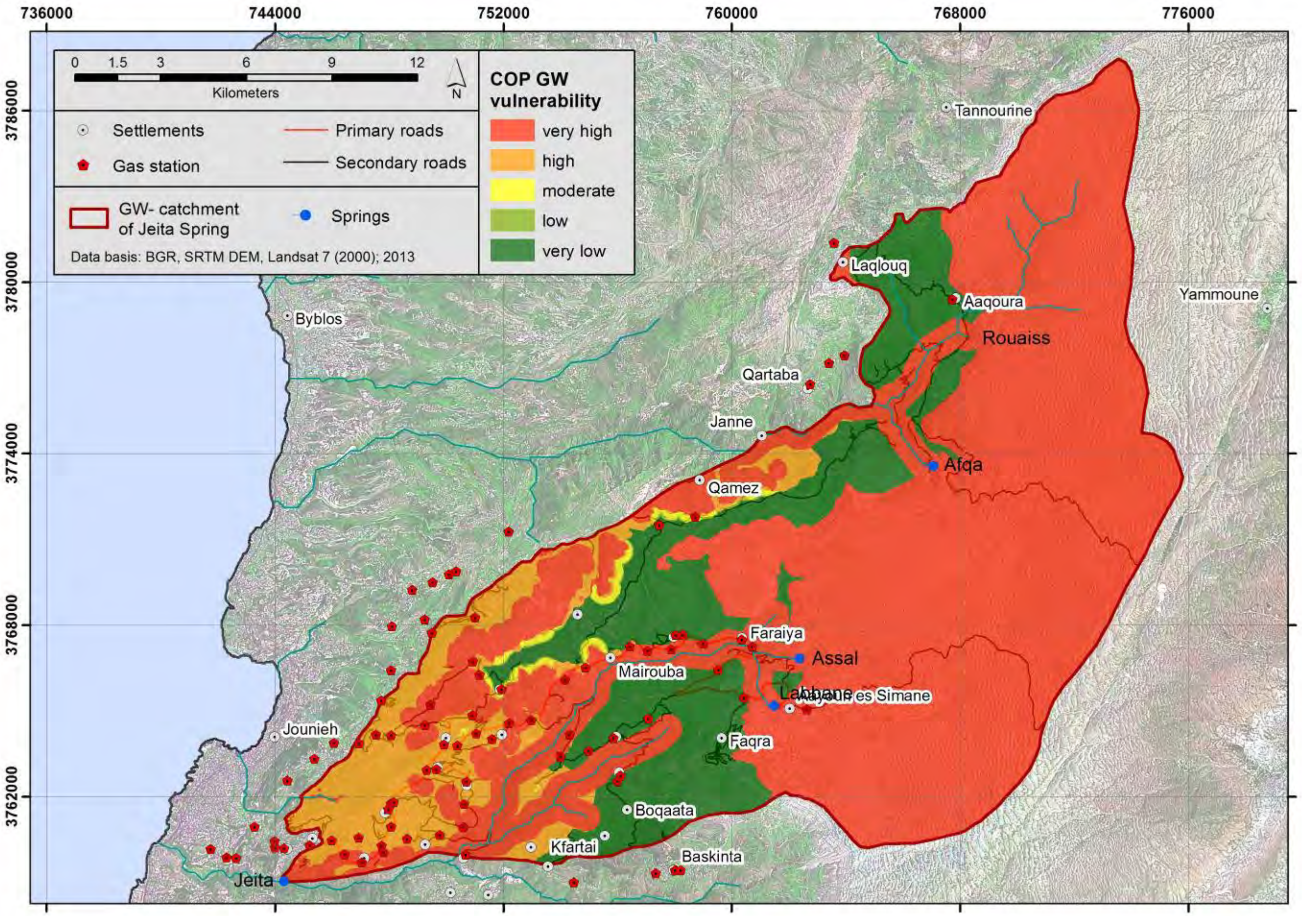
Annex 6.1: Groundwater Vulnerability Map using the COP Method



Annex 6.2: Proposed Groundwater Protection Zones



Annex 6.3: Groundwater Hazards Map



Annex 6.4: Gas Stations and Groundwater Vulnerability