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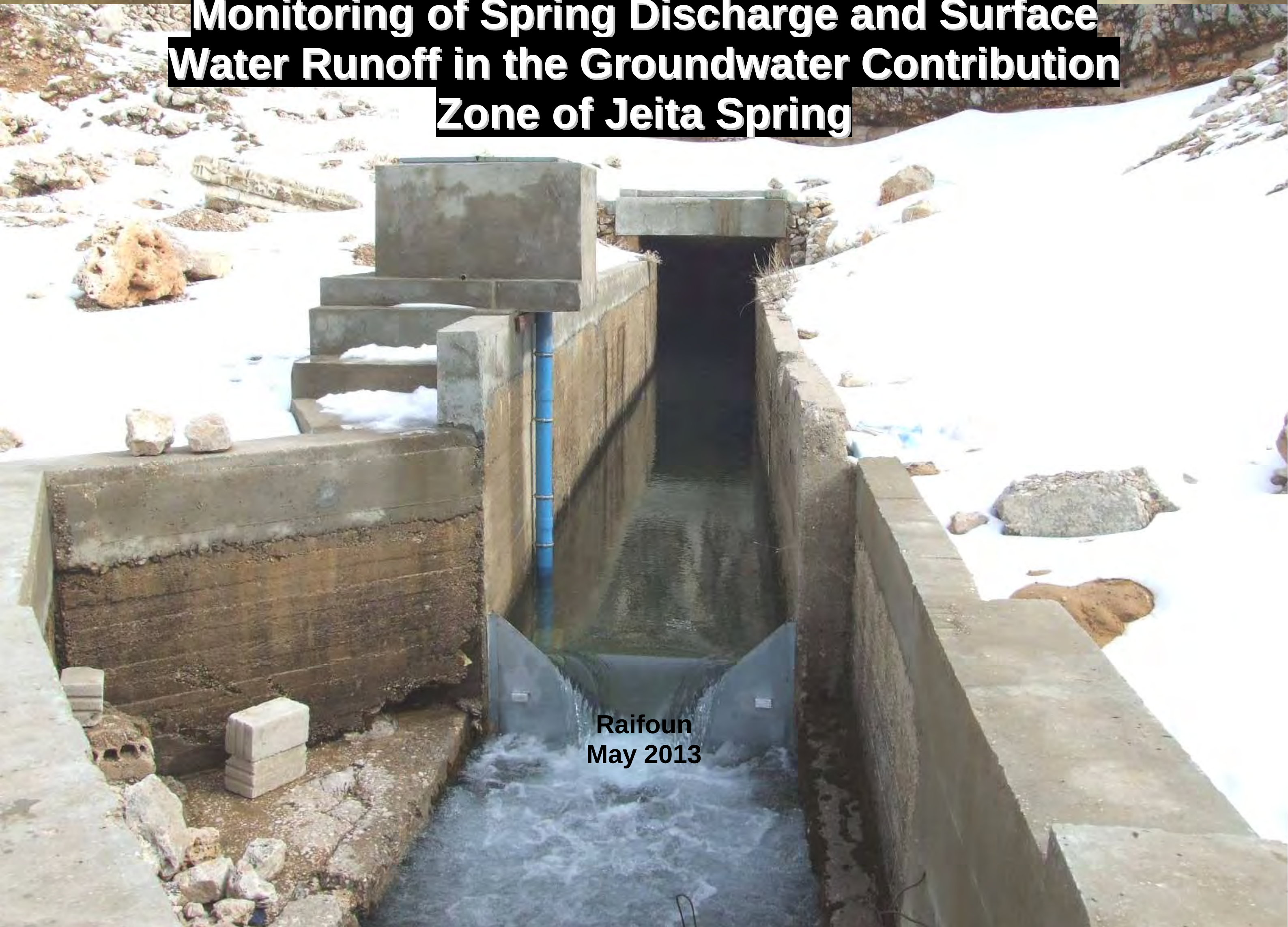
Protection of Jeita Spring

SPECIAL REPORT NO. 8

Monitoring of Spring Discharge and Surface Water Runoff in the Groundwater Contribution Zone of Jeita Spring



Raifoun
May 2013

Special Report No. 8: Monitoring of Spring Discharge and Surface Water Runoff in the Groundwater Contribution Zone of Jeita Spring

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asl	Above mean sea level
AFD	Agence Française pour le Développement
ADCP	Acoustic Doppler current profiler
AVSI	Italian NGO
BMZ	German Ministry of Economic Cooperation and Development
CDR	Council for Development and Reconstruction
CPT	Cone penetration test
DEMN	Digital elevation model
EIA	Environmental impact assessment
EIB	European Investment Bank
FAO	Food and Agriculture Organization
FC	Financial cooperation
GW	groundwater
IGN	Institut Geographique National
KfW	German Bank for Reconstruction and Development
LRA	Litani River Authority
MAPAS	Company operating Jeita Grotto
MCM	Million cubic meters
MoEW	Ministry of Energy and Water
PMF	Probable maximum flood
SW	surface water
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
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4	Geological Map, Tectonics and Karstification in the Groundwater Contribution Zone of Jeita Spring	September 2011
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7b	Vulnerability Mapping using the COP and EPIK Methods	October 2012
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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

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
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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	September 2012

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	Kashkoush Spring	
4	Preliminary Assessment of Jeita Cave Stability	April 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	In Progress

* prepared in cooperation with University of Goettingen

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0 Executive Summary

This report presents preliminary results of monitoring of spring discharge and the evaluation of surface water monitoring data by the Technical Cooperation (TC) Project Protection of Jeita Spring (implemented by BGR and CDR). This assessment provided basic data used for the water balance discussed in the WEAP model (SCHULER & MARGANE, 2013), the proposal of water resources management options (GITEC & BGR, 2011) and the final hydrogeological report (MARGANE et al., 2013).

Finding suitable base data for hydrogeological investigations in Lebanon is a challenge. There are too few monitoring stations and the existing ones often provide problematic data. Many of the existing stations monitoring surface and groundwater resources as well as climatic data are fairly old and were never or rarely maintained. The streamflow gauging stations at Rouaiss and Afqa are completely dilapidated and should be rebuilt. Surface water monitoring stations must be at suitable locations to provide useful data. Spring discharge must be monitored at adequate time intervals, suitable locations and with the right equipment to get a meaningful result. In a country where snow is an important factor, meteorological stations must have heating systems to be able to collect correct rainfall or wind direction data.

The result is that for most springs no adequate and correct spring discharge data or water quality data are available, that rainfall at elevations exceeding 800 m is highly incorrect, and that streamflow data often cannot be used. It is for this reason that no true water resources assessment has yet been done in any catchment and that Lebanon is far from being able to establish a nationwide water resources assessment. The non-availability of water balance data means wrong planning and failed investments and therefore it is not surprising to see that many large investment projects are based on fairly wrong assumptions and consequently have failed or are doomed to fail.

Too little effort is made by the responsible Lebanese government offices to establish and operate suitable monitoring systems. However, carrying out a water resources assessment for a catchment requires data with adequate accuracy. In no catchment of Lebanon, not even in the most extensively investigated Jeita catchment such data were available when our project started. The project therefore had to establish such monitoring stations. It is hoped that the Lebanese Government will follow up on our work and continue collecting data from those stations. It is urgently appealed to the Lebanese Government to create a water resources monitoring and assessment agency under the Ministry of Energy and Water.

Another critical issue is the lack of geoscientific expertise. Lebanon is one of the few countries worldwide affording not to have a geological survey. Hydrogeology is practically not taught at any Lebanese university. The consequence is that geoscientific and specifically hydrogeological expertise is often not integrated into investment planning, e.g. for wastewater projects, while one of the main reasons for such projects is to protect groundwater resources from pollution.

Using the equipment installed by the project, it was possible to assess the water balance for the Jeita groundwater catchment. The extent of this groundwater catchment was formerly totally unknown and it was believed that it must be similar to its surface water catchment, a very wrong assumption. The basic lesson learnt from the project is that more efforts need to be undertaken to study the groundwater system because groundwater is the most important source for drinking water and for the development of Lebanon.

To safeguard the quality of groundwater resources must be a national priority.

1 Introduction

The assessment of the water balance is the basis for a sustainable water resource management in a catchment. Jeita spring is the largest spring of Lebanon. It discharges from a groundwater catchment that covers an area of 406 km² and reaches to the snow covered high plateau with elevations up to 2628 m asl. Because of the high degree of karstification in this groundwater catchment, groundwater plays a much more important role compared to surface water. The water balance prepared by the BGR project (SCHULER & MARGANE, 2013) is based on this groundwater catchment.

Apart from precipitation, evapotranspiration, and groundwater flow, the quantification of surface water runoff and spring discharge are most important for the water balance equation of a catchment. Surface water runoff is commonly low in highly karstified areas, such as the Mount Lebanon mountain range, as much of the surface water may infiltrate into groundwater. In karst areas it is important to understand this surface water – groundwater interaction and it has to be investigated where and how much surface water is contributing to this indirect groundwater recharge.

In the Nahr el Kalb surface water catchment stream flow is not perennial but lasts only from November/December to June/July. In the upper reaches of Nahr Ibrahim, however, stream flow is perennial, although runoff is fairly low during the period from September to November. The reason for this is that the two main springs which feed surface water runoff in Nahr Ibrahim, Afqa and Rouaiss, permanently discharge from the Upper Cretaceous aquifer.

Due to the civil war from the mid-1970s to 1990, only limited runoff data are available for Lebanon, making for example flood frequency analysis difficult (SENE et al., 2001). Also for the site selection and operation of wastewater treatment plants it is essential to know quantities of runoff, for example to estimate the impact of treated wastewater discharge on surface water and for estimation of peak flood levels to avoid flooding at WWTPs, most typically located in the valleys. Especially in (semi-)arid regions, like Lebanon, a proper understanding of the runoff processes, as well as long-term streamflow records of the main rivers and springs are important due to the limited availability of water in the region. Although there are some existing streamflow gauging stations in the project area, these are mostly not at the optimal locations, are poorly maintained, the profiles have never been cleaned, and the measured streamflow was calibrated only at the time of installation but not thereafter. Due to the general negligence to water monitoring, most stations are in a state of disrepair. It is therefore suggested to install at least two new runoff gauging stations, monitoring streamflow of the most relevant ephemeral rivers within the Jeita catchment. The required amount of investment, approximately 250,000 USD, is fairly low in light of the potential benefits for the society.

Much of surface water runoff, generated in the catchments of Mount Lebanon, is discharged to the sea without being used. There is a large potential to make use of surface water either for domestic water supply or irrigation if the right locations for storage dam or artificial recharge dams (MAR) are chosen. However, this needs hydrological data which are representative for the envisaged site and a very thorough investigation of the geology and hydrogeology at potential dam sites. Due to the karstic nature of the terrain, hydrological investigations are needed to find out where surface water infiltrates into groundwater (effluent) and where rivers are fed by groundwater (influent). Some of those infiltration zones have been successfully located by the project by means of differential discharge measurements along river courses.

2 Project Area

The Nahr el Kalb surface catchment is located in central Lebanon and covers an area of 249 km². Elevation ranges from 60 m asl at Jeita Spring to 2628 m asl at Mount Sannine. Mean altitude is around 1475 m asl. However, as hydrogeological investigations have shown (MARGANE, 2012a, 2012b; MARGANE & DOUMMMAR, 2012, MARGANE et al., 2013), the groundwater catchment of Jeita spring covers only 65 % of the Nahr el Kalb surface water catchment, i.e. those parts north of Nahr el Kalb and Nahr es Hardoun. The Jeita GW catchment, altogether having a size of 406 km², also covers around 50 % of the neighboring surface water catchment to the north, Nahr Ibrahim (Figure 1). Due to the geological structure and tectonics, the groundwater catchment is significantly different from the surface water catchment, as is valid presumably for all catchments of the Mount Lebanon mountain range.

2.1 Climate

The climate in the Jeita spring catchment is strongly influenced by the Mediterranean Sea with winter precipitation from December to March and a dry season in the summer from June to October.

Currently collection of meteorological data in the Jeita catchment is only rudimentary (Figure 1). Inside the catchment there are only two stations, one located at Faqra Club (1,690 m asl), operated by the National Meteorological Service (NMS), the other at Faraya, near Chabrouh dam (1,555 m asl), operated by University Saint Joseph (USJ). Another three stations are located near the catchment, at Kaslik University (40 m asl), Hemlaya (~ 790 m asl) and Qartaba (~ 1100 m asl). None of the existing stations, neither now nor in the past, are/were able to record precipitation in the form of snow, due to the absence of a heating system. As can be clearly seen, the existing stations are not well distributed over the catchment. There are no stations at elevations higher than 1,690 m asl as well as very few in the mid altitudes (400-1,400 m asl) and high altitudes (> 1,800 m asl), which makes it extremely difficult to assess the rainfall volume in the catchment. It must be assumed that more than 80% of precipitation falls as snow at altitudes > 1,800 m asl. Here the land surface is highly undulating, due to the presence of more than 2,000 dolines in the GW catchment. Because of these land surface features and the prevailing and often very strong winds from WSW during winter (Atlas Climatique du Liban), snow height is highly variable. Any attempt to calculate snow volume, and thus snow water equivalent (SWE), based on currently available satellite systems are therefore foredoomed to fail, as the required XYZ accuracy is insufficient.

New meteorological stations were purchased and installed by the BGR project. Due to problems concerning import and permissions for installation, as well as uncertain future maintenance issues installation was only finalized towards the end of the project. The locations for those meteorological stations are shown in Figure 1. In addition, five rainfall samplers were installed before beginning of the rainfall in autumn 2012. Those collect rain water samples for hydroisotope analyses (^{18}O, ^{2}H) every 1st and 16th of the month but were also used to assess rainfall amounts during these periods (Figure 2).

The only valid previous meteorological assessment was done by FAO & UNDP (1973). The rainfall distribution based on this assessment is shown in Figure 3. The isohyetes were slightly modified in the plateau area, as it was recognized that commonly snow height decreases towards northeast, i.e. in the main wind direction. Other rainfall distribution maps, such as the one prepared by NMS (1977; Atlas Climatique, 2nd Edition) did not use the main criteria: prevailing wind direction and topography but are simple interpolations without using any criteria and are therefore unrealistic. Noteworthy is the fact that they highly underestimate precipitation at altitudes higher than 1,600 m, i.e. in all of the snow covered areas.

Because none of the stations operated by NMS can register precipitation falling as snow, due to the fact that they are not equipped with a heating system, not only the current but also all previous precipitation measurements at elevations > 800 m give wrong amounts of precipitation. During the snow sampling campaign for hydroisotope analyses in winter 2011/12, it was recognized that snow height partly reaches more than 10 m. Much of this snow accumulation in depressions or less wind exposed locations is caused by snow drift.

Figure 1: Preexisting (blue) and new (green) meteorological stations installed by BGR in the Jeita groundwater catchment

Figure 2: Rainwater sampling sites for stable isotope analyses in the Jeita groundwater catchment

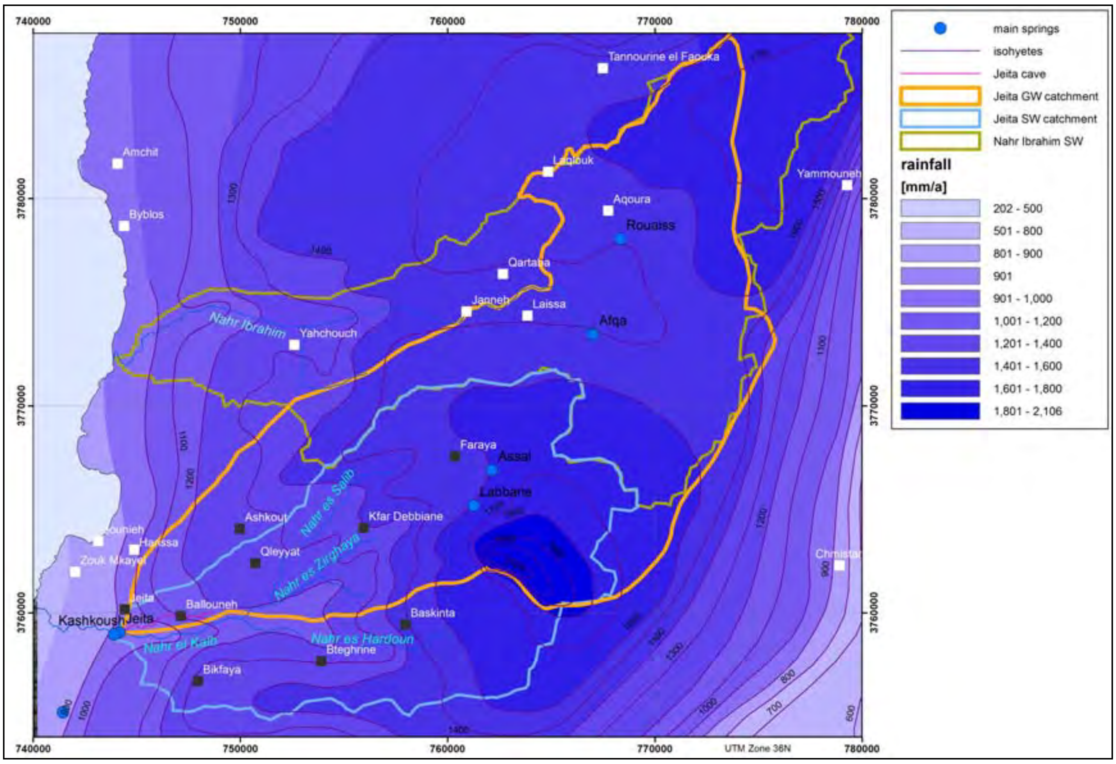

Figure 3: Rainfall distribution in the Jeita groundwater catchment (modified after FAO & UNDP, 1970)

2.2 Geology

The only previous available geological information from the project area (GW catchment of Jeita spring) was the geological map of DUBERTRET (1955) at scale 1:50,000. Field surveys conducted at the beginning of the project showed, however, that certain areas were not mapped correctly. Also the map was not detailed enough. For this reason the geology was mapped completely new by the BGR project (HAHNE et al., 2011; MARGANE et al., 2013). During the course of the project the boundaries of the GW catchment were changed several times, due to the results obtained from tracer tests (MARGANE et al., 2013). The first geological map (HAHNE, 2011) was prepared for the surface water catchment, which previously (UNDP, 1970) was assumed to be approximately the same as the groundwater catchment. The second geological map (MARGANE et al., 2013) shows only the geology in the Jeita GW catchment, as defined in May 2012 (Figure 4).

A lithostratigraphic classification of the geological units occurring in Lebanon was prepared by WALLEY (2001) (Fig. 5). The predominant units are the Sannine (C4) and Keserwan (J4) limestones. Those are affected by an intensive karstification (ABI RIZK & MARGANE, 2011). An extended karst network has developed in those two limestone units. The factors leading to the development of such an extended karst network are:

- both, the Jurassic and Upper Cretaceous limestones were exposed over a very long period;
- during the Quaternary the areas higher than ~ 800 m asl were covered by glaciers, leading to an intensive karstification, especially of the C4 and the uppermost J4 geological units;
- the entire Mount Lebanon mountain range was affected by intensive tectonic movements and 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.

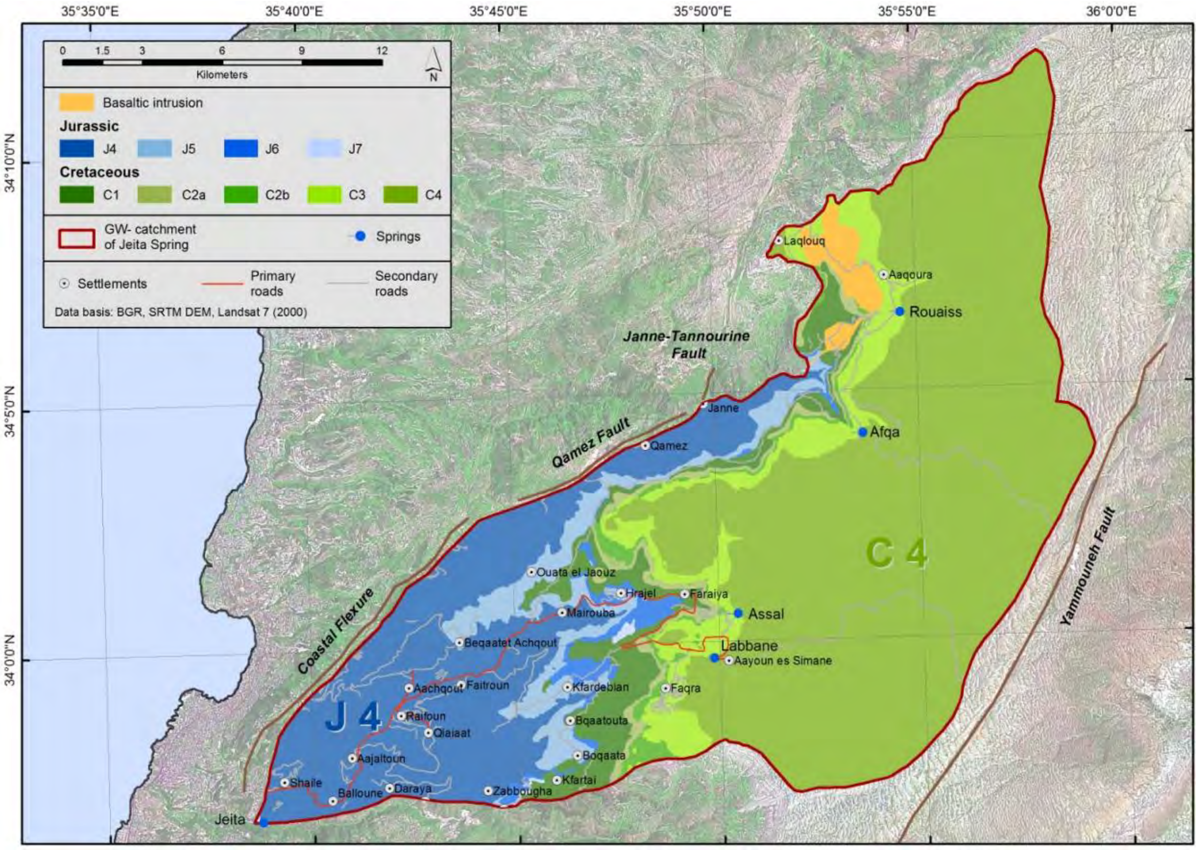

Figure 4: Geological map of the Jeita groundwater catchment

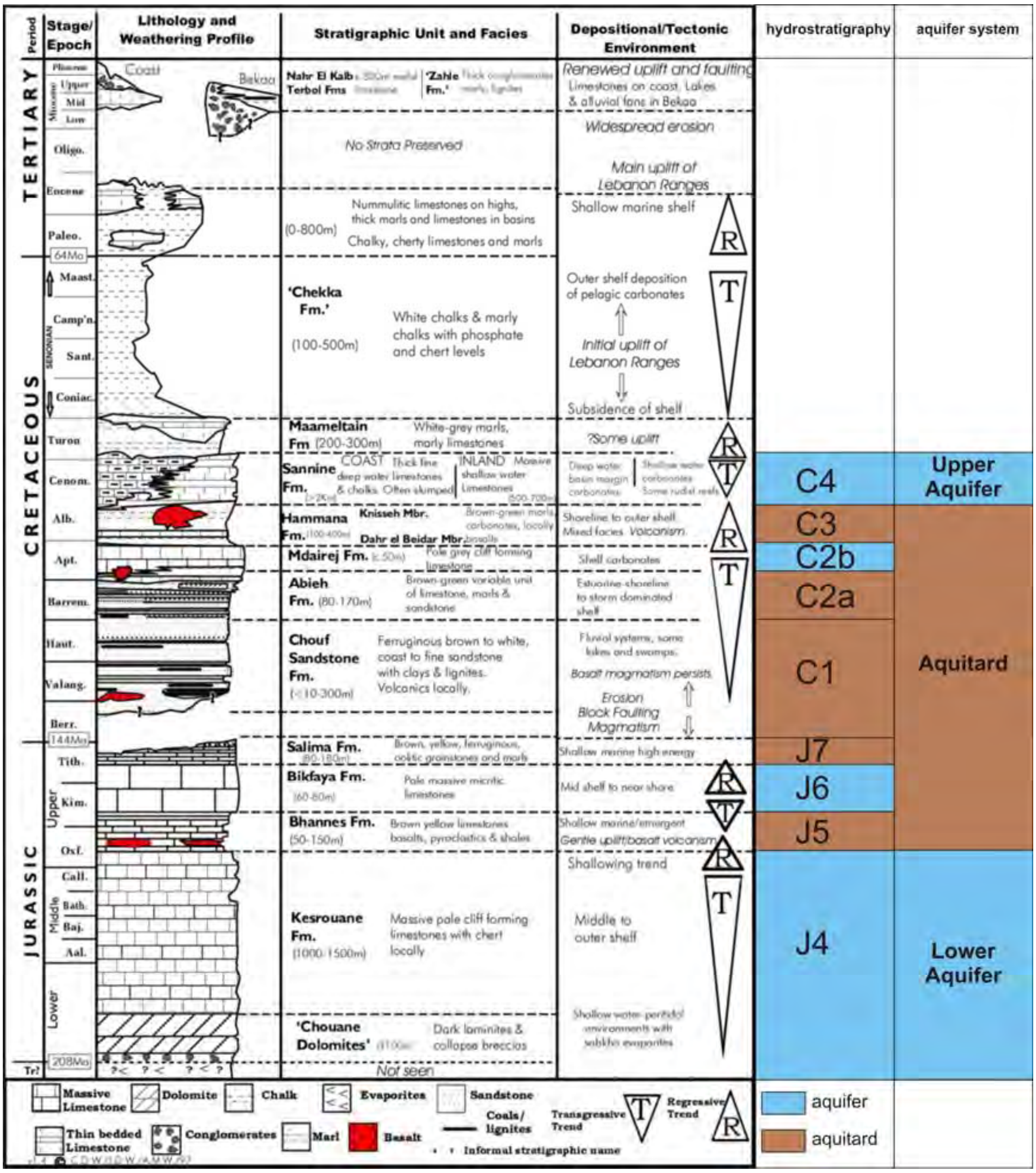

Figure 5: Geological and hydrogeological units and aquifer classification (modified after WALLEY, 2001)

2.3 Hydrogeology

Due to their thickness and extensive development of karst network, the Upper Cretaceous Sannine Formation (C4) and the Jurassic Keserwan Formation (J4) play the most important role in the groundwater system and for water supply. All other units are of comparably low thickness, less karstified and of less importance for water supply. There is a clear hydrogeological separation between the C4 and the J4 units, caused by low permeability in many of the units between (especially J5, C1, C2a, C3), which principally act as an aquitard. The intercalated aquiferous J6 (thickness is mostly much less than the 60-80 m specified in Figure 5) and C2b (thickness often not even reaching 20 m) units are of no relevance and often separated from the underlying J4 aquifer. The groundwater system can therefore be simplified (Figure 6):

- Lower Aquifer: J4
- Aquitard: J5-C3
- Upper Aquifer: C4

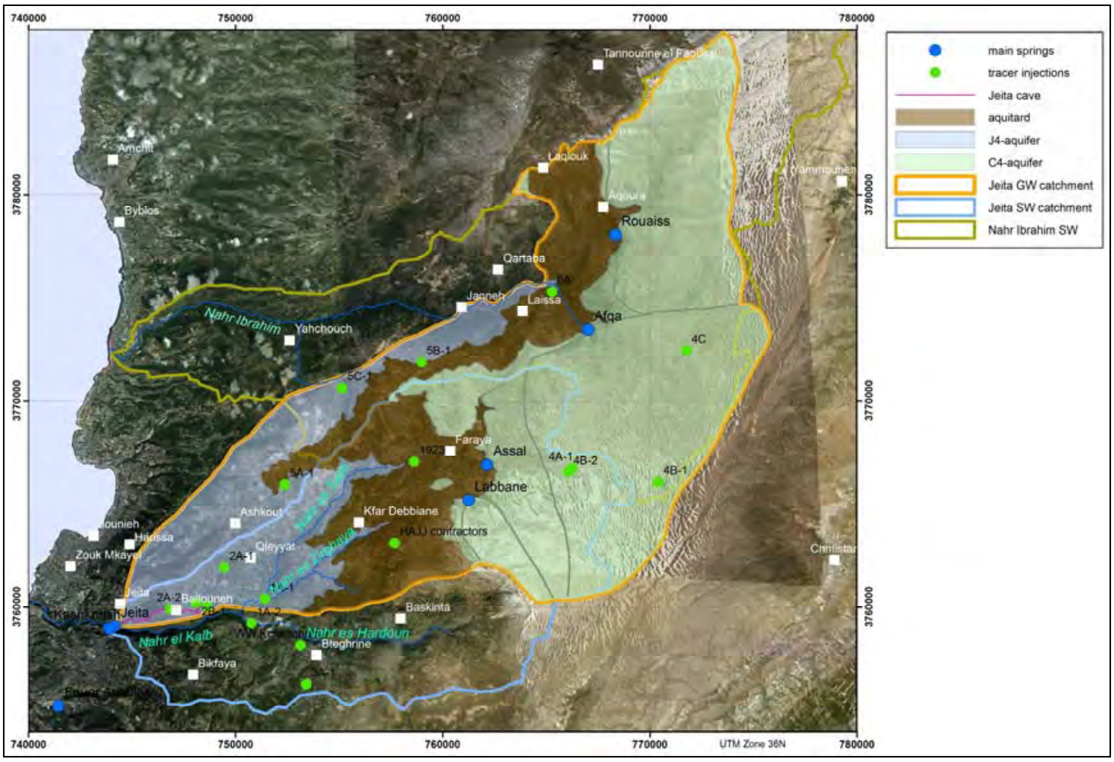

Figure 6: Subdivision of Groundwater System

(J4 - Lower Aquifer, C4 - Upper Aquifer)

A borehole inventory is currently not available. However, available information suggests that well over 700 private groundwater wells exist in the catchment (UNDP database; personal communication). There are no water level data, no drilling depth data and few coordinates to those wells so that unfortunately almost no water level information is present for the Jeita groundwater catchment.

The groundwater catchment has been delineated based on a number of tracer tests (MARGANE et al., 2013; Figures 6, 7). Groundwater flow velocities mostly are between 70 and 200 m/h but at times of peak flow can reach up to almost 2,000 m/h (MARGANE, 2011).

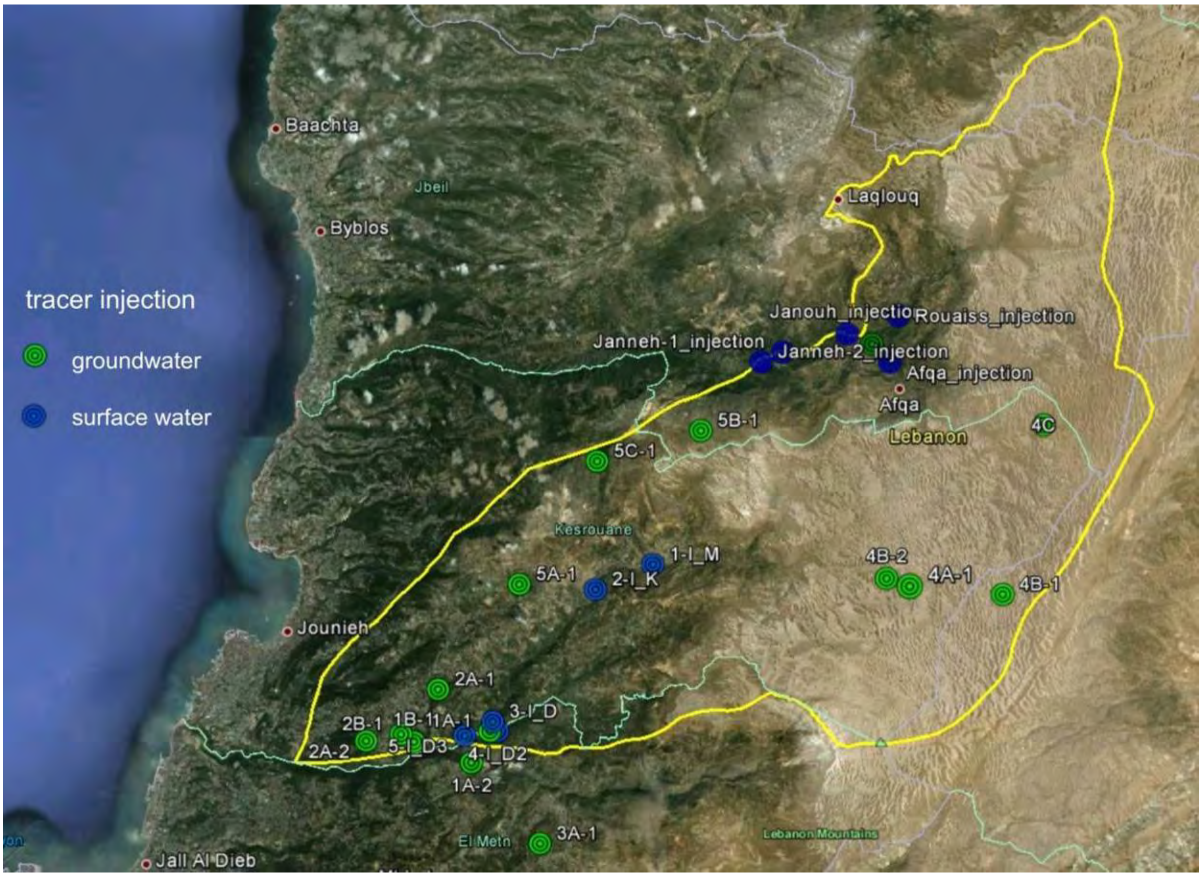

Figure 7: Boundary of Jeita groundwater catchment based on tracer tests

(remark: numbers refer to tracer tests documented in MARGANE et al., 2013)

2.4 Hydrology

The surface and groundwater catchments of Jeita spring are considerably different. (Figure 8). The reason is the geological structure as well as extended tectonic elements and lithological boundaries (basalt intrusions) which block groundwater flow and thus constitute hydraulic barriers. The Jeita groundwater catchment comprises around 50% of the neighboring Nahr

Ibrahim surface water catchment and does not comprise the southern part of the Jeita surface water catchment (Nahr el Kalb), where flow must partly be directed to Nahr Beirut.

This report refers to the available surface water in the Jeita groundwater catchment. Luckily the Nahr el Kalb surface water catchment represents the catchment with most streamflow gauging stations in Lebanon. Many of those stations are fairly old and date back to the French Mandate. Some stations were recently (2009) equipped with modern technique (electronic data recorders and loggers). All surface water gauging stations and springs in the Jeita surface and groundwater catchments are monitored by Litani River Authority (LRA). Details to those stations are documented in Chapter 3.1.

Within the Jeita surface water catchment of 249 km² four major sub-catchments can be distinguished: These are from north to south the Nahr es Salib (92.3 km²), the Nahr es Zirghaya (47.8 km²), the Nahr es Hardoun (48.8 km²) and the Nahr el Kalb (60.1 km²) catchments (see Figure 9).

A considerable part of the Jeita groundwater catchment is part of the Nahr Ibrahim surface water catchment and not monitored. Another major part belongs hydrologically to the valley between Aajaltoun and Harissa. Also large parts of the Nahr ed Dahab valley belong to the Jeita GW catchment. Flow in all those smaller surface water catchments is unmonitored.

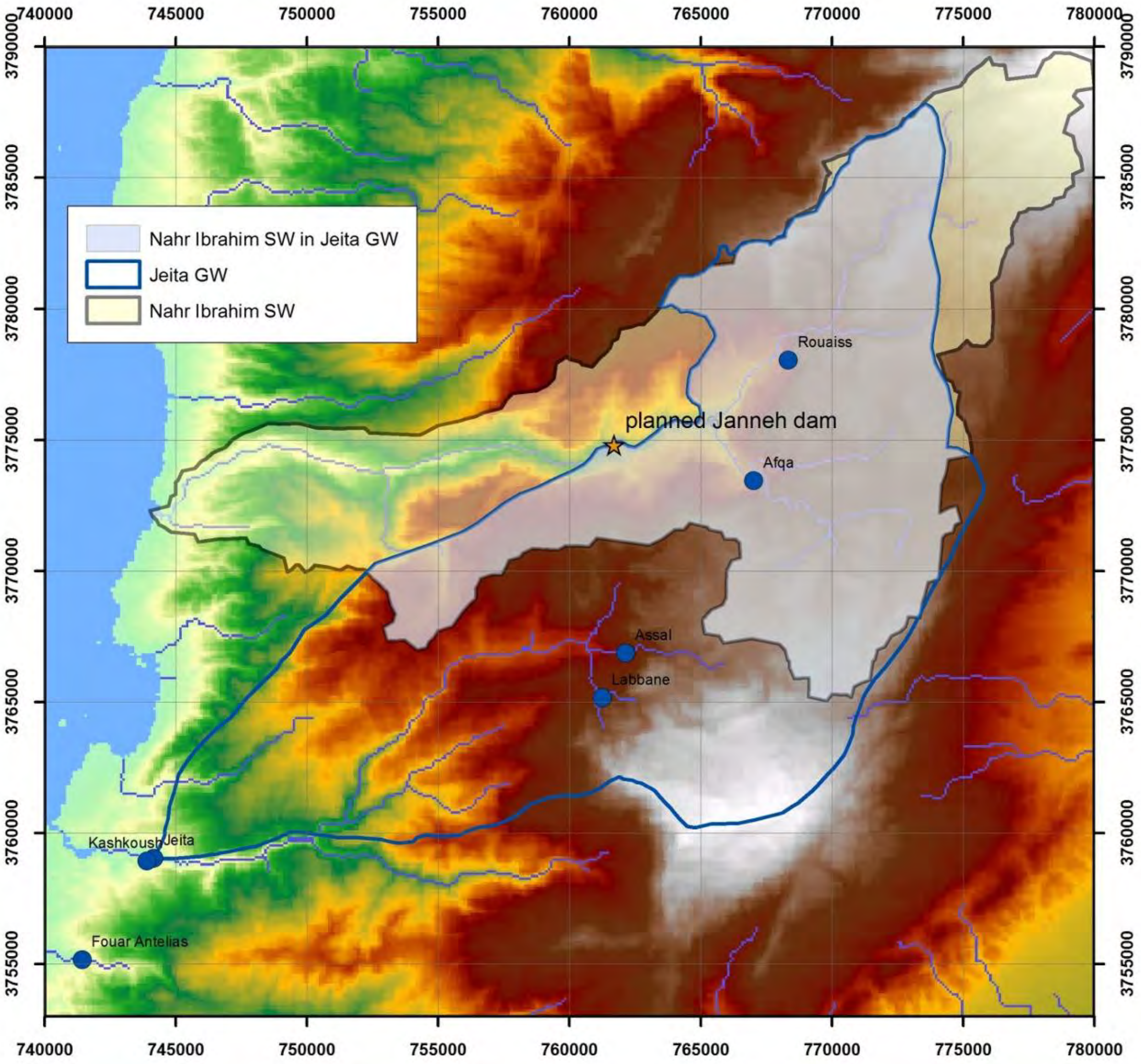

Figure 8: Large parts of the Nahr Ibrahim surface water catchment are part of the Jeita groundwater catchment

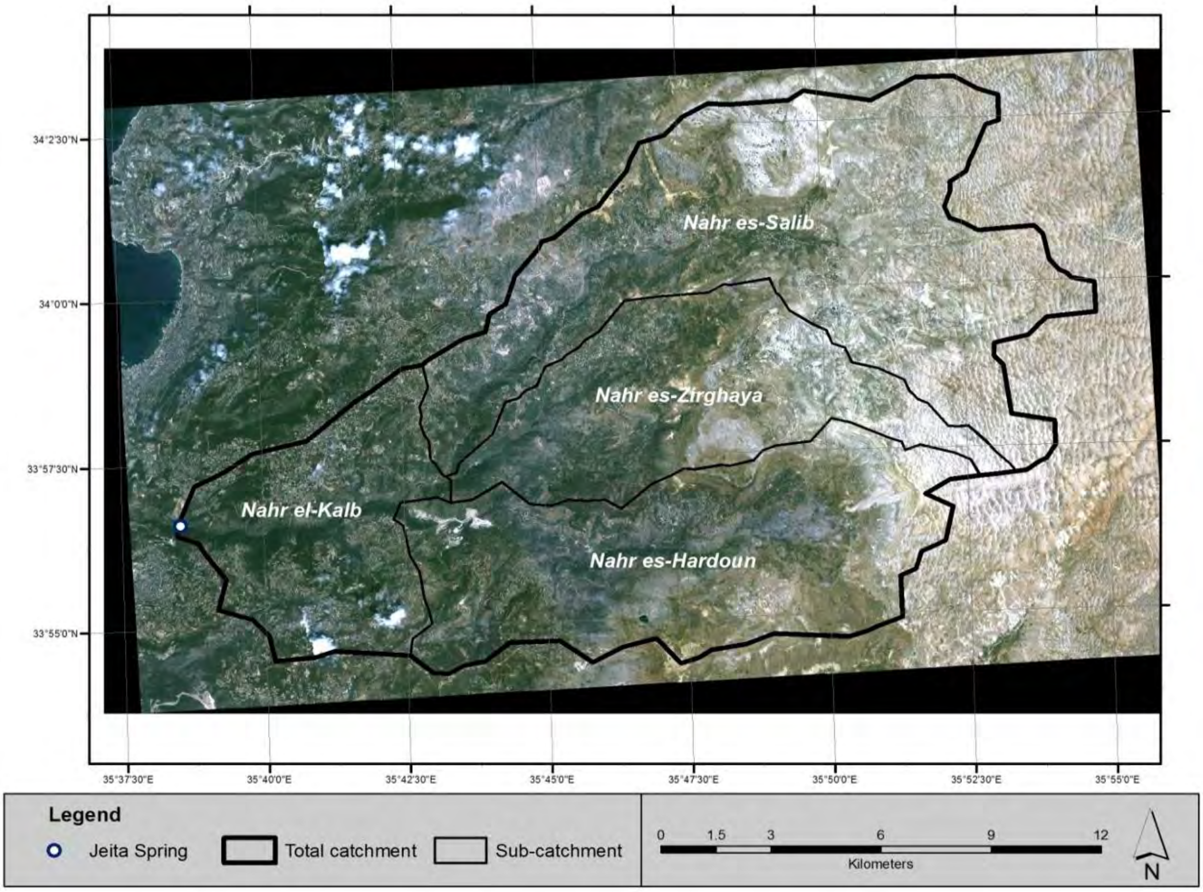

Figure 9: The Jeita surface water catchment and its sub-catchments

2.4.1 Springs

Jeita is the main spring in Lebanon and has the highest discharge in the catchment. It is the main source (~75%) of water supply for the capital Beirut and is thus of major strategic importance for the entire country. Based on previous measurements mean discharge of Jeita spring was assumed to be around 160 MCM/a (MARGANE, 2011; 80 – 290 MCM/a during water years 1966/67 – 1973/74). However, the related flow measurements were conducted at random and are thus inaccurate. Also it is not mentioned how and where flow was measured. According to UNDP (1972), flow at Jeita spring (= Jeita 60) was calculated based on correlation formula for Jeita 140 and Nahr el Kalb and can thus not be correct.

There are several small springs in the catchment, some of which are ephemeral. Two springs in the Nahr es Salib catchment are of relevance for water supply: Labbane and Assal with annual (2002- 2007) discharge rates of

25 to 55 MCM and 15 to 40 MCM, respectively (based on LRA records). Flows and water levels were recorded manually at irregular time intervals (often > 1 month) and used for calculation of monthly mean flow values by Litani River Authority. However, because water levels change quickly as a result of rainfall or snowmelt events within one month, random flow values cannot be representative for monthly flow volumes. At most springs water level – flow correlations are based on very few actual flow measurements and may therefore not be valid. Sometimes flow profiles changed over time and flows were not recalibrated. Often gauging stations are dilapidated and would need to be repaired and recalibrated. During snowmelt flow velocities at Labbane spring can reach up to more than 4 m/s for a short time period and flow can then not be recorded by propeller. Flow volumes are therefore very difficult to measure during peak flow using only random and discontinuous manual measurements. Moreover, due to the turbulent flow in most profiles, it is difficult to determine flow velocity by propeller measurements, the method used by LRA.

To overcome these problems, the BGR project tried to conduct flow measurements based on dilution tests. These can reach a much better accuracy, provided that dilution is perfect. For a perfect dilution the distance between injection and monitoring needs to be adequate. For high flow velocities, however, this could not be achieved, so that the rating curves could only be established for relatively low flow velocities and not for peak flow conditions. Around 300 such dilution tests were conducted in the four major springs: Jeita, Assal, Labbane and Kashkoush.

Using the continuous water level records, available for Jeita, Assal, Labbane and Kashkoush spring since 07/2010, correlations between water level and flow, so-called rating curves, were prepared in late 2012 but proved to be only partially satisfactory. In October 2011 an acoustic Doppler current profiler (ADCP) system was installed in Jeita in a measured profile. The system allows continuous measurements of flow velocity to establish continuous flow volume records. Another ADCP system was installed in October 2012 in Assal spring. Using these records of flow velocities and water levels, better rating curves could be derived for the calculation of flow volumes and flow volumes were then recalculated for all existing water level data.

Depending on the configuration of the groundwater catchment, some springs are perennial (Jeita, Afqa, Assal, Kashkoush), while others are intermittent (Rouaiss, Labbane, Qana, Hadeeth).

The following major springs are present in the Jeita groundwater catchment

(Table 1). Before this study, their location and elevation was often never surveyed.

Table 1: Main springs in the Jeita and Neighboring groundwater catchments

Name	LONG	LAT	Altitude	Annual discharge [MCM/a]
Jeita** ***	35.641960°	33.943574°	60	172[1]
Afqa**	35.893295°	34.067753°	1280	123.2[2], 139[3]
Rouaiss**	35.909024°	34.108946°	1336	~ 96.6[3]
Assal**	35.838548°	34.009853°	1540	~ 24.2[1]
Labbane**	35.828435°	33.994725°	1644	~14.4[4]
Qana	35. 807340°	34. 043017°	1610	~5[3]
Hadeeth	35.814693°	34.050545°	1460	~
Maghara	35.800561°	34.012126°	1220	~
Outside catchment				
Kashkoush***	35.639015°	33.942773°	55	~50[3]
Fouar Antelias	35.611439°	33.909452°	75	~18
Yammouneh	36.022219°	34.125982°	1400	-
Rim	35.870403°	33.887666°	1270	-

** springs monitored by LRA, *** springs monitored by WEBML

There is no publication where trustworthy spring discharge volumes are mentioned. The assessment provided by KHAIR et al. (1992) does not specify where and how mean flow data were taken. Apart from this, their delineation of groundwater catchments is rather crude. The reason for this very basic lack of information and misunderstanding is that discharge at most springs was never appropriately monitored. The springs monitored by Litani River Authority (LRA) and by Water Establishment Beirut and Mount Lebanon (WEBML) in the Jeita groundwater catchment and Nahr el Kalb surface water

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[1] BGR continuous flow measurements (and WEAP model)

[2] LRA records

[3] BGR estimation (no flow measurements; based on WEAP model)

[4] BGR estimation (based on irregular flow measurements and continuous water level measurements)

catchment are marked in Table 1. In most cases, however, the stations were established based on a wrong concept e.g.:

- profile too wide, recorder at place where flow is commonly turbulent (Afqa spring); or
- profile too small, straight-line section too short (Assal, Labbane, Kashkoush)

It is highly unfortunate that the water utilities or responsible governmental agencies previously did not invest in water supply structures that would also be suitable to measure water quality and quantity.

Figure 10: Location of relevant springs in the Jeita groundwater catchment and neighboring catchments

2.4.2 Rivers

Nahr el Kalb is the main river in the catchment, flowing from east to west, and discharging into the Mediterranean Sea. Sub-branches of Nahr el Kalb are: Nahr es Salib, Nahr es Zirghaya and Nahr es Hardoun (Figure 9). Under natural conditions, Nahr el Kalb receives water from the Assal, Labbane, Jeita and Kashkoush springs. However, much of this spring water is used either for drinking water supply or irrigation. Compared to Nahr es Salib and Nahr es Zirghaya, the Nahr es Hardoun seems to be of minor importance for the generation of total river discharge because it receives less snowmelt, due to its topographic situation. River beds are preserved in their natural shape and often contain large blocks of rocks with diameters of up to 3 meters. The gradients of Nahr el Kalb, including both branches, Nahr es Salib and Nahr es Hardoun, and Nahr Ibrahim are shown in Figure 12.

The following streamflow gauging stations are available in the Nahr el Kalb surface water catchment (Table 2; Figure 11):

Table 2: Streamflow gauging stations monitored by LRA in the Nahr el Kalb and Nahr Ibrahim surface water catchments

Name	IDN	LONG	LAT	Elevation [m asl]	
Nahr el Kalb – Sea mouth	228	35.606154°	33.950668°	12	
Nahr es Salib – Daraya	226	35.720599°	33.953806°	557	
Nahr es Salib – Hrajel	224	35.786458°	34.010501°	1178	
Nahr Ibrahim – Sea mouth	223	35.645278°	34.062778°	3	
Nahr Ibrahim – Rouaiss branch	222	35.895371°	34.106385°	1090	

Modified after LRA (Litani River Authority)

Figure 11: Stream flow gauging stations monitored by LRA in the Nahr el Kalb and Nahr Ibrahim surface water catchments

(yellow line: Jeita GW catchment; green line: Nahr Ibrahim SW catchment; blue line: Nahr el Kalb SW catchment)

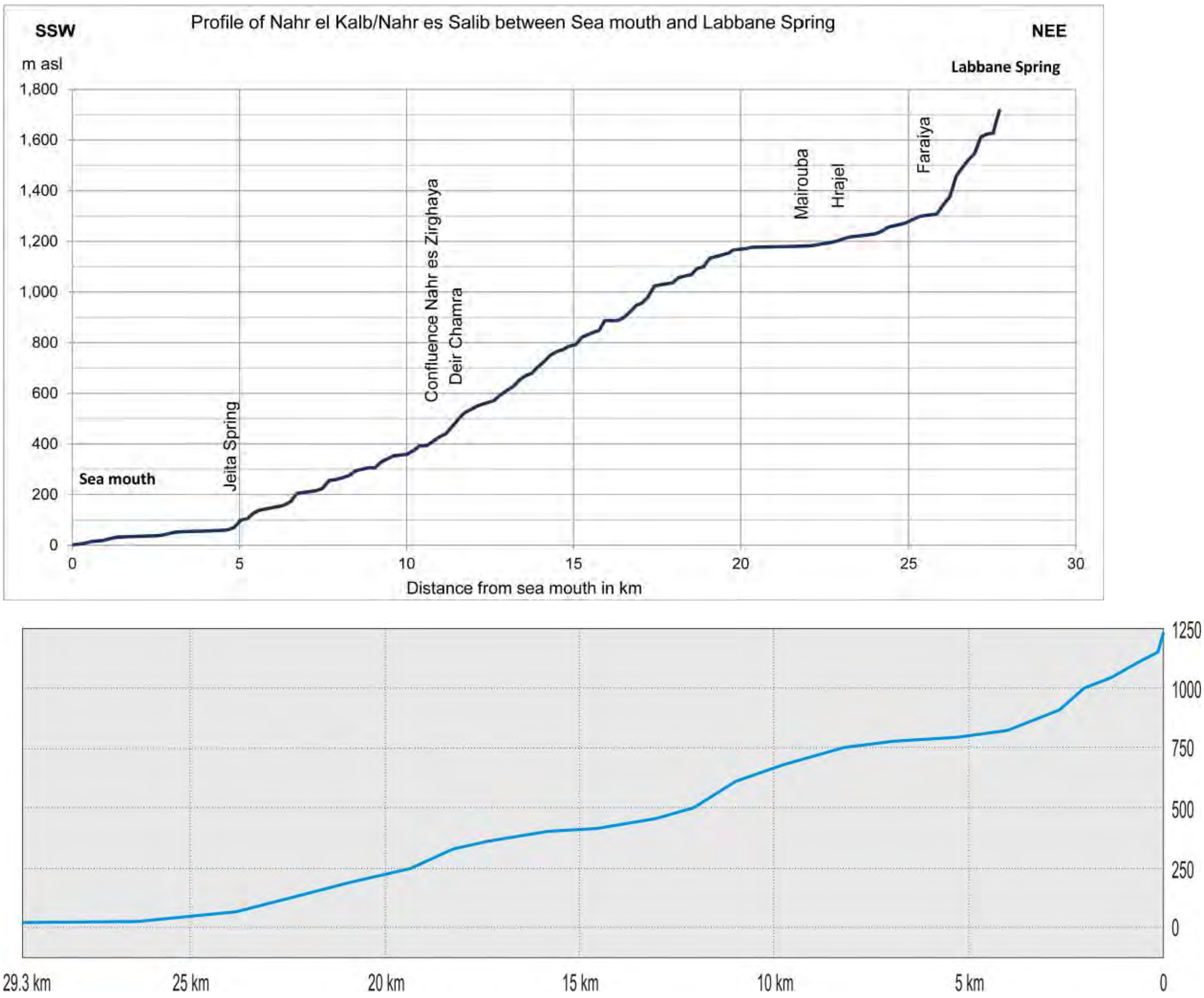

Figure 12: Gradients of Nahr el Kalb (up) and Nahr Ibrahim (down) rivers

As mentioned before, the Jeita groundwater catchment covers only the part north of Nahr es Hardoun of the Jeita surface water catchment. Fortunately, the boundary of the groundwater catchment is located close to streamflow gauging station 226 Daraya on the Nahr es Salib branch. Most of the surface water leaving the groundwater catchment is monitored here. But the Jeita groundwater catchment also covers around 50% of the neighboring surface water catchment to the north, Nahr Ibrahim. Surface water flow of Nahr Ibrahim is only measured near the seamouth. None of its sub-branches is monitored. Therefore, determining the amount of surface water reaching the infiltration zone in the Upper Nahr Ibrahim (MARGANE, 2012a, 2012b) was done using the WEAP model for the entire catchment (SCHULER & MARGANE, 2013).

Surface water runoff in the Nahr el Kalb catchment was calculated by BGR (GITEC & BGR, 2011).

2.4.3 Dams

Chabrouh Dam is the only dam located in the project area. It receives only little direct runoff from its upper catchment and most water stored in the dam is transferred to it by a channel from Labbane spring. Chabrouh dam provides drinking water for the Keserwan district between Faraiya and Junieh.

Two further dams have been proposed in or near the Jeita groundwater catchment: Boqaata (Kanaan) dam (tendered spring 2013) and Janneh dam (Upper Nahr Ibrahim; start of construction: February 2013). The planning of both dams considerably lacks geoscientific expertise as pointed out by GITEC & BGR (2011) and MARGANE (2012a, 2012b). Both dams are located in groundwater infiltration zones in the uppermost J4 aquifer and will probably fail to reach the targeted stored volume due to expected leakage losses into the underlying J4 aquifer.

2.4.4 Channels

A series of irrigation channels exist in the project area. They transfer water for agricultural usage from the Assal, Labbane and Qana springs mainly in the upper part of the catchment, especially around the villages of Kfar Debbiane, Bqaatouta, Boqaata, Faraiya, Hrajel and Mayrouba. However, most of those channels are rather old and dilapidated. Also sediments tend to accumulate in the channels so that water starts to overflow at certain points. Maintenance of these channels is very time consuming and expensive. The agricultural use of water is concentrated in this higher part of the Jeita catchment, at elevations between 1200 and 1600 m asl, because of its favorable soils with a sufficient water holding capacity and the moderate summer temperatures. The irrigation period lasts from mid June to mid September and this is the main period when spring water is allocated mainly for agricultural uses. However, the increased use of springs, also during the irrigation period, for domestic water supply has forced farmers to install ponds for water storage during times when water is sufficiently available. In the Jeita GW catchment around 500 irrigation ponds with stored volumes of around 5,000-10,000 m^3 are present.

Another channel transfers surface water from an intake dam in Nahr es Salib in Hrajel and an intake station further down Nahr es Salib near an old part of the village of Kfar Debbiane to the villages of Faitroun, Raifoun, Kleyyat, Daraya, Aajaltoun and Ballouneh. However, not much water arrives at the lower end of the system and streamflow in Nahr es Salib lasts commonly only until June/July.

Water from Jeita spring is distributed a) from near the former Kashkoush power plant to an irrigation area in Jeita municipality downhill of Jeita Country Club and b) from Mokhada via the so-called Wata canal to the municipalities of Zouk Mosbeh and Dbayeh. However, water uses from the Wata canal are more of industrial and commercial nature and not anymore for agricultural purposes as in the past.

A major closed canal connects Jeita spring with the Dbayeh drinking water treatment plant. This canal is also more than hundred years old and leaky. Tracer tests (GITEC & BGR, 2011) have shown that around 30% is already lost in the first third of the channel.

At Labbane Spring another channel transfers water to the Chabrouh dam during high flows following snowmelt (see 2.4.3). Around two thirds of the water from Labbane spring are used to fill Chabrouh dam. Another large quantity leaves Labbane spring during peak flow without being used, so that only a small proportion of water from Labbane spring is used for irrigation.

A survey of irrigation canals (SAADEH & MARGANE, 2013) and a water balance model using WEAP (SCHULER & MARGANE, 2013) have been prepared by the project, the results of which are not included in this report.

3 Analysis of existing data

Data of seven monitoring stations in the Nahr el Khalb catchment and two locations in the Nahr Ibrahim catchment are available. Litani River Authority (LRA) is responsible for most surface water and spring discharge monitoring stations in Lebanon and has conducted recording of daily streamflow data since the mid 1960s. Streamflow data from these stations are available since 1949/50 and were provided by LRA. However, there are huge data gaps during and after the civil war and there is a high uncertainty due to the applied measurement techniques so that there is not much confidence in these data. Water level data are not stored digitally. In 2009 most stations in Nahr el Kalb were upgraded to digital data loggers (OTT Thalimedes).

3.1 Surface Water Runoff

Nahr el Kalb Catchment

Streamflow in the Nahr el Kalb catchment is measured at three stations, as shown in Figure 13. Surface water runoff in Nahr es Salib, the northern branch of Nahr el Kalb, is measured by Litani River Authority near Daraya (LRA; Figure 15). LRA Station 226 at Daraya (573 m asl) was monitored between 1967 and 1974. After the civil war measurements resumed in 1997 and are carried out until today, currently using an OTT pressure transducer. Runoff in this northern part of Nahr el Kalb calculated by LRA shows an average of 99 MCM per water year (WY) for all 13 water years with records and of 97 MCM for the continuously monitored time period 1997/98 - 2009/10 (Figure 17). Total surface water runoff in Nahr el Kalb was measured close to the seamouth (LRA station 228; located some 1.5 km from the sea) during a similar time period in the past but flow was much higher in the 1960/70s, compared to the more recent and complete time period of 1997/98 - 2009/10. Here average runoff for all 20 WY was 340 MCM, while it was only 170 MCM during the time period 1997/98 - 2009/10. At Daraya, however, average flows were more or less the same during both time periods. The early 1960/70 time period can therefore not be considered. Flow in the higher part of Nahr el Kalb (Nahr es Salib) is monitored at Hrajel (station 224), approximately 5 km downstream of the two springs Assal and Labbane.

Comparing the flows during the water years 1997/98 - 2009/10, about 73 MCM/a or 43 % of the total runoff constitutes runoff from the southern branch of Nahr el Kalb and the surface catchment between Deir Chamra and Mokhada. In this part of Nahr el Kalb surface water runoff is not monitored. Surface water runoff in the southern branch of Nahr el Kalb occurs mainly during January to April, while surface water runoff in the Nahr es Salib branch occurs during a longer time period (November to June). During May and June surface water runoff comes mainly from snow melt in the higher parts of the surface water catchment. Contribution from snowmelt in the southern branch is much less than in the Nahr es Salib branch because due to the geological structure the C4 does not contribute to discharge in this region (MARGANE et al., 2013).

There is a strong interannual variation of between 38 and 227% at the seamouth and of only between 36% and 164% at Daraya (Figure 17).

The average monthly distribution is shown in Figure 18. Peak runoff occurs commonly between February and April.

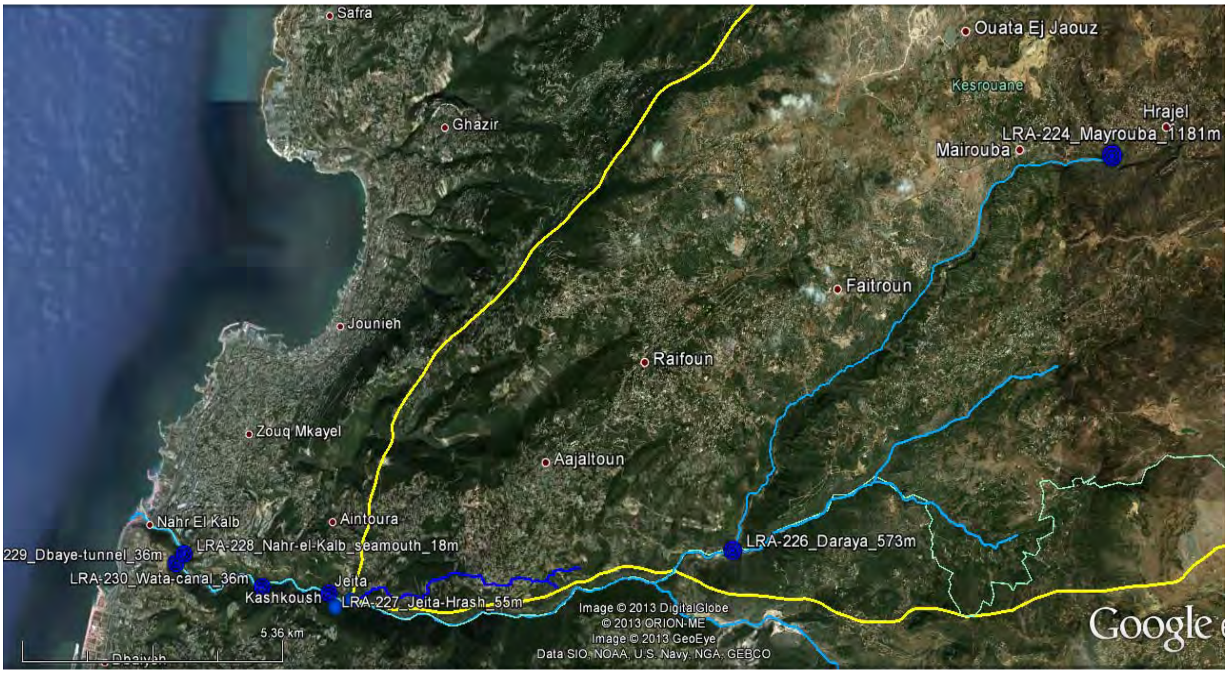

Figure 13: Location of streamflow monitoring stations in the Nahr el Kalb surface water catchment (compare Table 2)

Figure 14: Nahr el Kalb seamouth streamflow gauging station 228

Figure 15: Nahr es Salib Daraya streamflow gauging station 226

Figure 16: Nahr es Salib Hrajel streamflow gauging station 224

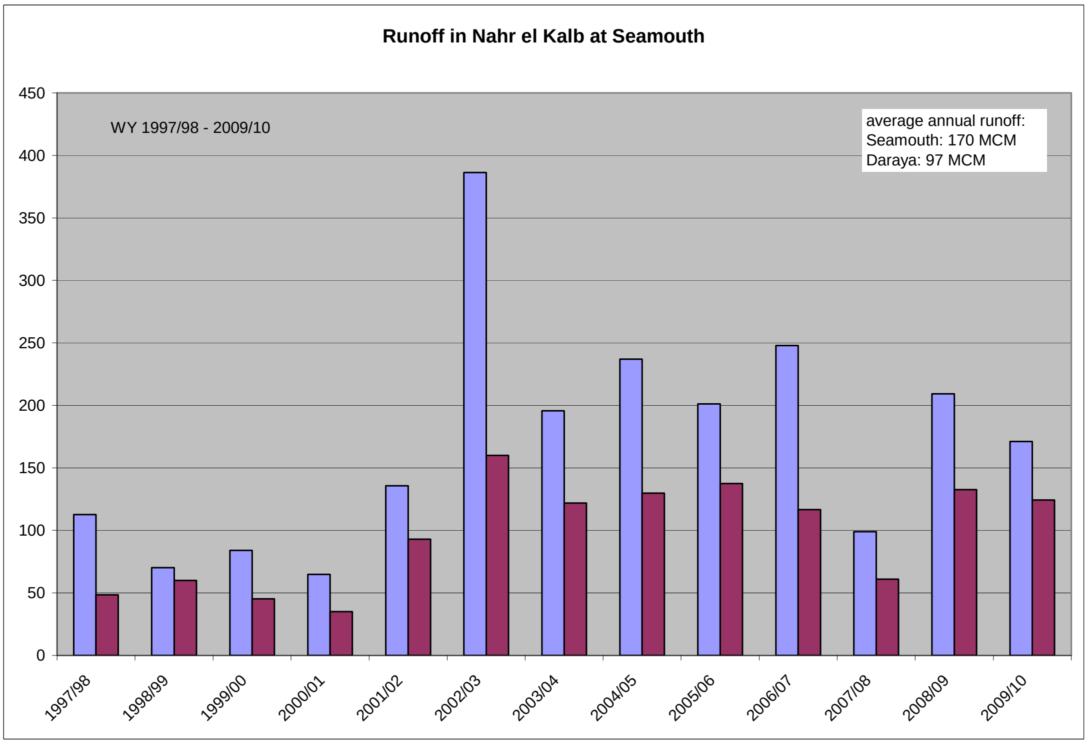

Figure 17: Annual Runoff (MCM) in Nahr el Kalb at Seamouth and at Daraya

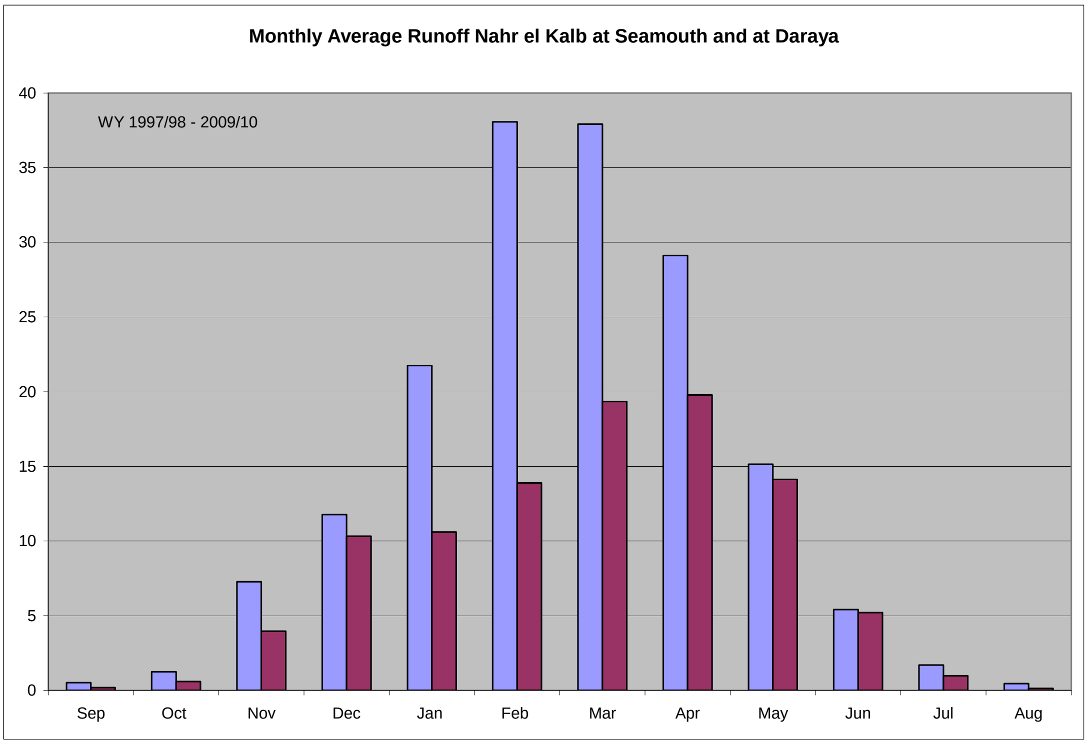

Figure 18: Monthly Average Runoff (MCM) in Nahr el Kalb at Seamouth and at Daraya

The installation of three Parshall flumes (USBR, 2001; see Chapter 5) is proposed by the BGR project to correctly measure runoff at certain locations. In the beginning it was planned to install three of these streamflow gauging stations but the required additional funds could unfortunately not be made available.

The data collected from the BGR and LRA stations were processed as shown in the following.

Spring Discharge Measurement

Spring discharge in the catchment is measured by LRA at the springs Jeita, Labbane, Assal, Rouaiss and Afqa.

LRA flow measurements of Jeita spring are not done at the spring itself but some 100 m downstream in the Jeita-Dbayeh canal (transmission mains; Figure 19). This canal can collect only a small proportion of Jeita spring flow so that it is not representative. During peak flow much of Jeita spring discharge is diverted to the river. Moreover, measurement takes place after water withdrawal by the Jeita pumping station, from where water is lifted towards Quornet el Hamra.

Discharge of Jeita spring (commonly referred to as Jeita 60) had until recently not been measured correctly. During the time period 1966/67-1973/74 the Office des Eaux de Beyrouth (OEB) had carried out measurements at the canal from Jeita to the Harash hydroelectric power plant. SALIBA (1977) gives the maximum amount to be diverted at this point as 15 m^3/s. Under current conditions this upper part of the canal can convey only a maximum of 4.3 m^3/s (GITEC & BGR, 2011). The previous flow measurement of OEB must have taken place at about the same place as the measurements carried out by LRA nowadays. The statement about a maximum capacity of 15 m^3/s, being almost 4 times as high as nowadays would thus seem completely unrealistic. Flow measurements were only made randomly (between once a week to once every two months, even during high flow periods) and amounts exceeding the maximum flow capacity of the canal and thus being discharged into Nahr el Kalb river at Jeita could not be measured.

Even measurements at the siphon terminale (commonly referred to as Jeita 140; SALIBA, 1977; UNDP, 1972), located some 5300 m upstream of the boat moorings and accessible through the Daraya tunnel probably also bear a high uncertainty due to the construction of the site. Reports documenting the construction of both sites and the calibration of the discharge measurements could not be found.

Completely unrealistic is the extrapolation by SALIBA (1977) of flows at Jeita 60 and Jeita 140 based on a correlation with flows in Nahr el Kalb, which have absolutely nothing in common.

Flow of Jeita spring is currently measured by LRA in the canal at the lower level of Jeita Grotto parking (Figures 19, 20). This measurement does not represent total flow of Jeita spring, because this measurement takes place after diversion of water exceeding the capacity of the intake (GITEC & BGR, 2011: max. 4.3 m³/s; only a max. of 3.1 m³/s actually arrives at Dbayeh after passing the tunnel). Measurements at this location only give the amount of water at the beginning of the conveyor before diversions and physical losses. Before entering the canal, however, access flow will be discharged at the diversion structure shown in Figure 21 where water is partly diverted to the river and partly to the Jeita irrigation canal. The threshold at which overflow in the outer dam starts is estimated at 6 m³/s.

Water Establishment Beirut and Mount Lebanon (WEBML) measures flow at Harash using a Marsh Mc-Birney FLO 450 flowmeter (http://www.hach.com/mmi) installed in 2003 through a CDR project.

The spring capture in its current configuration is the result of tinker work over almost 150 years (compare GITEC & BGR, 2011; Figure 24). Due to poor upkeep many parts are not operational anymore and only a minor quantity of the spring discharge can currently be captured. All old installations should therefore be removed and a new spring intake should be constructed (GITEC & BGR, 2011; Figure 25). Also it will be necessary to build new collector lines (there should be two separate lines, one on each side of the river with access roads for maintenance), and another larger tunnel. It is emphasized that there must be two separate and redundant conveyor lines, in case one of them is damaged.

Figure 19: Location Map showing Jeita Spring and the Infrastructure related to Jeita Spring Capture

Figure 20: LRA Discharge Monitoring Station at MAPAS parking

Figure 21: Diversion Dam

(irrigation water for the Kashkoush area is diverted into a small canal and water from Jeita can be discharged into Nahr el Kalb)

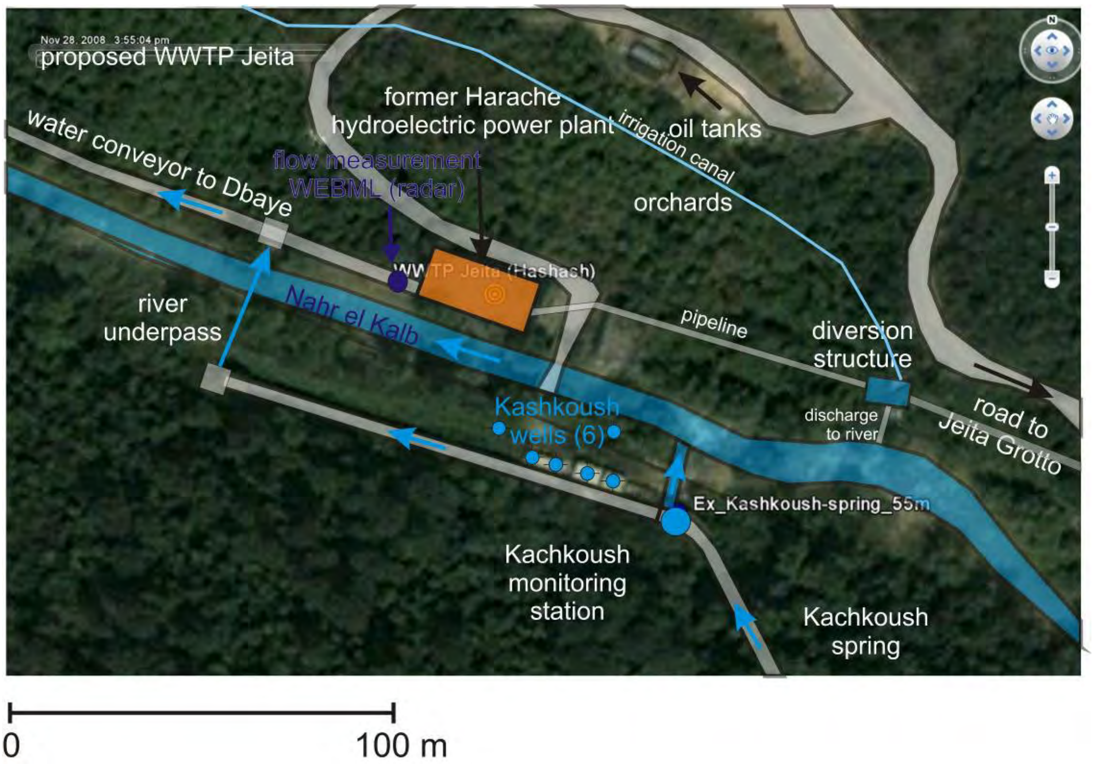

Figure 22: Location Map showing Kashkoush Well Field and Kashkoush Spring

Figure 23: Components of the Jeita - Dbayeh Transmission Mains

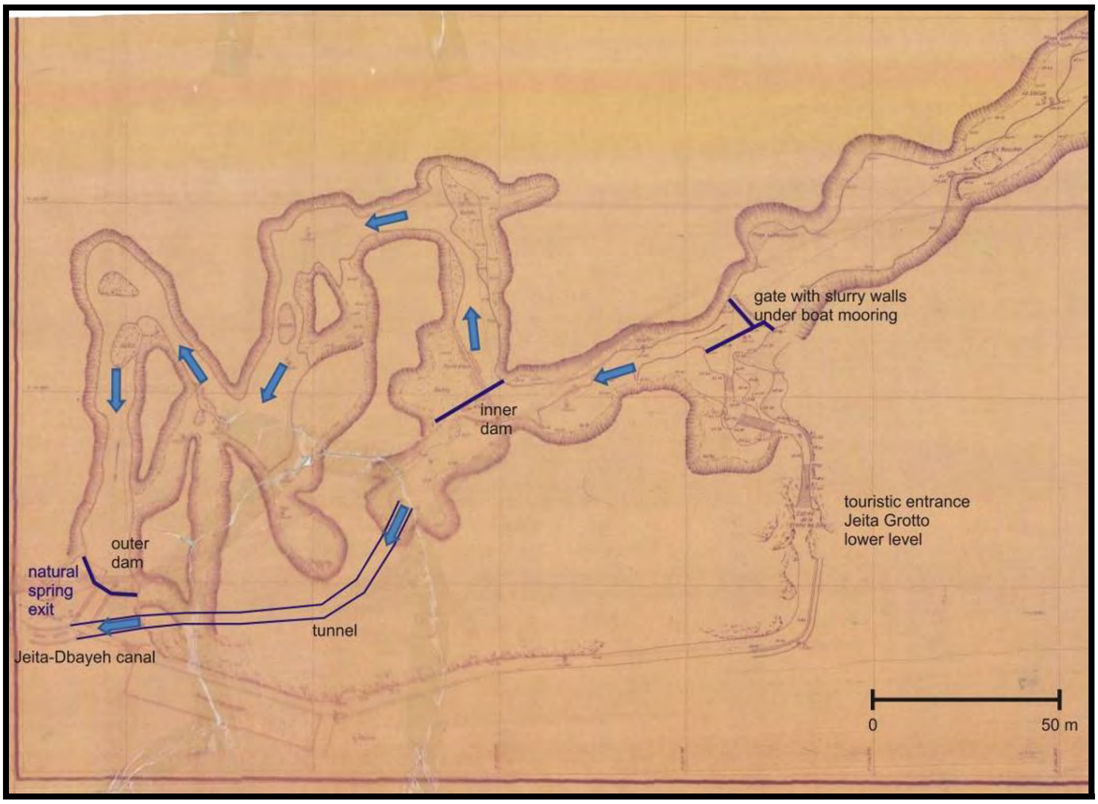

Figure 24: Jeita Spring Capture - Current Configuration

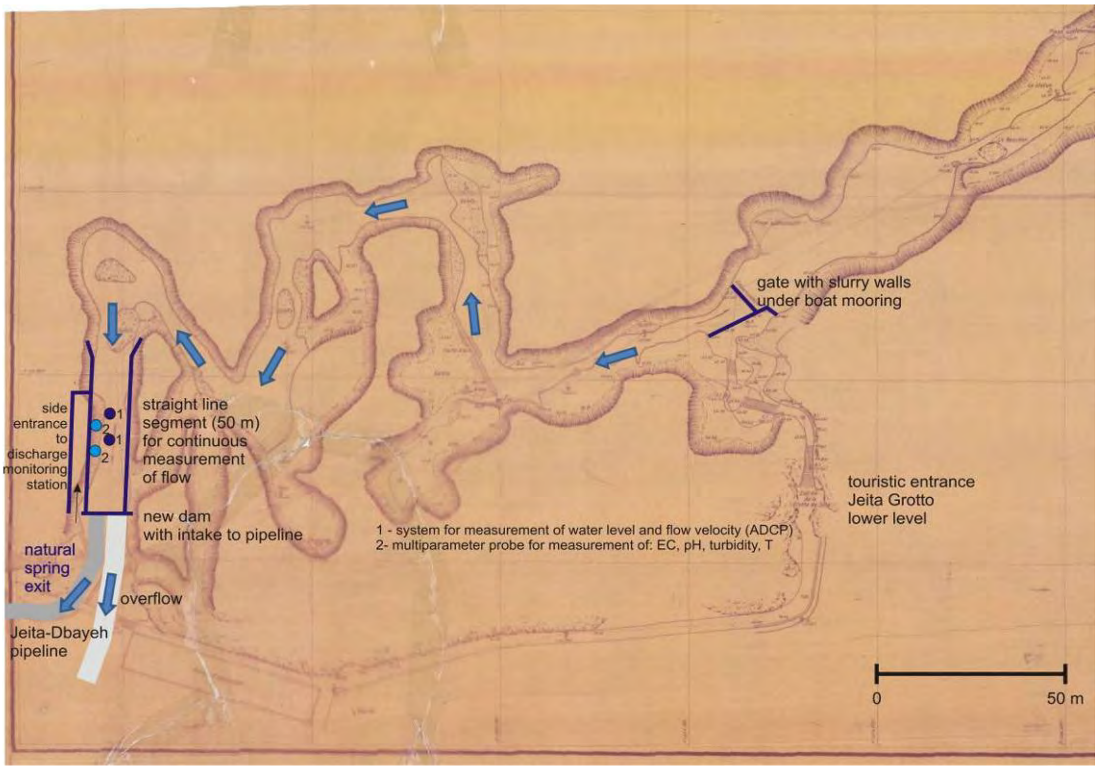

Figure 25: Jeita Spring Capture - New Configuration

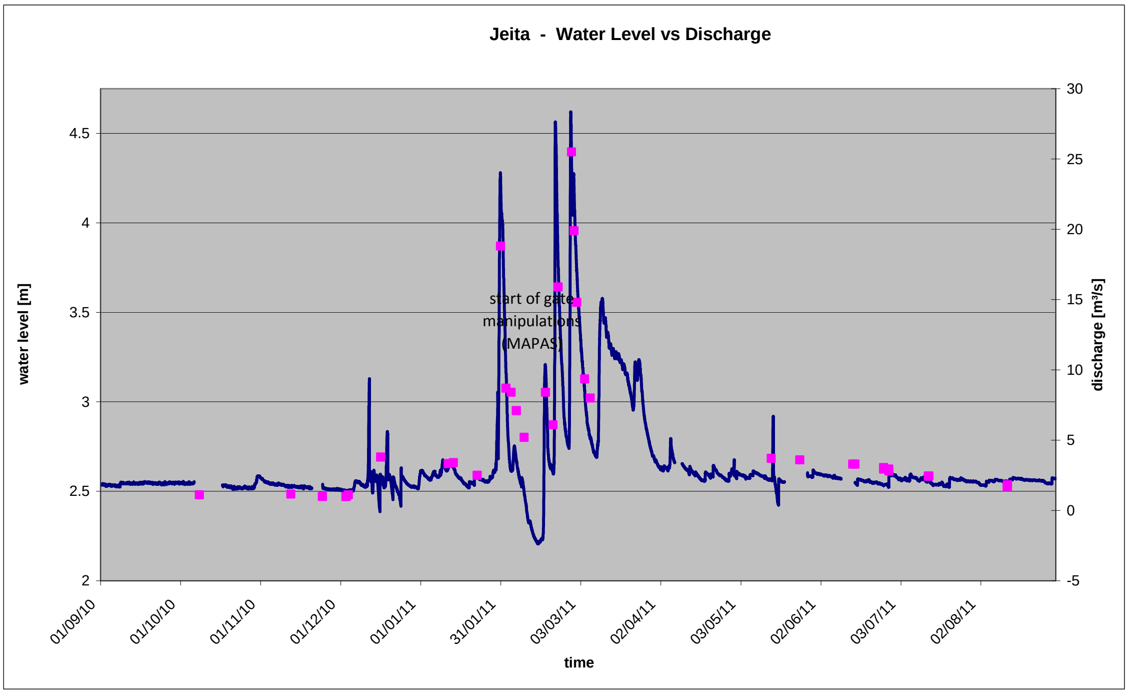

Figure 26: Water Level and Discharge of Jeita Spring during Water Year 2010/11

Spring discharge at Jeita was measured in the years between 1966 and 1973. No information about the method of data acquisition is available. An evaluation of spring discharge is available in ACE (1988) and was used as an initial assumption in the WEAP model prepared by BGR (SCHULER & MARGANE, 2013). At Labbane and Assal springs, monthly discharge data are available at least since 2002, however earlier data were not made available. Flow is measured by propeller, however sometimes, as e.g. at Hrajel, not at the location of the water level recorder. In the adjacent surface water catchment north of the Nahr el Kalb catchment, the Nahr Ibrahim surface water catchment, only one station at the seamouth measures flow. There are two other stations measured by LRA recording surface water runoff below the springs of Afqa and Rouaiss (MARGANE, 2012b), intended to record spring discharge. The Rouaiss spring discharge monitoring station (Figure 27), however, is located 1.4 km downstream of the spring and is not representative for spring discharge because it also receives a considerable amount of surface water runoff (GITEC & BGR, 2011). Furthermore, the Rouaiss station is in a very poor condition (Figure 27) and should not be used at all. It is recommended to establish a new station for Rouaiss spring discharge at the spring itself.

The water level recorded at the Afqa monitoring station 221 (Figure 28) is also not representative of spring discharge because it is located around 10 m upstream of the weir and in a highly turbulent place. Because of the desolate conditions and faulty concept, it is recommended to establish a new spring discharge monitoring station at Afqa spring.

Figure 27: Rouaiss spring discharge monitoring station 222

Figure 28: Afqa spring discharge monitoring station 221

Flows recorded by LRA at the Afqa and Rouaiss are displayed in Tables 3-4 and Figures 29-34. For the above mentioned reasons, measurements at both stations are not very reliable (MARGANE, 2012b).

Investigations conducted downstream of the Afqa and Rouaiss springs (MARGANE, 2012a, 2012b) show that surface water infiltrates into the uppermost, highly karstified section of the J4 geological unit and is believed to reach Jeita spring via a karst network. The infiltration zone is located near the confluence of the Afqa and Rouaiss branches of Nahr Ibrahim (Figure 35).

Table 3: Discharge of Afqa Spring Monitored by LRA during Water Years 2000/01 - 2009/10

	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	average
September	0.27	0.33	0.23	0.73	0.32	1.03	1.16	0.82	0.57	0.89	0.64
October	0.31	0.26	0.25	0.42	0.20	0.39	1.21	0.58	0.62	0.52	0.48
November	0.26	0.64	0.26	0.39	9.26	6.63	5.14	0.42	0.94	7.39	3.13
December	0.35	7.59	7.36	0.69	5.80	7.92	2.01	6.94	4.43	15.37	5.84
January	0.88	2.07	9.76	3.49	6.35	13.93	2.27	2.26	7.40	13.61	6.20
February	1.46	13.24	5.18	3.43	15.17	10.43	6.70	1.76	11.84	17.45	8.67
March	24.83	22.93	20.95	31.18	53.78	29.96	23.66	35.19	32.94	24.19	29.96
April	11.22	44.94	66.96	36.45	43.15	38.73	28.46	20.23	77.09	8.71	37.59
May	3.52	7.89	65.14	21.99	25.38	10.73	14.03	4.71	33.38	4.06	19.08
June	0.84	1.63	34.88	6.09	7.84	3.80	3.00	1.66	8.59	2.07	7.04
July	0.30	0.56	13.77	1.61	2.89	3.14	2.14	1.50	3.15	1.38	3.05
August	0.32	0.32	6.89	0.54	1.13	1.59	1.62	1.13	1.13	0.78	1.55
	44.55	102.40	231.63	107.03	171.26	128.27	91.39	77.21	182.08	96.43	123.22

Table 4: Discharge of Rouaiss Spring Monitored by LRA during Water Years 2000/01 - 2009/10

	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	average
September	0.61	0.55	0.36	0.76	0.51	0.40	0.49	1.07	1.24	0.25	1.31	0.62
October	0.64	1.52	0.52	0.45	0.33	0.70	0.79	1.44	1.69	0.45	0.76	0.85
November	0.57	1.58	0.51	0.64	9.39	3.94	7.49	1.41	2.03	3.51	1.29	3.11
December	1.01	6.22	2.80	0.69	10.59	5.23	1.21	12.05	4.78	7.88	3.58	5.24
January	3.40	3.14	11.27	4.78	14.37	18.01	2.00	2.11	11.18	11.36	9.89	8.16
February	4.86	14.22	15.31	10.53	21.73	19.38	15.74	3.06	17.92	36.54	33.68	15.93
March	25.74	17.60	21.93	41.89	63.90	79.93	61.17	30.74	46.09	21.94	61.82	41.09
April	12.52	24.72	50.45	44.02	96.80	131.32	54.71	13.57	72.42	6.42	58.04	50.69
May	2.30	5.59	52.23	24.52	28.70	42.86	20.00	6.56	31.72	3.78	17.94	21.82
June	0.81	1.58	19.07	3.43	3.95	2.93	2.84	1.90	7.46	1.67	2.24	4.56
July	0.49	0.73	4.93	1.49	1.04	1.28	0.97	1.25	2.93	1.66	0.51	1.68
August	0.34	0.54	2.63	0.96	0.69	1.14	0.66	1.32	2.21	1.61	0.50	1.21
	53.27	77.97	181.99	134.14	252.00	307.11	168.05	76.47	201.65	97.07		154.97

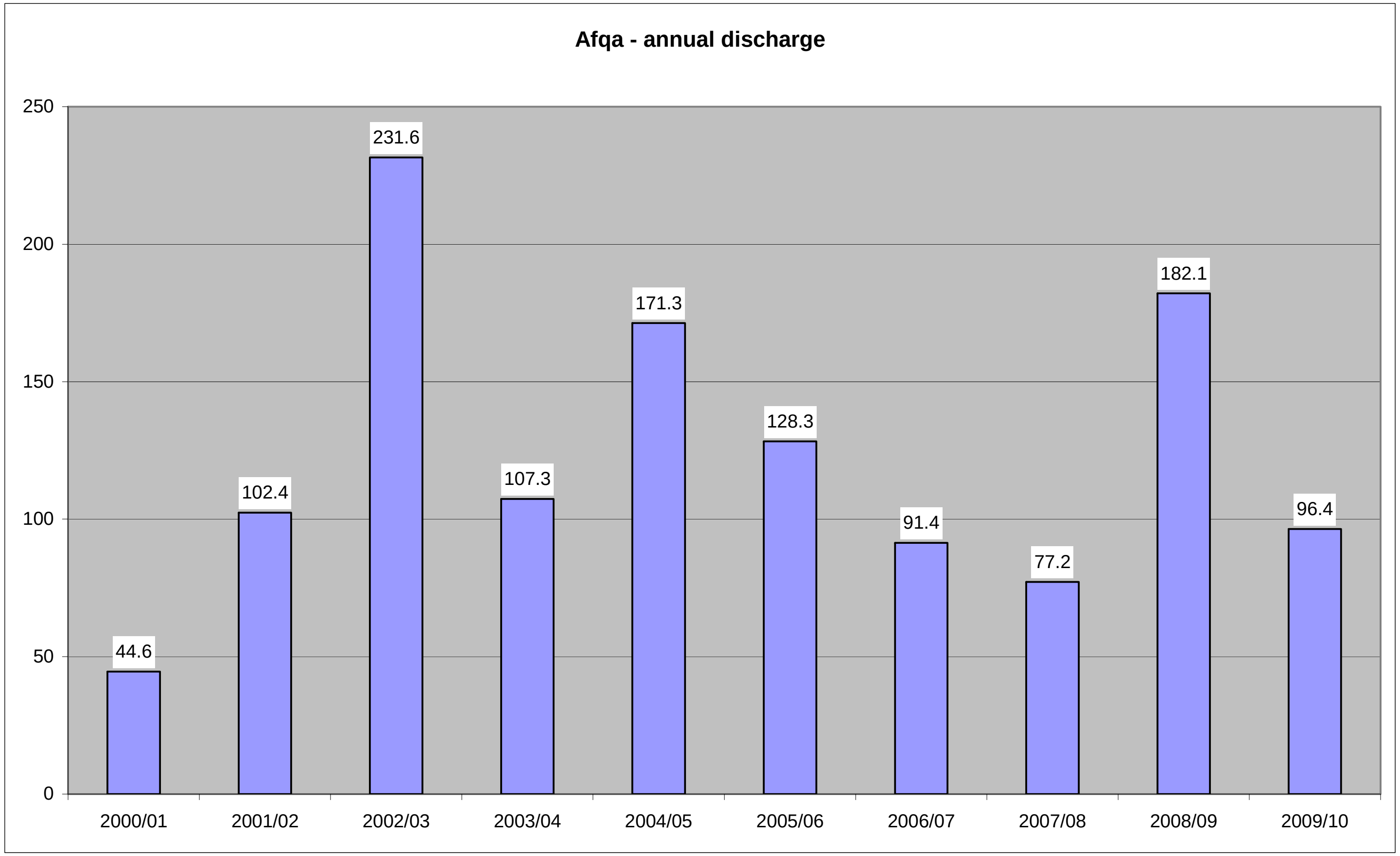

Figure 29: Annual Discharge of Afqa Spring during Water Years 2000/01 - 2009-10 [MCM]

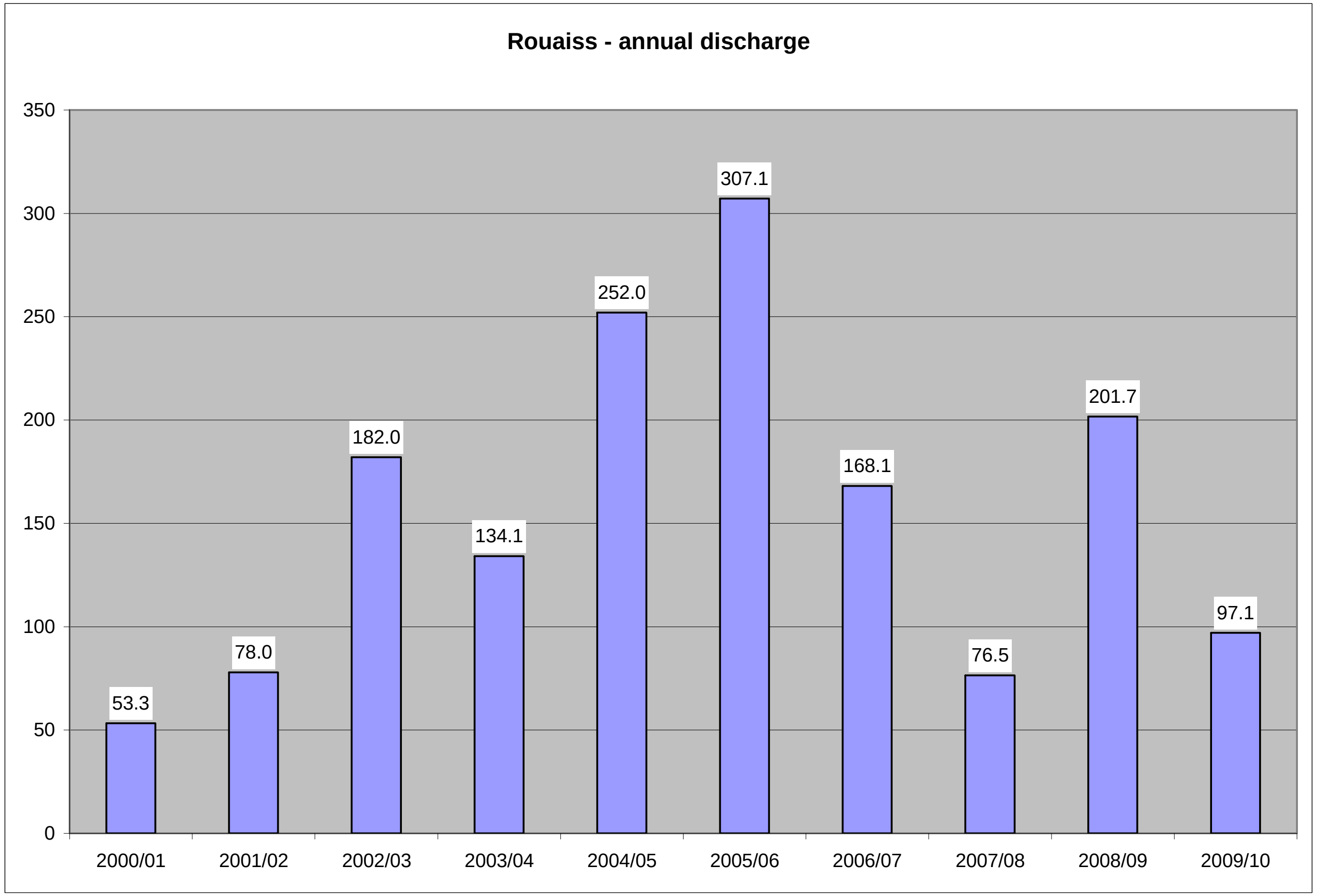

Figure 30: Annual Discharge of Rouaiss Spring during Water Years 2000/01 - 2009-10 [MCM]

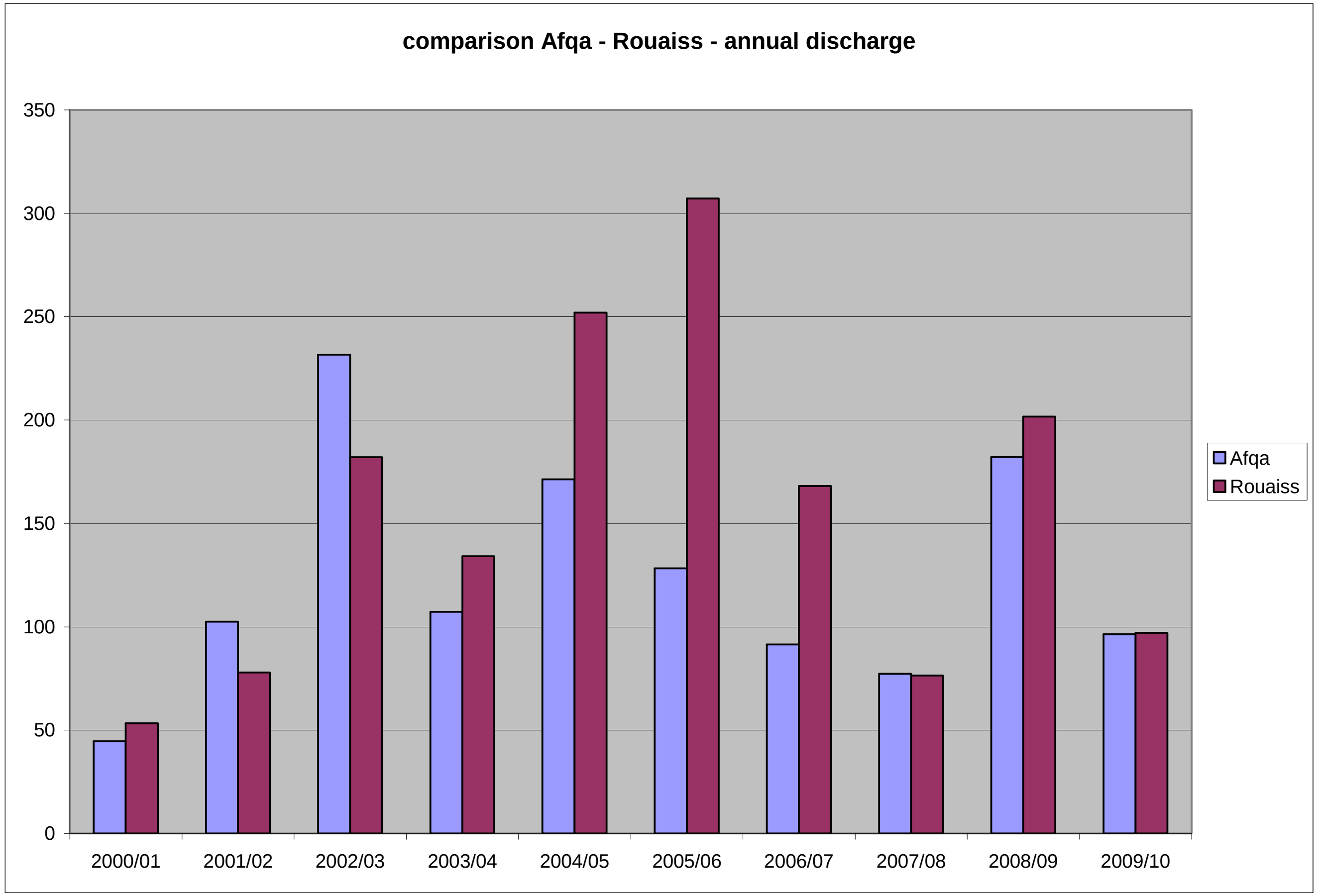

Figure 31: Comparison of Annual Discharge at Afqa and Rouaiss Springs [MCM]

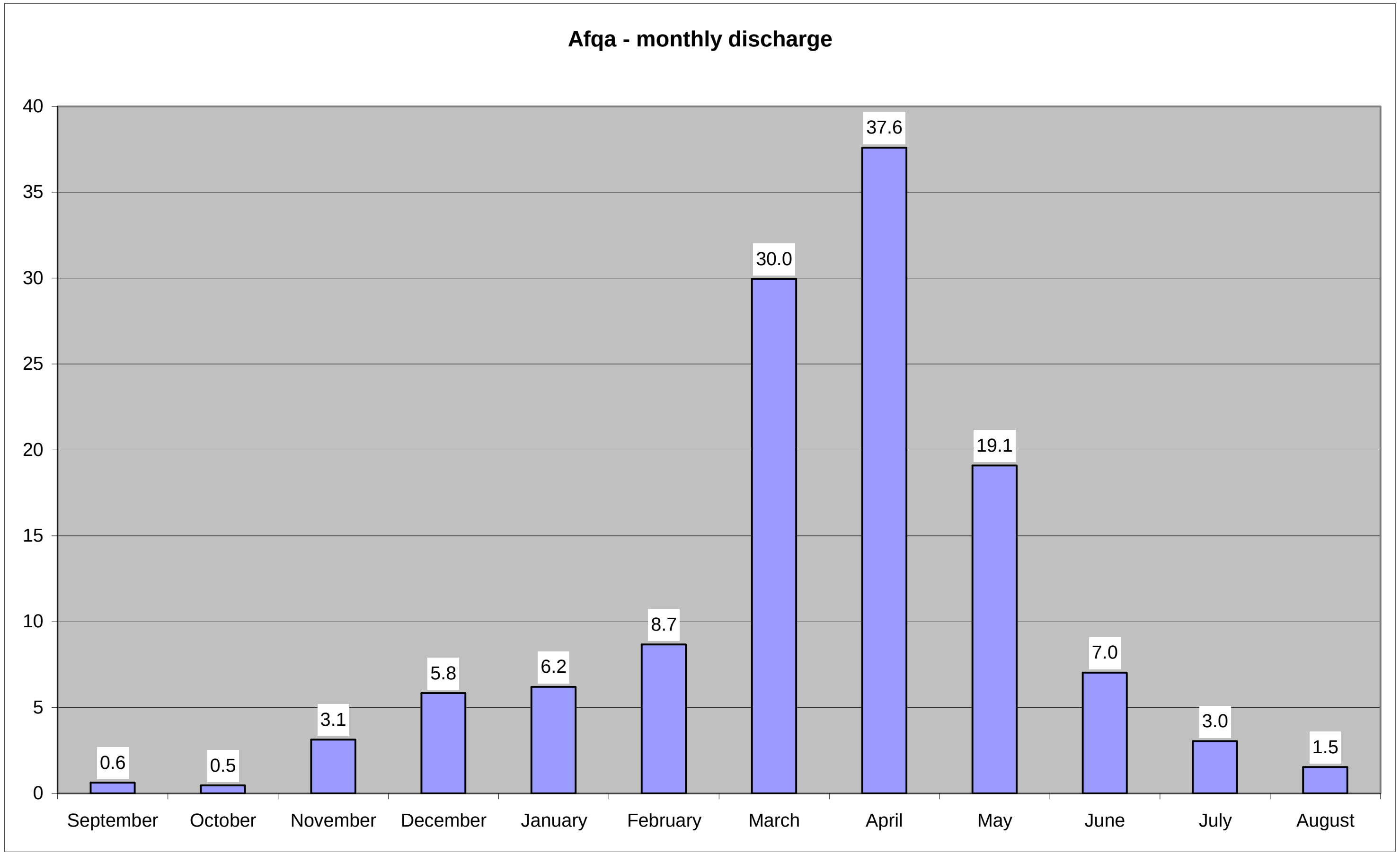

Figure 32: Average Monthly Discharge of Afqa Spring during Water Years 2000/01 - 2009-10 [MCM]

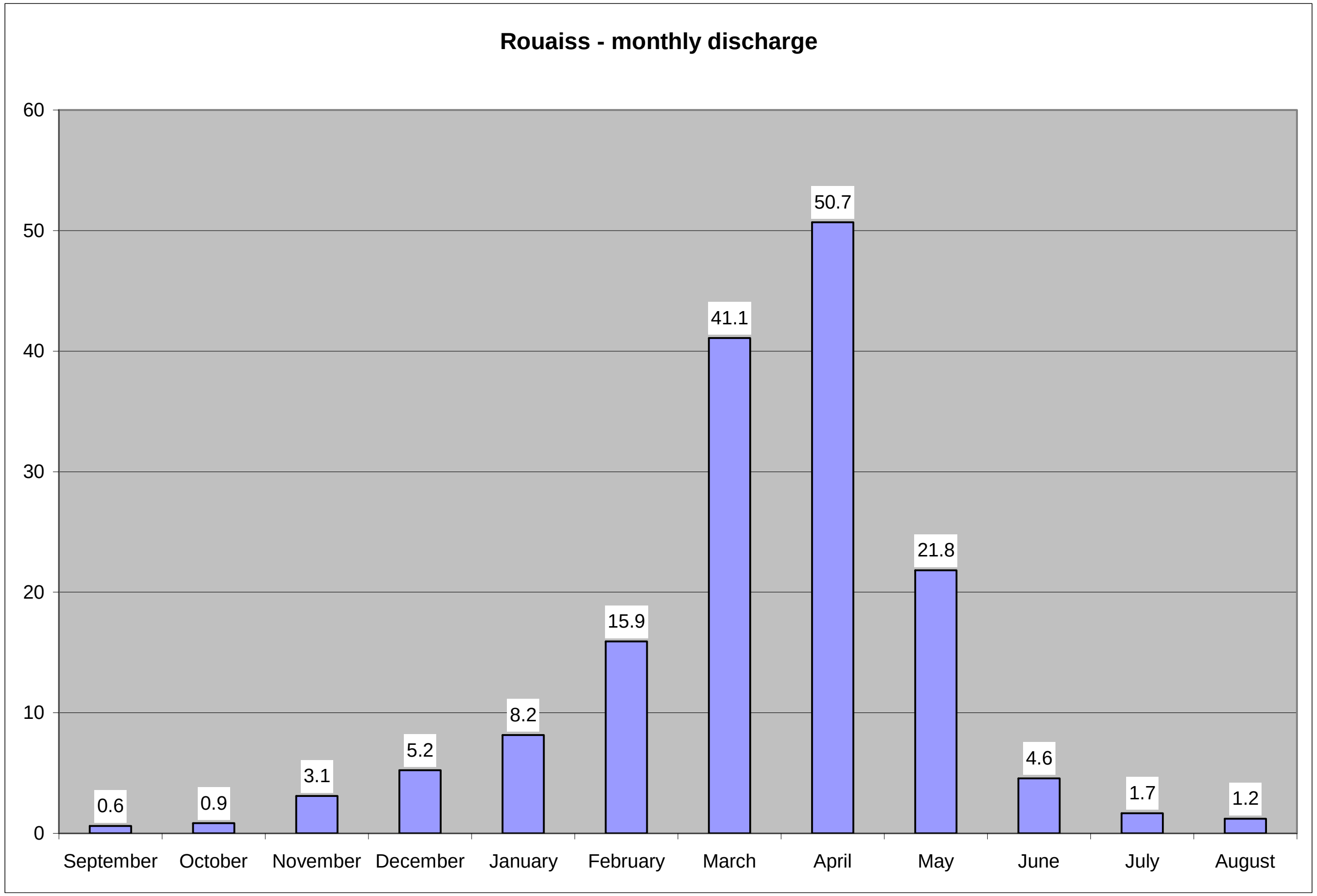

Figure 33: Average Monthly Discharge of Rouaiss Spring during Water Years 2000/01 - 2009-10 [MCM]

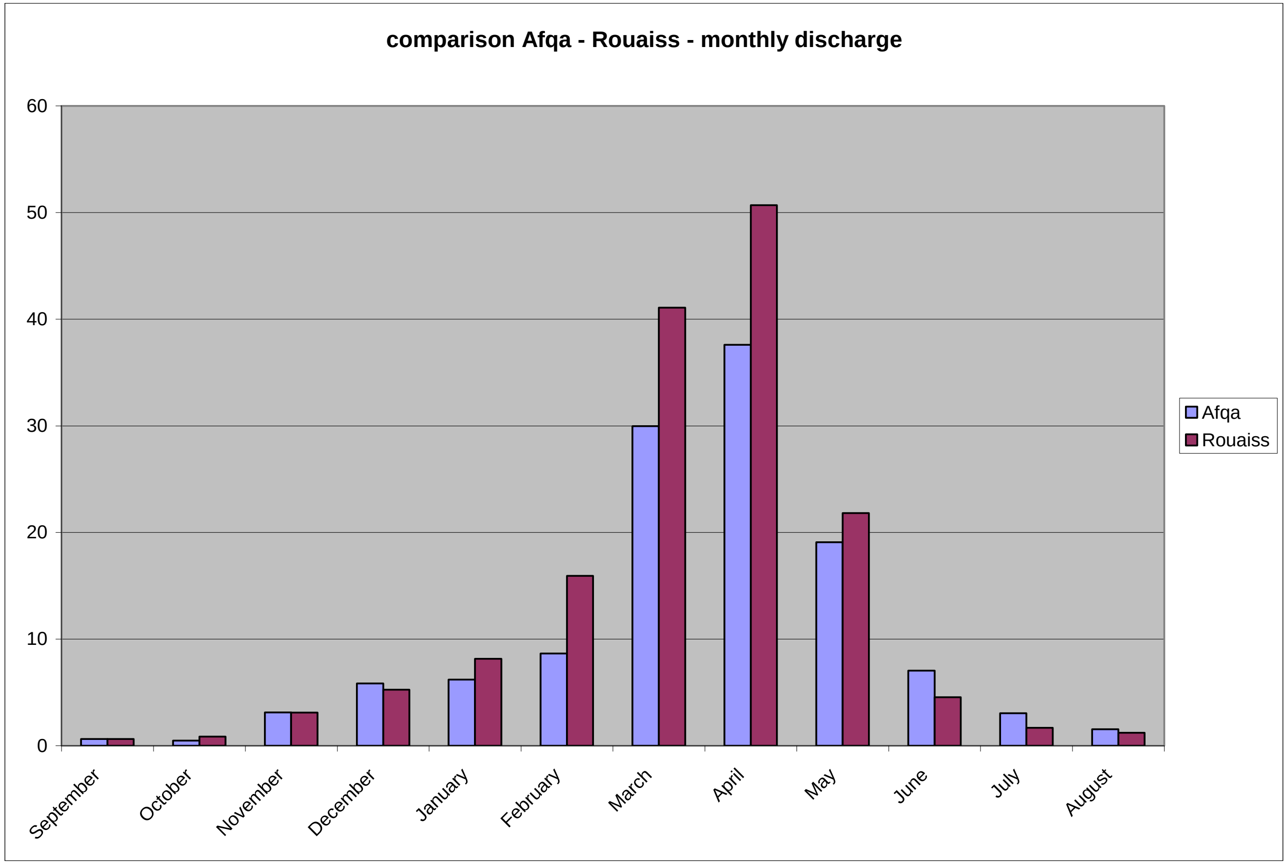

Figure 34: Comparison of Monthly Average Discharge at Afqa and Rouaiss Springs (Water Years 2000/01 - 2009-10) [MCM]

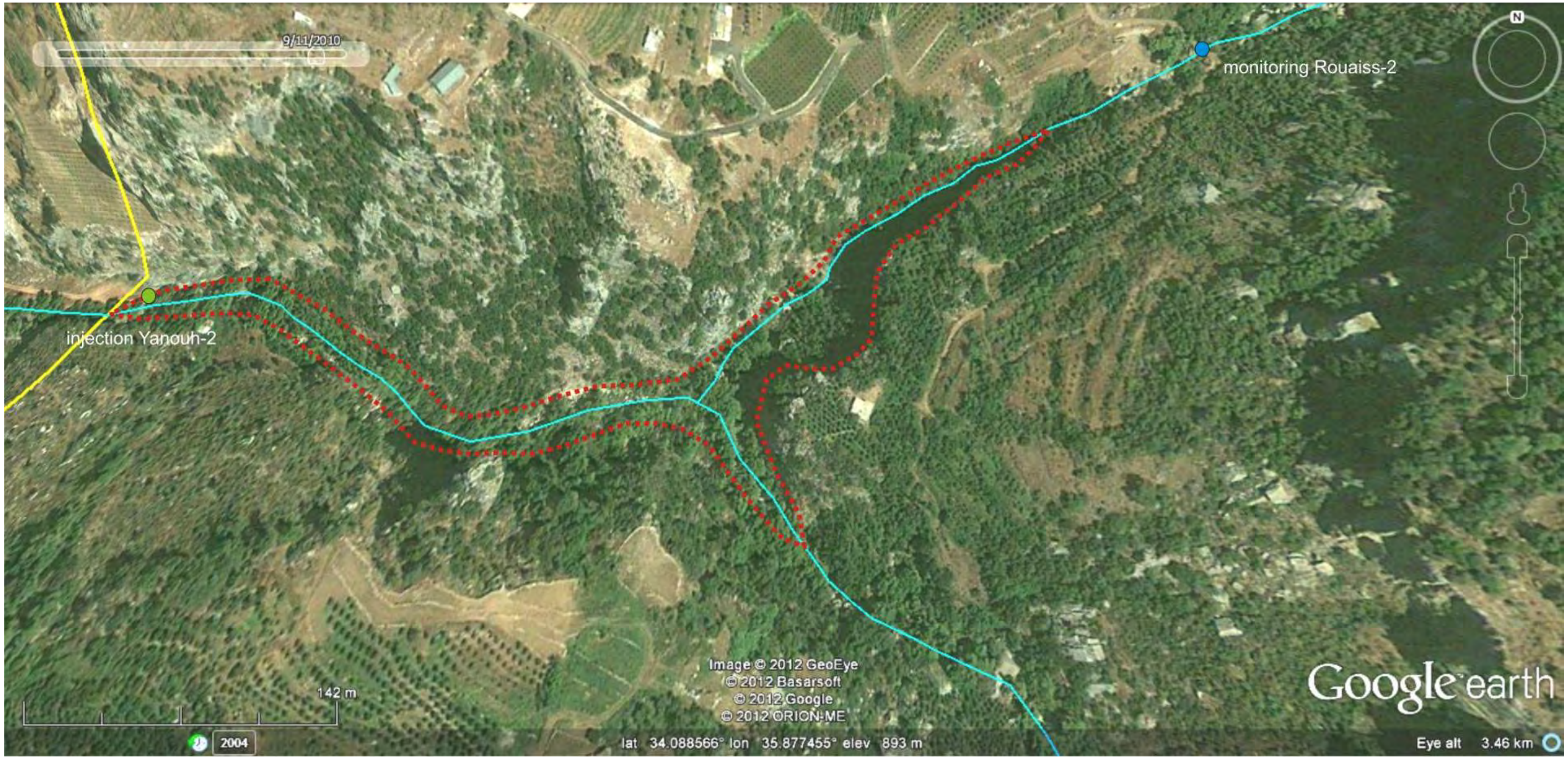

Figure 35: Assumed Main Infiltration Area (red line) in the Upper Nahr Ibrahim Valley (near confluence), adopted from MARGANE (2012b)

The individual catchments contributing to Jeita spring are shown in Figure 36. It becomes clear that, due to the karstic nature of the aquifer system, the surface water catchments are considerably different from the groundwater (GW) catchments. As this is not only the case in the Jeita GW catchment, this fact needs to be considered during any future water study in Lebanon. Jeita spring receives about 46% of its water from this infiltration zone in Nahr Ibrahim (SCHULER & MARGANE, 2013). The Jeita groundwater catchment covers around 60 % of the Nahr Ibrahim surface water catchment (329 km²). Around 49 % of the Jeita groundwater catchment lies within the Nahr Ibrahim surface water catchment.

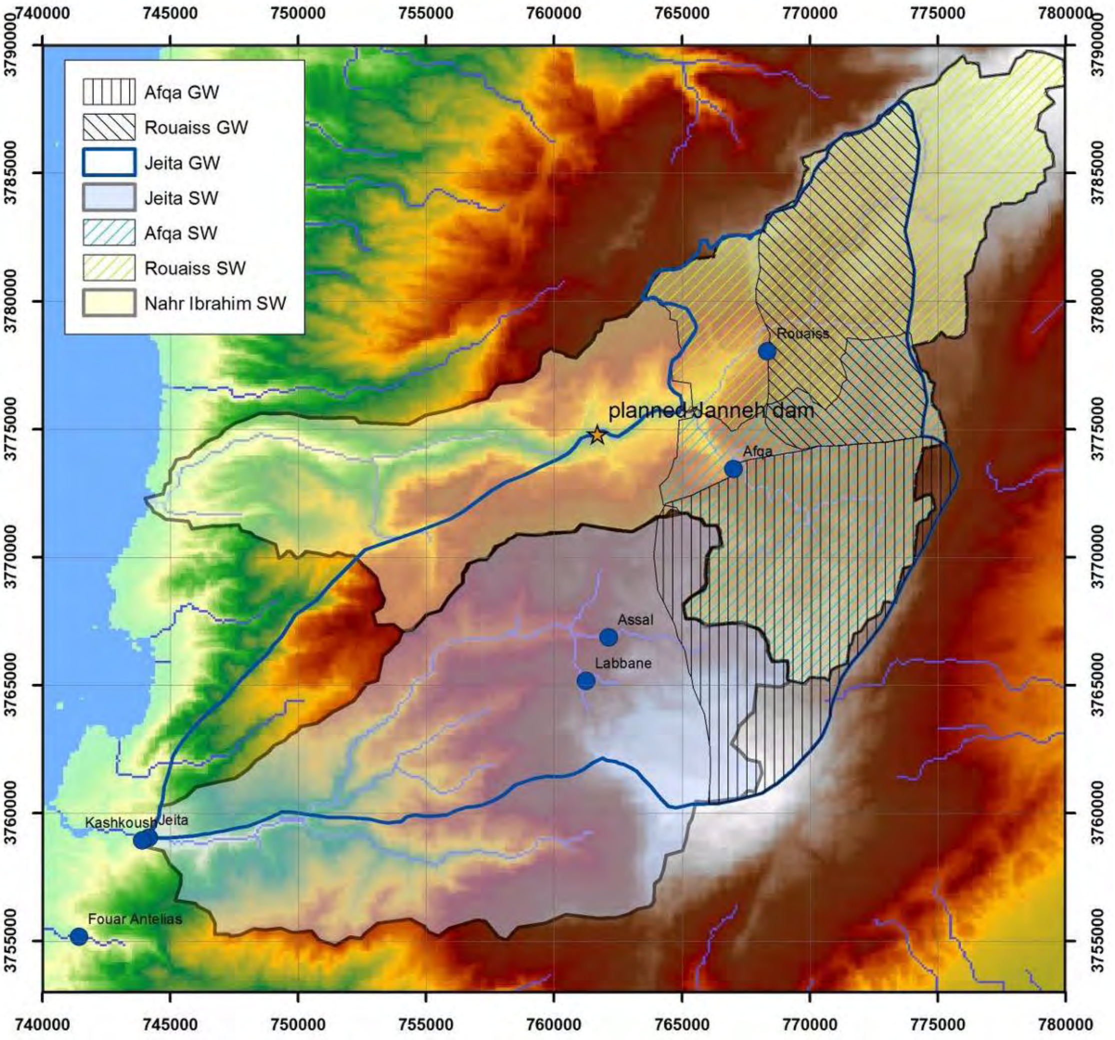

Figure 36: Groundwater contribution zone of Jeita spring in relation to the Nahr Ibrahim and Nahr el Kalb surface water catchments

Figure 37 shows monthly average discharge / runoff data in MCM for seven gauges in the Jeita SW catchment plus two gauges in the Nahr Ibrahim catchment, located within the Jeita GW catchment. Surface water runoff in general is highest from March to May depending on the altitude of the measurement gauge. Precipitation falling as snow in the middle and predominantly in the upper catchment is stored for months and released during snowmelt. Especially data from gauges at higher elevation in the Jeita catchment (Labbane and Assal) show latest peak flows in May due to lower temperatures at these altitudes (1644 m and 1540 m, respectively). At the Nahr el Kalb seamouth station (228), which is influenced by snowmelt from lower parts of the catchment earlier in the year and precipitation falling as rain, an average monthly peak flow of 46.3 MCM was calculated for March. Maximum surface runoff measurements at Daraya or Hrajel (in the center of the catchment) do not exceed half of that runoff showing max. values of 19.1 MCM per month.

Highest average monthly surface water runoff was measured below the springs of Rouaiss and Afqa, situated in the higher altitudes of the Nahr Ibrahim SW catchment. High flow rates exceeding 50 MCM per month give the potential of great quantities, flowing in the subsurface towards Jeita. Unfortunately no surface runoff data from lower altitudes in the Nahr Ibrahim catchment were available to recognize these high transmission losses in the river during the time of the planning for Janneh dam. **In order to avoid such planning mistakes in the future, it is highly recommended to install surface water gauging stations at all proposed locations of dams and monitor potential losses (effluent flow conditions) in the river section covering at least the proposed dam area.**

Monthly low flows occur at the end of the dry season in the months between August and October. Riverbeds usually fall completely dry and no runoff is measured. On the other side, a closer look at the design of the rudimentary surface water runoff gauges reveals a high threshold of minimum flows to be recorded. However, visual observations in these months confirm no flows at most gauges in the dry season.

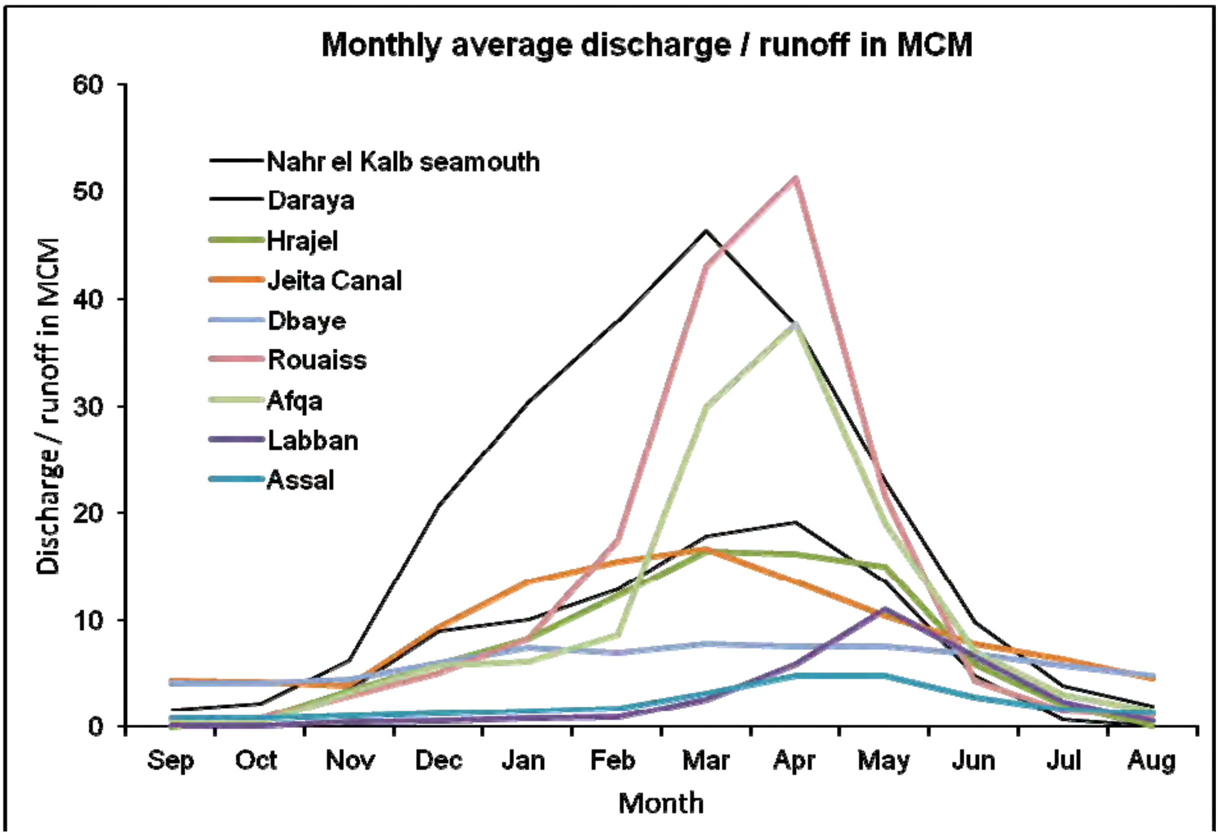

Figure 37: Average monthly discharge in MCM for nine spring and river gauges

Available runoff data are visualized in three time series for the periods 1965/66–1974/75, 1991/92–1999/00 and 2000/01–2009/10 (Figures 38 to 40). A slight trend might be visible but not significant for the maximum runoff at Nahr el Kalb seamouth, which is decreasing over time. Runoff measurements at Nahr el Kalb seamouth show highest annual discharge in the first half of the first time series 1965/66–1974/75, compared to the two more recent time series. Except one value in each of the two following time series, surface water discharge into the Mediterranean was smaller than 250 CM (Figures 39 and 40). In general no clear trend of low or high discharge years over time can be determined.

Data of the more recent time series (2000/01–2009/10) shows best data availability for the nine stations in total. In contrast to the time series 1991/92–1999/00 a slight trend in overall increasing discharge might be interpreted since 2002. This must be taken with caution due to missing data for several years especially between 1991/92 and 1999/2000 (Figure 39).

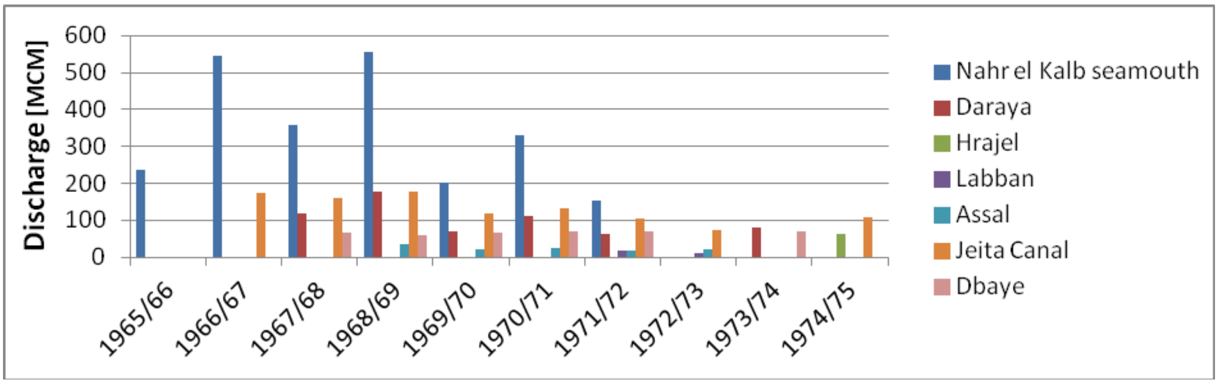

Figure 38: Average annual discharge in MCM (1965/66 – 1974/75)

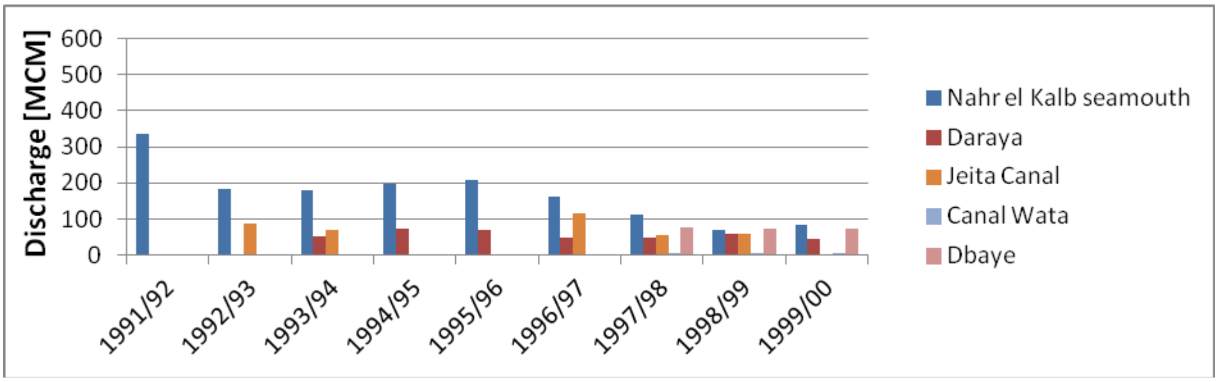

Figure 39: Average annual discharge in MCM (1991/92 – 1999/00)

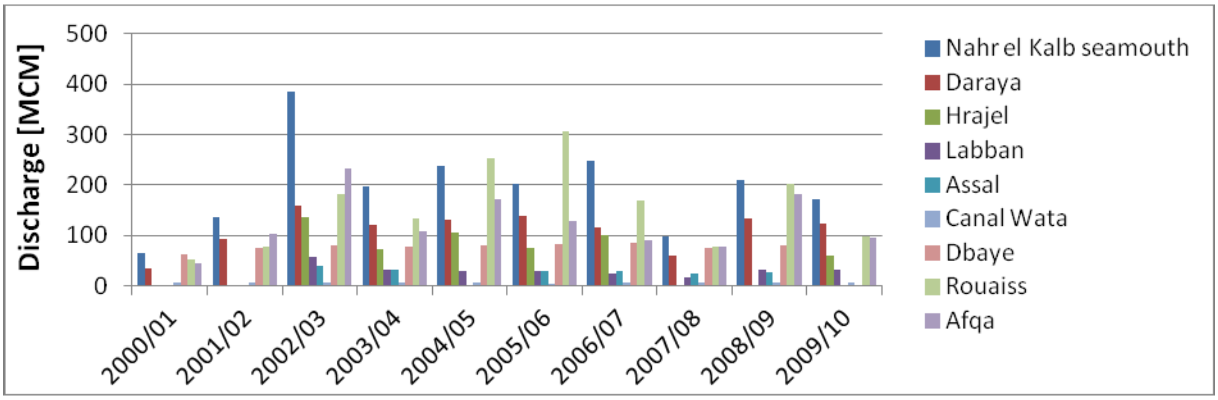

Figure 40: Average annual discharge in MCM (2000/01 – 2009/10)

4 Discharge measurements by the BGR project

The first spring discharge measurements by the BGR project “Protection of Jeita Spring” were conducted middle of 2010. Water level sensors (In-Situ Troll 9500) were installed at 5 different locations:

- approx. 800 m upstream of the outlet of the Jeita spring,
- approx. 5800 m upstream of Jeita spring in the Daraya tunnel,
- at Labbane and Assal springs in the upper Nahr es Salib catchment, and
- at Kashkoush, which is situated some hundred meters downstream of Jeita.

Concerning the multiparameter data, only data related to spring flow will be discussed in this report.

Altogether around 300 dilution tests using uranine and salt were performed to calculate a stage-discharge relationship for each spring. Data was recently analyzed for consistency and homogeneity. It is assumed, that a logarithmic trend line is the best fit for the regular and irregular channels of each spring. Except at Daraya tunnel a linear relationship seems to give a better fit. By these rating curves continuous discharge values can now be established by the measurements of water level. This is not true for Jeita, where additional methods, such as measurement of flow by ADCP, are applied as explained in the following.

4.1 Jeita and Daraya tunnel

4.1.1 Stage-discharge relationship

Because Jeita Grotto is the main touristic attraction of Lebanon it is highly regulated. Around 400,000 visitors (2011) visit the spring each year. It is an important source of income for the country. Much effort is done keep the cave clean and to regulate the climatic and hydrological conditions in the cave. Discharge of Jeita spring is regulated by two weirs at the embarkation point for tourist boats, to maintain a constant water level at this point. The consequence is that near this point, different quantities of discharge show the same water level and no stage-discharge relationship can be derived. The influence of the operation of this weir reaches for upstream and therefore water level and flow measurements by the BGR project were done around 500 m upstream of this point.

In July 2010 an In-Situ Troll 9500 multiparameter probe was installed in Jeita Grotto, at approximately 500 m upstream of the tourist boat embarkation point (Figure 41). The water level and electric conductivity data, recorded with the Troll 9500 are shown in Figure 42. Unfortunately the EC probe was malfunctioning during much of 2012.

Figure 41: Multiparameter probe Troll 9500 installed in Jeita

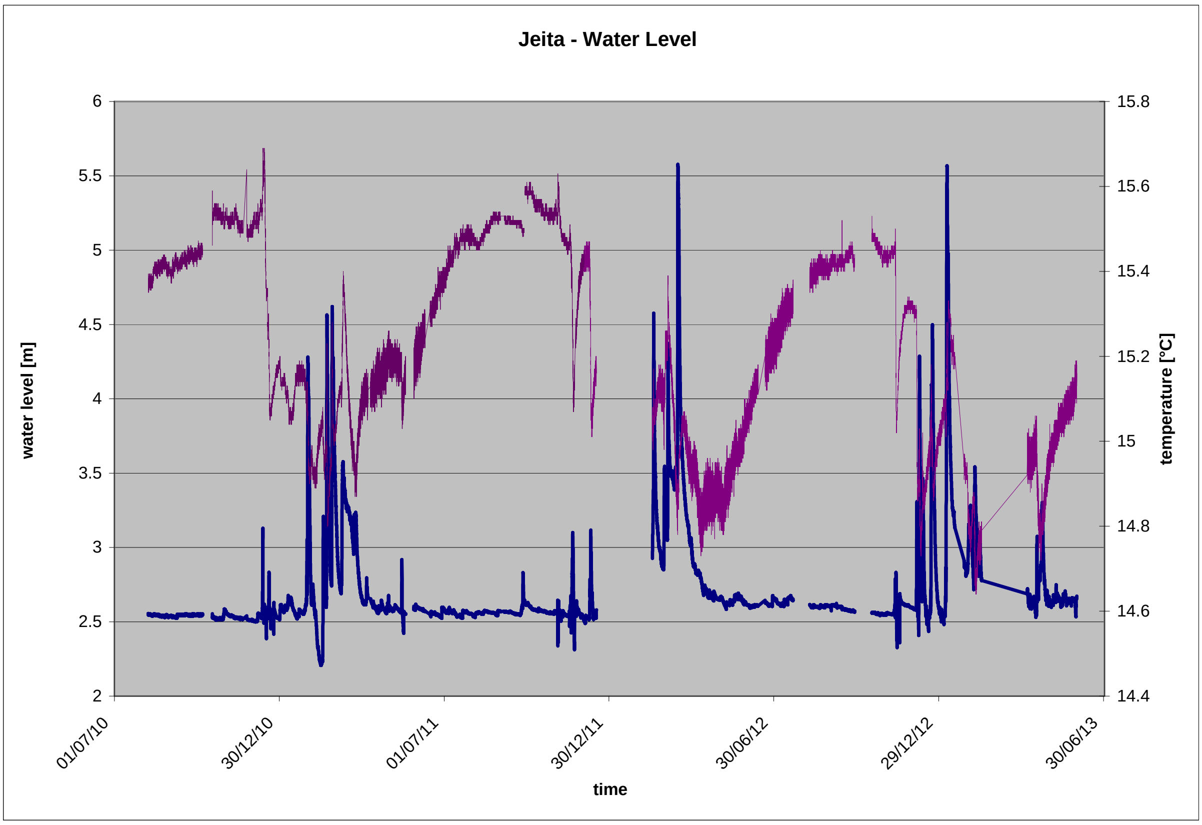

Figure 42: Water level and temperature recorded at Jeita with Troll 9500

Even some influence during low flow conditions could be determined and it is difficult to establish a stage-discharge relationship for discharge values below 5 m³/s (~ 2.7 m). It can be assumed that no regulations occur at higher discharge rates. A stage-discharge correlation was calculated for Jeita based on 25 tracer dilution tests conducted in Jeita (Figure 43; Table 5). This correlation is logarithmic. As can be seen, values of certain discharge show higher stage values than other values with same discharge at Jeita. R^2 is more than 0.95, indicating a reasonable fit for the stage-discharge relationship. This function, however, was not used, because calculated flow considerably deviates from observed flow at higher water levels due to the highly irregular section. A separate linear correlation was done for values smaller than 5 m³/s (Figure 44; $R^2 = 0.91$).

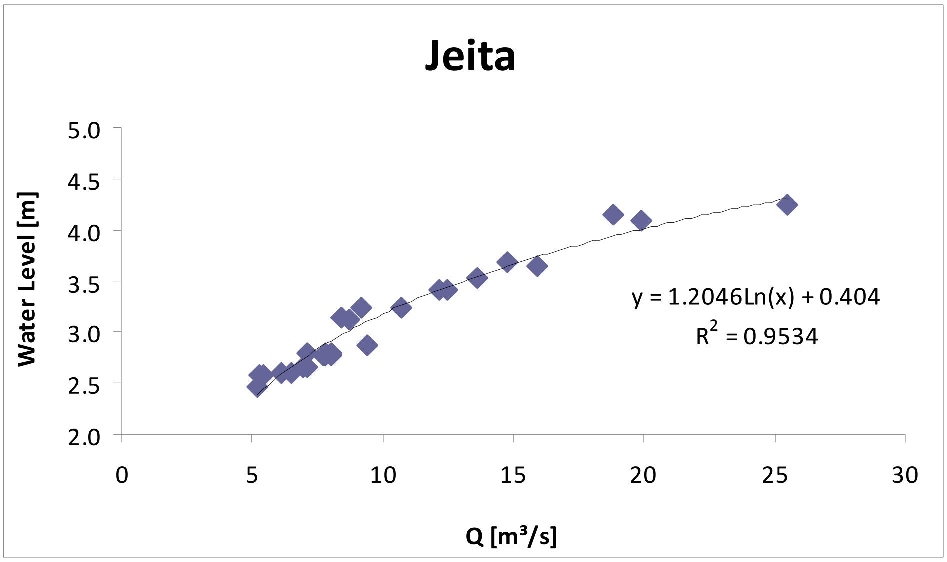

Figure 43: Stage-Flow relationship at Jeita (only values above 5 m³/s)

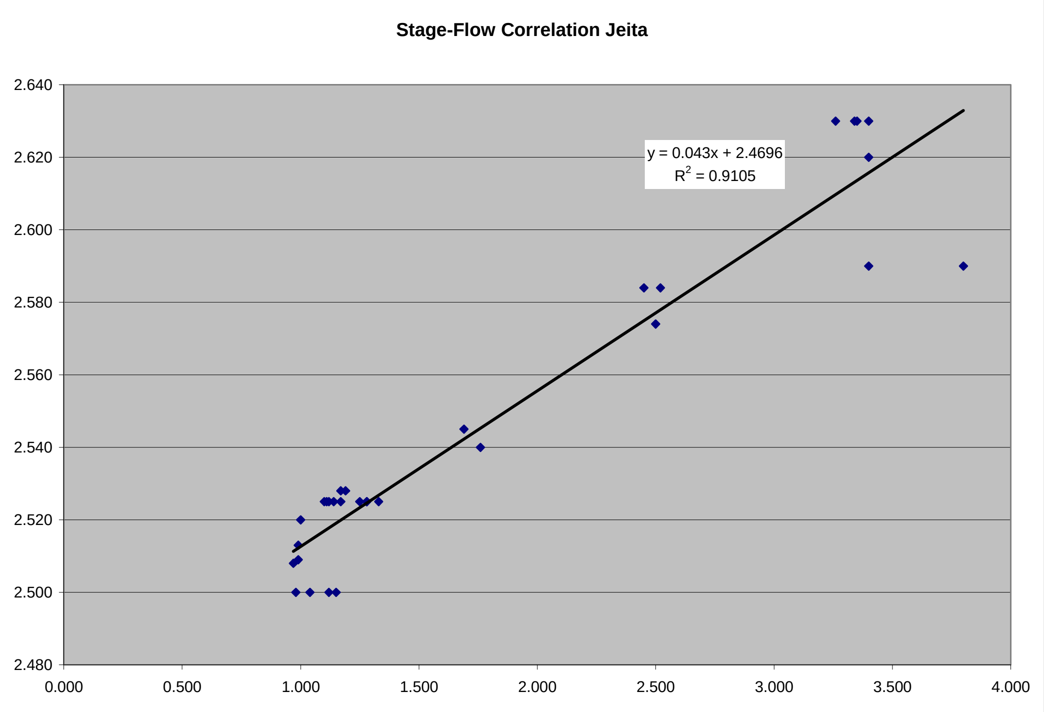

Figure 44: Stage-Flow relationship at Jeita (values below 5 m³/s)

Table 5: Dilution Tests at Jeita for Determination of Stage - Flow Correlation

Date & Time	discharge [m³/s]	location	test number	amount	water level [m]	travel time [min]
17/08/2010 13:40	1.760	Daraya-Jeita		10 g	2.540	672.000
18/08/2010 13:30	1.690	Jeita	Test-1	5 g	2.545	
07/10/2010 10:50	1.170	Jeita	Test-2	20 g	2.525	
07/10/2010 10:50	1.330	Jeita	Test-2	20 g	2.525	
07/10/2010 10:50	1.280	Jeita	Test-2	20 g	2.525	
08/10/2010 10:22	1.110	Jeita	Test-3	20 g	2.525	
08/10/2010 10:22	1.250	Jeita	Test-3	20 g	2.525	
08/10/2010 10:22	1.100	Jeita	Test-3	20 g	2.525	
08/10/2010 14:56	1.140	Jeita	Test-4	20 g	2.525	
08/10/2010 14:56	1.280	Jeita	Test-4	20 g	2.525	
08/10/2010 14:56	1.120	Jeita	Test-4	20 g	2.525	
12/11/2010 12:43	1.170	Jeita	Test-1	5 g	2.528	
12/11/2010 16:43	1.190	Jeita	Test-2	5 g	2.528	
24/11/2010 11:52	1.000	Daraya-Jeita		10 g	2.520	1062.000
26/11/2010 15:20	0.990	Jeita	Test-2	5 g	2.513	
27/11/2010 9:23	0.990	Jeita	Test-3	5 g	2.509	
28/11/2010 12:00	0.970	Jeita	Test-4	5 g	2.508	
03/12/2010 11:45	0.980	Jeita	Test-1	5 g	2.500	
03/12/2010 11:45	1.040	Jeita	Test-1	5 g	2.500	
04/12/2010 9:40	1.120	Daraya-Jeita		10 g	2.500	1127.000
04/12/2010 11:52	1.150	Jeita	Test-2	5 g	2.500	
16/12/2010 14:02	5.300	Jeita	Test-1	21.9 g	2.590	
16/12/2010 14:02	3.400	Jeita	Test-1	21.9 g	2.590	
16/12/2010 17:46	5.400	Jeita	Test-2	20 g	2.590	
16/12/2010 17:46	3.800	Jeita	Test-2	20 g	2.590	
11/01/2011 11:14	3.340	Jeita	Test-1	20 g	2.630	
11/01/2011 11:14	3.260	Jeita	Test-1	20 g	2.630	
11/01/2011 13:44	3.400	Jeita	Test-2	20 g	2.630	
11/01/2011 13:44	3.350	Jeita	Test-2	20 g	2.630	
13/01/2011 11:08	3.400	Daraya-Jeita		20 g	2.620	574.000
21/01/2011 14:48	2.450	Jeita	Test-1	10 g	2.584	
21/01/2011 14:48	2.520	Jeita	Test-1	10 g	2.584	
22/01/2011 12:47	2.500	Jeita	Test-2	10 g	2.574	
22/01/2011 12:47	2.500	Jeita	Test-2	10 g	2.574	
31/01/2011 10:42	18.800	Daraya-Jeita		50 g	4.146	169.000
02/02/2011 11:01	8.700	Daraya-Jeita		50 g	3.120	279.000
04/02/2011 11:12	8.400	Daraya-Jeita		50 g	2.614	264.000
06/02/2011 10:21	7.100	Daraya-Jeita		50 g	2.656	255.000

Date & Time	discharge [m³/s]	location	test number	amount	water level [m]	travel time [min]
09/02/2011 10:21	5.200	Daraya-Jeita		30 g	2.456	295.000
17/02/2011 13:38	8.400	Daraya-Jeita		60 g	3.135	230.000
20/02/2011 10:45	6.100	Daraya-Jeita		30 g	2.603	278.000
21/02/2011 10:35	76.000	Daraya-Jeita		80 g	4.431	164.000
22/02/2011 9:13	15.900	Daraya-Jeita		60 g	3.668	252.000
27/02/2011 10:30	25.500	Daraya-Jeita		100 g	4.232	167.000
28/02/2011 10:30	19.900	Daraya-Jeita		55.84 g	4.104	184.000
01/03/2011 10:50	14.800	Daraya-Jeita		51.75 g	3.686	194.000
04/03/2011 10:36	9.360	Daraya-Jeita		50 g	3.015	233.000
06/03/2011 13:52	8.000	Daraya-Jeita		40 g	2.796	251.000

During low flow periods dilution tests give accurate values for boths injection points, Jeita and Daraya, while during high flow periods (> 5 m³/s) injections were only done in Daraya. Uncertainties occur due to the accuracy of discharge measurements, the accuracy of stage measurements, and the difficulties of conducting dilution tests at high discharges. Most discharge measurements at high stage were performed by injecting uranine tracer at Daraya tunnel which was monitored downstream at Jeita. Tracer tests showed that all water passing the siphon terminale also passes Jeita and there is no outflow from the system so that no tracer substance is lost. There is an inflow from the north, detected in 2004 by divers of Jeita Grotto and located some 750 m upstream of the boat mooring. However, this inflow has no influence on the tracer tests. Two dilution tests conducted by the BGR project in this northern and in the main branch show that around 15% of total flow come from this northern branch. This smaller northern branch of Jeita Grotto probably collects water from the northern part of the catchment.

At Daraya tunnel relationship between water level and discharge was fit by a linear regression line with R² close to 0.98. The linear relationship between water stage and discharge is most probably observed due to the small range of low flow measurements. Discharge was only measured up to 7 m³/s at Daraya tunnel. At high flows, velocities become that high that an injection and detection is not possible at the same stretch. Also the entire station will be flooded by the overflowing dam, making measurements impossible.

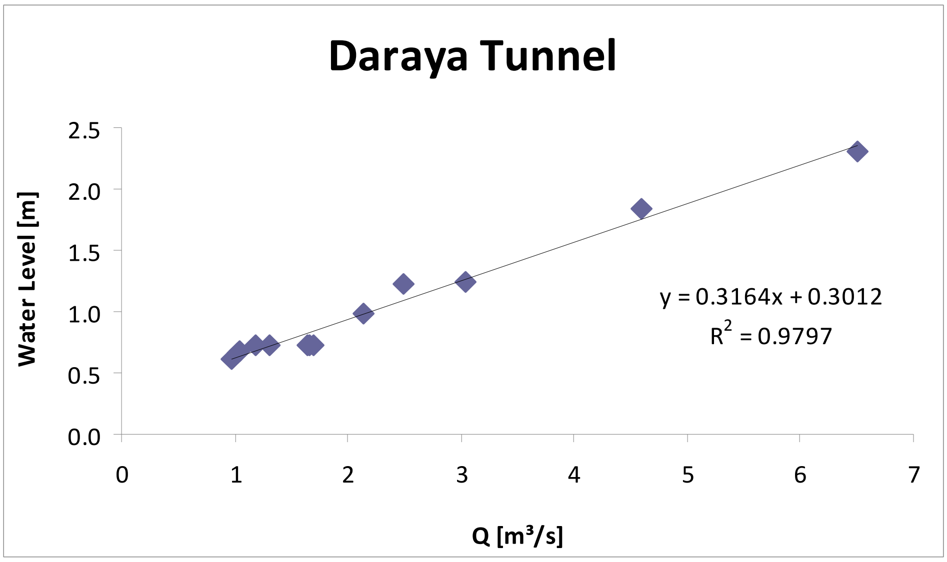

Figure 45: Linear stage-discharge relationship at Daraya tunnel

4.1.2 Flow velocity measurements

Water flow in Jeita Grotto follows an irregular course inside the cave. Discharge therefore might be defined as an underground river flowing from siphon terminal (Daraya tunnel) approximately 6 km downstream to Jeita spring. There is no other outflow from this cave and discharge is measurable like in a any natural stream. Because of its touristic relevance flow measurements were only possible in the part not accessible for tourists, i.e. more than 300 m upstream of the boat mooring. From a hydrological perspective different methods may be applied to determine river discharge. Because a stage-discharge relationship at Jeita spring is difficult, or at low flows even impossible to derive (see Chapter 4), flow velocity is now continuously monitored by an ADCP (acoustic Doppler current profiler; Figures 46, 47). A vertically looking “Shallow Water” (SW) ADCP by SonTek (Argonaut SW) was selected for the installation at Jeita. It operates in a range of 0.3 m to 5 m water depth with a resolution of 0.1 cm/s. The device calculates flow velocities in a vertical axis in the middle of the stream (2D measurement) by detecting the shift in frequency of a reflected acoustic signal - called Doppler effect (SONTEK, 2009). This is done by emitting a sound pulse of 3 MHz in and countercurrent to the direction of water flow, by an angle of 45 degrees. The signal then gets reflected by suspended particles which are assumed to have the same flow velocity as the water. The speed of sound depends on the density of the water. Water temperature is continuously recorded and sound speed is automatically calculated by the ADCP. Salinity influences density and was assigned in the program. Because salinity is very low, the influence of salinity is also very low. A signal to noise ratio (SNR) is also recorded by the ADCP displaying the strength of the received signal. SNR depends on the amount of suspended load and total turbidity. Suspended load in natural discharge waters is usually sufficient for noise reflection. At high flows when turbidity rises, it is assumed that the ADCP will still accurately operate at Jeita. With the occurrence of the first rain at the end of September 2011, velocity data were recorded accurately even though turbidity was highly visible inside the grotto.

In order to facilitate profile measurements, a rectangular aluminum frame was installed (Figure 48). Because of the irregular shape of the riverbed (narrowing to the top and increasing width to the bottom) profile calculations are continuously conducted (Figure 49). The ADCP is capable to calculate flow velocities for different vertical cells (maximum 10), which can be assigned to the respective cross sections. This is done automatically by calculating differences in travel times of the sound signal, similar to the measurement of water stage by a separate, third vertical beam.

The ADCP was installed in the middle of the riverbed, approximately 500 m upstream of the tourist boat embarkation point and approx. 300 m downstream of the confluence of a small northern branch which was recently discovered. A 30 m long straight-line section was selected for the installation of the device. It was installed on top of a platform, well fixed in the sediment and 30 cm above the riverbed preventing it from sedimentation. Discharge measurements have been collected for a period of more than one year. With the help of flow velocity data, discharge determination at Jeita Grotto is not only dependent on water stage alone. As described before water level is additionally recorded by the ADCP in order calculate flow volumes based on stage, measured velocities and the profile. This is done using the software ViewArgonaut (Figure 50). The Argonaut SW is operated by 2 parallel 12V batteries (for motor bikes) which allow measurements for around 4 weeks at a 20 minute interval. After every readout the measurements have to be restarted. Records are stored in separate files which have to be collated manually.

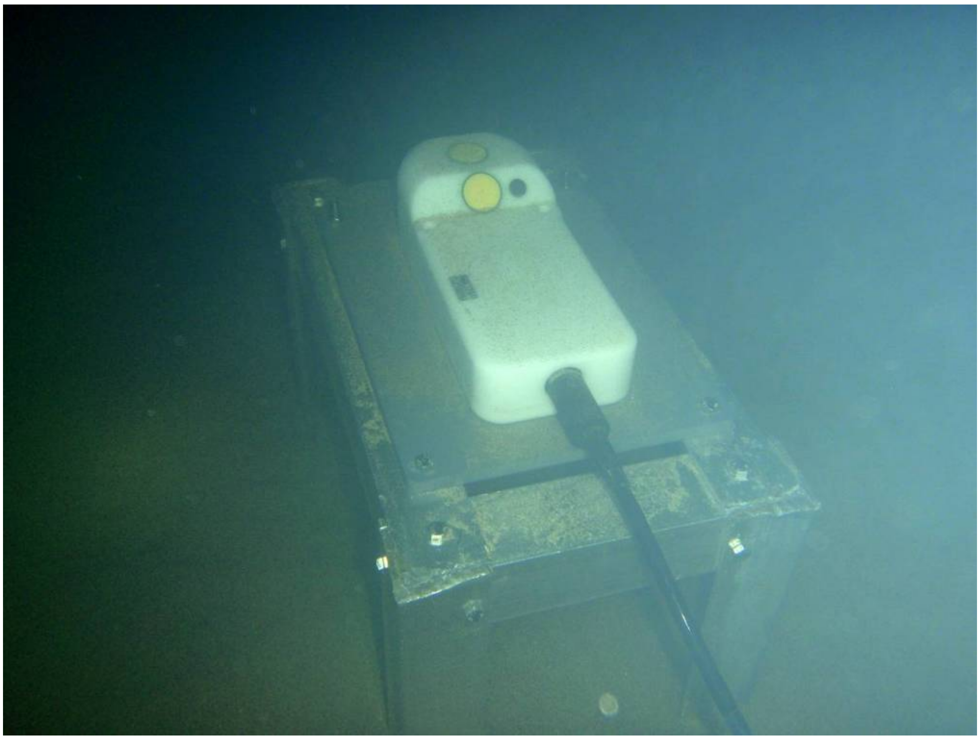

Figure 46: Sontek ADCP (Argonaut SW) installed in Jeita Grotto on a platform

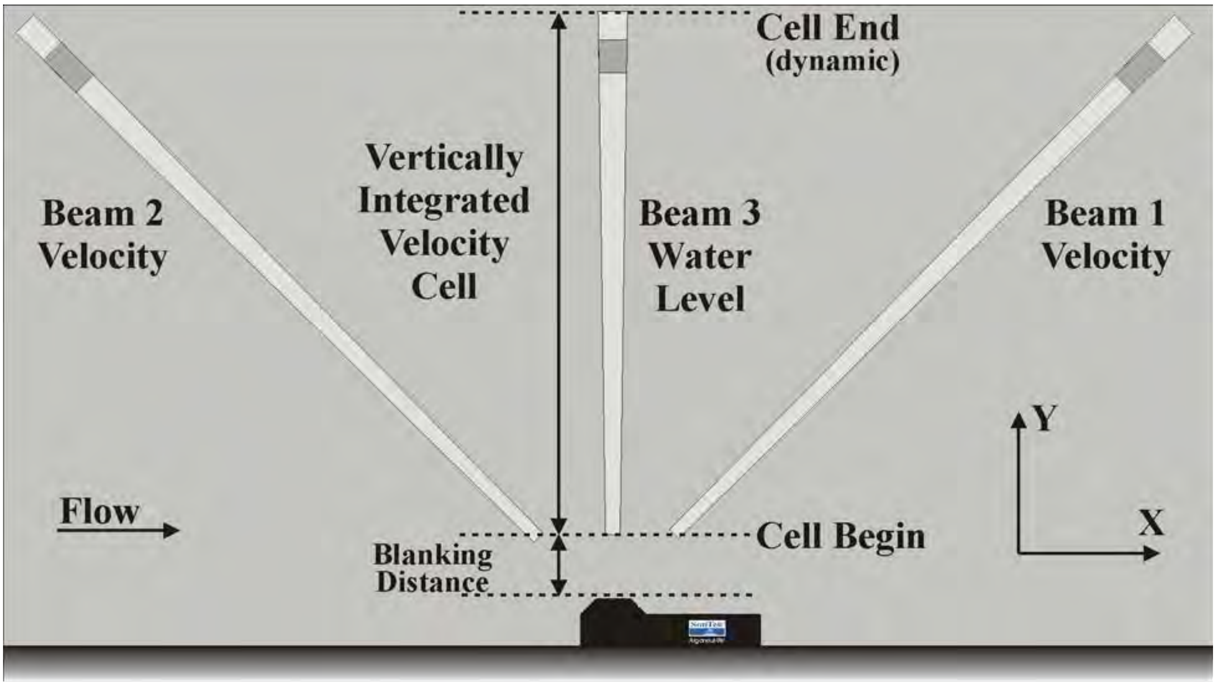

Figure 47: Schematic explaining the measurement configuration of a vertically looking Argonaut SW

Figure 48: Aluminum frame for measurement of flow-through profile at ADCP

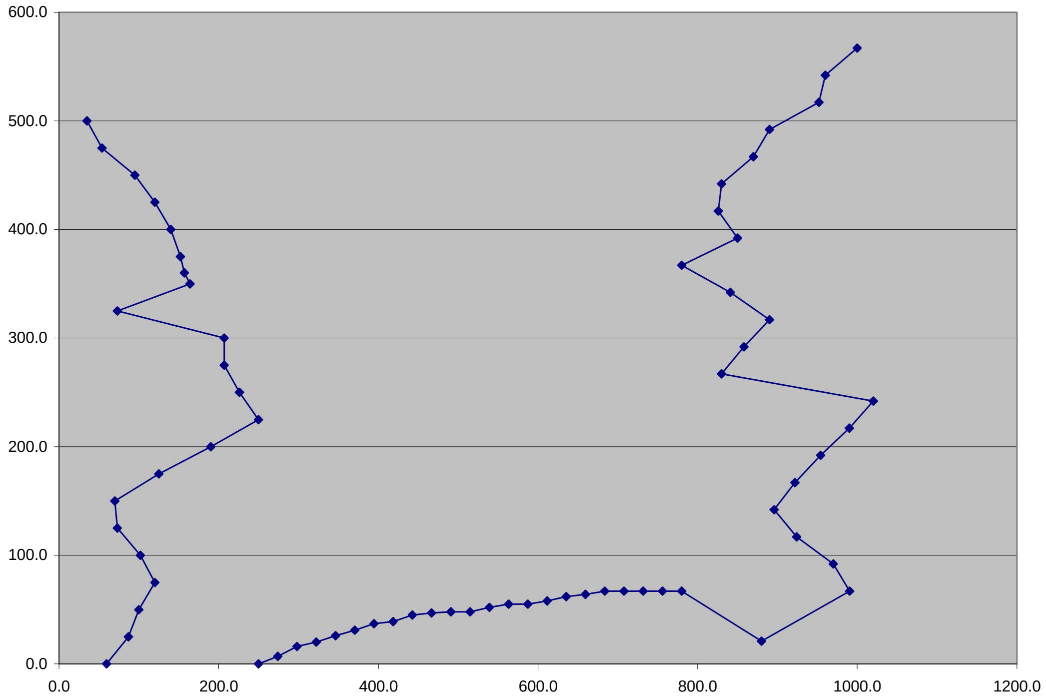

Figure 49: Profile at ADCP

(looking downstream; measurements in cm; reference elevation y=50 cm at x=500 cm)

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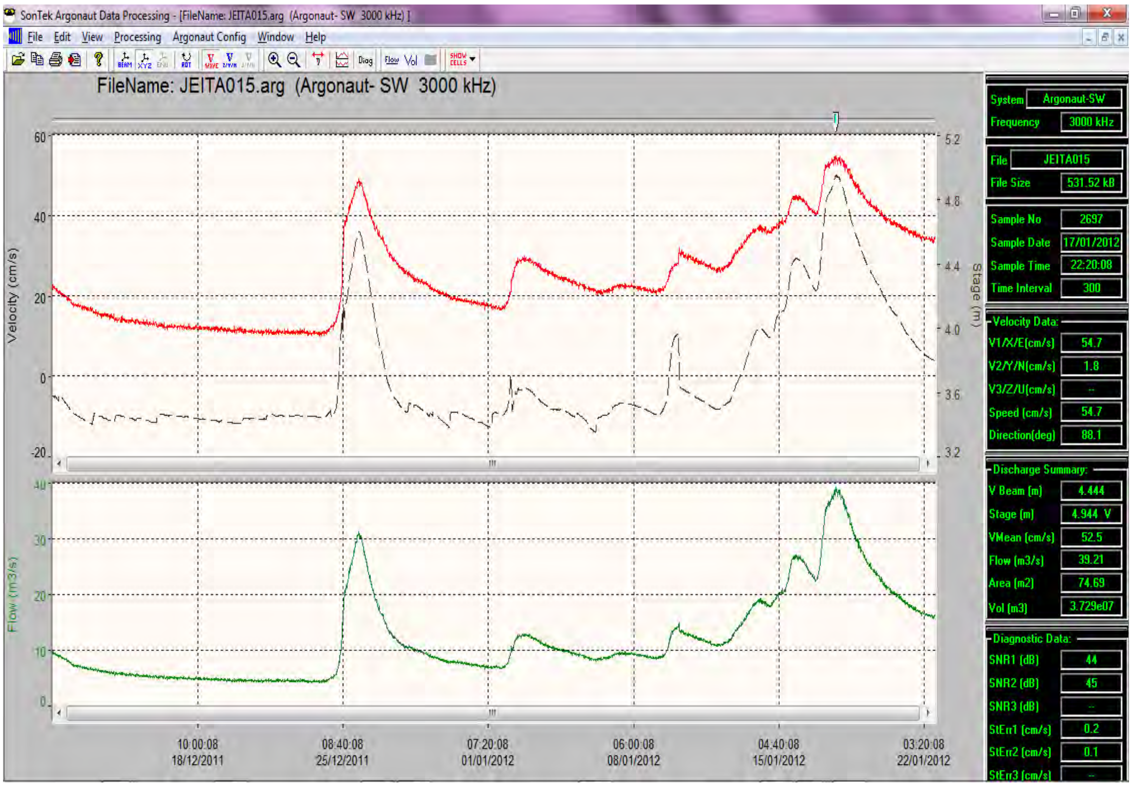

System: Argonaut-SW
Frequency: 3000 kHz
File: JEITA015
File Size: 531.52 kB
Sample No: 2697
Sample Date: 17/01/2012
Sample Time: 22:20:08
Time Interval: 300

Velocity Data:
V1/X/E(cm/s): 54.7
V2/Y/N(cm/s): 1.8
V3/Z/U(cm/s): --
Speed (cm/s): 54.7
Direction(deg): 88.1

Discharge Summary:
V Beam (m): 4.444
Stage (m): 4.944 V
VMean (cm/s): 52.5
Flow (m3/s): 39.21
Area (m2): 74.69
Vol (m3): 3.729e07

Diagnostic Data:
SNR1 (dB): 44
SNR2 (dB): 45
SNR3 (dB): --
StErr1 (cm/s): 0.2
StErr2 (cm/s): 0.1
StErr3 (cm/s): --

Figure 50: Evaluation of ADCP data from Argonaut SW installed in Jeita Grotto

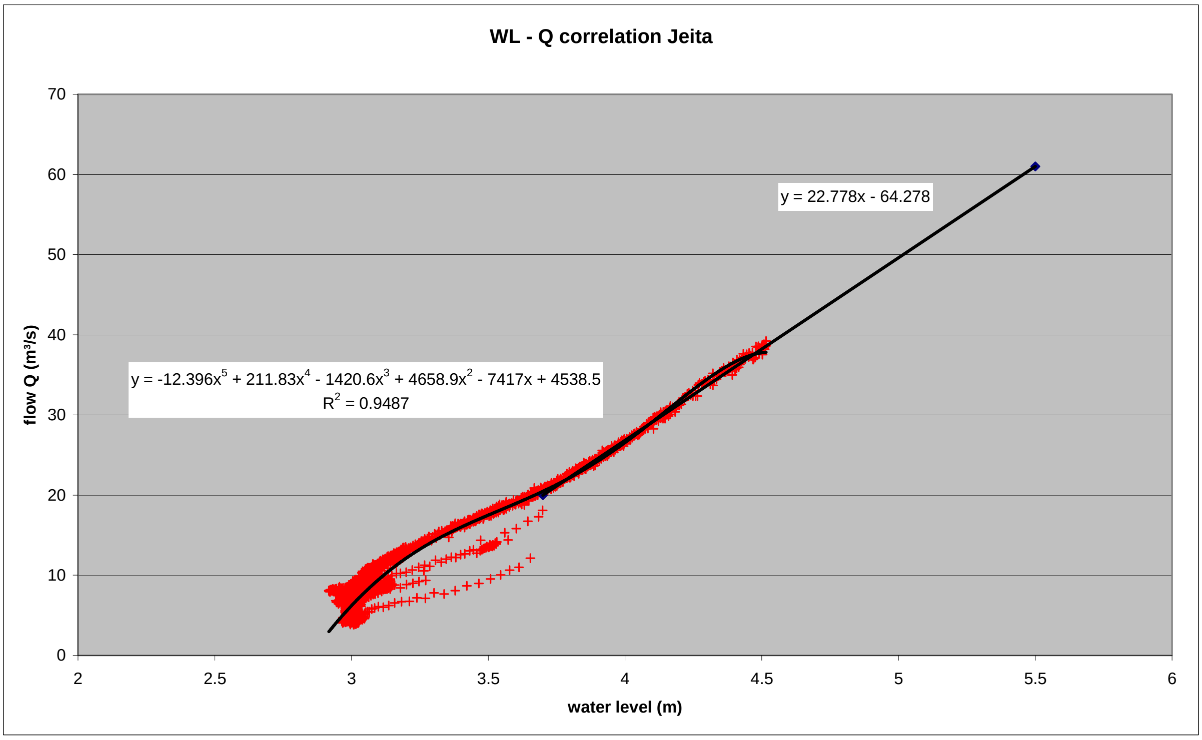

Figure 51: Stage - Flow correlation for Jeita ADCP and Troll

(for flow correlation of water levels for 2.7 - 4 m and for >4 m)

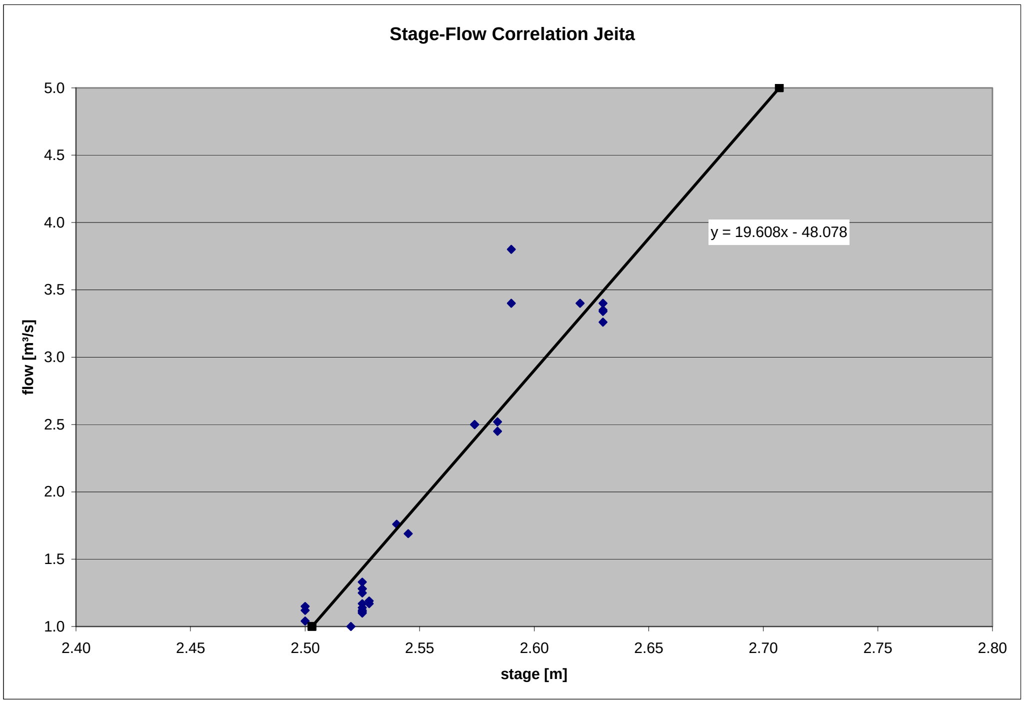

Figure 52: Stage - Flow correlation for Jeita Troll using Tracertests

(for flow correlation of water levels < 2.7 m)

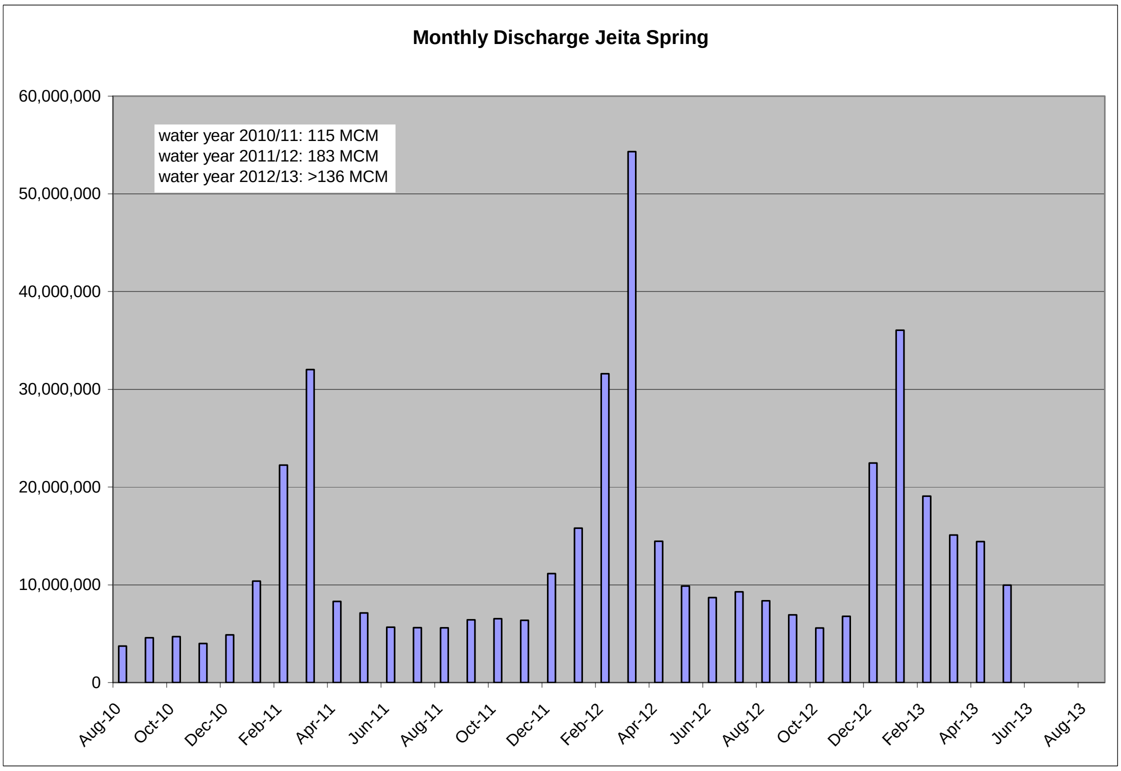

Figure 53: Monthly Discharge of Jeita Spring (31.05.2013)

The flow measurements of the ADCP are much more accurate than tracer tests, especially at higher flows. Unfortunately the ADCP did not always function well and could not always be accessed to change the batteries so that no continuous data are available for the ADCP. The ADCP, however, provided an excellent stage-flow correlation which was used in combination with the Troll water level data give a good fit for all values between 2.7 and 4 m using a polynomial 5th order correlation with a R^2 fit of 0.95 (Figure 51; y = -12.396x5 + 211.83x4 - 1420.6x3 + 4658.9x2 - 7417x + 4538.5, where y = flow and x = stage). This correlation was used for calculation of all previously collected stage data (difference in reference level: 0.428 m). For water levels > 4 m a straight-line correlation was chosen (Figure 51; y = 22.778x - 64.278). For those < 2.7 m also a straight-line function (Figure 52; y = 19.608x - 48.078) was used.

For the future it is recommended to install all flow measurements at the proposed new spring capture (GITEC & BGR, 2011) and to have two sets of ADCP flow measurements and two sets of multiparameter probes to be operated simultaneously in order not to lose data.

4.2 Assal Spring

Assal and Labbane are two major springs in the Jeita catchment, discharging from the Upper Cretaceous C4 geological unit. At Assal water discharges from two springs (Figures 54-56). Discharge from both springs is channeled in rectangular concrete canals. At the Assal main spring the width of the section is 2.49 m (measured at ADCP). There are several outlets before the water is channeled to a distribution building and flow is therefore difficult to measure at one location. The BGR project decided to install measurement devices in the main (western) spring because it discharges approximately more than 75% of all flow. From spring 1 there is an outlet, which is permanently open, for irrigation. At the place where spring 1 and 2 join there is an overflow, which is, however, rarely active. After this junction, water is flowing into a building where it is distributed for the various intended purposes (Figures 54, 58).

LRA conducts flow measurements approximately every two weeks (personal communication) at the locations shown in Figure 58. Measurements of the overflow to the river, however, does not make sense, because part of this overflow originated from spring 1 and is therefore accounted for twice.

The BGR project installed a multiparameter probe (In-Situ Troll 9500) inside the main branch of Assal spring in August 2010 (Figure 55). The probe is installed inside a PVC casing with a perforated bottom cap and protected by a metal SEBA cap. The lower 1 m of the casing is slotted with 0.75 mm slit width (GWE Pumpenboese KVcasing/screens DN 115). This is the standard installation for all multiparameter probes done by the project. The multiparameter probe measures water level (m; with barometric correction), temperature (°C), electric conductivity (µS/cm), pH, turbidity (NTU), ORP (mV) and RDO.

Between 08/2010 and 12/2011, 40 dilution tests were done at Assal spring at different stages (Table 6). A good stage-discharge relationship could be established for the these measurements in the main spring, showing an R^2 higher 0.97 (Figure 59).

A SonTek iQ ADCP with 5 beams (one vertical beam for stage measurement, 4 beams for flow measurement) was installed in October 2012 for continuous measurement of flow. Data acquisition and processing with the iQ is much easier than with the SonTek Argonaut SW, installed in Jeita. While data recording needs to be restarted in Jeita after every readout, this is not required for the iQ so that data are stored continuously and in one file only. The flow data of the SonTek iQ, currently available, are displayed in Figure 59. The iQ ADCP will be continued to be monitored and related data will be presented in Technical Report No. 4, the main hydrogeological report.

Figure 54: Assal spring (before installation of the multiparameter probe)

Figure 55: Multiparameter probe Troll 9500 installed in Assal spring

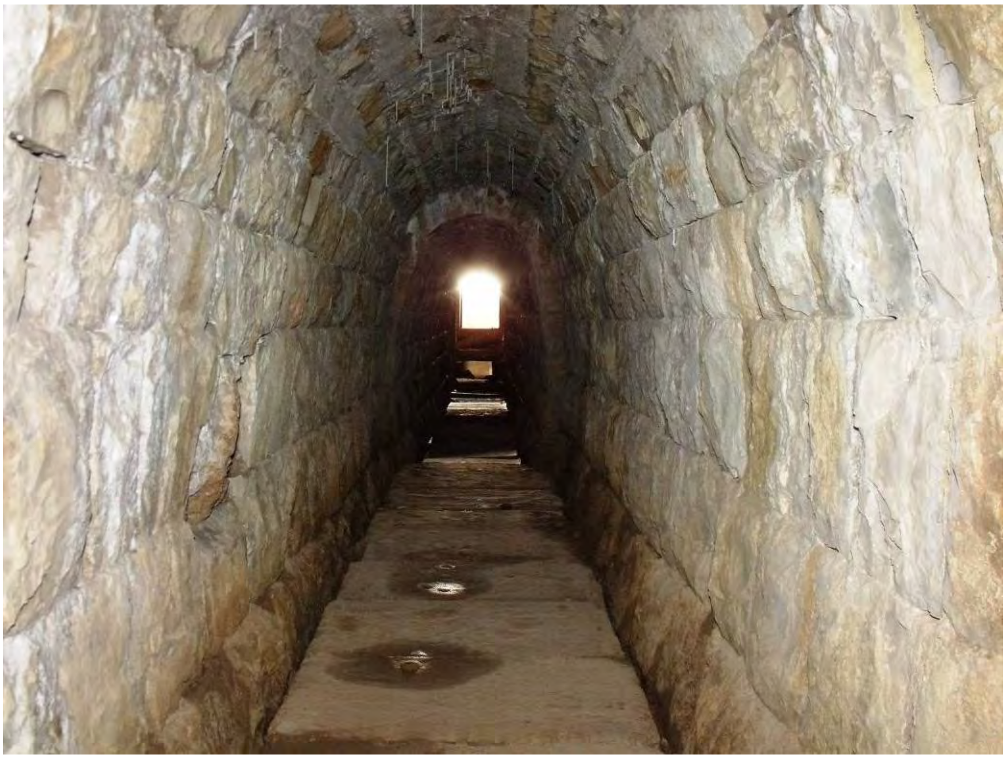

Figure 56: Smaller Unmeasured Branch of Assal spring (spring 2)

Figure 57: Water distribution at Assal spring

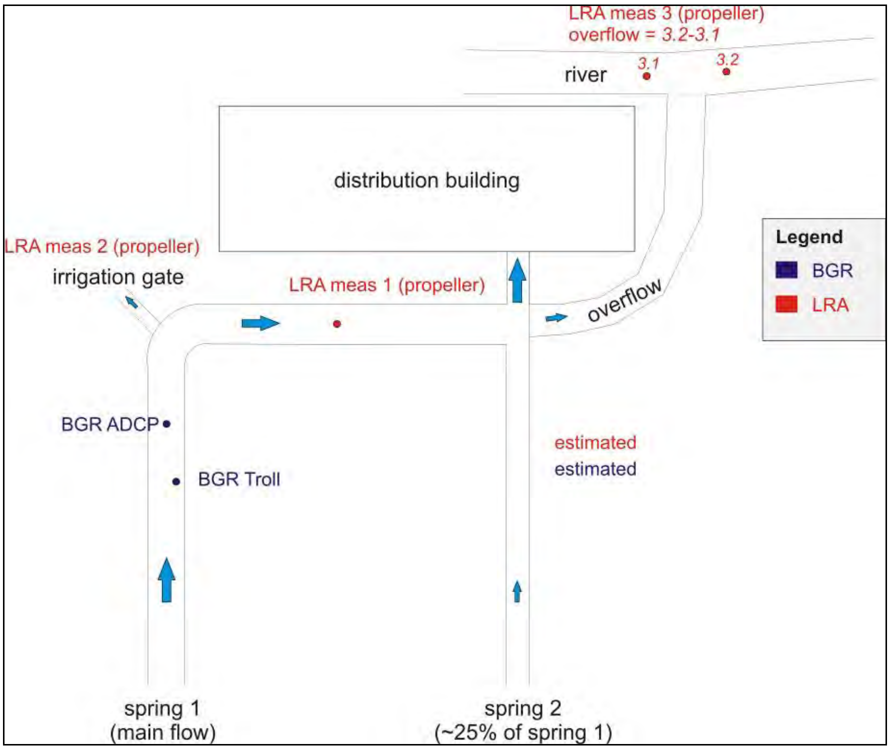

Figure 58: Schematic sketch showing spring discharge, monitoring and usage at Assal spring

Table 6: Dilution Tests at Assal spring used for Determination of Stage - Flow Correlation

Date & Time	Test-Number	Tracer amount	Discharge [m³/s]	water level [m]
13/08/2010 10:18	Test-1	2 kg salt	0.216	0.317
13/08/2010 10:36	Test-2	2 kg salt	0.204	0.317
18/08/2010 10:38	Test-1	2 g	0.183	0.313
18/08/2010 11:00	Test-2	2 g	0.171	0.313
18/08/2010 10:38	Test-1	2 kg salt	-	0.313
18/08/2010 11:00	Test-2	2 kg salt	0.198	0.313
10/10/2010 10:19	Test-1	2 kg salt	0.074	0.275
10/10/2010 10:19	Test-2	2 kg salt	0.089	0.275
16/11/2010 12:32	Test-1	2 kg salt	-	0.270
16/11/2010 12:58	Test-2	2 kg salt	0.092	0.270
16/11/2010 13:26	Test-3	5 kg salt	0.108	0.270
25/11/2010 10:27	Test-1	3 kg salt	0.091	0.272
25/11/2010 11:09	Test-2	5 kg salt	0.096	0.272
25/11/2010 10:27	Test-1	1 g	0.089	0.272
25/11/2010 11:09	Test-2	1 g	0.085	0.272
15/12/2010 17:00	Test-1	1 g	0.147	0.278
15/12/2010 17:20	Test-2	1 g	0.153	0.278
10/01/2011 12:02	Test-1	3 kg salt	0.123	0.368
10/01/2011 12:21	Test-2	3 kg salt	0.125	0.368
10/01/2011 12:02	Test-1	0.5 g	0.142	0.368
10/01/2011 12:21	Test-2	0.5 g	0.142	0.368
23/01/2011 10:24	Test-1	0.5 g	0.142	0.284
12/02/2011 10:43	Test-1	0.5 g	0.580	0.555
12/02/2011 10:55	Test-2	0.5 g	0.440	0.555
12/02/2011 11:05	Test-3	0.5 g	0.390	0.555
01/03/2011 14:00	Test-1	1 g	0.580	0.620
01/03/2011 14:10	Test-2	1 g	0.490	0.620
09/03/2011 16:19	Test-2	0.5 g	0.680	0.690
09/03/2011 16:26	Test-3	0.5 g	0.630	0.690
30/03/2011 16:21	Test-1	0.5 g	0.670	0.695
30/03/2011 16:25	Test-2	0.5 g	0.690	0.695
30/03/2011 16:29	Test-3	0.5 g	0.660	0.695
15/05/2011 11:30	Test-1	0.25 g	0.970	0.720
15/05/2011 11:35	Test-2	0.25 g	0.980	0.720
15/05/2011 11:41	Test-3	0.25 g	0.920	0.720
23/05/2011 13:30	Test-1	0.5 g	1.130	0.750
23/05/2011 13:35	Test-2	0.5 g	1.100	0.750
03/09/2011 11:51		0.25 g	0.220	0.444
03/09/2011 11:59		0.25 g	0.220	0.444
03/09/2011 12:06		0.25 g	0.230	0.444

* tracer if not specified: uranine

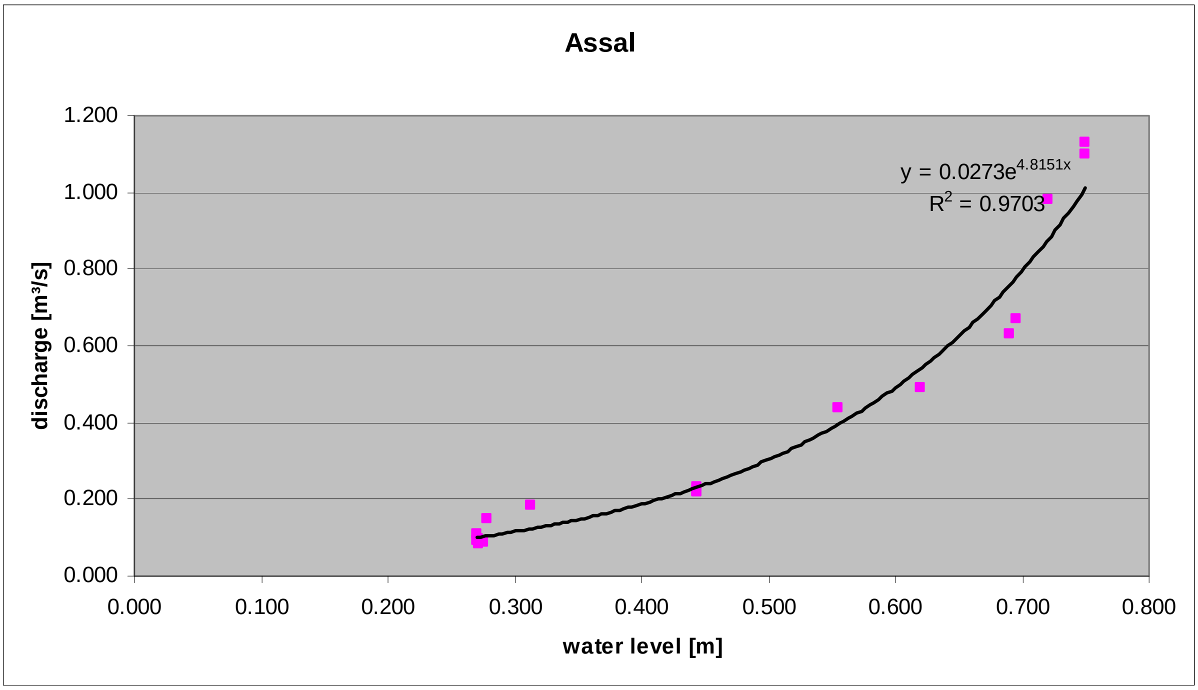

Figure 59: Stage-discharge relationship at Assal

Based on the above stage-discharge correlation, a discharge of 15.03 MCM for the water year 2010/11 and 22.44 MCM for the water year 2011/12 was calculated (Figure 60). Discharge in water year 2012/13 is expected to be even higher. Under the assumption that around 25% discharge from the smaller unmeasured part of the spring, average discharge of Assal spring is expected to be around 24 MCM, only. Estimates by LRA, based on approx. monthly propeller measurements are in the range of 32 MCM and are clearly overestimating flow.

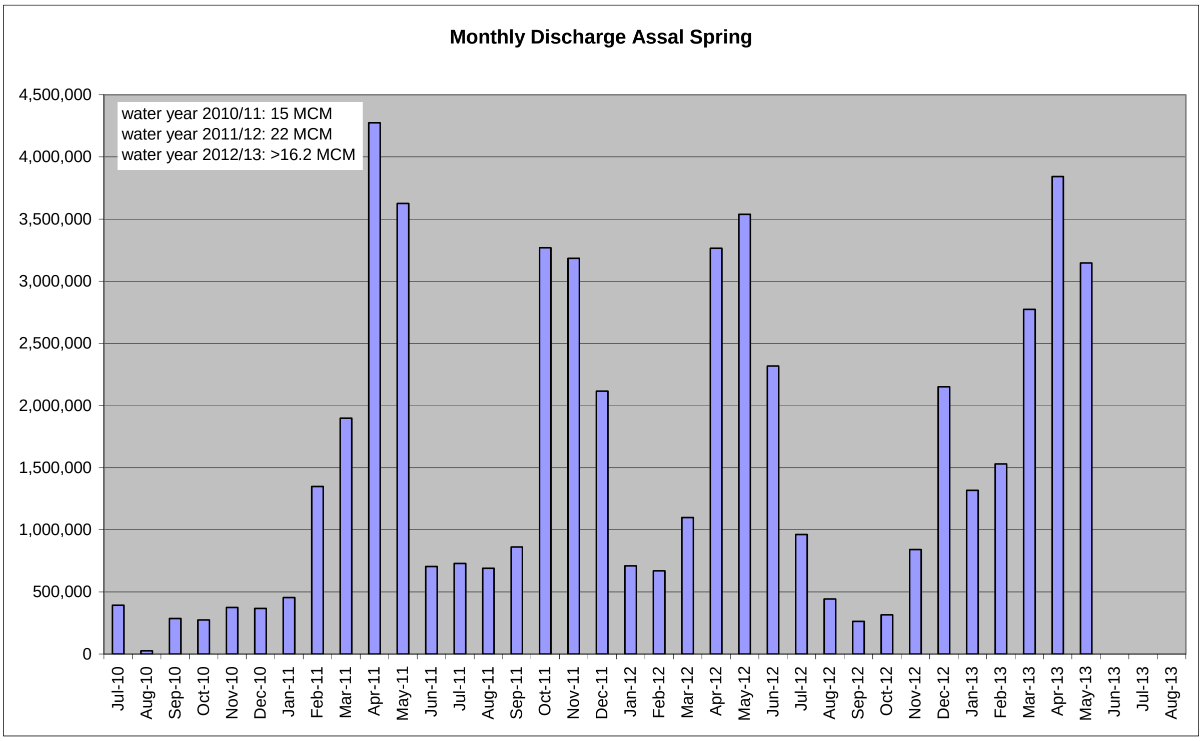

Figure 60: Monthly discharge of Assal Spring (01.06.2013)

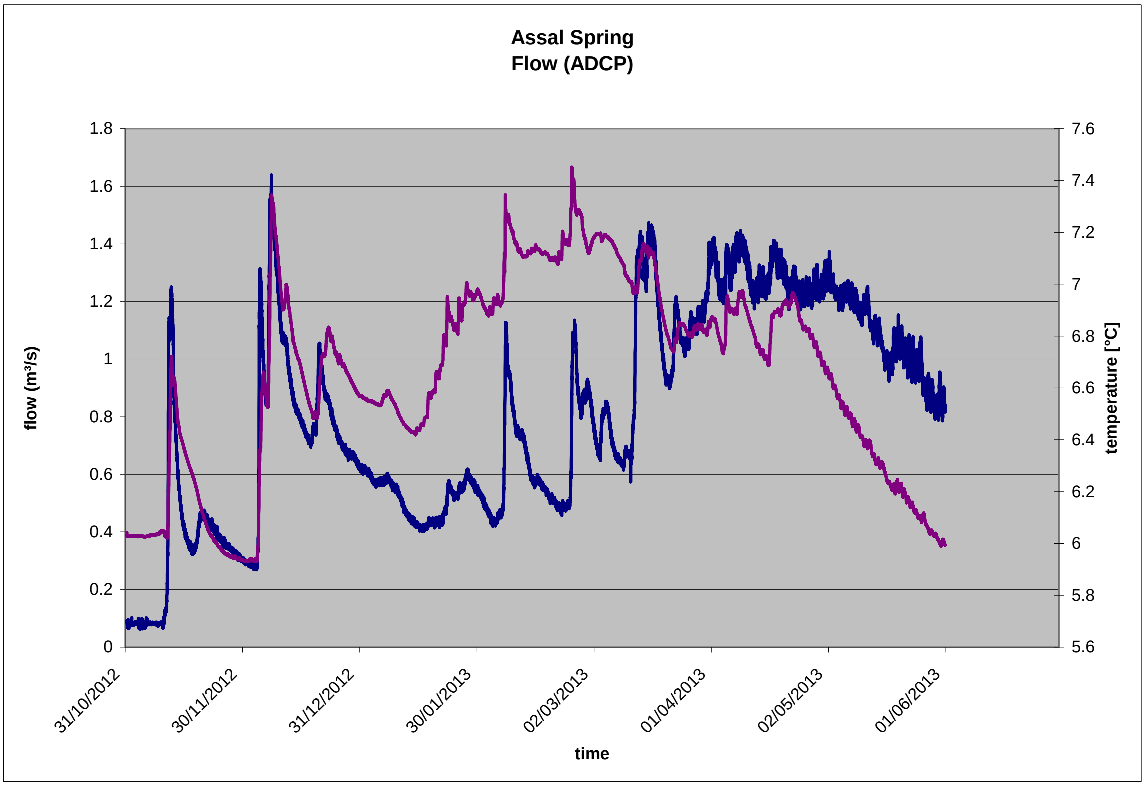

Figure 61: Flow (blue) and temperature (purple) data of Assal Spring acquired by the Sontek iQ ADCP (01.06.2013)

4.3 Labbane Spring

The rectangular section at Labbane has a width of 1.90 m (measured at weir; Figure 62). Also there an In-Situ Troll 9500 multiparameter probe was installed in August 2010 (Figure 62) in a casing identical to that of Assal spring. The multiparameter probe measures water level (m; with barometric correction), temperature (°C), electric conductivity (µS/cm), pH, turbidity (NTU), ORP (mV) and RDO. The Troll 9500 is accessible from a locked concrete box (Figure 63).

At Labbane spring 33 dilution tests were performed at different flows (Table 7). However tests at water levels > 0.8 m (with weir) could not be done because the required distance between point of injection and point of measurement could not be established. Low flows at Labbane spring are also difficult to record because of the wide rectangular structure of the canal. A metal weir was therefore incorporated but was destroyed in May 2011 by farmers from Kfar Debbiane.

Figure 62: Labbane spring with multiparameter probe (in blue PVC casing) protected by a locked concrete box

Figure 63: Head of PVC casing in concrete box with perforated hole for vented cable of multiparameter probe, connected to COM 300 unit for telemetric data transfer

Figure 64: Triangular metal weir (120°) destroyed in May 2011 by farmers from Kfar Debbiane - measurement of tracer arrival using an Albillia fluorometer

Table 7: Dilution Tests at Labbane spring used for Determination of Stage - Flow Correlation

Date & Time	Test-Number	Tracer amount	Discharge [m³/s]	Water level [m]
13/08/2010 10:18	Test-1	1 kg salt	0.014	
13/08/2010 10:18	Test-2	1 kg salt	0.014	
18/08/2010 9:45	Test-1	1 g	0.031	0.076
18/08/2010 10:02	Test-2	1 g	-	0.076
18/08/2010 9:45	Test-1	1 kg salt	0.019	0.076
18/08/2010 10:02	Test-2	1 kg salt	0.020	0.076
16/11/2010 10:44	Test-1	1 kg salt	0.016	0.217
16/11/2010 11:25	Test-2	1 kg salt	0.025	0.217
25/11/2010 12:37	Test-1	1 kg salt	0.010	weir leaking
25/11/2010 13:25	Test-2	1 kg salt	0.009	weir leaking
25/11/2010 12:37	Test-1	0.25 g	0.011	weir leaking
25/11/2010 13:25	Test-2	0.25 g	0.010	weir leaking
12/01/2011 10:41	Test-1	2 kg salt	0.051	0.430
12/01/2011 11:01	Test-2	3 kg salt	0.047	0.430
12/01/2011 10:41	Test-1	0.25 g	0.061	0.430
12/01/2011 11:01	Test-2	0.25 g	0.056	0.430
23/01/2011 13:05	Test-1	0.5 g	0.043	0.445
23/01/2011 13:20	Test-2	0.5 g	0.043	0.445
23/01/2011 13:35	Test-3	0.5 g	0.043	0.445
12/02/2011 13:30	Test-1	4 kg salt	0.156	0.575
12/02/2011 13:40	Test-2	4 kg salt	0.154	0.575
12/02/2011 13:50	Test-3	4 kg salt	0.147	0.575
12/02/2011 13:30	Test-1	0.5 g	0.145	0.575
12/02/2011 13:40	Test-2	0.5 g	0.143	0.575
12/02/2011 13:50	Test-3	0.5 g	0.145	0.575
04/03/2011 13:05		0.5 g	0.290	0.720
04/03/2011 13:10		0.5 g	0.270	0.720
30/03/2011 16:55	Test-1	0.5 g	0.440	0.745
30/03/2011 17:00	Test-2	0.5 g	0.420	0.745
30/03/2011 17:05	Test-3	0.5 g	0.440	0.745
15/05/2011 12:44	Test-1	0.5 g	1.620	0.820
15/05/2011 12:49	Test-2	0.5 g	1.380	0.820
15/05/2011 12:54	Test-3	0.5 g	1.650	0.820

* tracer if not specified: uranine

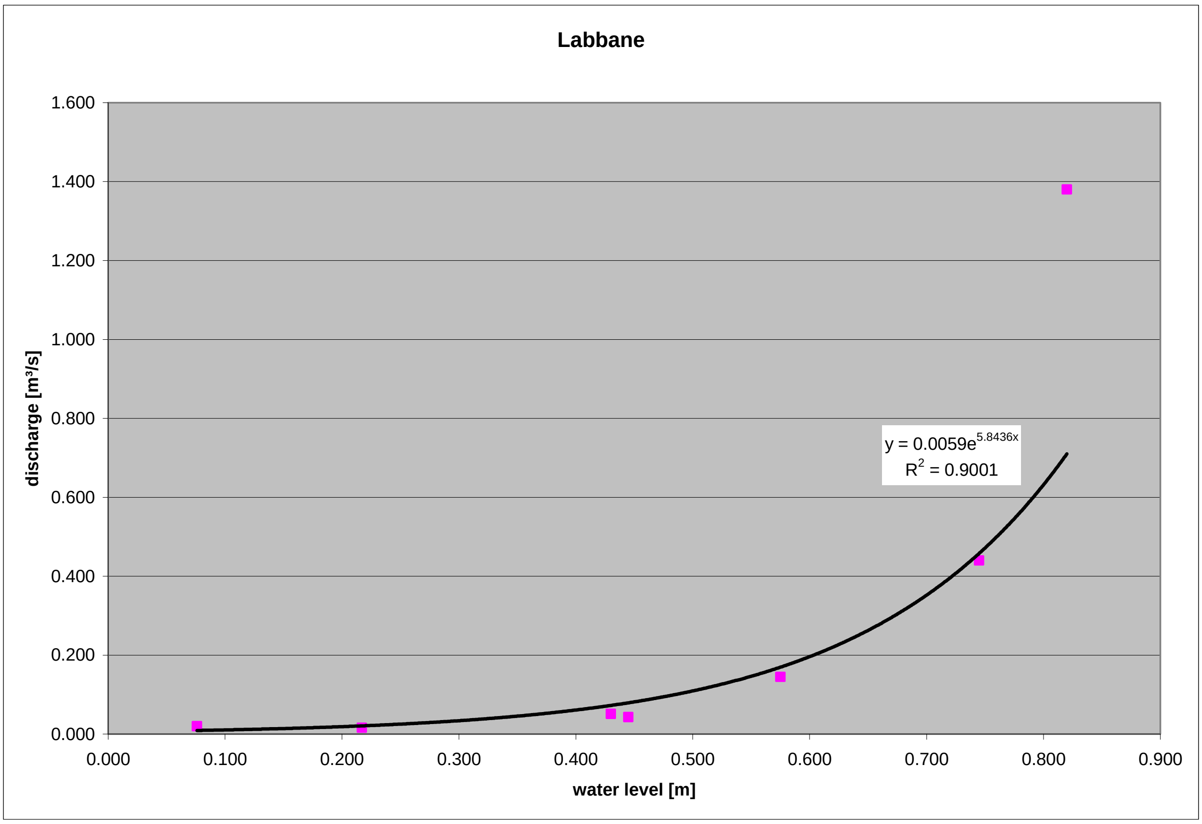

Figure 65: Stage-discharge relationship at Labbane

The stage-flow correlation at Labbane spring is relatively week, as it was only established through dilution tests. Moreover, this correlation is only valid until April 2011, because then the weir was stolen.

It is highly recommended to install an ADCP, such as the SonTek iQ, in Labbane spring. However, then the spring needs to be better protected against vandalism. After the very negative experience with the Kfar Debbiane farmers association, the project did not want to risk such equipment to be vandalized.

The current situation, where the spring is freely accessible and anybody could throw into the water whatever he wants is irresponsible. During winter 2011/12 a skidoo was found in the reservoir (MARGANE et al., 2013), risking a serious oil contamination. In spring 2013 waste, including pesticide containers, was dumped close to the reservoir.

4.4 Kashkoush

Kashkoush spring is located approximately 500 m downstream of Jeita and discharges into the Nahr el Kalb and/or into the Jeita-Dbayeh conveyor. Before being used for water supply in the Greater Beirut Area, Kashkoush spring discharged into the Nahr el Kalb River around 120 m upstream of the current location of the spring capture. The new spring capture was constructed in 1995, funded by Kuwait Fund (construction works by GIBBS & partners). It conveys the spring through a 170 m long tunnel to a diversion structure. Before arriving there, flow is measured using ultrasonic methods (Figure 67).

The groundwater catchment of Kashkoush spring has not yet been determined. During all tracer tests conducted in the Jeita GW catchment, Kashkoush spring was monitored, however, no tracer ever arrived at Kashkoush spring. However, a number of facts indicated that this spring receives much of the groundwater recharge in the southern part of the Nahr el Kalb surface water catchment:

- The wastewater generated in the southern part of the Nahr el Kalb surface water catchment, i.e. in the villages of Btegrine, Kchenchara, Hemlaya, Mar Boutros, Beit Chebab and Bikfaya, is collected in a network established during the early 1980, which, however, now is dilapidated and leaky. This network channels all untreated wastewater to the Nahr el Kalb river course. During spring 2012, extensive pollution occurred at Kashkoush spring due to a concentrated wastewater discharge northwest of Kchenchara (CHRABIEH & MARGANE, 2012). This is also documented in the high turbidity that was observed until mid June 2012 (Figure 71).

- From the quarries and rock cutting industries in the Abou Mizaine area, large quantities of limestone sludge are periodically discharged into the river course. Turbidity in Kashkoush spring was observed to rise after such discharge events.

- The HAJJ contractors sandstone quarry washes the sand to filter out fine sediments and then periodically discharges the fine sediments from their ponds (MARGANE & CHRABIEH, 2012). This causes high turbidity at Jeita spring and Dbayeh, resulting in problems of raw water treatment, to the effect that during such turbidity peaks contaminated water is fed into the drinking water network of the Greater Beirut Area. During the same time when these turbidity peaks were observed at Jeita spring, approximately 24 h after injection, they were also observed in Kashkoush spring. The turbidity peak in Kashkoush is, however, much lower compared to Jeita. This means that part of this high turbidity water infiltrates in the riverbed of Nahr el Kalb, between Deir Chamra and Kashkoush.

The tracer test conducted on 12 October 1996 in the Attine Azar sinkhole by LABAKY

(1998) proved that a connection with the Faouar Antelias spring exists (mean arrival time: 327 h; distance 18,000 m). Very minor fractions also supposedly arrived in Daychouniyeh spring, Kashkoush spring, Jeita spring, Jeita boreholes and Mar Antonios boreholes, although altogether not even one percent of the tracer. However, during the test 'torrential rains' occurred, which may have lead to wrong readings of the concentrations due to elevated turbidity. Unfortunately turbidity was not measured during the test. Therefore the result of this test is not conclusive for all other above mentioned springs, except for Faouar Antelias.

Dilution tests and stage-discharge measurements were also performed at Kashkoush, even though this spring is not part of the Jeita groundwater catchment. Also at Kashkoush spring an In-Situ Troll 9500 multiparameter probe was installed in August 2010 (Figure 66) in a casing identical to that of Assal spring. The multiparameter probe measures water level (m; with barometric correction), temperature (°C), electric conductivity (µS/cm), pH, turbidity (NTU), ORP (mV) and RDO. The Troll 9500 is accessible from a locked SEBA cap.

At Kashkoush spring 27 dilution tests were performed at different flows (Table 8). However tests at water levels > 0.5 m could not be done because access to the straight-line channel from which water exits the spring was not possible then due to high flow velocities. However, maximum water level recorded by the multiparameter probe reached 2.15 m. At a stage of 1.8 m the radar sensor (Figure 65), installed through a CDR project in 2003 and monitored now manually by WEBML, is also flooded. According to personal communication with the manufacturer (Marsh McBinnie), the instrument is not suited for installation in Kashkoush spring (compare GITEC & BGR, 2011).

Kashkoush spring shows much higher discharge rates than Assal or Labbane and its water is also used as drinking water supply for Beirut. Therefore and because in the beginning the catchment was unclear, it was considered to be important to record discharge quantities of this spring as well. Dilution tests were conducted with uranine tracer at different stage level. It must be kept in mind, however, that similar to the other springs in the project area, dilution tests at Kashkoush are difficult to perform due to the configuration of the spring capture. Only two reliable results at flows greater 0.6 m^3/s were achieved and used for the discharge-stage relationship (see Figure 69). The correlation for flows at water levels > 0.5 m is therefore attached with a high level of uncertainty. The flow obtained using the above mentioned stage-flow correlation is: 54.1 MCM in water year 2010/11 and 84.0 MCM in water year 2011/12 (Figure 70). Discharge in water year 2012/13 was already close to 70 MCM on 31.05.2013 and is expected to be at least the same as in 2011/12. Based on the discharge measurements of the project, the long-term annual average discharge of Kashkoush spring is estimated at 70 MCM.

Figure 66: BGR Monitoring of Kashkoush Spring Water Quality and Discharge

(data can be sent via telemetric transfer to Dbayeh treatment plant for quality control and discharge management)

Figure 67: WEBML Monitoring of Kashkoush Spring Discharge

(since 2003 water level and flow velocity data were sent via telemetric transfer to Dbayeh; this system is currently out of order)

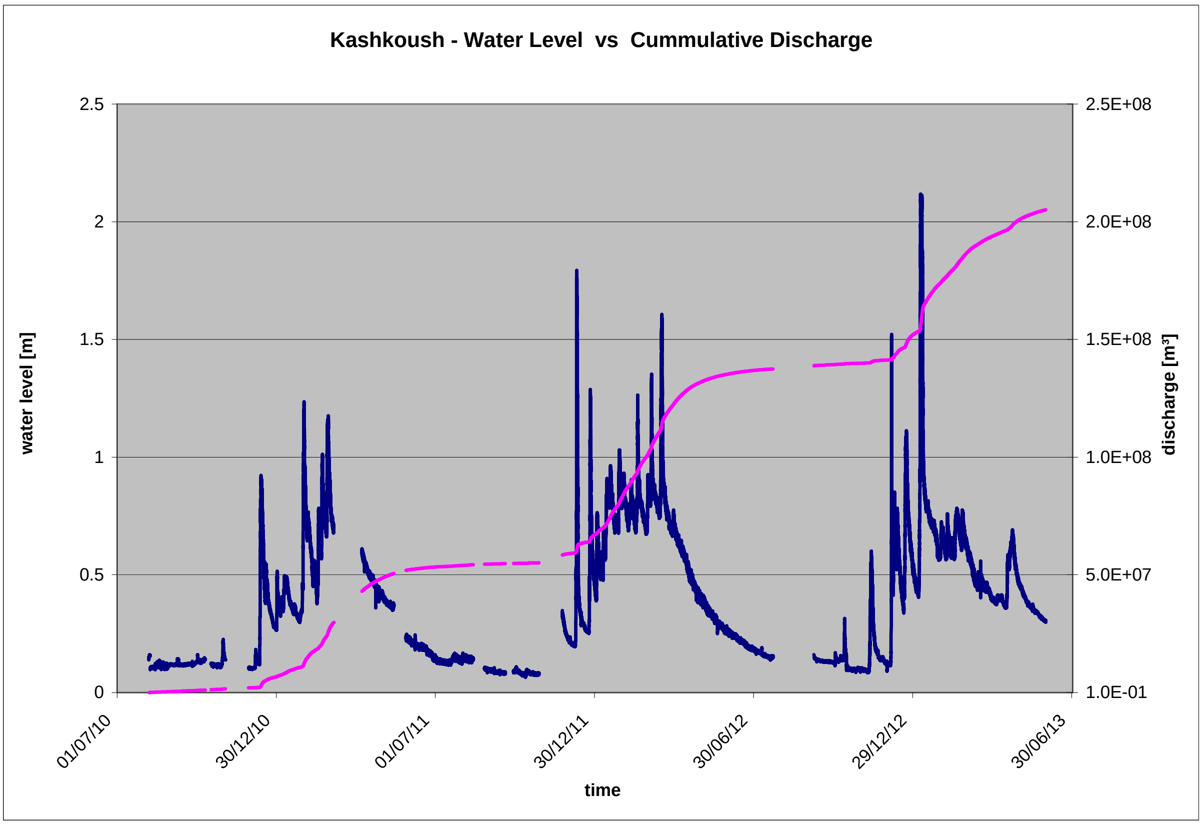

Figure 68: Water level measurements (blue) and calculated discharge (pink) at Kashkoush spring (31.05.2013)

Table 8: Dilution Tests at Kashkoush spring used for Determination of Stage - Flow Correlation

Date & Time	Test-Number	Tracer amount	Discharge [m³/s]	Water level [m]
04/05/2010 13:55	Test-1	2 g	0.490	
04/05/2010 13:55	Test-1	2 g	0.501	
12/08/2010 10:10	Test-1	2 kg salt	0.350	0.105
12/08/2010 10:10	Test-2	2 kg salt	0.370	0.105
12/08/2010 10:10	Test-1	2 g	0.400	0.105
12/08/2010 10:10	Test-2	5 g	0.440	0.105
15/10/2010 10:15	Test-1	5 kg salt	0.293	0.160
15/10/2010 10:30	Test-2	5 kg salt	0.300	0.160
15/10/2010 10:15	Test-1	2 g	0.340	0.160
15/10/2010 10:30	Test-2	2 g	0.330	0.160
15/10/2010 10:40	Test-3	2 g	0.412	0.160
15/10/2010 10:50	Test-4	2 g	0.360	0.160
10/11/2010 15:24	Test-1	5 kg salt	0.220	0.145
10/11/2010 15:34	Test-2	5 kg salt	0.310	0.145
29/11/2010 9:54	Test-1	5 kg salt	0.268	0.135

Date & Time	Test-Number	Tracer amount	Discharge [m³/s]	Water level [m]
29/11/2010 10:10	Test-2	5 kg salt	0.275	0.135
29/11/2010 9:54	Test-1	2 g	0.452	0.135
29/11/2010 10:10	Test-2	2 g	0.355	0.135
11/01/2011 15:37	Test-1	10 g	3.030	0.480
11/01/2011 15:47	Test-2	10 g	2.900	0.480
11/01/2011 15:57	Test-3	10 g	3.210	0.480
21/01/2011 13:40	Test-1	1 g	2.400	0.432
21/01/2011 13:45	Test-2	1 g	2.000	0.432
21/01/2011 13:50	Test-3	1 g	2.200	0.432
13/08/2011 13:28	Test-1	0.25 g	0.570	0.225
13/08/2011 13:33	Test-2	0.25 g	0.585	0.225
13/08/2011 13:38	Test-3	0.25 g	0.565	0.225

* tracer if not specified: uranine

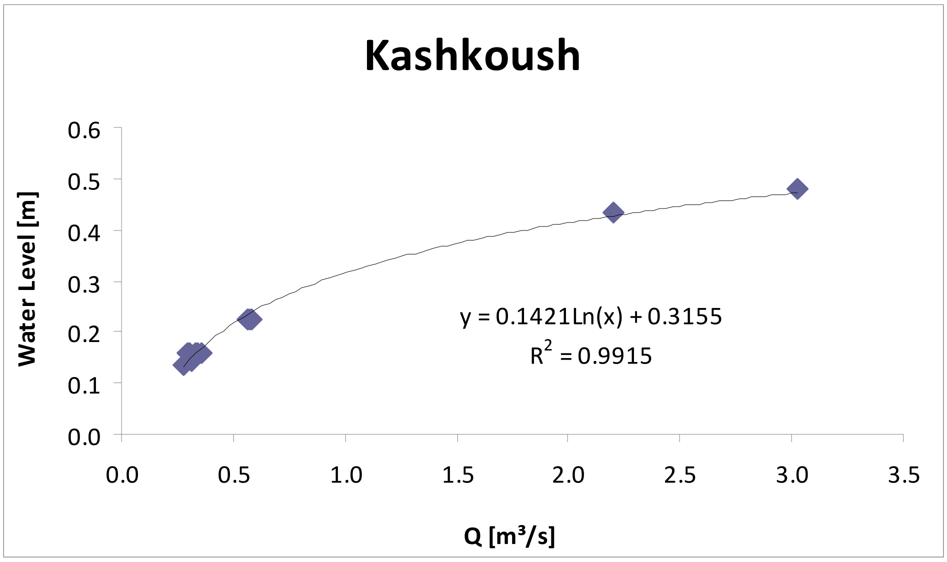

Figure 69: Stage-discharge relationship at Kashkoush

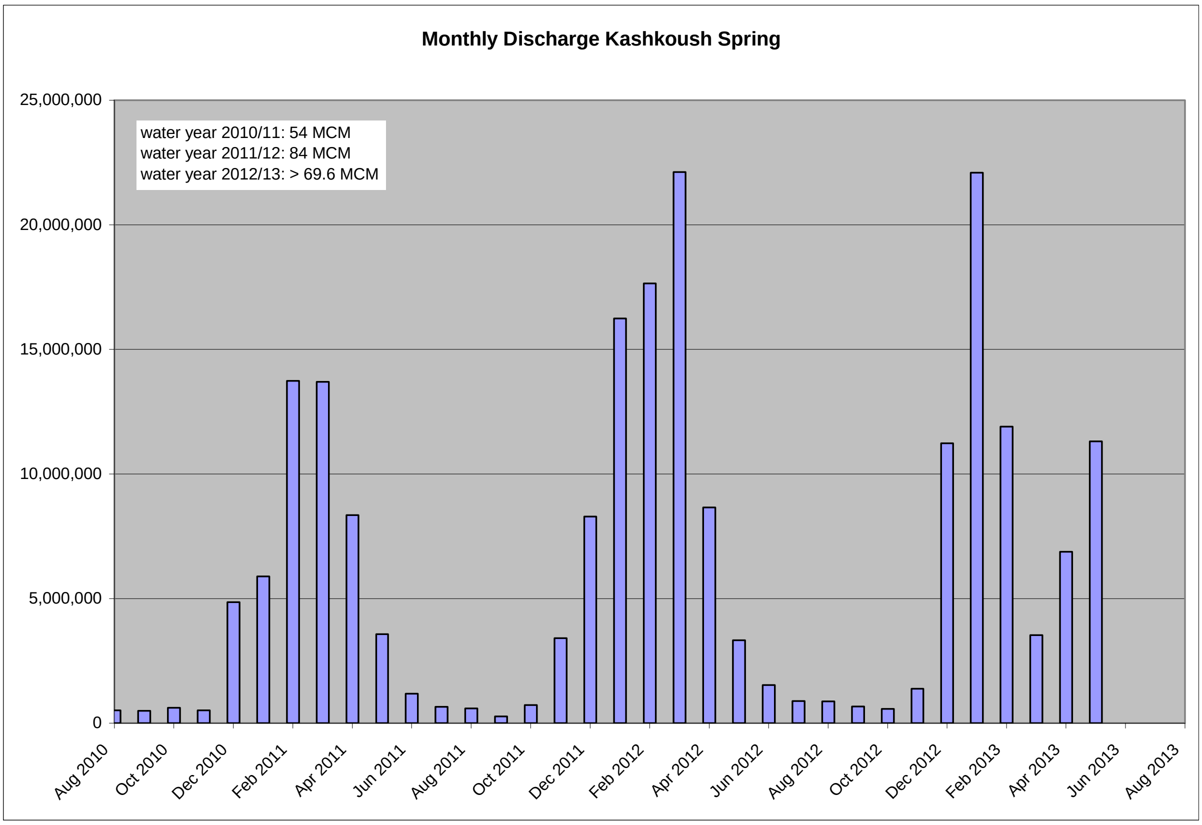

Figure 70: Calculated Flow of Kashkoush Spring (31.05.2013)

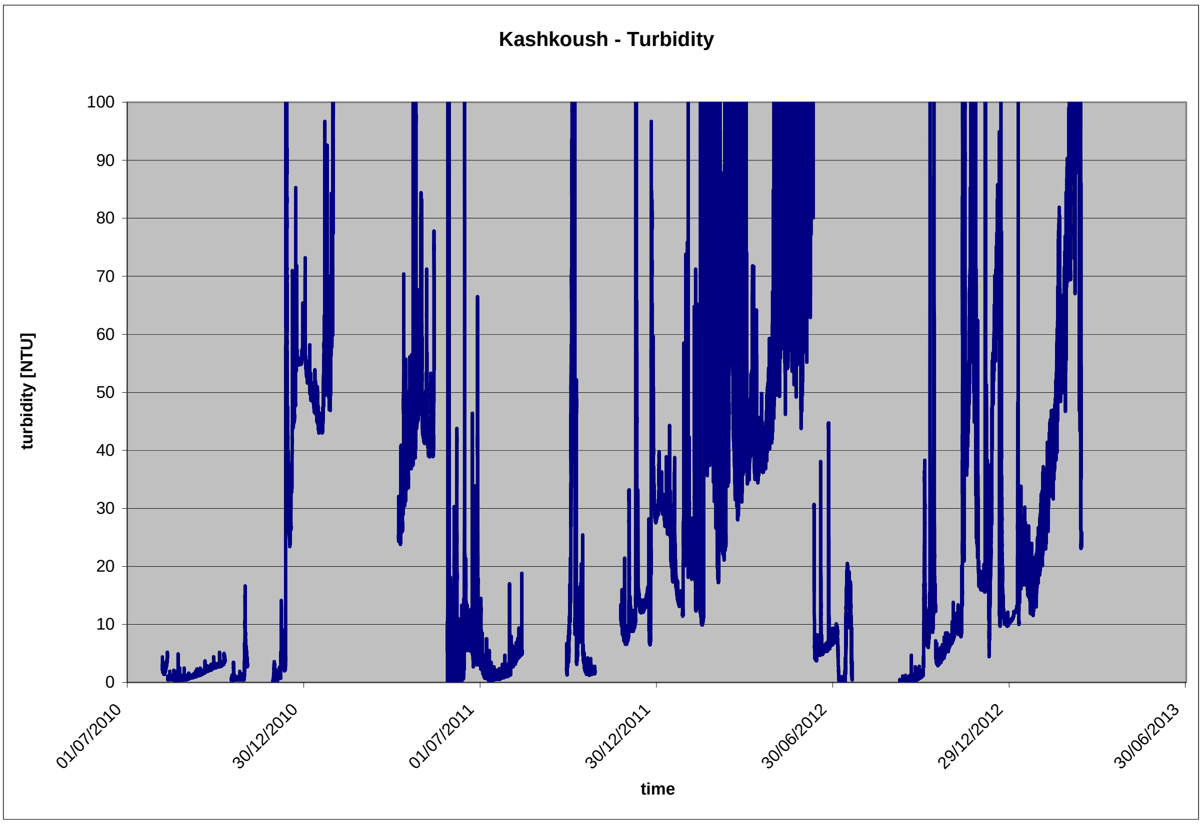

Figure 71: High Turbidity of Kashkoush Spring

5 Planned discharge measurements

For continuous streamflow measurements it is proposed to install new runoff gauges in the catchment. By these measurements discharge from different sub-catchments can be determined in a high resolution in time. This will add important information to the understanding of the dynamics and runoff processes in the Jeita groundwater catchment, for instance related to events of torrential rain or snowmelt, both at lower elevations (800-1600 m asl on the J4 aquifer and on the aquitard) and at higher elevations (> 1600 m asl on the C4 aquifer). It will help to quantify groundwater recharge by measuring the infiltration of surface water runoff into groundwater. Additionally such runoff data is of major importance when flood frequency estimations will be applied. Further, the accuracy of existing data may be improved and can be corrected by the installation of new runoff gauges.

Streamflow in the natural riverbeds in the project area is usually turbulent, because of great roughness due to large boulders with diameters up to 2 - 3 m, local pool and riffle systems, and a generally high expected sediment load. It is therefore difficult to accurately determine river discharge in the catchment. For the existing gauge at Daraya, a stage-discharge relationship was tried to be established by hydraulic wing measurements, conducted by Litani River Authority (LRA). Such method seems improper for runoff measurements due to the extreme unconformable flow. Moreover peak runoff shows heavy bed load and integration of different wing point measurements will not provide reliable results for total runoff calculations. The fact that geometry of the river bed changes with time, additionally exacerbates the use of the stage-discharge relationship. Nonetheless, by the installation of proper measurement constructions like a flume or a weir, this relationship can more easily and more accurately be determined and valuable data can be gathered.

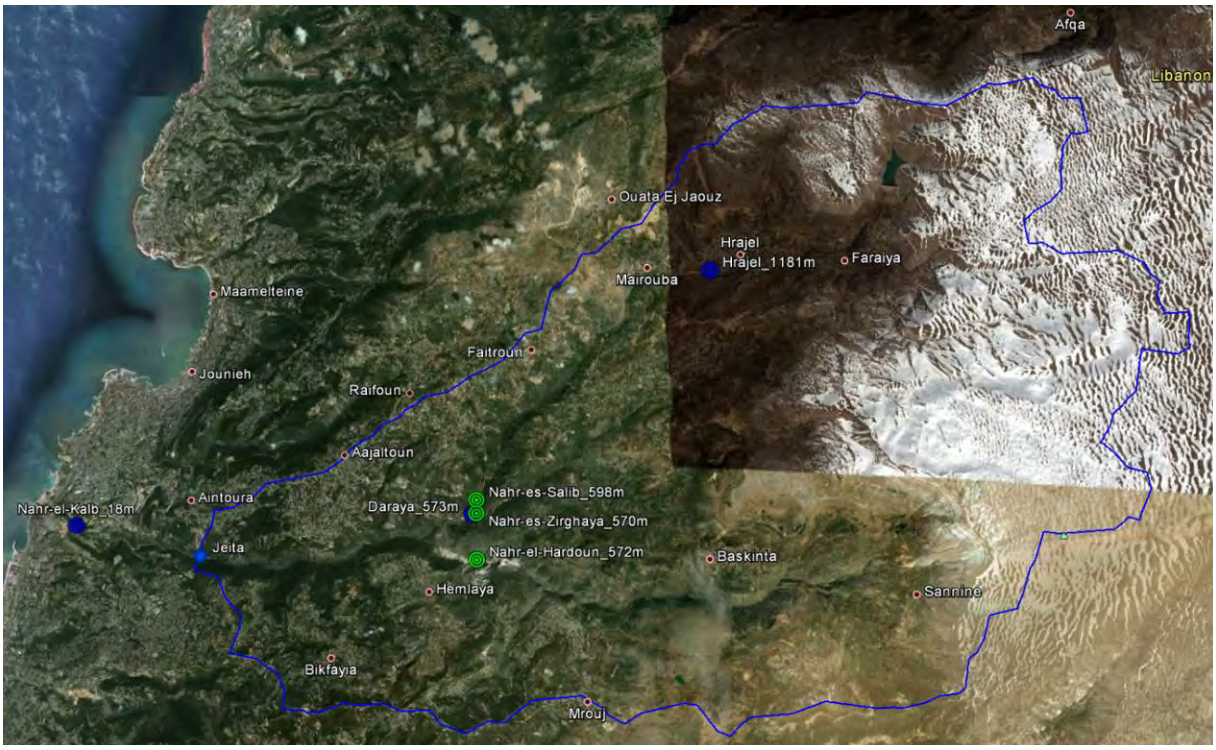

Figure 72: Jeita Surface Water Catchment with existing (blue) and planed (green) Runoff Gauges

5.1 Site Selection

To determine partial discharge of the Jeita catchment, runoff gauges should be set up at the outlet of each of the three sub-catchments. Approximately 330 m and 70 m upstream of the confluence of Nahr es Salib and Nahr es Zirghaya, respectively, two bridges provide good locations for the installation of flumes. The short distance between these bridges and the confluence of these sub-catchment rivers ensure a correct measurement of total surface runoff. Bridges are easy accessible for maintenance, visual observations, and runoff evaluation even in periods of high flow.

By banking up a ramp on one of the flanks, access is also provided for heavy construction machinery.

For the third sub-catchment Nahr es Hardoun, the situation is more difficult. Approximately 2 km upstream of the confluence with Nahr el Kalb, a bridge in the Nahr es Hardoun catchment provides a fair location for the installation of a runoff gauge in the future. Even though the riverbed is rectified at this location, providing a general good gauging site, construction-waste dumps narrow the riverbed and make it impossible to determine stage-discharge relationship at the moment (see Figure A6). These rock waste dumps occur directly before and after the bridge. It is proposed to set up a fence at this location in accordance with the responsible ministry so that the dumping of waste into the riverbed is prevented and a flume can be installed.

5.2 Runoff estimation

Maximum runoff estimation is necessary to determine the dimensions and characteristics of a flume or weir to be installed. Discharge of the ephemeral rivers Nahr es Salib, Nahr es Zirghaya, and Nahr es Hardoun ranges from zero flow in the months of the dry period to maximum flows in the periods of rain and snowmelt. Several methods for the determination were applied to estimate maximum runoff in the ephemeral rivers. Mean runoff is also of concern, because it determines the range in which a device should operate most accurately. Minimum runoff below a certain threshold may not be recorded or be rather inaccurate.

A first approach was established to calculate maximum flow by rainfall-runoff analyses. Catchment areas of the Nahr es Salib and the Nahr es Zirghaya were calculated using DEM data (SRTM). Probable maximum precipitation was estimated. Areas for the permeable Middle Cretaceous in the upper catchment areas, the Lower Cretaceous aquitard, and the Upper Jurassic limestone aquifer in the lower catchment areas were distinguished. The highly karstified terrain, favoring fast infiltration as well as quick response in spring discharge makes a rainfall-runoff correlation difficult. The release of melting water from snow in spring time even exacerbates the calculation of maximum (and mean) discharge of the sub-catchments. Because of these uncertainties, reliable results could not be established by rainfall-runoff analyses.

To determine the maximum runoff, paleo-flood analyses were used as an indirect method of runoff estimation (SIMMERS, 2003). Channel widths are measured at sections where gauges are planned to be installed. At Nahr es Salib 1/3 of the width underneath the bridge (around 8 m) seems to serve as active riverbed at high floods. Maximum water level was tried to be determined by surveying erosion marks and deposits of fine materials (silt), driftwood or organic debris (e.g. plastic bags). Maximum water depth is extremely difficult to determine and is suggested to be around 3 m. Taking tree growth in the riverbed into consideration, provides reasonable results of maximum discharge within a certain period of time. In the Nahr es Zirghaya at least 15 to 20 year old trees were found to grow in the middle of the river bed (Figure A3). This suggests that high floods are rare, with mean discharge not harming tree growth. On the other hand, total energy of maximum runoff was also taken into account by looking at the dimension of the deposited rocks in the river. Also at Nahr es Zirghaya boulders with diameters of around 2 m were found on top of the basement of the bridge (Figure A4). This suggests extreme forces to move such rocks downstream at times of peak flow.

Because of the high uncertainties of this empirical method, flood frequency estimation of a nearby gauge was performed, from which discharge of the sub-catchments might be derived. The estimation of maximum discharge was done by using runoff data from the Daraya gauge some hundred meters downstream the confluence of Nahr es Salib and Nahr es Zirghaya. Flood frequency estimations were calculated for this station and maximum floods for the two upper sub-catchments were estimated by this result. Runoff data at Daraya is supposed not to be very trustworthy because of the before described methods of measurement (Chapter 4). Still, this data can serve as an approximation for the expected maximum river flow. Daily average runoff data in m³/s are available for 19 years in total. These years are the hydrological years of 1974/75, 1981-1985, and 1994-2007 with 1996/97 data missing. The three years 1980/81, 1982/83, and 1984/85 show lack of data in the months of highest discharge and where therefore not taken into account for flood estimates. Other years show also lack of data for several days but are expected to include maximum measured discharge of that year. Maximum runoff was selected for each of the 16 hydrological years (Table 9). Average (arithmetic mean, Xm), standard deviation (σ), and skewness (Cs) were calculated to determine the probable maximum flood (PMF), which is assumed to have an annual exceedance probability of 1%. Because Cs > 1, the Pearsson III distribution was applied, that is commonly used to estimate probabilities of extreme events. Dependent on the skewness (here 1.04, see

Table 9), Pearsson III K-values were selected from the table (NACHTNEBEL, 2007). For return periods of 20 a, 50 a, and 100 a. PMF [m³/s] was then calculated for each return period by applying

$$PMF = Xm + K * \sigma \quad \text{.} \tag{Eq. 1}$$

PMF with a return period of 100 a or an annual exceedance probability of 1% is therefore assumed to be 55.1 m³/s (see

Table 9). For return periods of 50 a and 20 a PMFs are 49.6 m³/s and 42.1 m³/s, respectively. One must keep in mind, that these values are calculated for the Daraya station after the confluence of Nahr es Salib and Nahr es Zirghaya.

For the transformation of PMFs to each sub-catchment, runoff data from the Hrajel station in the upper Nahr es Salib were used. Data for the station Hrajel are only available for the years 1974/75 and 2002 – 2007 (compare Figures 38 and 40). Analyzing and comparing maximum discharge with the station at Daraya (after the confluence with Nahr es Zirghaya) shows no correlation. This is, because maximum runoff at Daraya is not always generated equally by each of the two sub-catchments. Still, it is assumed that highest discharge at Nahr es Salib sub-catchment is around 75 % of total calculated PMF at Daraya (55.1 m³/s). Thus, if data is trusted, maximum flood discharge for the Nahr es Salib would be 41.3 m³/s.

Taking results from paleo-flood estimates into account, it is assumed that maximum discharge at Nahr es Zirghaya is around 10 m³/s less than at Nahr es Salib, i.e. 32 m³/s. This is also suggested by the evaluation of contributing spring discharge within the catchments, which is highest at Nahr es Salib where Labbane and Assal spring are located. PMF for Nahr es Zirghaya is therefore assumed to be 32 m³/s.

Empirical analysis and shape of the riverbed suggest that discharge at Nahr es Hardoun is lowest of all sub-catchments. Still, scarcity of data makes an evaluation of probable maximum floods at Nahr es Hardoun more difficult. Thus it is suggested to adopt the PMF value of the adjacent Nahr es Zirghaya catchment. Probable maximum flood with annual exceedance probability is therefore determined to be 32 m³/s at Nahr es Hardoun.

Table 9: Flood frequency estimation for return periods of 20 a, 50 a, and 100 a

Number	**Q-max [m^3/s]**	**Xi-Xm**	**(Xi-Xm)^3**
1	7.8	-13.0	-2190.7
2	8.3	-12.5	-1947.3
3	9.6	-11.2	-1400.2
4	9.8	-11.0	-1326.5
5	10.1	-10.7	-1220.8
6	14.6	-6.2	-236.9
7	18.0	-2.8	-21.7
8	18.3	-2.5	-15.4
9	23.0	2.2	10.8
10	24.0	3.2	33.2
11	24.3	3.5	43.3
12	24.8	4.0	64.6
13	26.0	5.2	141.6
14	28.2	7.4	407.3
15	36.2	15.4	3661.2
16	49.6	28.8	23919.0
Sum	**332.6**	0.0	19921.6
Average (X_m)	**20.79**		
St. dev (σ)	**11.34**		
Skewness (Cs)	**1.04**		
Return period (δt)	**20 a**	**50 a**	**100 a**
K (Pearsson III)	1.9	2.5	3.0
PMF [m^3/s]	**42.1**	**49.6**	**55.1**

5.3 Gauge Design

First of all it must be considered, that by the construction of a flume underneath a bridge, a sufficiently large section remains to accommodate the maximum potential flow. It is recommended to construct Parshall flumes at the selected sites. The advantages of Parshall flumes are accurate measurements of discharge without having to establish the full range of a stage-discharge relationship. They are well reviewed and stage-discharge relationships are known for a great number of standardized flumes (VLOTMAN, 1989; CLEMMENS et al., 2001). Flumes must be very precisely constructed using the dimensions stated in the established literature to ensure a correct relationship of stage and discharge. Using the expected maximum discharge values, derived in Chapter 5.2, it is suggested to construct a 20´ and a 25´

Parshall flume at the two selected locations at Nahr es Zirghaya and Nahr es Salib, respectively. Total length of the 20´ and 25´ Parshall flumes are 13.107 m and 13.441 m, respectively. Large Parshall flumes consist of three sections: the converging section where flow approaches (maximum widths: 9.144 m and 10.668 m, respectively) the throat section (being the narrowest section with widths of 6.096 m and 7.620 m, respectively), and the diverging section at the outlet (maximum widths: 7.315 m and 8.941 m, respectively). All measures are listed in Table 10, also see Figure 73.

The construction of the flumes should be conducted during summer time, when no discharge is expected. It must be ensured, that no flow occurs on the sides of the flume, it should therefore end on one side of the bridge. Further, it must be considered, that no underflow occurs underneath the flume structure. Thus it is suggested to clean the riverbed from smaller rocks before starting to build the concrete flume structure. Using metal reinforced concrete will give more stability to the flume. A maximum height of 1.5 m from the base of the bridge is suggested for the basement of the flumes. This guarantees that the opening underneath the bridge is still large enough to accommodate peak floods even exceeding the PMF. Upstream conditions ideally should promote laminar flow conditions at the flume inlet. Therefore, slope of the channel should be less than 2 % for big flumes and river courses should be straight upstream of the flume. Dimensions as listed in Table 10 must carefully be considered when constructing a flume. It is of mayor importance to horizontally level the base of the converging section, where measurements take place. Yearly conditions of the flume must be checked. Damages have to be repaired to ensure a correct stage-discharge relationship over time. If sedimentation occurs, the flume must be cleaned after each rainy season.

5.3.1 Runoff gauging at Nahr es Salib

Taking a maximum discharge of 41.3 m³/s and a free board of 10 % into account, the flume should be capable to measure discharges of 45.5 m³/s. Free board is defined as the difference between max. water level and the upper edge of the flume. Thus it is recommended to install a 25’ Parshall flume at Nahr es Salib. With this flume discharge between 0.38 m³/s and 47.14 m³/s can be recorded. The lower end of the flume should be placed 6 m downstream of the lower end of the bridge's side wall, to ensure a frontal approach stretch of at least 10 m (6 times maximum stage, h_a max. of 1.83 m for 25´ Parshall flume) upstream of the flume. This should be considered, because upstream runoff water approaches the bridge with an angle of about 35 deg. Also because there is a high variability in slope within short distance along the river, a stretch of 10 m minimum in front of the flume should be considered to act as a stilling zone. The riverbed should be cleaned from large boulders and slope should be less than 2 %. By this stretch measurement errors at the converging section will be minimized (VLOTMAN, 1989). To exemplify, Figure A5 shows a drawing of how the Parshall flume should be placed underneath the bridge at the outlet of the Nahr es Salib catchment.

PMF:	41.3 m^3/s
Channel:	Natural stream
Approaching flow:	Looking upstream, discharge approaches the bridge from the left with an angle of approximately 35 deg
Bed load:	Big rounded rocks with diameters up to 3 m
Bridge dimensions:	Height 12 m Length 19 m Width 19.5 m
Access:	Banking up a ramp is possible on the lower right flank (downstream view)
Runoff gauge	25´ Parshall flume

5.3.2 Runoff gauging at Nahr es Zirghaya

Because of the mentioned paleo-flood observations and the shape of the riverbed it is assumed that PMF at Nahr es Zirghaya is around 10 m^3/s less than PMF at Nahr es Salib. This empirical but conservative approximation suggests a PMF of 32 m^3/s for the Nahr es Zirghaya catchment. Adding a free board of 10 %, the flume should be designed to measure a discharge of at least 35.2 m^3/s. Thus it is recommended to install a 20’ Parshall flume at Nahr es Salib. With this flume discharge between 0.31 m^3/s and 37.91 m^3/s can be recorded. The flume should be placed directly underneath the bridge, closing up with its left wall (downstream view). A frontal approach stretch of at least 10 m (6 times maximum stage, h_a max. of 1.83 m for 25´ Parshall flume) should be considered, ensuring measurement errors of less than 3% (VLOTMAN, 1989). The 10 m long stretch should be as plain as possible (less than 2 %), and also cleared from large boulders.

PMF:	32 m^3/s
Channel:	Natural stream
Approaching flow:	flow approaches frontal at bridge
Bed load:	Big rounded rocks with diameters up to 2 m
Bridge dimensions:	Height 17 m Length 11 m Width 20 m
Access:	Banking up a ramp is possible on the lower left flank (downstream view)
Runoff gauge:	20´ Parshall flume

5.3.3 Runoff gauging at Nahr es Hardoun

The bridge 2 km upstream of the confluence with Nahr el Kalb provides a fair location for the installation of a runoff gauge in the Nahr es Hardoun catchment. At the time being waste dumps in the riverbed make the installation of a flume impossible at the selected site (see Chapter 5.1). After resolving this problem it is possible and recommended to also install a 20´ Parshall flume at this site, to cover the entire Nahr el Kalb surface water catchment with runoff gauges.

PMF:	32 m³/s
Channel:	Rectified stream below bride with plain river bed
Approaching flow:	Flow approaches frontal at bridge
Bed load:	Rounded rocks with diameters up to 2 m, cleaned channel downstream
Bridge dimensions:	Height 10 m Length 15 m Width 12 m
Access:	Possible access to riverbed 350 m downstream of bridge
Runoff gauge	20´ Parshall flume
Problems:	Construction-waste dumps in the riverbed

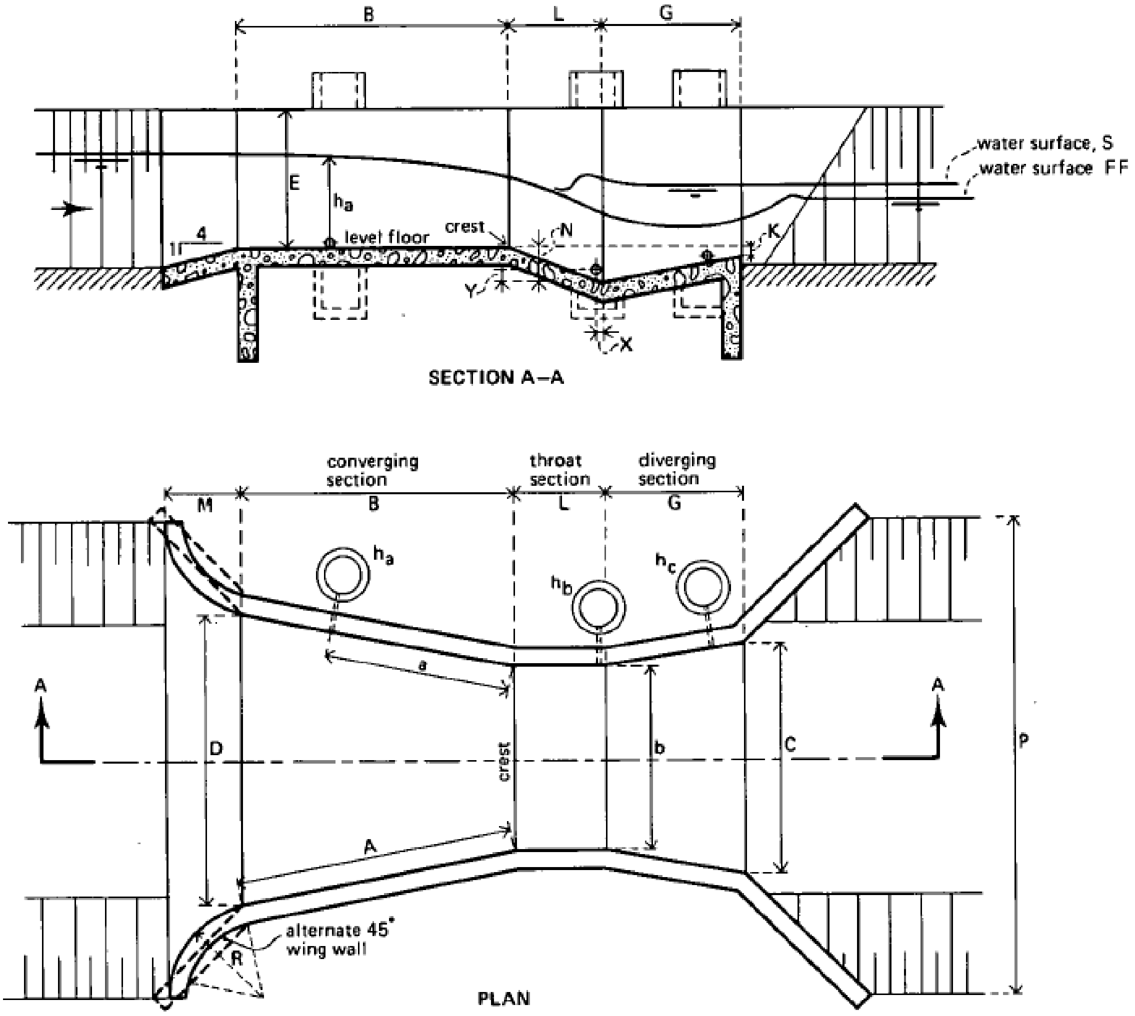

Figure 73: Parshall flume profile (top) and plan view (bottom) (VLOTMAN, 1989)

Table 10: Parshall flume dimensions in millimeters as shown in Figure 73

	b	a	B	C	D	E	L	G	K	N	X	Y
20´	6096	2845	7620	7315	9144	2134	1829	3658	305	686	305	229
25´	7620	3353	7620	8941	10668	2134	1829	3962	305	686	305	229

5.3.4 Stilling wells

Stilling wells are necessary to place a stage recorder in a still and protected place at the desired point of measurement. For the calibrated 20´ and 25´ flumes one measured stage at h_a (Figure 73) will provide reasonable results to determine discharge (Figure 73). Stilling wells h_b and h_c may be installed as reference level but are not recommended to be installed in this case. As it is necessary to build the flumes with exact dimensions, it is also necessary to place the stilling well exactly at distance a, relative to the throat section (Table 10). Discharge values for different stage measurements can be derived from tables of the established literature (VLOTMAN, 1989). The stilling well should be constructed by leaving a vertical space in the wall of the flume of 0.1 m times 0.1 m. A metal door in front with a screening near the bottom of the flume will protect it from vandalism and gives easy access for readout and maintenance. It is recommended to use standard pressure sensors for the continuous recording of water level (e.g. In-Situ Level Troll 500 or Schlumberger Baro-Diver, which often can measure water level, temperature and electric conductivity at the same time). These devices are robust, reliable, and operate autarkic over up to 5 years without the need to change batteries. It must be noted that barometric pressure must be corrected, which is already integrated in the above mentioned devices.

6 Literature

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Appendix

Figure A1: Surface water runoff gauge at Nahr el Khalb seamouth

Figure A2: Surface water runoff gauge at Hrajel

Figure A3: Tree in the riverbed of Nahr es Zirghaya (proposed section for a flume)

Figure A4: Boulder on top of basement structure at the bridge of Nahr es Zirghaya

Figure A5: Proposed Flume underneath the bridge at Nahr es Salib

Figure A6: Construction waste dumps into the Nahr es Hardoun