REPUBLIC OF LEBANON
Council for Development and Reconstruction
CDR
Beirut

FEDERAL REPUBLIC OF GERMANY
Federal Institute for Geosciences and Natural Resources
BGR
Hannover


TECHNICAL COOPERATION

PROJECT NO.: 2008.2162.9

# Protection of Jeita Spring

## SPECIAL REPORT NO. 5

# Artificial Tracer Test 4B - May 2011

**Raifoun**
**February 2012**

Artificial Tracer Test 4B - May 2011

Authors: Joanna Doummar[1], Dr. Armin Margane (BGR), Dr. Tobias Geyer[1], Prof. Martin Sauter[1]

Commissioned by: Federal Ministry for Economic Cooperation and Development (Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung, BMZ)
Project: Protection of Jeita Spring
BMZ-No.: 2008.2162.9
BGR-Archive No.: xxxxxxx
Date of issuance: February 2012
No. of pages: 17

[1] University of Goettingen/Germany

# PROTECTION OF JEITA SPRING - LEBANON -

# - REPORT III -

# ARTIFICIAL TRACER TESTS- MAY 2011

**JOANNA DOUMMAR (1)**, ARMIN MARGANE (2), TOBIAS GEYER (1), MARTIN SAUTER (1)

(1) Applied Geology, University of Göttingen, Goldschmidtstraße 3, 37077 Göttingen, Germany

(2) Federal Institute for Geosciences and Natural Resources (BGR), P.O. Box 51 01 53, 30631 Hannover, Germany

Submission of Final Report: February 2012

Total Number of Pages: 17

# TABLE OF CONTENTS

# LIST OF FIGURES



# LIST OF TABLES

# 1. INTRODUCTION

This report presents the results of the work undertaken in the Framework of the Cooperation between the Institute for Geosciences and Natural Resources in Germany (BGR) and Georg-August University in Göttingen as partial fulfillment of contract 10037409. The work undertaken is part of the German-Lebanese Technical Cooperation Project Protection of Jeita Spring funded by the German Ministry of Economic Cooperation and Development (BMZ) and implemented on the German Side by BGR. This is the third report submitted as part of the cooperation mentioned above.

This report presents the preliminary results of the tracer test conducted in May 2011 to delineate the potential hydrogeological connection if any, between point sources on the upper catchment area of Jeita spring. Section 1 provides the motivation and objectives of the tracer test. Section 2 discusses the methods, material and field work performed during this study. It includes a description of the various tracer tests performed in May 2011. The methods for tracer tests evaluation along with the modeling tools are exposed in Section 3. Section 4 presents the results of the TBCs analysis. The latter mainly tackles aquifer dynamics and behavior as depicted in May 2011 and gives insights into the velocities and dispersivities in the Cretaceous system of the upper catchment area. Finally Section 5 presents some conclusions and recommendations.

## 1.1 GENERAL

Jeita spring, located in the lower reaches of the Nahr el Kalb catchment, is an important karst spring located about 14 km northeast of Beirut in the Keserwan district. It constitutes the main water source for the Beirut Area and its northern suburbs for domestic use. In the Jeita karst aquifer, flow is governed by open channel flow/ full pipe hydraulics. Previously it was assumed that Jeita spring drains a catchment of about 288 $km^2$ extending east in the Lebanese Mountains (Figure 1-1; Bakic, 1970). The catchment of Jeita spring was defined mainly based on topographical boundaries, i.e. it was assumed that the groundwater catchment more or less coincides with the surface water catchment. Very little was known about hydrogeological connections between various locations in the catchment and the Jeita spring. The upper surface catchment area of Jeita spring, located above 1500 m asl, is drained by two springs: Assal and Labbane. The catchment of Afqa spring, discharging like Assal and Labbane springs from the Upper Cretaceous aquifer, was previously unknown. Assal and Labbane springs were according to previous studies believed to contribute to the discharge of Jeita spring, either through infiltration of surface water runoff into the Jurassic system or potential downward leakage from the Cretaceous system into the Jurassic aquifer. Afqa spring discharges into Nahr Ibrahim, located to the north of the Nahr el Kalb catchment.

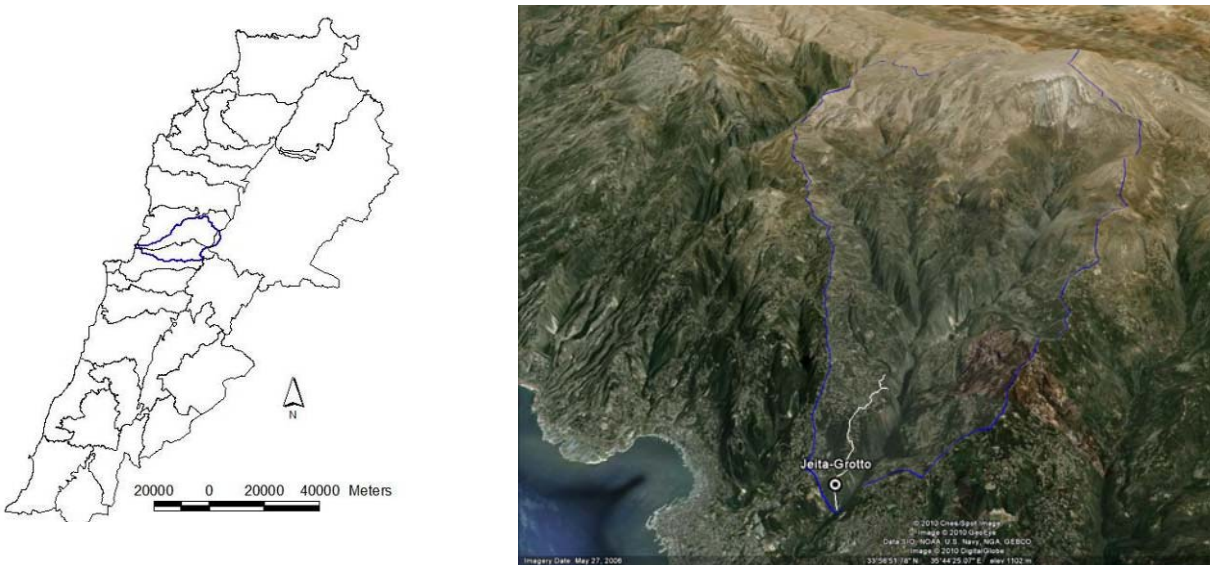



**Figure 1-1 Location of Jeita Spring and Catchment (blue line) in Lebanon (Google Earth)**

## 1.2 OBJECTIVES OF THE TRACER TEST

The main goal of the artificial tracer tests was to investigate hydrogeological connections between rapid and slow recharge point sources in the catchment area/sub catchment areas suspected to contribute to the total recharge of Jeita spring.

The objectives of the tracer test were mainly to:

- Identify a potential hydrogeological connection between the injection site (on the upper catchment) and the three springs Assal, Labbane and Afqa; indirectly a connection with the Jeita spring and Kashkoush spring was also targeted.
- Delineate the boundary of the catchment area.
- Characterize hydrodynamic flow and transport parameters of the Cretaceous aquifer system (flow velocities; mean and maximum, transit times, longitudinal dispersivities, mass restitution, etc…) during high flow periods.

# 2. FIELD WORK AND METHODOLOGY

## 2.1 MATERIALS

The tracers, uranine (sodium fluorescein, acid yellow 73, BASF, CAS 518-47-8, $C_{20}H_{10}O_5Na_2$), eosin Y (acid red 87, eosin, CAS 17372-87-1, $C_{20}H_6Br_4Na_2O_5$) and sodium naphthionate ($C_{10}H_8NNaO_3S$) were selected as they are considered non-toxic. Uranine, eosin and naphtionate tracers can be measured simultaneously on-site with low detection limits. Uranine is sensible to photochemical decay and is only highly adsorptive under increasing acidity (Ford and Williams, 2007) and can be considered as a conservative tracer in carbonate aquifers. Naphtionate can also be regarded as a conservative tracer, as shown in previous tracer tests undertaken in the study area. In this test naphthionate was used in combination with uranine to evaluate its behavior in the tested waters and in order to distinguish the potential arrival of tracer substances from another tracer test conducted in March 2011. Little is known about eosin, which is reported to have been used successfully in tracer tests in karst aquifers (Perrin and Lütscher, 2008).

Concentration of tracer was monitored in the springs and stream with field fluorometers (GGUN-FL30 serial numbers 525, 526, 531, 532, 533; Schnegg, 2002). The equipment continuously measures dye concentration at the monitoring site at specific intervals with three incorporated photo diodes, able to detect emissions at wave lengths of dyes of interest in this study. The field fluorometers, which detect signals as millivolts, were calibrated for uranine, eosin, and naphtionate. The dissimilarity and lag between the luminescence wavelengths of both uranine and eosin enables the distinction between both dye types during analysis and hinders the significance of overlaps. Uranine has a spectrum of luminescence ranging between 490 nm and 524 nm, whereas that of eosin extends between 515 nm and 535 nm, while that of naphtionate extends from 325 nm to 420 nm. In the presence of one tracer, the calibration file allows a direct conversion of the electrical signal into concentration in micrograms per liter. In the presence of two or more tracers, the lamps are calibrated for up to three dyes; therefore, based on a system of three linear equations, the electrical signal is transformed into three signals representative of concentrations of both tracers (Schnegg, 2002). The limit of detection of the field fluorometer is dye at a concentration of 0.02 µg/l for uranine and 0.2 µg/l for eosin (Schnegg, pers. comm.). The limit of detection of naphtionate is usually 0.07 µg/l. However it is worth noting that the background concentration of naphtionate in Jeita waters was relatively high, reaching 8 ppb. Correction for the presence of background tracer concentration was also taken into account. It is worth noting that the threshold of tracer detection signal limit for the field fluorometer is 1000 µg/l, beyond this limit, samples need to be also diluted until achieving a detectable signal.

## 2.2 FIELDWORK

### 2.2.1 Injections

Two tracer tests (4B) were undertaken on **May 18, 2011**, under high flow conditions. The sites are located on the Upper Cretaceous rock units in the upper part of the catchment. The tests were undertaken during the snowmelt period, where rapid snowmelt due to rapid rise of temperatures helped in flushing the tracer into the subsurface.

At the first site (4B-1) 10 kg of eosin were injected on May 18, 2011, and flushed with 10 $m^3$ of water provided from a fire truck over 30 min (Figure 2). Additional flushing by melting snow is estimated at 7 $m^3$/h. Further to the east, on the same day, 5 kg of uranine and 10 kg of naphtionate were injected in a sinkhole (4B-2) and likewise flushed with 10 $m^3$ over 30 minutes securing a flushing and percolation conditions (flushing rate about 5 l/s). Flushing by melting snow is estimated at 10 $m^3$/h. The overall flushing rates are considered sufficient to ensure percolation of the tracer into the underground. The characteristics of the injection points are provided in Table 2-1.

A B

**Figure 2-1 Injection of 5 kg of uranine/ 10kg naphtionate into the doline 4B-2 (Photo A) and 10 kg of eosin into the doline 4B-1 (Photo B)**

**Table 2-1 Location of Tracer Injection Points for Tracer Test 4B**

| INJECTION POINT | COORDINATES (ALTITUDE) (m) | INJECTION TIME | FLUSHING VOLUME | COMMENTS |
|---|---|---|---|---|
| Test 4B-1 | 35.927745° E<br>34.000299° N<br>(2102) | 18.05.2011<br>(10:35) | 10 m³<br>(over 30 min)<br>rate of flushing: 5 l/s<br>plus natural flushing by melting snow:<br>4B-1: 7 m³/h<br>4B-2: 10 m³/h | 10,000 grams of eosin<br>(infiltration rate was relatively favorable to ensure good percolation of the tracer) |
| Test 4B-2 | 35.88087° E<br>34.00572° N<br>(1990) | 18.05.2011<br>(13:35) | | 5,000 grams of uranine<br>10,000 grams of naphtionate<br>(infiltration rate was relatively favorable to ensure good percolation of the tracer) |

### 2.2.2 Observation points

Five field spectrofluorometers with data loggers (525, 526, 531, 532 and 533) were deployed for automatic sampling at:

- Jeita spring (entrance; 533),
- Nahr El Kalb River (525) at Jeita spring,
- Assal spring (531),
- Labbane spring (532),
- Afqa spring (526).

Manual samples were not collected for the purpose of this tracer test, as field fluorometers were checked constantly every 24 hours.

A detailed description of the observation points is provided in Table 2-2.

Table 2-2 Observations Points of Tracer Test 4-B

| AQUIFER | OBSERVATIONS POINTS | LATITUDE LONGITUDE Z (m asl) | LINEAR DISTANCE TO INJECTION (m) | SAMPLING | SAMPLING INTERVAL | COMMENTS |
|---|---|---|---|---|---|---|
| Cretaceous | 1 Assal spring | 35.838420° E 34.009919°N 1540 | 4B-1: 8,350 4B-2: 4,000 | automatic | 2 min | GGUN-FL30 531 |
| | 2 Labbane spring | 35.828263° E 33.995265°N 1540 | 4B-1: 9,200 4B-2: 5,000 | automatic | 2 min | GGUN-FL30 532 |
| | 3 Afqa spring | 34.066575° E 35.892335° N 1205 | 4B-1: 8,000 4B-2: 6,800 | automatic | 2 min | GGUN-FL30 526 |
| Jurassic | 4 Jeita Grotto (entrance) | 35.646168° E 33.945592° N 70 | 4B-1: 26,830 4B-2: 22,800 | automatic | 2 min | GGUN-FL30 533 |
| | 5 Nahr El Kalb River | 35.642854° E 33.943238° N 140 | 4B-1: 27,300 4B-2:23,300 | automatic | 2 min | GGUN-FL30 525 |

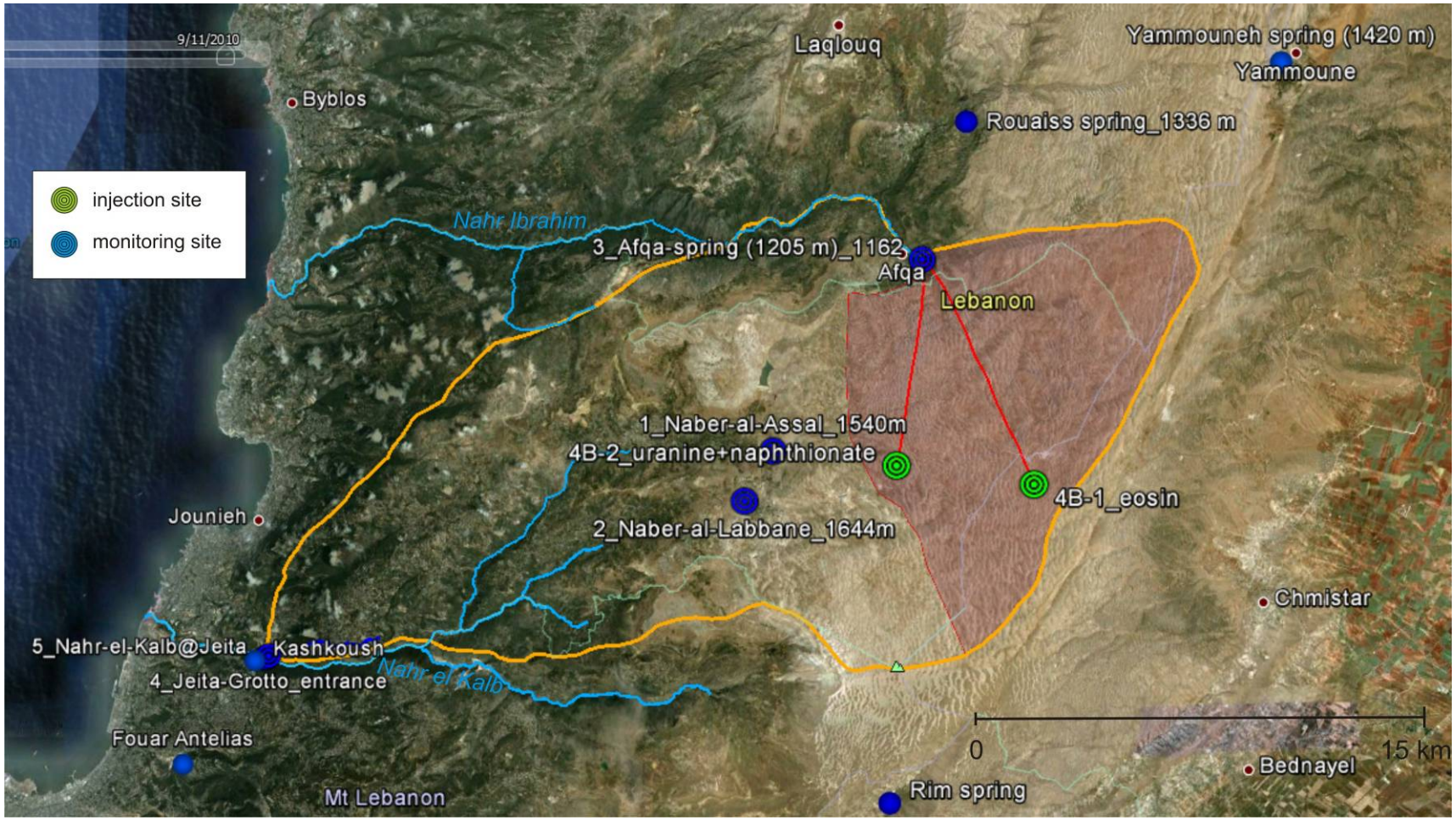



**Figure 2-2 Map showing the Set-Up (Injection Points and Observation Points) of Tracer Test 4B undertaken on May 18, 2011 (Google Earth)**

(orange line: assumed groundwater catchment of Jeita spring; red filled area: assumed subcatchment of Afqa spring)

## 2.3 DISCHARGE MEASUREMENTS

Flow rate measurements were mainly performed based on the dilution gauging methods using uranine. The dilution method relies on calculating the discharge rate based on a tracer breakthrough curve (TBC). The integration of the concentration over time allows the estimation of the discharge rate as shown in Equation 1.

$$Q = \frac{M}{\int c(t)dt} \quad (1)$$

*Where*
*Q is the discharge rate [L³/T]*
*M is the injected salt or dye tracer mass [M]*
*c is concentration [M/L³]*
*t is time [T]*

The spring discharges at the various discharge points were measured at different intervals before, during, and after the tracer test period. The discharge rates at the observation points where the tracer test was positive are shown in Table 2-2. Discharge rates are very important for the calculation of restitution rates at the monitoring sites. Under the given conditions at Afqa spring it is rather difficult to conduct flow measurements using tracers. It is believed that the second test yielding a discharge value of 6.6 $m^3/s$ is more representative.

**Table 2-2 Discharge Rates Measured at the Positive Observations Points**

| OBSERVATION POINT | METHOD | DATE | DISCHARGE RATE | COMMENTS |
|---|---|---|---|---|
| Afqa spring | Dilution with uranine | 23.05.2011 (11:09) | 7.5 $m^3/s$ | The value of 6.6 $m^3/s$ was adopted for this tracer test. |
| Afqa spring | Dilution with uranine | 23.05.2011 (11:25) | 6.6 $m^3/s$ | |

# 3. EVALUATION AND MODELING

Tracer breakthrough curves (TBCs) were analyzed graphically, using Excel sheets, and numerically with the software CXT- Stanmod (Toride et al. 1999). The *Advection-dispersion Model (ADM)* was adopted for the modeling of the TBC. The software allows the calculation of various process parameters based on fitting with observed tracer breakthrough curves. These are tracer recovery (*R*), restitution "key" times (*t*), flow velocities (*v*), longitudinal dispersion (*D*), dispersivity (α), and Peclet numbers.

## 3.1 PARAMETERS

### 3.1.1 Tracer recovery

Tracer concentration data were plotted versus time to reconstruct a Tracer breakthrough curve. Recovery *R* was calculated based on the TBC, upon integration of the concentration multiplied by flow data over the tracer restitution period, from its first detection until end of tailing based on Equation 2 (EPA/600/R-02/001, 2002).

$$R = \frac{1}{M}\int_{t=0}^{\infty} c(t)Q(t)dt \quad (2)$$

Recovery rates provided in this study are valid only in the case where the tracer is considered to be conservative and to have been totally conveyed into the saturated zone, rather than being partially trapped in the unsaturated zone or in soil superficial layers as a result of poor flushing.

### 3.1.2 Flow velocities

Mean ($v_m$), maximum ($v_{max}$), and peak ($v_p$) flow velocities were calculated respectively based on the mean residence time, the time of first detection, and time of peak detection. The mean residence time represents the time where half of the recovered tracer mass has elapsed at the observation point. It is calculated by (EPA/600/R-02/001, 2002):

$$t_d = \int_{t=0}^{\infty} \frac{c(t)Q(t)tdt}{c(t)Q(t)dt} \quad (3)$$

### 3.1.3 Longitudinal dispersivity and dispersion

The shape of the dye hydrograph provides an indication of the longitudinal dispersion of the tracer, as the retrieved TBC is one-dimensional. As a matter of fact, variance of the TBC allows the estimation of dispersivity (α) and longitudinal dispersion ($D_L$), neglecting molecular diffusion as shown in Equation 4. Dispersion portrayed by the variance of the TBC is due to variation in velocities during transport. It usually reflects the degree of heterogeneity of the flow path. The longitudinal dispersion is highly positively correlated with the effective velocity and dispersivity.

$$D_L = \alpha_L \cdot v_m + D^* \quad (4)$$

*$D_L$ being the longitudinal dispersion coefficient [L²/T]*
*$\alpha_L$ being the dispersivity of the tracer [L]*
*$v_m$ being the effective velocity calculated based on mean residence time [L/T]*
*$D^*$ being the molecular diffusion coefficient (neglected in this case) [L²/T]*

## 3.2 MODELING (1-D ADVECTION-DISPERSION MODEL (ADM))

The ADM was used to analyze the Tracer Breakthrough Curves (TBC) resulting from the tracer test undertaken in May 18, 2011. The ADM, governed by Equation 5, is based on the variation of the concentration of tracer with time as inversely proportional to the flow rate at the observation point, the reciprocal of the Peclet number ($P_D$). The Peclet number (ratio of distance over longitudinal dispersivity, or the ratio of longitudinal dispersion to distance and mean velocity) shows the respective contribution of each of the advection and diffusion in the transport mechanism. It is defined by the ratio of the linear distance over the dispersivity. A peclet number that is greater than 6.0 characterizes mass transfer dominated by advection processes rather than diffusion processes (EPA/600/R-02/001, 2002).

This parameter has an implication on the dependence of each of the velocity and dispersivity on the physicochemical characteristics of the tracer, which are relatively insignificant where advection plays an important role in mass transport processes (EPA/600/R-02/001, 2002).

$$C(t) = \frac{M}{Qtm\sqrt{4\pi P_D \left(\frac{t}{t_m}\right)^3}} \exp\left(-\frac{\left(1-\frac{t}{tm}\right)^2}{4P_D\frac{t}{tm}}\right) \quad (5)$$

The software Stanmod (CXTFIT) was used for the modeling of TBCs resulting from a conservative tracer Dirac pulse test using the Advection-Dispersion Model (ADM). The latter does perform automatic runs. Initial estimates for fitting parameters have to be introduced in the model. Observed values are input as concentration in micrograms per liter (µg/l) as a function of time in hours. At the beginning of the modeling, the maximum and minimum ranges were significantly high. With an iteration number often set to 50, the system returns a best fit for the observed values. Upon refinement of the curve, range between maxima and minima was reduced to a one final set of dispersion and mean velocity. The *massive flux* required by the model is the integral of the concentration as a function of time (*∫C(dt)*).

# 4. RESULTS OF THE TRACER TEST

Tracer breakthrough curves (TBC) were retrieved only in the Afqa spring (fluorometer 526). Tracer was not restituted in any of the other observation points (Figure 4). The tracer test undertaken on May 18, 2011, was therefore positive delineating a connection between the injection point and the Afqa spring. The tracer test shows that the two points 4B-1 and 4B-2 do not contribute to (and are not located on the catchment areas of) the Labbane or Assal springs. From the result of the tracer test no conclusion can be drawn concerning a possible connection of Afqa with Jeita spring. Graphical interpretation of the TBC is presented in Table 4-1.

Even though true distances are usually more sinuous and therefore greater (Field, 2000; Göppert and Goldscheider, 2007), linear distances between the injection point and the observation point are usually considered for velocity calculations, i.e. the calculated flow velocity is a lower bound of the average flow velocity. The distances adopted for the calculation of velocities between Afqa spring and injection points 4B-1 and 4B-2 are 8000 m and 6800 m, respectively.

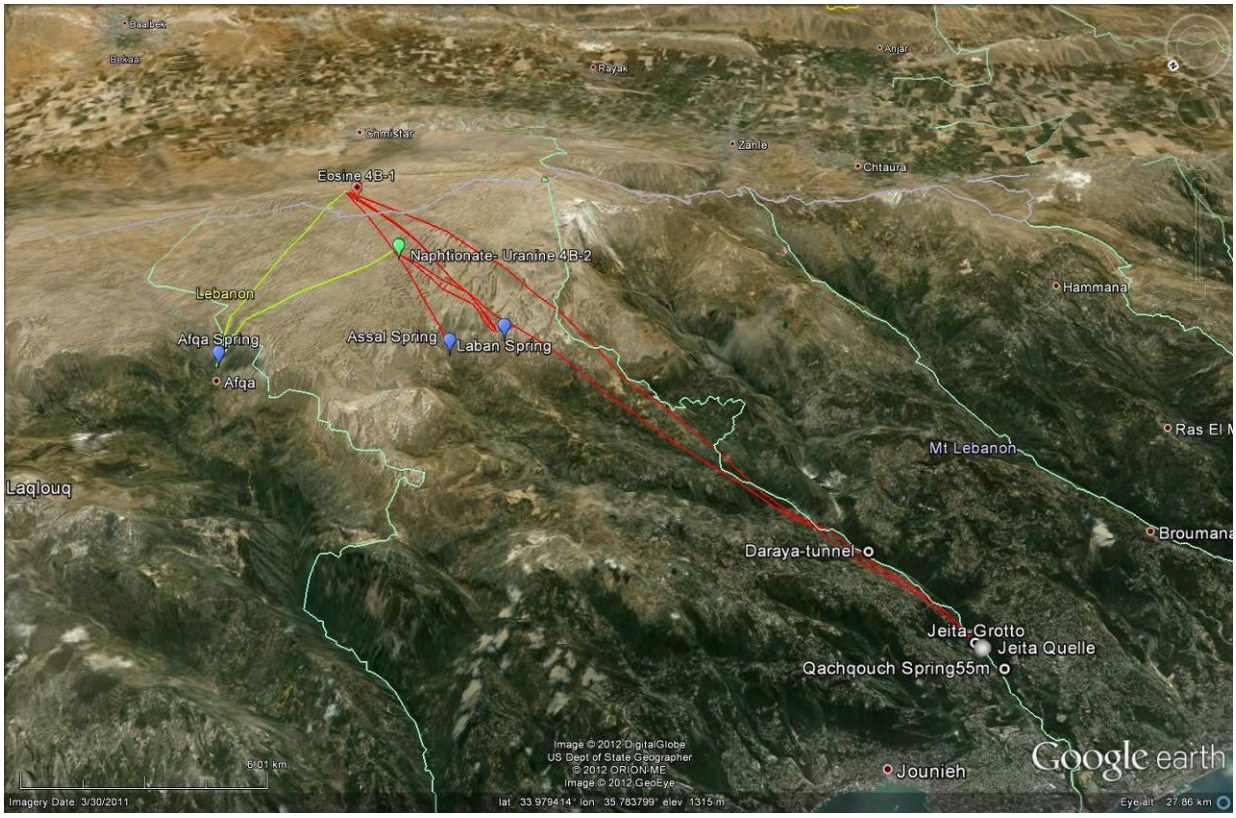



**Figure 4-1** **Results of the tracer test 4B (Green lines showing positive connection and red lines showing negative connection between the injection point and the observation point; Google Earth)**

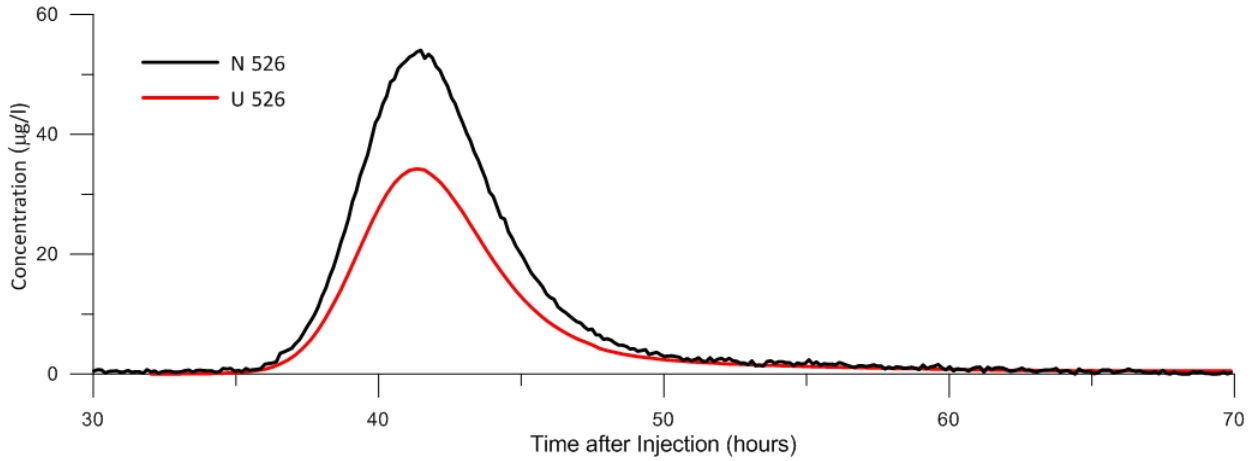



**Figure 4-2 Observed TBCs restituted in Afqa Spring from both Injection Points 4B-2 (526)**

(N: naphtionate; U: uranine)

**Table 4-1 Graphical Interpretation of the TBC´s resulting from the Tracer Tests (May 2011)**

| OBSERVATION POINT | PEAK (µg/l) | TRACER FIRST ARRIVAL (hours) | MAXIMUM VELOCITY (m/hours) | PEAK CONCENTRATION TIME (hours) | VELOCITY TO PEAK CONCENTRATION (m/hours) | RESTITUTION (%) |
|---|---|---|---|---|---|---|
| 4B-1 Eosin | 1 | 55.5 | 144 | 59.3 | 135 | 1.38 |
| 4B-2 Naphtionate | 52.8 | 36.18 | 188 | 41.6 | 163 | 74% |
| 4B-2 Uranine | 34 | 36.18 | 188 | 41.6 | 163 | 100% |

## 4.1 TRACER BREAKTHROUGH CURVES 4B-1 (AFQA SPRING)

Eosin was first detected in fluorometer 526 in the in the Afqa spring about 55 hours after injection. The maximum peak observed in 526 is 1 µg/L, yielding respective velocities to peak concentration ($v_p$) of 135 m/hour. The TBC is characterized by data noise and an irregular shape. The peak velocity as calculated in both TBC is 144 m/hour. Based on the discharge rate (6.6 $m^3$/s) measured under prevailing flow conditions, a recovery of approximately not more than 1.5 % of eosin was achieved, probably due to retention of tracer in soil at the bottom of the doline where tracer was injected.

Based on the modeling of the TBCs using the ADM model with CXTFIT (Figure 4-1), the mean velocity over a distance of 8000 m between the injection point and the spring at the Afqa spring is about 129 m/hour. Peclet number is 697, reflecting the prevailing advective component of the transport through the karst system. Longitudinal dispersion is estimated to be 1480 $m^2$/h yielding a longitudinal dispersion of 11.5 m. The estimated values are given with a mean square error of 0.0145 μg/l. The coefficient of correlation between observed and modeled values is acceptable and is on average 0.78, especially with the presence of noise in the TBC.

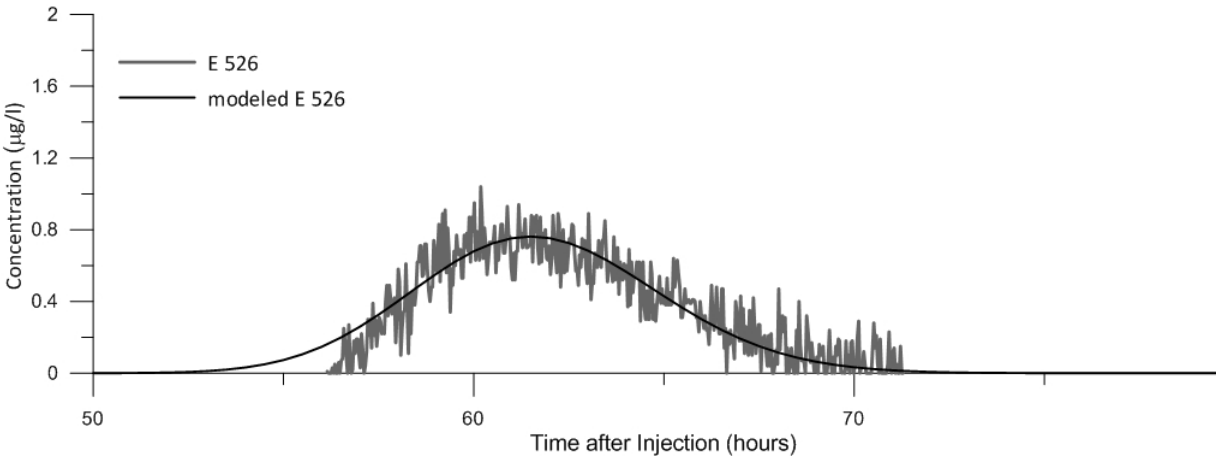
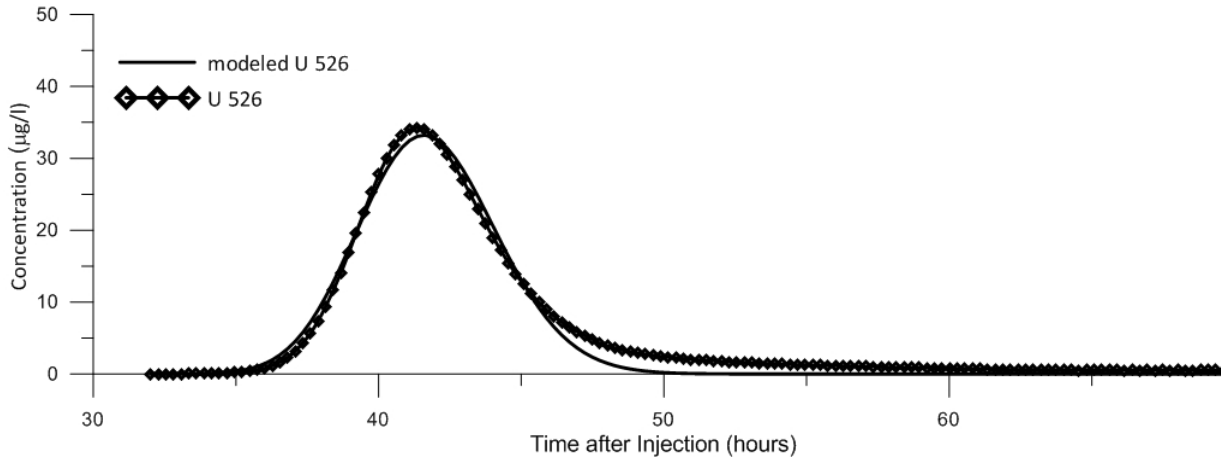



**Figure 4-1 Observed and modeled TBC restituted in the Afqa Spring (Injection Point 4B-1; 526)**

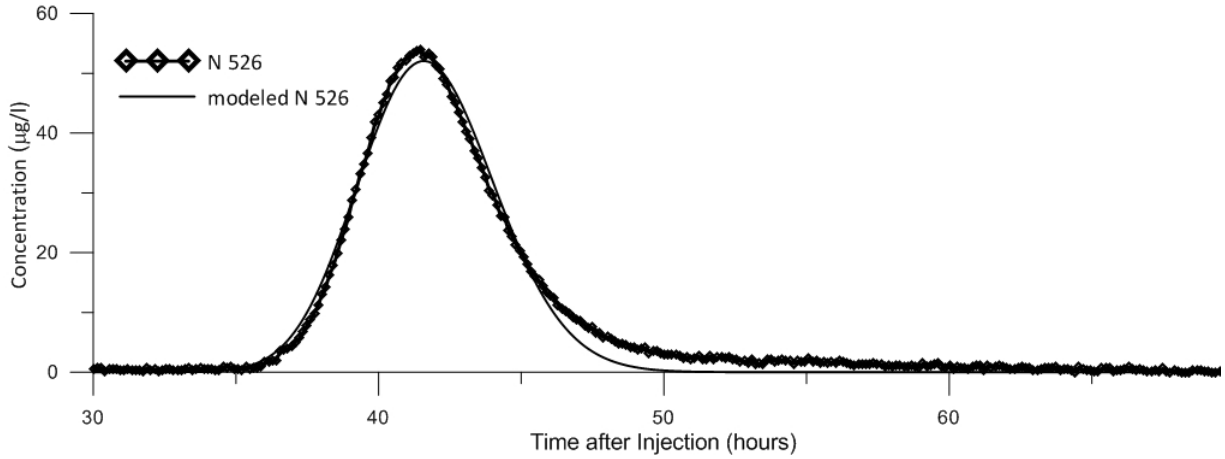
## 4.2 TRACER BREAKTHROUGH CURVES 4B-2 (AFQA SPRING)

Uranine/ naphtionate were first detected in Afqa about 36 hours after injection. The maximum peaks of uranine and naphtionate observed in 526 are 34 and 52.8 μg/L, respectively and were reached about 42 hours after injection. The peak velocity calculated over a distance of 6800 m is 163 m/hour. Based on the discharge rate (6.6 $m^3$/s) under prevailing flow conditions, a recovery of approximately 100 % of uranine was achieved, whereas only 74 % of naphtionate were restituted. A negligible tailing over about 5 hours is observed in the tracer breakthrough curve (TBC).

Based on the modeling of the TBCs using the ADM model with CXTFIT (Figure 4-2), the mean velocity over a distance of 6800 m between the injection point and Afqa spring is 163 m/hour. Peclet numbers is about 610 reflecting the prevailing advective component of the transport through the karst system. Longitudinal dispersion is about 1800 $m^2$/h, yielding a longitudinal dispersion of 11 m. The estimated values are given with a mean square error of 0.5 μg/l for uranine and 2.6 for naphtionate. The coefficient of correlation between observed and modeled values is 0.98 for both TBCs.




A




B

**Figure 4-2 Observed and modeled TBCs restituted in Afqa Spring in A) Uranine and B) Naphtionate**

**Table 4-2 Summary of the Modeling Results of the Tracer Test (4-B) undertaken on May 18, 2011**

| PARAMETERS | SYMBOL | UNITS | 4B-2 URANINE (AFQA SPRING) (526) | 4B-2 NAPHTIONATE (AFQA SPRING) (526) | 4B-1 EOSIN (AFQA SPRING) (526) |
|---|---|---|---|---|---|
| Distance | D | m | 6800 | 6800 | 8000 |
| Discharge | Q | $m^3$/sec | 6.6 | 6.6 | 6.6 |
| **ADVECTION DISPERSION METHOD (ADM)** | | | | | |
| Mean velocity | v | m/hour | **163** | **163** | **129** |
| Mean transient time | $t_m$ | hours | 41.72 | 41.72 | 62 |
| Dispersion | D | $m^2$/hour | 1840 | 1800 | 1480 |
| Dispersivity | A | M | 11.3 | 11 | 11.5 |
| Peclet number | $P_D$ | - | 602 | 616 | 697 |
| Massive flux | M | µg•h/l | 200 | 310 | 6.1 |
| Restitution rate | R | % | 95 | 73.66 | 1.45 |
| **Statistical parameters** | | | | | |
| Coefficient of correlation | $R^2$ | - | 0.985 | 0.987 | 0.78 |
| Mean square error | MSE | µg/l | 5.4E-01 | 2.65E-00 | 1.45E-02 |

# 5. CONCLUSIONS

Based on the tracer test undertaken on May 18, 2011, the following conclusions can be reached:

- A hydrogeological connection was established between the injection point (4B-2) and Afqa spring with a restitution rate of 100 % (uranine), which rules out any other possible direct connection with any other springs of the Cretaceous formation (Labbane and Assal). A direct connection between the injection points and Jeita spring (downward leakage through the Upper Jurassic - Lower Creataceous aquitard or reinfiltration into the Jurassic aquifer in Nahr Ibrahim) could not be proven by this test, however, the test was not designed to draw such a conclusion. A much higher amount of tracer and more extended monitoring period would have been needed for such a test. While uranine is highly conservative, the lower recovery rate of naphthionate (74 %) might be due to the high background value (8 ppb in Afqa waters).
- Only 1.5 % of eosin arrived from injection point 4B-1 at Afqa spring, and did not arrive at any other observation point. Such low recovery rate can be due to injection conditions. It might also be that water is partially diverted to the eastern flank of Mount Lebanon, as the point 4B-2 is located already east of the topographical divide. This test will therefore be repeated under more favorable infiltration conditions during the high-flow period with uranine.
- Similar transport parameters can be deduced from the TBC for the Cretaceous aquifer, notably with regards to mean velocity (about **163 m/hour**) in the case of uranine and naphtionate injected in a sinkhole and **129 m/hour** in the case of eosin injected in a doline with some soil cover.
- The average longitudinal dispersivity is about **11 m** for all the tracer tests, with longitudinal dispersion varying in the sinkhole (uranine and naphtionate) between 1800 and 1840 **$m^2$/hour** and 1480 **$m^2$/hour** for eosin.

# 6. REFERENCES


- Auckenthaler A, Huggenberger P, 2003.Pathogen Mikroorganismen in Grund und Trink Wasser. Transport Nachweissmethoden Wassermanagement. Birkhauser. p 80-91
- Bakic, M., 1972. Jeita the Famous Spring of Lebanon, United Nation Development Report. UN. Beirut. 1-149 pp
- EPA/600/R-02/001, 2002. The QTRACER2 program for tracer-breakthrough curve analysis for tracer tests in karstic aquifers and other hydrologic systems. Washington, D.C.: U.S. EPA.
- Field M.S, and Pinsky P.F. 2000. A two region non equilibrium model for solute transport in solution conduits in karstic aquifers. Journal of contaminant hydrogeology 44, 1, p 329-351
- Field M.S., and Nash S.G., 1997. Risk assessment methodology for karst aquifers: (1), estimating karst flow parameters. Environmental monitoring and Assessment. 47, 1, p 1-21
- Ford D., Williams D.W., 2007. Karst hydrogeology and geomorphology. Unwin Hyman, Boston
- Geyer T., Birk S., Licha T., Liedl R., and Sauter M., 2007. Multi tracer approach to characterize reactive transport in karst aquifers. Groundwater. Vol 45, 1. p 36-46
- Göppert N and Goldscheider N. 2008. Solute and colloid transport in karst conduits under low and high flow conditions. Groundwater, 46, 1 p. 61-68.
- Perrin J., and Lütscher M. 2008. Inference of the structure of karst conduits using quantitative tracer tests and geological information: example of the Swiss Jura. Hydrogeology Journal. 16: p. 951–967
- Schnegg P.A, 2002. An inexpensive field fluorometer for hydrogeological tracer tests with three tracers and turbidity measurement. Groundwater and Human development. Ed. E Bocanegra, D Martine, and H Massone. Mar del Plata, Argentina. p. 1483-1488
- Toride, N., F.J. Leij, and M.T. van Genuchten. 1999. The CXTFIT code for estimating transport parameters from laboratory or field tracer experiments. U.S. Salinity Laboratory Agricultural Research Service, U.S. Department of Agriculture Riverside, California. Research Report 137.