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# Protection of Jeita Spring

## SPECIAL REPORT NO. 11

# Artificial Tracer Test 5C - September 2011

**Raifoun**
**February 2012**

Artificial Tracer Test 5C - September 2011

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# PROTECTION OF JEITA SPRING - LEBANON -

# - REPORT V -

# ARTIFICIAL TRACER TESTS- SEPTEMBER 2011

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# 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 the Jeita Spring funded by the German Ministry of Economic Cooperation and Development (BMZ) and implemented on the German Side by the BGR. This is the fifth report submitted as part of the cooperation mentioned above.

This report presents the preliminary results of the tracer test conducted in September 2011 by the BGR to delineate the potential hydrogeological connection if any, between a point source located outside the surface water catchment of Jeita spring, where a conservative tracer was injected in a borehole and monitored downstream in Jeita spring at the beginning of the cave (siphon terminale) as well as at the outlet. 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 tracer test performed in September 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 flow dynamics and behavior under the prevailing low flow conditions in September 2011 and gives insights into the velocities and dispersivities in the saturated zone over the tracer transport distance. 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 1-1-1; 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.

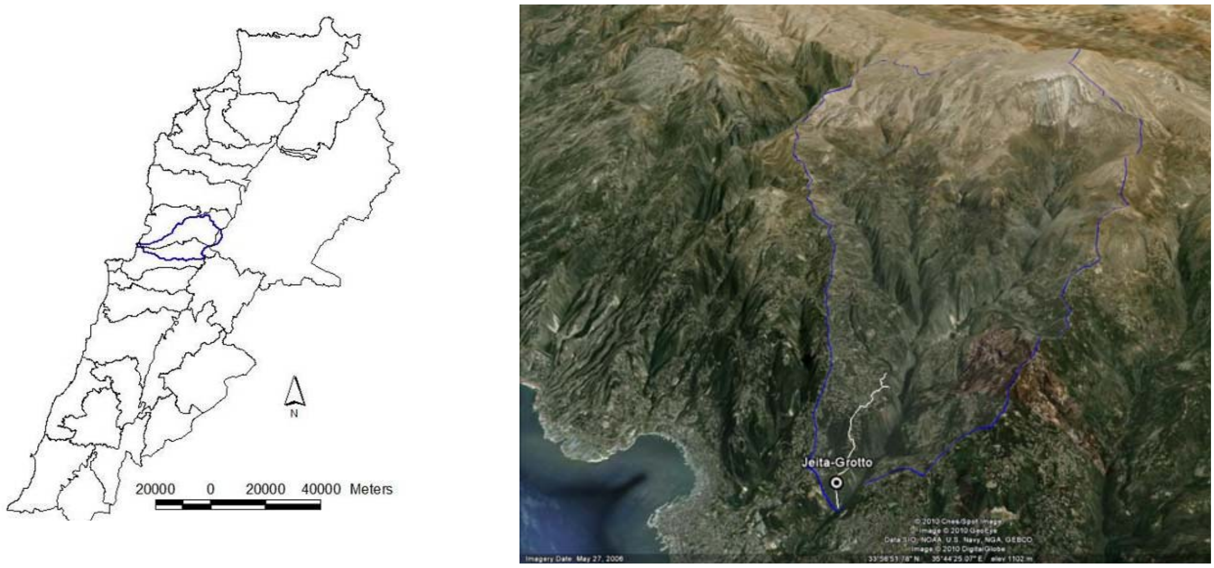


**Figure 1-1** **Location of Jeita Spring and potential Groundwater Catchment (blue line) in Lebanon (Google Earth)**

## 1.2 OBJECTIVES OF THE TRACER TEST 5C

The Objectives of the tracer test were mainly to:

- Identify a potential hydrogeological connection between the injection site (beyond the northern water divide of the Nahr El Kalb River catchment) and Jeita spring. The injection site is a well tapping the Jurassic formation (J4); therefore the tracer test can provide insight into transport behavior in the saturated zone.
- Better delineate the northern boundary of the catchment area.
- Characterize hydrodynamic flow and transport parameters of the Jurassic Aquifer system (flow velocities; mean and maximum, transit times, longitudinal dispersivities, mass restitution, etc…) during low flow periods in September 2011.

# 2. FIELD WORK AND METHODOLOGY

## 2.1 MATERIALS

The tracers uranine (sodium fluorescein, acid yellow 73, BASF, CAS 518-47-8, $C_{20}H_{10}O_5Na_2$) and sodium naphthionate ($C_{10}H_8$ $O_3N$ S Na) were selected as they are considered non toxic. Uranine 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 therefore be considered as a conservative tracer in carbonate aquifers. Naphtionate has a high background value in the tested waters varying between 4 and 8 µg/l. It is usually regarded as conservative tracer as shown in previous tracer tests undertaken in the study area. In this test naphthionate was used with uranine to evaluate its behavior in the tested waters.

Concentration of tracer was monitored in the springs and stream with field fluorometers (GGUN-FL30 serial numbers 525, 526, 531, 532 and 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 and naphtionate. Data were provided by the BGR along with the calibration files. The dissimilarity and lag between the luminescence wavelengths of both uranine and naphtionate 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, 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 electrical signal into concentration in micrograms per liter. In the presence of two or more tracers, the photo diods 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 (Schnegg, pers. com.). The limit of detection of naphtionate is usually 0.07 µg/l. However it is worth noting that the concentration of naphtionate in Jeita waters was relatively high, reaching up to 8 ppb. Correction for the presence of background tracer concentration was also taken into account.

## 2.2 FIELDWORK

### 2.2.1 Injections

The injection site is the Mshati Well No. 1 (Lat 34.04536°; Long 35.76395°) in Mshati north el Ouata El Jaouz in Keserwan area. 10 kg of uranine and 10 kg of naphtionate were injected in the well on September 16, 2011, at 09:52 am in the Mshati well. The Mshati well is located at an elevation of 1083 m a.s.l and penetrates the Jurassic aquifer (J4) to a total depth of 400 m (WEBML pers. comm.).

### 2.2.2 Observation points

Five field spectrofluorometers with dataloggers (525, 526, 531, 532, and 533) were deployed for automatic sampling in:

- Jeita spring (at the entrance; 525 and 533),
- Jeita spring at the "siphon terminale" (Daraya tunnel, 531),
- the northern branch in the Jeita cave (branch discovered during exploration of the Jeita caves by divers in 2004; 526), and
- Yahchouch spring located to the north of the injection well (532).

Manual samples were not collected for the purpose of this tracer test, as field fluorometers were checked constantly by the BGR. Data collected from the various fluorometers were provided to the University of Goettingen by the BGR for the purpose of this report. The distance to siphon terminale (Daraya) was considered linear (12420 m), whereas the distance to Jeita spring (touristic entrance) was calculated considering the distance to siphon terminale added to the distance within the cave (5300 m) which amounts to 17720 m). A detailed description of the observation points is provided in Table 2-2.

**Table 2-1 Observations Points Tracer Test 5-C**

| OBSERVATIONS POINTS | LATITUDE LONGITUDE Z (m asl) | LINEAR DISTANCE TO INJECTION (m) | SAMPLING | SAMPLING INTERVAL | COMMENTS |
|---|---|---|---|---|---|
| Jeita Spring (touristic entrance) | 35.646168° E 33.945592° N 70 | 17720 | automatic | 2 min | GGUN-FL30 525, 533 |
| Jeita Spring Northern branch | 35.653066° E 33.945400° N (-) | 15000 | automatic | 2 min | GGUN-FL30 526 |
| Jeita Spring Siphon Terminale | 35.690799° E 33.951422° N 140 | 12420 | automatic | 2 min | GGUN-FL30 531 |
| Yahchouch Spring | 35.741039° E 34.063419° N 603 | 2930 | automatic | 2 min | GGUN-FL30 532 |

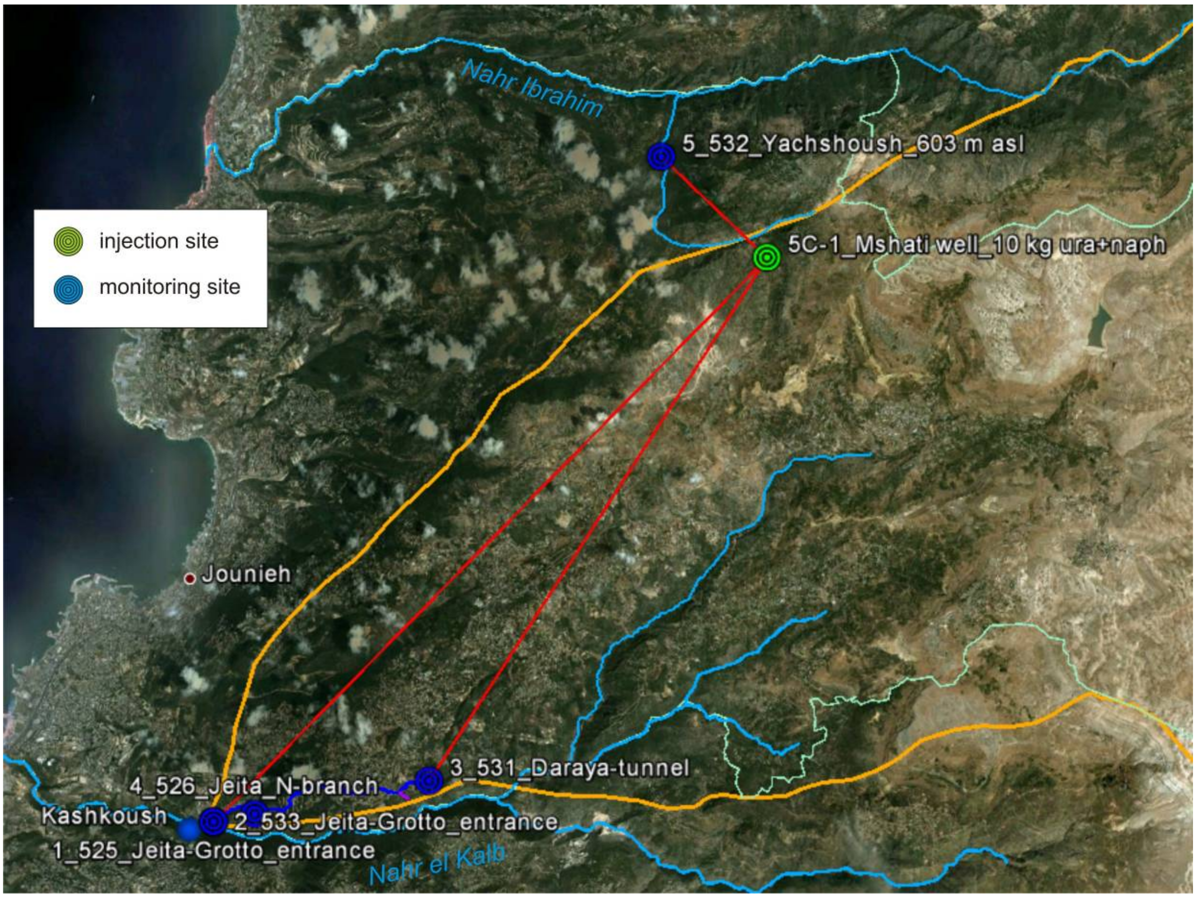


**Figure 2-1 Map showing the Set-Up (Injection Points and Observation Points) of Test 5C undertaken on September 16, 2011 (Google Earth)**

### 2.2.3 Discharge Measurements

Flow rate measurements were mainly performed based on the dilution gauging methods using dye tracers. 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:

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

*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 data for the dilution tests performed at different intervals after the tracer test period in order to determine the discharge of the monitored springs were provided by BGR. 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.

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

<table>
<tr><th>OBSERVATION POINT</th><th>METHOD</th><th>DATE</th><th>DISCHARGE RATE</th><th>COMMENTS</th></tr>
<tr><td>Jeita Spring<br>(touristic entrance)</td><td>Dilution with uranine</td><td>07.10.2011</td><td>1.69 m³/s</td><td rowspan="2">The discharge rate at the siphon terminale was not measured. It can be tentatively extrapolated based on the discharge rate at the Jeita outlet (see touristic entrance)</td></tr>
<tr><td>Jeita Spring<br>(Siphon Terminale)</td><td></td><td></td><td>(-)</td></tr>
</table>

# 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 the Peclet number. Due to the tailing displayed by the TBCs, a perfect fit was not achieved with the ADM model.

## 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 3 (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 well or fissures.

### 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)

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

### 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 flowpath. The longitudinal dispersion is highly positively correlated with the effective velocity and dispersivity.

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

*$D_L$ 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 TBC resulting from the tracer test undertaken on September 16, 2011. The ADM, governed by Equation 6, 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 dispersion/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).

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

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 in Jeita spring in both, the siphon terminale (Daraya tunnel) and at the touristic entrance. Tracer was not restituted in any of the other observation points, namely the northern branch as well as the Yahchouch spring north to the injection point (Figure 4-1). The tracer test undertaken on September 16, 2011, was therefore positive delineating a connection between the injection point and Jeita spring especially at the siphon terminale and the touristic entrance. The tracer test shows that the Mshati well is not hydrologically connected to the Yahchouch spring or to the northern branch in Jeita grotto. The naphtionate breakthrough curves (Figure 4-2) show high discrepancies and couldn't therefore be interpreted or modeled. The following section includes the interpretation of the uranine breakthrough curves (Figure 4-3). Graphical interpretation of the TBC is presented in Table 4-1. The modeling results are summarized in Table 4-2.

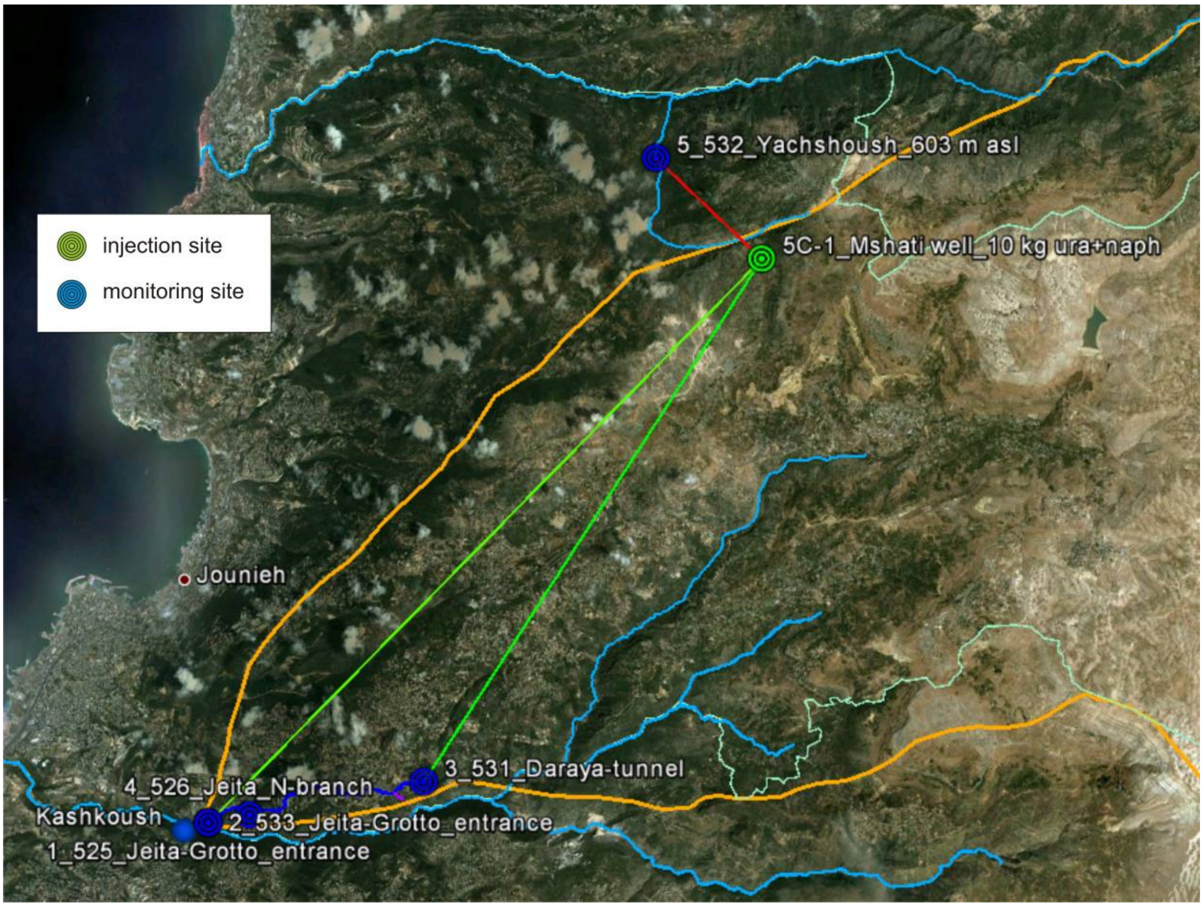


**Figure 4-1 Results of Tracer Test 5C**

(green lines: connection proven; red lines: no connection; orange line: assumed groundwater catchment of Jeita spring; Google Earth)

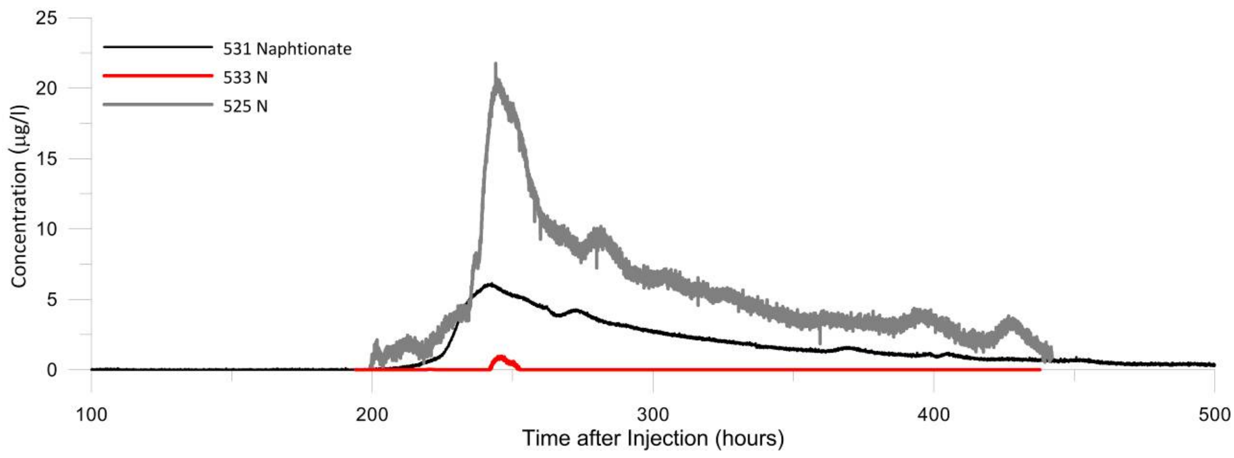


**Figure 4-2** **Observed TBCs restituted in Jeita Spring at the Siphon Terminale (531) and at the Touristic Entrance (525, 533) for both tracers; N: naphtionate**

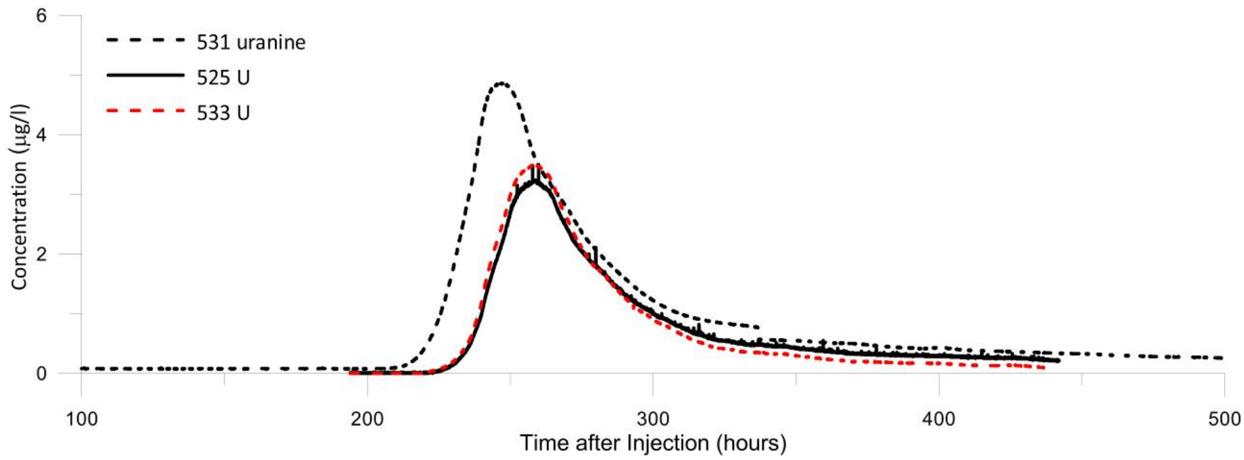


**Figure 4-3** **Observed TBCs restituted in the Jeita Spring (525, 533) for both tracers; U: uranine**

**Table 4-1** **Graphical Interpretation of the TBC´s resulting from the Tracer Test with uranine (September 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 (%) |
|---|---|---|---|---|---|---|
| Jeita Spring Touristic Entrance 525 | 3.15 | 220.23 | 80 | 253 | 70 | 12 |
| Jeita Spring Touristic Entrance 533 | 3.32 | 220.23 | 80 | 253 | 70 | 11 |

| OBSERVATION POINT | PEAK (µg/l) | TRACER FIRST ARRIVAL (hours) | MAXIMUM VELOCITY (m/hours) | PEAK CONCENTRATION TIME (hours) | VELOCITY TO PEAK CONCENTRATION (m/hours) | RESTITUTION (%) |
|---|---|---|---|---|---|---|
| Jeita Spring Siphon Terminale 532 | 4.67 | 207.57 | 60 | 243 | 51 | - |

## 4.1 TRACER BREAKTHROUGH CURVES- JEITA SPRING (SIPHON TERMINALE)

Uranine was detected in fluorometer 531 installed at the siphon terminale about 207 hours after injection. This transit time is equivalent to a maximum velocity of about 60 m/h. The maximum uranine peak was reached 243 hours after injection and amounted to 4.67 µg/l. The velocity to peak concentration is 51 m/hour. The total restitution is difficult to assess given that an accurate discharge of Jeita spring at the siphon terminale is difficult to measure and was not provided. Naphtionate (Figure 4-4) was also detected in fluorometer 531 about 206 hours after injection, nevertheless, uranine cannot be considered retarded with respect to naphtionate, however the peak concentration reached after 240 hours after injection was about 6 µg/l. The TBC of uranine portrays a significant tailing which is difficult to reproduce with the Advection Dispersion model. However the latter model can give good estimates of the mean velocity.

Based on the modeling of the TBCs using the ADM model with CXTFIT (Figure 4-5), the mean velocity over a distance of 12420 m between the injection point and Jeita spring at the siphon terminale is about 48 m/hour. Peclet number is 281, reflecting the prevailing advective component of the transport through the karst system. Longitudinal dispersion is estimated to be 2140 $m^2$/h yielding a longitudinal dispersion of 44.2 m. The tailing is not accounted for in the modeled curve with the ADM; therefore the estimated recovered mass is underestimated with respect to the full recovered mass. The estimated values are given with a mean square error of 0.131 µg/l. The coefficient of correlation between observed and modeled values is acceptable and is on average 0.883.

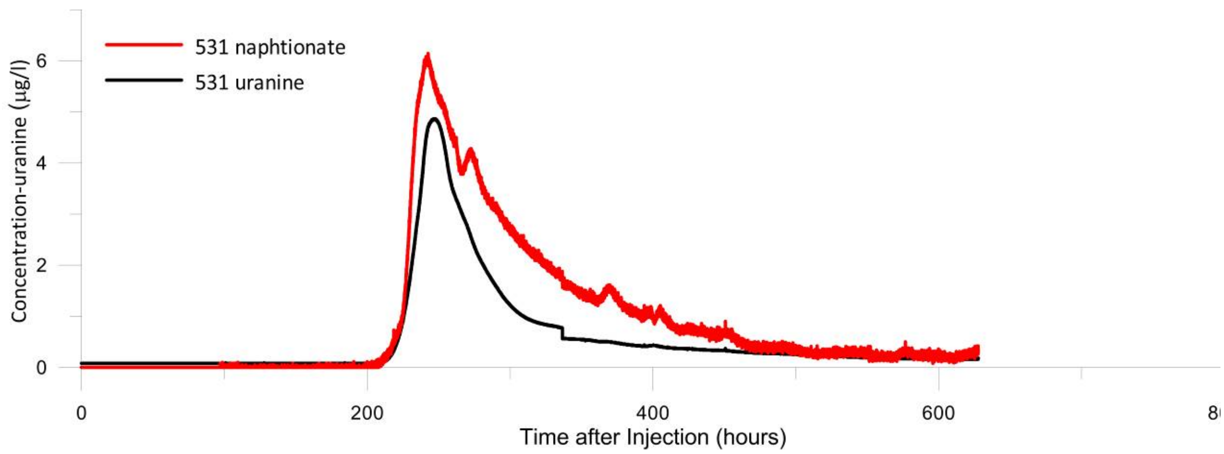


**Figure 4-4 Observed TBC (uranine and naphtionate) restituted in Jeita Spring at the Siphon Terminale (injection point Mshati well; 531)**

## 4.2 TRACER BREAKTHROUGH CURVES IN JEITA SPRING AT THE TOURISTIC ENTRANCE

Uranine was first detected in the Jeita cave in both, fluorometers 525 and 533 about 220 hours after injection. The maximum peaks of uranine observed in 531 and 525 are 3.32 and 3.15 µg/L, respectively, and were reached about 253 hours after injection. The peak velocity calculated over a distance of 17720 m is 70 m/hour. Based on the discharge rate (1.69 $m^3$/s) estimated with the dilution method, a recovery of approximately 11 % - 12 % of uranine was achieved. A tailing is also observed in the tracer breakthrough curve (TBC) generated at Jeita spring touristic entrance.

Based on the modeling of the TBCs in 525 and 533 using the ADM model with CXTFIT (Figure 4-6), the mean velocity over a distance of 17720 m between the injection point and Jeita spring is 66-67 m/hour. Peclet numbers is on average 265 reflecting the prevailing advective component of the transport through the karst system. Longitudinal dispersion ranges between 3000 and 3600 $m^2$/h, yielding a longitudinal dispersion of 44-54 m. The variation in the dispersion is due to the different tailings observed in each of the TBCs. The difference in the TBC observed could only be a result of errors of calibration or measurements. However, the significant tailing was not accounted for in the ADM model. The estimated values are given with a mean square error of 0.11 µg/l for 525 and 0.07 for 533. The coefficient of correlation between observed and modeled values is 0.92 for the fluorometer 533 and 0.85 for fluorometer 525. The mass recovery from both TBCs (525 and 533) is about 9 % of the total injected mass.

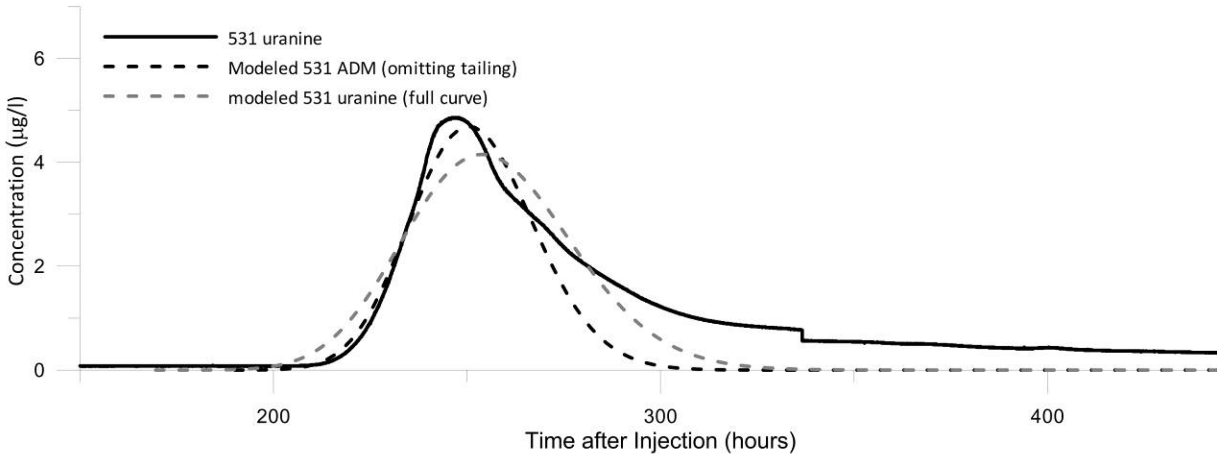


Figure 4-5 Observed and modeled TBC (uranine) restituted in Jeita Spring at the Siphon Terminale (Injection point Mshati well; 531)

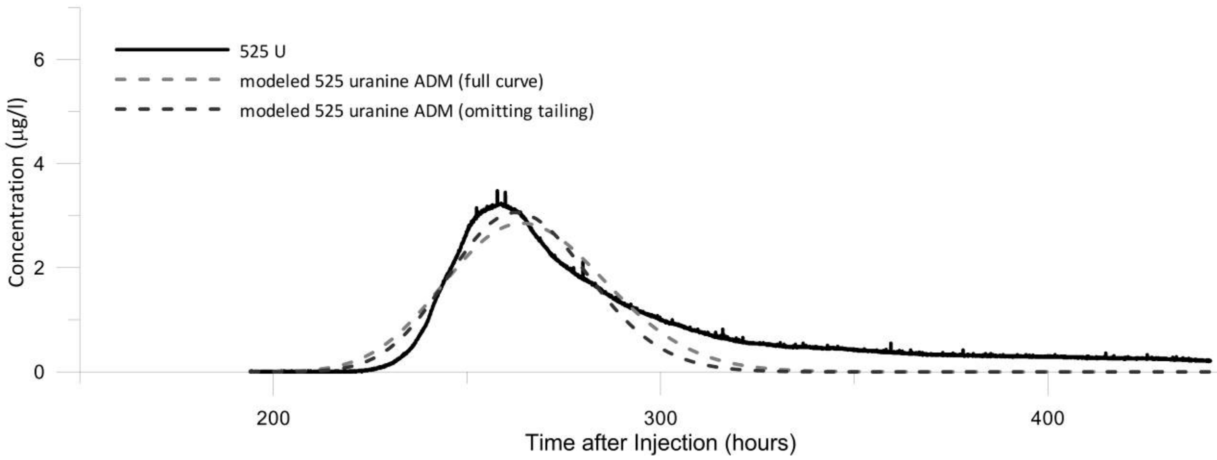


Figure 4-6 Observed and modeled TBC (uranine) restituted in Jeita Spring at the Siphon Terminale (injection point Mshati well; 531), the models shows also the best fit obtained where the tailing of the TBC was omitted as the ADM is unable to model it

**Table 4-2 Summary of the Modeling Results of Tracer Test (5C) undertaken on September 16, 2011**

| PARAMETERS | SYMBOL | UNITS | 5C URANINE (JEITA SPRING TOURISTIC ENTRANCE) (525) | 5C URANINE (JEITA SPRING TOURISTIC ENTRANCE) (533) | 5C URANINE (JEITA SPRING-SIPHON TERMINALE) (531) |
|---|---|---|---|---|---|
| Distance | D | m | 17720 | 17720 | 12420 |
| Discharge | Q | $m^3$/sec | 1.69 | 1.69 | - |
| ADVECTION DISPERSION METHOD (ADM) | | | | | |
| Mean velocity | v | m/hour | 66.5 | 67.1 | 48.4 |
| Mean transient time | $t_m$ | hours | 266.47 | 264.08 | 256.61 |
| Dispersion | D | $m^2$/hour | 3600 | 2970 | 2140 |
| Dispersivity | A | M | 54.1 | 44.3 | 44.2 |
| Peclet number | $P_D$ | - | 327 | 400 | 281 |
| Massive flux | M | µg•h/l | 148 | 150 | 224 |
| Restitution rate | R | % | 9.00% | 9.13% | - |
| **Statistical parameters** | | | | | |
| Coefficient of correlation | $R^2$ | - | 0.850 | 0.920 | 0.884 |
| Mean square error | MSE | µg/l | 1.11E-01 | 7.47E-02 | 1.31E-01 |

# 5. CONCLUSIONS

Based on the tracer test undertaken on September 16, 2011, the following conclusions can be reached:

- A hydrogeological connection was established between the injection point (5C) and Jeita spring at both, the touristic entrance and the siphon terminale (Daraya tunnel). The low restitution rate not exceeding 15% (uranine) might be due to the fact that uranine was not properly channeled from the well into definite flow pathways and stagnated in the well. This tracer test shows that the northern part in Wata el Jaouz area contributes to the recharge area of the Jeita spring, and should therefore be incorporated in the catchment area of the Jeita system.
- The maximum velocities in the fissured Jurassic aquifer under the low flow periods prevailing in September 2011 during the tracer test are the velocities estimated from the TBC arriving at Daraya and are in the range of 40 m/h, the velocities for mixed fissured saturated zone and subsurface channel are the velocities estimated from the TBC depicted at the outlet of the spring and are in the range of 67 m/h. Velocities within the cave system can be calculated based on both TBCs and vary between 530 and 700 m/h. These results are concordant with results of mean velocities from previous tracer experiments.
- The average longitudinal dispersivity is about **40-50 m** for all the tracer tests. The discrepancy between the dispersivity values is mainly due to the significant tailing.
- Given that no mass losses occur between Jeita spring at the siphon terminale and the touristic entrance from previous tracer tests, the discharge of the spring at the siphon terminale could be estimated based the restitution rates achieved in the Jeita spring at the outlet. The additional amount of additional inflow between the two points must be in the range of about 300-400 l/s, to have the same mass recovery at the two points. Therefore, the discharge at siphon terminale during tracer test 5C was about 1.3-1.4 $m^3/s$.

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