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. 2

Artificial Tracer Tests 2 - August 2010

Raifoun
November 2010

Artificial Tracer Tests 2 - August 2010

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: November 2010
No. of pages: 16

[1] University of Goettingen/Germany

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

PROTECTION OF JEITA SPRING - LEBANON -

- REPORT -

ARTIFICIAL TRACER TESTS - AUGUST 2010

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

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 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 second report submitted as part of the cooperation mentioned above.

This report presents the preliminary results of the tracer test conducted in August 2010 to delineate the hydrogeological connection between point sources in the catchment area of the 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 August 2010, Section 3 presents the results of the TBCs analysis. The latter mainly tackles aquifer dynamics and behavior as depicted in August 2010 and gives insights into the velocities and dispersivities in the Jurassic Jeita system. Finally Section 5 presents some conclusions and recommendations.

1.1 GENERAL

The Jeita Spring is an important karst spring located north to Beirut in Jounieh area. It constitutes the main water source for the Beirut Area and its northern suburbs for domestic use. Governed by open channel flow/ full pipe hydraulics, the Jeita Spring drains a catchment of about 288 km^2 extending east in the Lebanese Mountains (Figure 1-1). The catchment of the Jeita spring is defined to date mainly based on topographical boundaries. Very little is known about the connection between various locations on the catchment and the Jeita Spring.

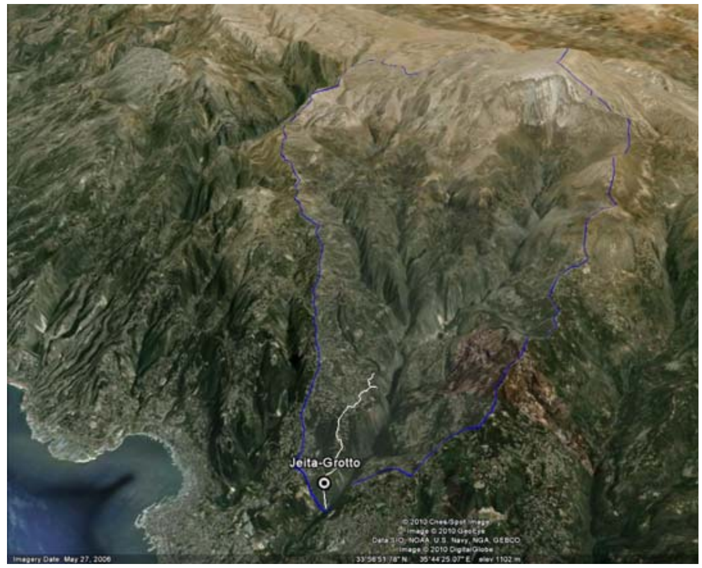


Figure 1-1 Location of Jeita Spring and Catchment in Lebanon (GoogleMaps)

The total yearly precipitation on the Jeita catchment is estimated at about 407 Mm^3, out of which only about 52.3 % are infiltrated, whereas about 15 % and 32.7 % are lost in surface runoff and evapotranspiration respectively.

The Jeita cave is developed in limestone of Jurassic age over a total length (including subsidiaries) of 9000 m. The topography of the grotto was established underground as well as on the surface. The Jeita Cave is also accessible from a tunnel located downstream to Ballouneh Village, about 4500 m east to the Jeita Spring.

1.2 OBJECTIVES OF THE TRACER TEST

The main goal of the artificial tracer tests was to investigate hydrological connections between rapid and slow recharge point source in the catchment area/ subcatchment areas suspected to contribute to the total recharge of the Jeita Spring. These areas are as follows:

1) A north south trending fault zone located north to the Jeita cave trace, where a 3 m * 2 m * 2 m hole was artificially drilled in the heavily fractured valley,

2) A pit located in a construction site destined for future waste water discharge for a building in Ballouneh Area,

3) A sinkhole located about 250 m north from the cave trace. The sinkhole “Houet Ras el Astar” was discovered by The SCL (Spéléo Club du Liban; personal communication).

The Objectives of the tracer tests were mainly to:

- Identify a potential hydrogeological connection between the injection site and the Jeita spring and possibly other springs existing in the catchment
- Characterize hydrodynamic flow and transport parameters of the Jeita Aquifer system (mean and maximum flow velocities and transit times, longitudinal dispersivities, mass restitution, etc…) during low flow periods in comparison to high and medium flow periods.

Additional tracer tests were conducted within the cave over a distance of 4800 m to assess water velocities, dilution effects and potential tracer mass losses only within the cave. This information is crucial for interpretation of all further tracer tests performed in the catchment.

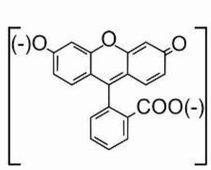
2. FIELD WORK AND METHODOLOGY

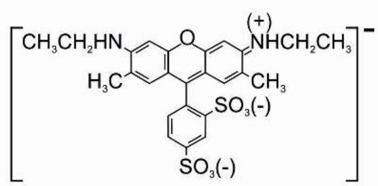
2.1.1 Materials

The tracers Fluorescein (Sodium fluorescein, BASF, CAS 518-47-8, $C_{20}H_{10}O_5Na_2$) and Amidorhodamin G (=Sulphorhodamine G; CAS 5873-16-5; acid red 50; $C_{25}H_{26}$ N_2O_7Na) and Na-Na-Naphtionate ($C_{20}H_8O_3N$ S Na) were selected as they are considered non toxic. Both Fluorescein and Amidorhodamin G tracers can be measured simultaneously on-site with low detection limits. Na-Naphtionate has a high background value in the Jeita waters varying between 4 and 8 µg/l. Fluorescein, sensible to photochemical decay, is only highly adsorptive under increasing acidity (Ford and Williams, 2007) and can be considered as conservative tracer in carbonate aquifers. Geyer et al. (2007) reported that Amidorhodamin G is considered as a reactive tracer, showing slight retardation with respect to Fluorescein (Figure 2-1).

Name	Uranine	Amidorhodamine G
Chemical formula (salts)	$C_{20}H_{10}O_5Na_2$	$C_{25}H_{26}N_2O_7S_2Na$

Structural formula (anions)





acid strength increasing

Figure 2-1 Chemical structures of the selected tracers (modified from Geyer et al. 2007)

Concentration of tracer was monitored in the springs and stream with field fluorometers (GGUN-FL30 serial numbers 524, 525, 526, 532, 533, 531; Schnegg 2002). This equipment measures continuously dye concentration at the monitoring site every 2 minutes with two incorporated lamps able to detect emission at wave lengths of dyes of interest in this study. The field fluorometers, which detect signals as millivolts, were calibrated for Fluorescein, Amidorhodamin G, and Na-Naphtionate. The dissimilarity and lag between the luminescence wavelengths of both Fluorescein and Amidorhodamin G enables the distinction between both dye types during analysis and hinders the significance of overlaps. Fluorescein has a spectrum of luminescence ranging between 490 nm and 524 nm, whereas that of Amidorhodamin G extends between 535 nm and 552 nm, while that of Na-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 lamps are calibrated for the 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 fluorescein and 0.2 µg/l for Amidorhodamine G. The limit of detection of Na-Naphtionate is usually 0.07 µg/l. However it is worth noting that the concentration of Na-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.

2.1.2 Fieldwork

2.1.2.1 Injections

Two tracer tests were undertaken on the **2nd of August 2010** under extreme low flow conditions. The injection points were an artificially drilled hole (Ajaltoun hole; Figure 2-2) along the "Fault zone" in Ajaltoun area and an artificially drilled pit, respectively. The latter is supposed to serve for waste water discharge of a building in construction (Nassar pit). The holes were flushed with about 5 m³ of water prior to tracer Injection. About 10 kg of Na-Naphtionate and Fluorescein were injected In the Ajaltoun hole and 5 kg of AG were injected in the Nassar pit. Both sites were flushed with 60 m^3 of water each over a period ranging between 2-3 hours (with water tanks). However it is to be noted that the infiltration rate was very low in the Nassar Pit, which did not allow any percolation of the AG. The latter tracer test was considered not successful. On the **30th of August 2010**, the Ajaltoun hole was flushed with additional 40 m^3 of water in an attempt to accelerate the flow, and achieve retrieval of the injected tracer.

Figure 2-2 Injection of 10 kg of Na-Naphtionate and Fluorescein into the Ajaltoun artificially dug hole

On **the 20th of August 2010**, 5 kg of Na-Naphtionate and 5 kg of AG were injected into a doline in the area of new Ajaltoun (sinkhole Ras el Astar; Figure 2-3). This sinkhole was explored by the SCL, and is peported to be about 22 m deep.

Figure 2-3 Injection of 5 kg of Na-Naphtionate and Amidorhodamine G into the sinkhole "Ras el Astar" in New Ajaltoun

On the **27th of August 2010**, the sinkhole was flushed with additional 40 m^3 in order to depict whether quantities of tracer remained stuck in the doline especially that the sinkhole is apparently used as a waste dump and is clogged partially with waste.

On the **28th of April 2010**, 50 grams of AG were released in the Jeita underground river at the "siphon terminal" of the Daraya Tunnel.

It is worth noting that 7 g and 10 g of fluorescein were released respectively on the **10th of August 2010** and the **17th of August 2010** at the "siphon terminal" as a result of discharge dilution measurements in Daraya. The results observed at the level of the installed fluorometer near the cave entrance are also regarded for analysis.

Table 2-1 Injections Points

INJECTION POINT	COORDINATES LAMBERT - UTM (Z) (m)	INJECTION TIME	FLUSHING VOLUME (m^3)	COMMENTS
Ajaltoun hole	147 515 226 005 36 749452.38 37 61910.24 (854)	02.08.2010 (12:11)	60	10 kg of Fluorescein and Na-Naphtionate Infiltration rate was relatively favorable to ensure good percolation of the tracer
		17.08.2010 (09:00)	40	Flushing of the hole

Nassar Pit	144 603 223 808 36 746818.14 37 59902.28 (652)	02.08.2010 (12:11)	60	5 kg of AG Infiltration rate was very low to ensure percolation of the tracer- Failed
Ras El Astar Sinkhole	146 033 224 109 36 748102.40 37 60197.83 (656)	20.08.2010 (11:40)	60	5 kg of Na-Naphtionate and AG
		27.08.2010 (15:40)	40	Flushing of the sinkhole
Daraya Tunnel	146135 223503 36 748257.41 37 59654.21 (140)	17.08.2010 (13:40)	-	50 g of AG
		10.08.2010 (16:00)	-	7 g
		17.08.2010 (13:00)	-	10 g

2.1.2.2 Observation points

During the first two tracer tests, two Field spectrofluorometer with dataloggers were installed in the Jeita spring 500 m inside the cave (525,533) and in the Siphon terminal (532,526) 4800 m from the cave touristic entrance) and one was installed in the Qachqouch spring (531) for automatic sampling. Manual samples were collected between 02.08.2010 and 20.08.2010.

During the tracer tests undertaken with the cave, one fluorometer (525) was installed 715 m inside the cave, upstream to a potential additional inlet. Fluorometer 533 was installed 500 m upstream of the cave entrance.

During the tracer test investigating Ras El Astar sinkhole, fluorometer 526 was installed at the cave entrance, whereas fluorometer 533 was kept at 500 m inside the cave. A detailed description of the observation points is provided in Table 2-2.

Figure 2-4, Figure 2-5 and Figure 2-6 show the set ups of the three tracer tests undertaken during low flow periods respectively on the 2nd, 17th, and 20th of August 2010.

Table 2-2 Observations Points

OBSERVATIONS POINTS	X,Y,Z (LAMBERT, m)	SAMPLING	TIME SPAN	SAMPLING INTERVAL	COMMENTS
Jeita Grotto (+500m)	142603 223385 95	Automatic	17.04.2010-11.05.2010	2 min- 5 min	GGUN-FL30 serial number 525

OBSERVATIONS POINTS	X,Y,Z (LAMBERT, m)	SAMPLING	TIME SPAN	SAMPLING INTERVAL	COMMENTS
Jeita Grotto (+715m)	142603 223385 95	Automatic	17.08.2010 (14:00)- 18.08.2010 (10:00)	2 min	GGUN-FL30 serial number 525
Jeita Grotto Beginning of the Touristic Section (+0m)	142233 223115 90	Automatic	17.08.2010 -30.08.2010	2 min	GGUN-FL30 serial number 526
Jeita Grotto Daraya Tunnel	146135 223503 140	Automatic	02.08.2010- 17.08.2010	2 min	GGUN-FL30 serial number 526
Jeita Grotto Daraya Tunnel	146135 223503 140	Automatic	02.08.2010- present	2 min	GGUN-FL30 serial number 532
Qachqouch Spring	141946 223006 60	Automatic	02.08.2010- present	2 min	GGUN-FL30 serial number 531

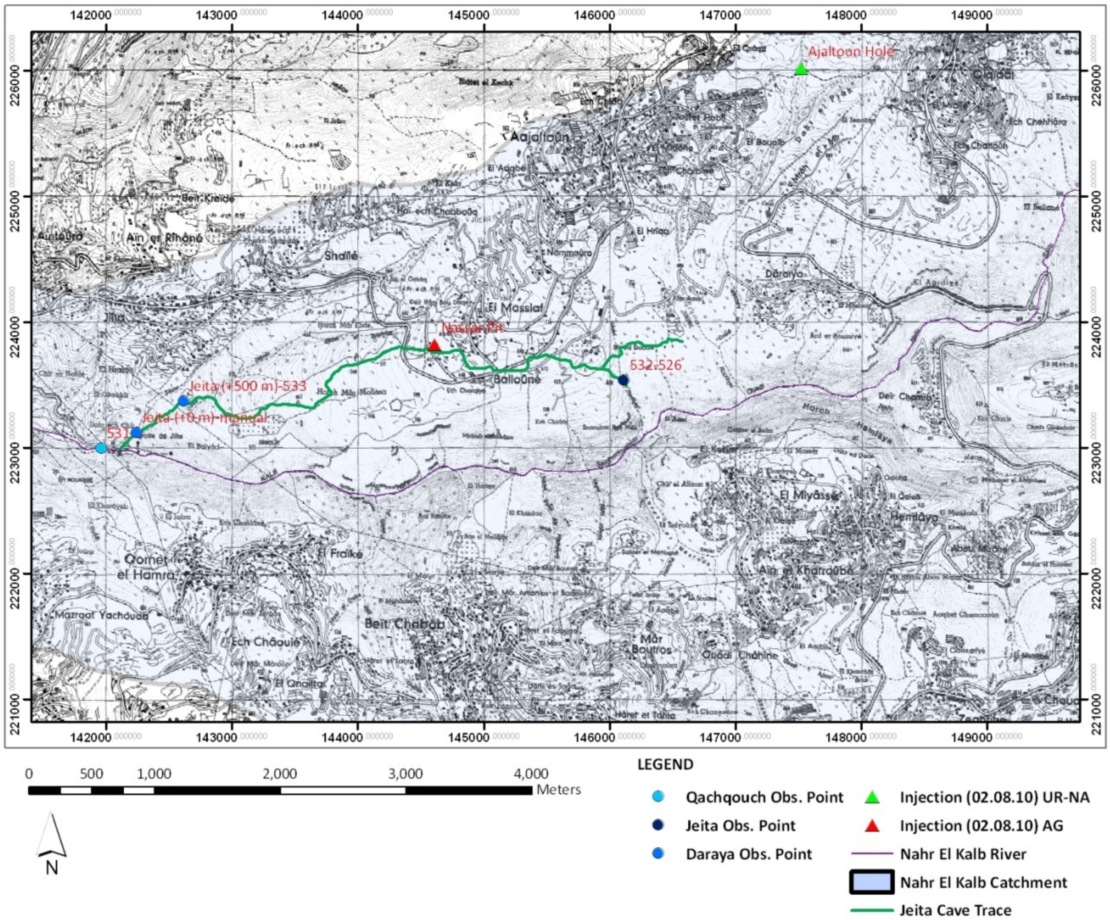


Figure 2-4 Map showing the Set-Up (Injection Points and Observation Points) of Tracer Test 1 undertaken on August 2nd 2010

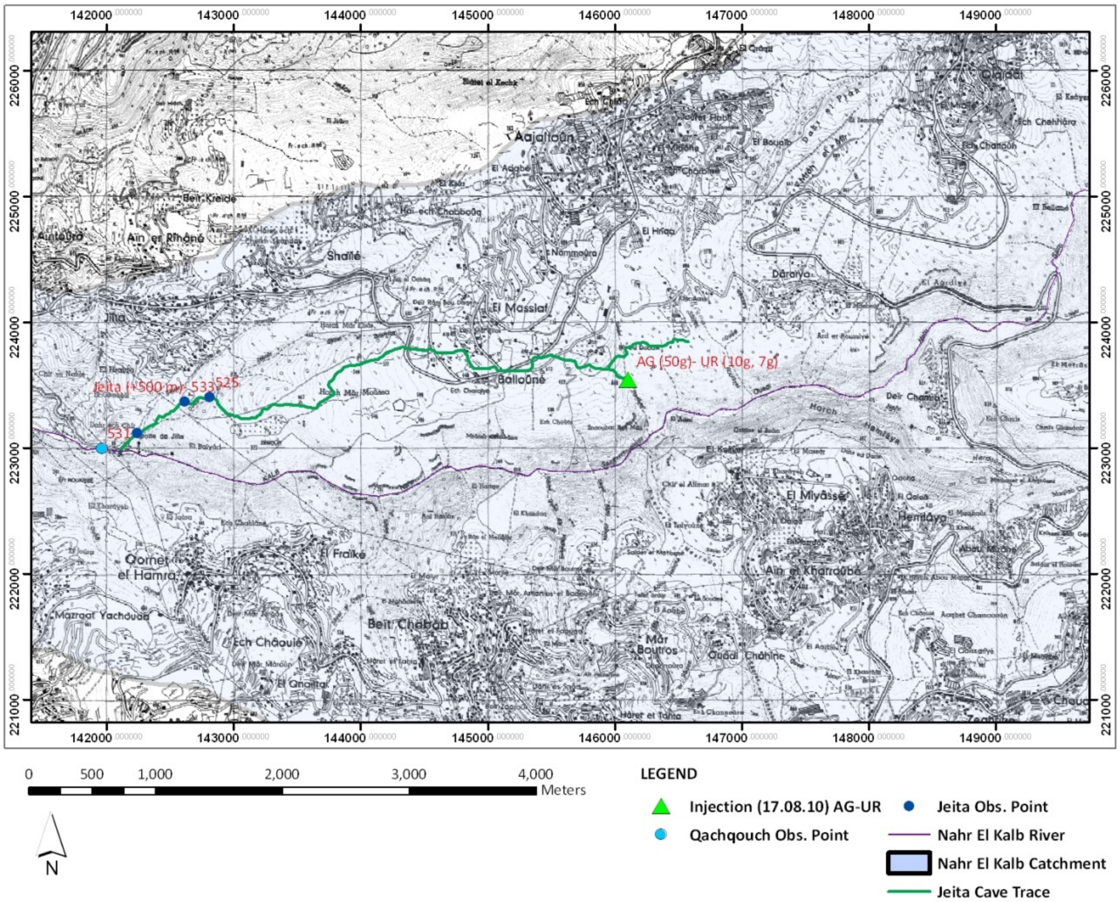


Figure 2-5 Map showing the Set-Up (Injection Points and Observation Points) of Tracer Test 2 undertaken on the 17th of August 2010

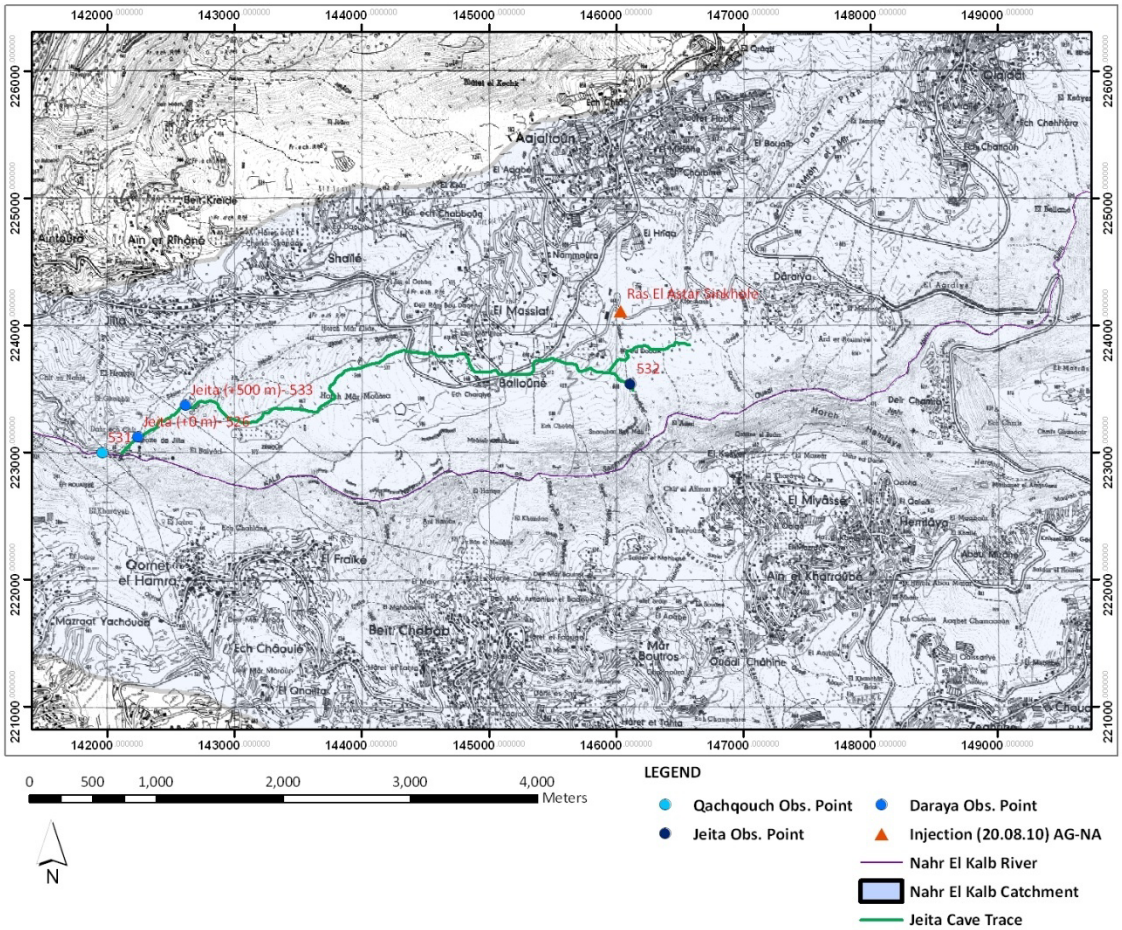


Figure 2-6 Map showing the Set-Up (Injection Points and Observation Points) of Tracer Test 3 performed on the 20th of August 2010

2.1.3 Discharge Measurements

Flow rate measurements were mainly performed based on the dilution gauging methods using salt and Fluorescein. The dilution method relies on calculating the discharge rate based on a tracer breakthrough curve (TBC). In the case of salt, a TBC of electrical conductivity is measured and translated to salt concentration with the help of a calibration function. The integration of the concentration over time allows the estimation of the discharge rate as shown in Equation 1.

A Calibration curve (rating curve, Equation 2) of salt concentration as a function of conductivity was constructed for the Daraya tunnel and Qachqouch spring prior to discharge measurement.

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

Where
Q is the discharge rate [L^3/T]
M is the injected salt or fluorescein mass [M]
c is concentration [M/L^3]
t is time [T]

$$c = a[EC] + b \qquad (2)$$

EC is the Electrical conductivity
a is the slope of the linear relationship between C and EC
b is the intersection of the calibration curve with the y axis

The spring discharge at the various discharge points were measured at different intervals during the tracer test period. The discharge rates are shown in Table 2-2. Discharge rates are very important for the calculation of restitution rates are the springs. The degree of uncertainty in the measurements reaches about 0.1-0.3 m^3/sec due sometimes to incomplete dilution and short distance tests during discharge measurements using the dilution methods.

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

OBSERVATION POINT	METHOD	DATE	DISCHARGE RATE	COMMENTS
Jeita Grotto	Dilution with fluorescein	10.08.2010 18.08.2010	Obsolete results	Fluorescein dilution was not successful due to relatively short distance (14 m) and consequent incomplete dilution
Jeita Grotto	Dilution with Salt	10.08.2010 18.08.2010	1.9 m3/s ±0.3 m^3/sec	
Jeita Grotto Daraya Tunnel	Dilution with fluorescein	09.08.2010 17.08.2010 30.08.2010	Obsolete results	Fluorescein dilution was not successful due to relatively short distance (14 m) and consequent incomplete dilution
Jeita Grotto Daraya Tunnel	Dilution with Salt	09.08.2010 17.08.2010 30.08.2010	1.0 m^3/sec ±0.1 m^3/sec	The salt measurements fall within appropriate ranges, when Compared with velocity measurement regarded as representative of the maximum discharge.

3. EVALUATION AND MODELING

Tracer breakthrough curves (TBCs) were analyzed graphically, using Excel sheets, and numerically with the software CXTFIT- Stanmod (Toride et al. 1999). Two model approaches, the *Advection-dispersion Model (ADM)*, and the *two region non equilibrium model (2RNEM)* were adopted for the modeling of the TBC, especially in the presence of overlaps in the tracer breakthrough curve and to reproduce tailing in most of the retrieved TBCs. 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 PRELIMINARY EVALUATION

3.1.1 Parameters

Tracer breakthrough curves (TBCs) were analyzed graphically, using Excel sheets, and numerically with the software CXTFIT- Stanmod (Toride et al. 1999). Two model approaches, the *Advection-dispersion Model (ADM)*, and the *two region non equilibrium model (2RNEM)* were adopted for the modeling of the TBC, especially in the presence of overlaps in the tracer breakthrough curve and to reproduce tailing in most of the retrieved TBCs. 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.

3.1.1.1 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).

$$R = \frac{1}{M}\int_{t=0}^{\infty} c(t)Q(t)dt \qquad (3)$$

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.

3.1.1.2 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)

$$t_d = \int_{t=0}^{\infty} \frac{c(t)Q(t)tdt}{c(t)Q(t)dt} \qquad (4)$$

3.1.1.3 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 5. 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.

$$D_L = \alpha_L \cdot v_m + D^* \qquad (5)$$

D_L being the longitudinal dispersion coefficient [L²/T]
α_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

3.2.1.1 1-D advection-dispersion model (ADM)

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 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).

$$C(t) = \frac{M}{Qtm\sqrt{4\pi P_D\left(\frac{t}{t_m}\right)^3}}\exp\left(-\frac{\left(1-\frac{t}{tm}\right)^2}{4P_D\frac{t}{tm}}\right) \quad (6)$$

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 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)*).

The fitting allows to inversely estimate the mean velocity and dispersion (Göppert and Goldscheider, 2007). This model is however unable to account for tailing observed in TBCs. This phenomenon can generally be described by mass-transfer between mobile and immobile fluid regions, flow channeling and multi-dispersion.

3.2.1.2 Two region Non equilibrium model (2RNEM)

The two region non-equilibrium model is based on the assumption that the solute is present under two forms of fluid regions, a mobile fraction, such as in the conduits and main flow direction pathways, and an immobile fraction, which is hosted in dead end passages and sediments pools (Field and Pinsky, 2000, Geyer et al., 2007). The latter fraction is thought to be released slowly with time, which explains in some cases, the tailing observed in most of the tracer breakthrough curves.

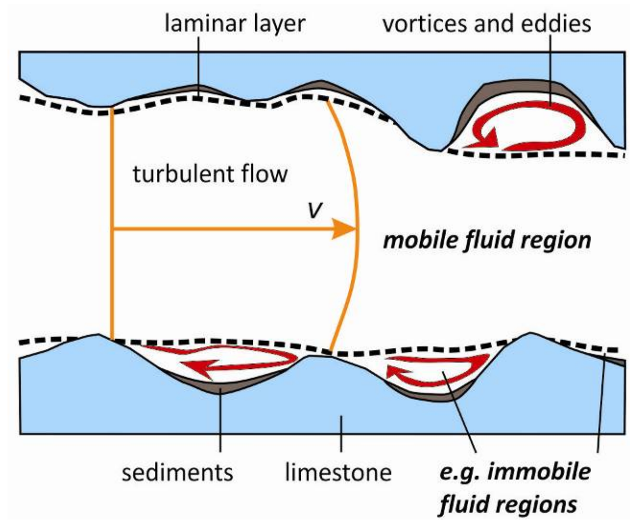


Figure 3-5 Conceptual model of flow within a karst conduit (from Geyer et al. 2007).

This Two region Non equilibrium model accounts for conservative transport processes, including advection, dispersion and mass transfer between the immobile and mobile phase. The corresponding equations are (Toride et al. 1999)

$$\theta_m \frac{\partial c_m}{\partial t} = D\frac{\partial^2 c_m}{\partial x^2} - v\frac{\partial c_m}{\partial x} - \omega(c_m - c_{im})$$

$$(1-\theta_m)R\frac{\partial c_{im}}{\partial t} = \alpha(c_m - c_{im}) \qquad (7)$$

Where v is the average velocity [L/T]
D is the dispersion coefficient [L²/T]
θ_m *is fraction of the mobile fluid phase [-]*
ω is the first order mass transfer coefficient [1/T]
c_{im} *and* c_m *are the respective concentration of mobile and immobile fluid phase [M/L³]*
x is the space coordinate [L]
t is time [T]

In a first approach, fluorescein and amidorhodamin G are assumed as conservative tracers in this study. Therefore reactive transport processes like e.g. ion exchange, complexation and decay will be neglected.

Tracer injection is simulated by a Dirac pulse, i.e. tracer injection period is negligible compared to the observed tracer travel time. Calibration with CXTFIT can be performed inverse, i.e. the model iterates, based on transport preset parameters, in order to reproduce observed tracer. The parameters that are adjusted for the model are β, ω, velocity *v* and dispersion *D*.

4. RESULTS OF THE TRACER TEST

The first two tracer tests undertaken on the 2nd of August were negative. The latter does not rule out the connection between the Injection points and the Jeita cave. The tracer test undertaken on Ras El Astar Sinkhole was positive delineating a connection between the sinkhole and the Jeita cave. The tracer however did not appear in the Daraya Tunnel. The results of the tracer test performed within the cave will also be discussed hereafter. 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. Distances were defined as follows and didn't account for turtuosity or change in altitude, except in the Jeita cave, where the flowpath is known:

- The distance between the Daraya Tunnel and Jeita Cave (525; +715 m inside the cave) was estimated at 4585 m.
- The distance between the Daraya Tunnel and the Jeita spring (+ 500 m) is about 4800 m.
- The distance between Ras El Astar Sinkhole and the Jeita spring (at the touristic entrance; 526) is about 6500 m, whereas the distance between the sinkhole and the Jeita Spring (at 533; + 500 m) is about 6000 m.
- The distance within the cave was calculated based on the cave trace and accounts for turtuosity.

4.1 TRACER TEST (02ND OF AUGUST 2010)

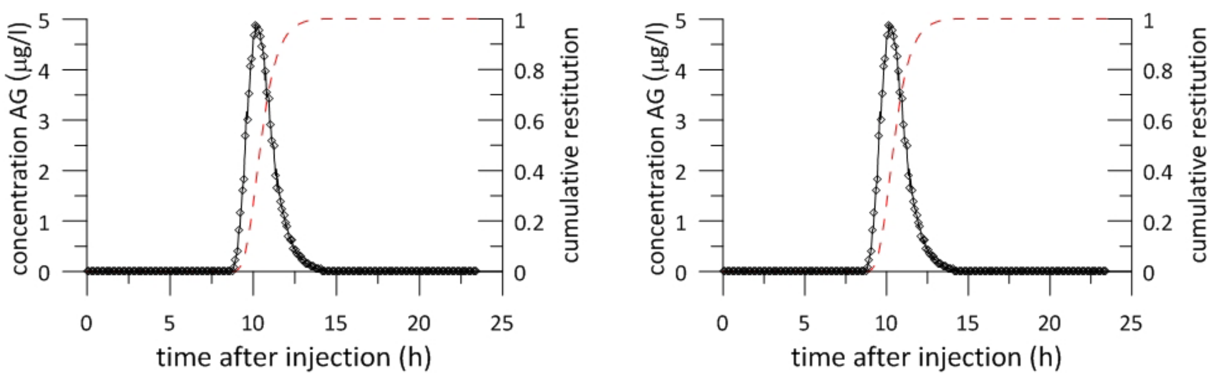
The tracer tests undertaken in Ajaltoun and Nassar Pit in Ballouneh resulted in being negative, as no tracer was retrieved in any of the observation points. The samples collected manually between August 02nd 2010 and August 20th 2010 revealed no presence of any of the tracers. The fluorometers installed at the various observation points did not detect arrival of any tracer substance.

4.2 TRACER BREAKTHROUGH CURVES- TRACER TEST (WITHIN THE CAVE)

The tracer (50 g AG) injected within the cave on the 17th of August was retrieved at fluorometers 525 (+ 715 m) and 533 (+500 m). Below is a detailed description of the results.

The AG started to appear 8.8 hours and 9.4 after injection respectively in 525 and 533. Mean residence times are calculated to be respectively 10 and 11 hours in 525 and 533. Consequently, velocities within the cave range between 420-440 m/h on the 17-18 of August 2010. No prominent tailing is observed. According to discharge rates prevailing at that time, the complete mass of injected AG was retrieved in both fluorometers. The maximum concentration observed is about 4.5 µg/L (533; Figure 4-1) and 4.86 µg/L (525; Figure 4-1). Dilution with respect to 525 is observed in the fluorometer 533 (Figure 4-2) located downstream to a potential inlet. If considered that complete restitution occurred at the the fluorometer 533, the dilution results from additional volume in the range of 80 L/s.

A similar result is also obtained from the retrieved TBC resulting from the injection of 10 g of uranine in Daraya tunnel shortly before injecting the AG. Based on modeling of the obtained curve, longitudinal dispersivities within the cave are in the range between 10-12 m.



A B

Figure 4-1 TBC of Amidorhodamine G released in Daraya on the 17th of August 2010 respectively in fluorometers 525 (a) and 533 (b)

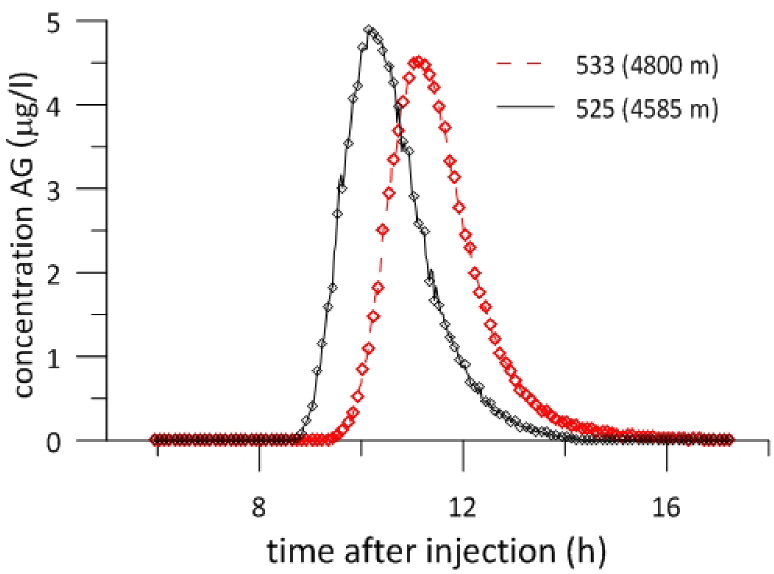


Figure 4-2 **TBCs of Amidorhodamine G released in Daraya on the 17th of August 2010. Note the lower concentration retrieved in 533 due to a potential dilution between 525 and 533.**

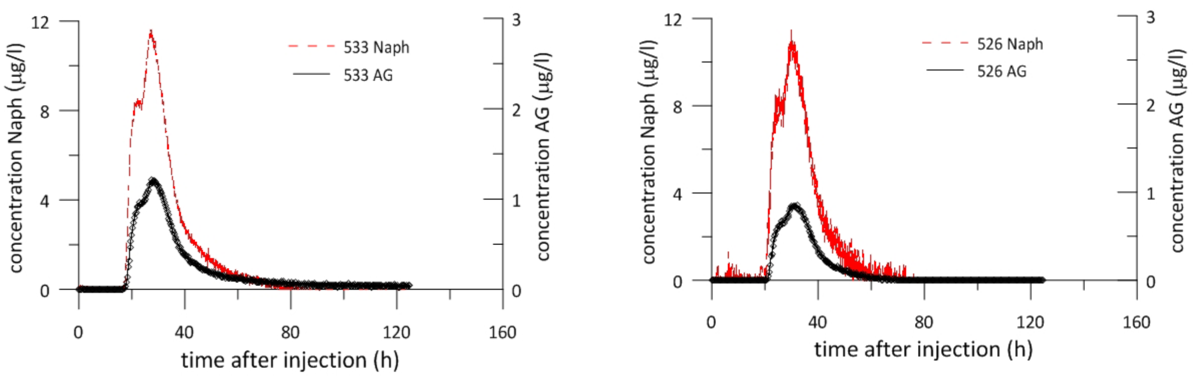
Table 4-1 **Graphical Interpretation of the TBC´s resulting from the Tracer Tests (August 2010)**

OBSERVATION POINT DISTANCE FROM INJECTION POINT	TRACER FIRST ARRIVAL (hours)	MAXIMUM VELOCITY (m/hours)	PEAK CONCENTRATION TIME (hours)	PEAK VELOCITY (m/hours)	RESTITUTION (%)
TRACER TEST (AJALTOUN ARTIFICIAL HOLE) – 02 AUGUST 2010 – AJALTOUN					**NEGATIVE**
TRACER TEST (NASSAR PIT)- 02 AUGUST 2010- BALLOUNEH					**NEGATIVE**
OBSERVATION POINT DISTANCE FROM INJECTION POINT	**TRACER FIRST ARRIVAL (hours)**	**MAXIMUM VELOCITY (m/hours)**	**PEAK CONCENTRATION TIME (hours)**	**PEAK VELOCITY (m/hours)**	**RESTITUTION (%)**
TRACER TEST (AMIDORHODAMINE) - 17 AUGUST 2010- DARAYA-JEITA					
Jeita Grotto (+715m; 525) 4585m	8.8	521	10.1	453	100
Jeita Grotto (+500m;533) 4800m	9.4	510	11.2	428	100
Qachqouch Spring					**NEGATIVE**
TRACER TEST (FLUORESCEIN) – 17 AUGUST 2010 – WITHIN THE CAVE					
Jeita Grotto (+715m;525) 4585m	9.1	503	10.06	455	29
Jeita Grotto (+500m;533) 4800m	9.5	505	10.86	441	37
TRACER TEST (AMIDORHODAMINE)- 20 AUGUST 2010- RAS EL ASTAR SINKLHOLE					
Jeita Grotto (+500m;533) 6000m	15.6	384	Peak 1: 22 Peak 2: 26.7	272 224	2.97
Jeita Grotto (+0m;526) 6500m	19.2	338	Peak 1: 25 Peak 2: 30.7	260 211	1.80
TRACER TEST (NA-NAPHTIONATE)- 20 AUGUST 2010- RAS EL ASTAR SINKLHOLE					
Jeita Grotto (+500m;533) 6000m	14.7	442	Peak 1: 21 Peak 2: 26.6	285 225	22.42

Jeita Grotto (+0m;526) 6500m	18.4	353	Peak 1: 23.8 Peak 2: 29.3	273 221	22.43

4.3 TRACER BREAKTHROUGH CURVES- TRACER TEST RAS EL ASTAR SINKHOLE

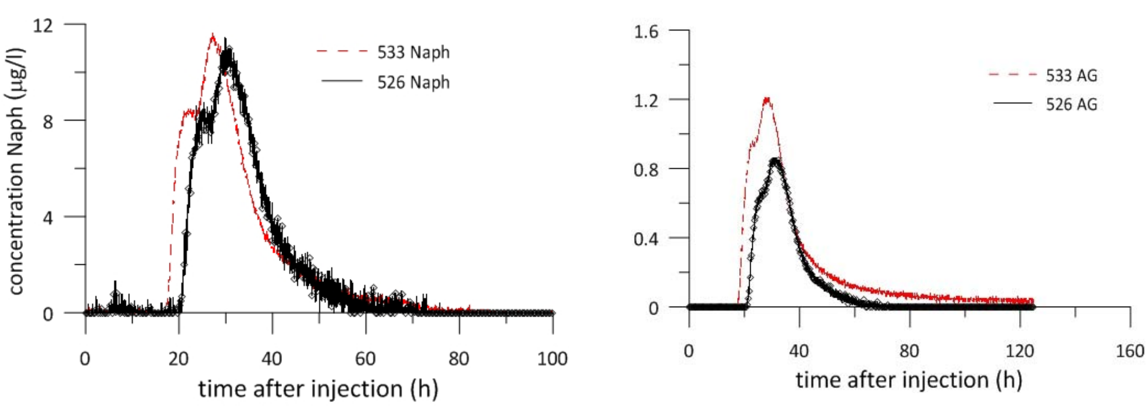
The tracers AG and Na-Naphtionate were first detected in 533, after about 15.6 hours, then in 526, after about 19.2 hours after injection. The maximum peak of Na-Naphtionate observed in 533 is about 11.29 µg/L, whereas a peak of 11 µg/L was depicted in the TBC curve at 526.



A B

Figure 4-3 TBCs of Amidorhodamine G and Na-Naphtionate injected in the Ras El Astar Sinkhole on the 20th of August 2010 respectively in fluorometers 533(a) and 533 (b)

Based on discharge rate (1.6 m^3/s) under prevailing flow conditions, approximately 148 g of AG and 1200 g of Na-Naphtionate were restituted in the TBC retrieved at 500 m inside the cave (533), whereas only 80 g of AG and 1200 g of Na-Naphtionate were retrieved at the Jeita Spring outlet at the touristic entrance (526): This slight variation of peak concentration and total restituted massive flux as portrayed in Figure 4-1 may be the result of dilution occurring between 526 and 533 and/or an error in the calibration.

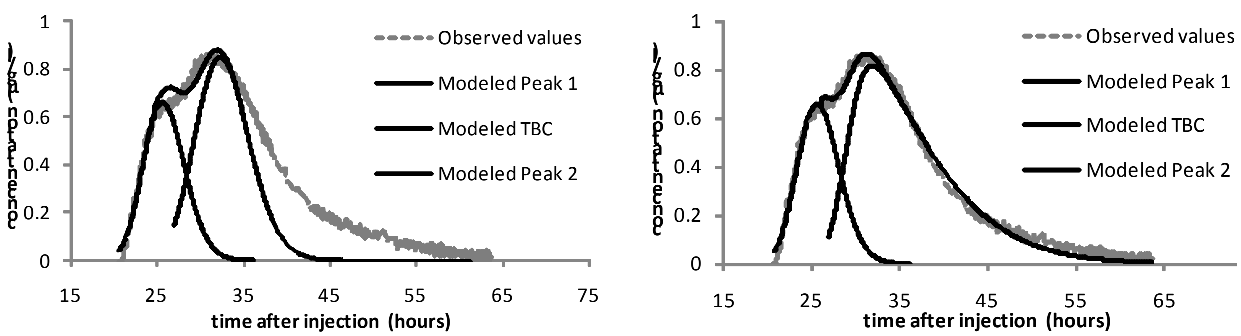


A B

Figure 4-4 Comparison of TBCs of Na-Naphtionate and Amidorhodamine G injected in the Ras El Astar Sinkhole on the 20th of August 2010 retrieved in fluorometers 533(a) and 526 (b)

The TBC portrays two main peaks resulting from two separate groundwater flow pathways. If the TBC is regarded as one curve, the mean velocity is estimated to about 199 m/h.

If the TBC is modeled using a multi peak approach, then the first rapid flow path is characterized by a mean velocity of 250 m/h and a longitudinal dispersivity of 27 m, whereas the second slower pathway is characterized by a mean velocity of 199 m/h and a dispersivity of 30 m. As portrayed by



A b

Figure 4-5 Multi peak modeling with ADM (a), and 2NREM (b) of the TBC resulting from the tracer test performed on the 20th of August 2010

Table 4-2 and 4-3 show the hydrodynamic parameters namely mean velocity and dispersivities resulting from modeling of the TBCs using the ADM and 2NREm models with CXTFIT. In general for all modeled TBCs, Peclet numbers ranges between 200 and 900, reflecting the prevailing advective component of the transport through the karst system. Recovery rates obtained with the CXTFIT fall in the same range of that calculated by manual integration. It is worth noting that AG was retarded with respect to Na-Naphtionate with a factor of retardation estimated at 1.03, i.e., about 1 hour delay over the entire distance.

Table 4-2 Summary of the Modeling Results of the Tracer Tests Undertaken within the cave in August 2010

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO (+715M)	JEITA GROTTO (+500M)	JEITA GROTTO (+715M; 525)	JEITA GROTTO (+500M; 533)
SIPHON TERMINAL –JEITA			TRACER TEST (50 g AG) - 17. AUGUST 2010		TRACER TEST (510 g FL) - 17. AUGUST 2010	
Distance	D	m	4585	4800	4585	4800
Discharge	Q	m^3/sec	1.575	1.655	1.575	1.65
ADVECTION DISPERSION METHOD (ADM)						
Mean Velocity	v	m/hour	**440**	**424**	**454**	**437**
Mean transient time	t_m	hours	10	11	10	11
Dispersion	D	m^2/hour	5240	4680	2720	3070
Dispersivity	A	M	11.9	11	6	7
Peclet number	P_D	-	385	435	765	683
Massive Flux	M	µg•h/l	8.8	8.4	0.522	0.624
Restitution Rate	R	%	99.79	99.79	29.60	37.07
Statistical parameters						
Coefficient of Correlation	R^2	-	0.98	0.985	0.98	0.994
Mean Square Error	MSE	µg/l	5.33E-02	3.36E-02	3.95E-04	1.16E-04
TWO REGION NON EQUILIBRIUM MODEL (2NREM)						
Mean Velocity	v	m/hour	**440**	**424**	**454**	**436**
Mean transient time of mobile phase	t_m	hours	10.4	11.3	10.1	11.0
Dispersion	D	m^2/hour	5240	4660	2800	2390

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO (+715M)	JEITA GROTTO (+500M)	JEITA GROTTO (+715M; 525)	JEITA GROTTO (+500M; 533)
Partition coefficient	β	-	0.95	0.95	0.921	0.971
Mass transfer coefficient	ω	1/hour	1.8E-01	1.6E-01	0.404	0.47
Dispersivity	α	m	11.9	11	6.2	5.5
Peclet number	P_D	-	385	437	743	876
Massive Flux	M	µg•h/l	8.86	8.45	0.526	0.626
Restitution Rate	R	%	100.47	100.39	29.82	37.18
Statistical parameters						
Coefficient of Correlation	R^2	-	0.98	0.985	0.982	0.995
Root mean Square Error	RMSE	µg/l	5.40E-02	3.37E-02	3.96E-04	9.96E-01
Dilution amount between 525 and 533			80l/s			

Table 4-3 Summary of the Modeling Results of the Tracer Tests Undertaken on August 20th, 2010

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO (+50M; 533;FC)	JEITA GROTTO (+0M; 526;FC)	JEITA GROTTO (+0M; 526;FC)	JEITA GROTTO (+0M; 526; PEAK1)	JEITA GROTTO (+0M; 526; PEAK2)
SIPHON TERMINAL –JEITA			TRACER TEST (5KG AG- 5KG NA-NAPHTIONATE) - 20. AUGUST 2010				
Distance	D	m	6000	6500	6500	6500	6500
Discharge	Q	m^3/sec	1.65	1.65	1.65	1.65	1.65
Tracer	-	-	AG	Na-Naphtionate	AG	AG	AG
ADVECTION DISPERSION METHOD (ADM)							
Mean Velocity	v	m/hour	**201**	**204**	**199**	**251**	**199**
Mean transient time	t_m	hours	32	32	33	26	33
Dispersion	D	m^2/hour	35000	35500	30300	6890	6050
Dispersivity	A	M	174.1	174	152.3	27.5	30.4
Peclet number	P_D	-	32	37	43	237	214
Massive Flux	M	µg•h/l	21.8	176	14	22	38
Restitution Rate	R	%	2.49	20.1	1.6	0.44	0.75
Statistical parameters							
Coefficient of Correlation	R^2	-	0.96	0.97	0.98	0.984	0.984
Mean Square Error	MSE	µg/l	3.23 E-03	2.95E-03	1.67E-03	9.51E-04	1.66E-03
TWO REGION NON EQUILIBRIUM MODEL (2NREM)							
Mean Velocity	v	m/hour	**200**	**199**	**194**	**251**	**178**
Mean transient time of mobile phase	t_m	hours	32.5	32.7	33.5	25.9	36.5

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO (+50M; 533;FC)	JEITA GROTTO (+0M; 526;FC)	JEITA GROTTO (+0M; 526;FC)	JEITA GROTTO (+0M; 526; PEAK1)	JEITA GROTTO (+0M; 526; PEAK2)
Dispersion	D	m^2/hour	7240	18900	14300	6890	2470
Partition coefficient	β	-	0.554	0.839	0.833	-	0.833
Mass transfer coefficient	ω	1/hour	0.122E-02	3.1E-04	3.1E-04	-	3.1E-04
Dispersivity	α	m	36.2	95	73.1	27.2	13.9
Peclet number	P_D	-	152	68	237	237	468
Massive Flux	M	µg•h/l	20.3	175	14	22	10.1
Restitution Rate	R	%	1.93	19.97	1.6	0.44	1.15
Statistical parameters							
Coefficient of Correlation	R^2	-	.0.964	0.98	0.98	0.984	0.994
Root mean Square Error	RMSE	µg/l	0.298E-02	2.91E-03	1.18E-03	9.51E-04	4.78E-04

5. CONCLUSIONS

Discharge rates of the Jeita Spring have been estimated at **1.65 m^3/s** (with an error of ±0.2 m^3/s) during the month of August based on various dilution measurements. Discharge rates of the Jeita Spring in Daraya are estimated at about **1 m^3/s** (with an error of ±0.1 m^3/s) as portrayed by dilution tests conducted in August 2010.

Based on the tracer test undertaken on August 20th, 2010, a hydrogeological connection was established between the Ras El Astar Sinkhole (which is believed to have a direct access to the cave) and the Jeita Spring at various points within the cave and at the outlet. Similar hydrodynamic parameters can be deduced from the TBC retrieved in Fluorometers 526 and 533 for both Na-Naphtionate and AG, notably with regards to velocity (about **200 m/h**) and dispersivity (**30 000 m^2/h**). However amounts of AG restitution (**about 2%**) appear to be 10 times less than that of Na-Naphtionate (**about 20 %**), with the AG TBC slightly retarded with respect to that of Na-Naphtionate due to the reactivity of the Amidorhodamine G.

Two main flow paths (modeled using a multi peak approach) can be identified in the retrieved TBC as follows:

1. A flowpath characterized by velocities of about **250 m/h**, diverting about 36% of the tracer retrieved mass with dispersivities of about **33 m**.
2. A flowpath characterized by slower velocities of about **199 m/h**, diverting 54% of the total restituted mass, with dispersivities of about **26 m**.

The tailing in the AG and Na-Naphtionate TBC is prominent due an important portion of immobile phase released with time, the portion of mobile phase is estimated according to 2NREM to be about 0.83.

Velocities within the cave are of the range of **400 m/h** as portrayed by tracer tests using both Fluorescein and AG. The dispersivities within the cave are in the range of **10-12 m**.

Assuming a velocity of 400 m/h over the entire length of the cave (4800 m), the mean transit time of the tracer in the cave is about 10-12 hours. The total transit time of the tracer during the tracer test conducted on August 20. 2010, was about 33 hours. Therefore the transit time of the tracer before reaching the cave can be estimated at 21-23 hours. Velocities in the unsaturated zone (related to a shaft/fast flow pathway) are in the range of 30-40 m/h.

Based on the tracer test undertaken within the cave, no loss of tracer was observed (restitution of the injected 50g AG). However an additional inflow of about **70-90 l/s** (0.07-0.09 m^3/s) can be inferred from the dilution effect depicted between TBC's restituted in 525 and 533 (respectively located at + 715 m and + 500 m from cave entrance).

Even though AG and Fluorescein injected on 02nd of August 2010 were not detected in any of the observation point, a hydrogeological connection between the injection point at Abu Mizane and the Jeita spring cannot be ruled out. The tests could have been negative as a result of poor infiltration rates during injection and poor conditions of the injection hole.

6. REFERENCES

- Auckenthaler A, Huggenberger P, 2003. Pathogen Mikroorganismen in Grund und Trink Wasser. Transport Nachweissmethoden Wassermanagement. Birkhauser. 80-91 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 MS, 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, 329-351 pp
- Field MS., and Nash S.G., 1997. Risk assessment methodology for karst aquifers: (1), estimating karst flow parameters. Environmental monitoring and Assessment. 47, 1, 1-21 pp
- 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. 36-46 pp
- Göppert N and Goldscheider N. 2007. Solute and colloid transport in karst conduits under low and high flow conditions. Groundwater, 73, 3.
- 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. 1483-1488 pp
- 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.