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Protection of Jeita Spring

SPECIAL REPORT NO. 1

Artificial Tracer Tests 1 - April 2010

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GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

PROTECTION OF JEITA SPRING - LEBANON -

- SPECIAL REPORT -

ARTIFICIAL TRACER TESTS - APRIL 2010

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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.

About 67% of the area in Lebanon consists of karstified (6,900 km^2) rock sequences. The project area is the Jeita karst catchment drained by the Jeita spring. It is considered one of the most important springs in Lebanon, which provides the Capital Beirut with water for domestic use.

One part of this project is to provide assistance to the Lebanese Council for Development and Reconstruction (CDR), as one of the partners of BGR, as well as other relevant national institutions or donor agencies, among others the main German implementing agency for financial cooperation, the KfW Entwicklungsbank (KfW), the European Investment Bank (EIB) and the Italian Protocol, concerning the site searching for wastewater collection and treatment facilities in the groundwater contribution zone of the Jeita spring, herein referred to as the project area.

The KfW project - Protection of Jeita spring - is planning to establish wastewater treatment plants and collector lines in the area. One treatment plant is planned to be constructed on the catchment area of the Jeita spring. Prior to the installation of the latter, it is primordial to understand the groundwater flow dynamics within the karst system in order to depict the impact of such a potential source of contamination on the Jeita spring.

In addition of being used to acquire various transport parameters in karst aquifer such as peak concentration, velocities, dispersivities, persistence of the tracer in water, and percentage of recovery, tracer tests are also adopted in various studies as to simulate a substitute potential pollutant such as fecal bacteria (Orth et al., 1997, Autckenhaler, 2002; Göppert and Goldscheider, 2007). A good knowledge of transport in a karst aquifer helps define adequate management, remediation or prevention measures.

This report presents the results of the tracer test conducted in April 2010 to delineate the hydrogeological connection between the location of a potential WWTP and the Jeita spring. Section 1 provides a description of the study area, Section 2 discusses the methods, material and field work performed during this study. It includes a description of the various tracer tests performed in April 2010, Section 4 presents the analytical results, whereas Section 5 presents the modeling results. The latter mainly tackles aquifer dynamics and behavior as depicted in April 2010 and gives insights into the velocities and dispersivities in the Jurassic Jeita system. Finally Section 6 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.

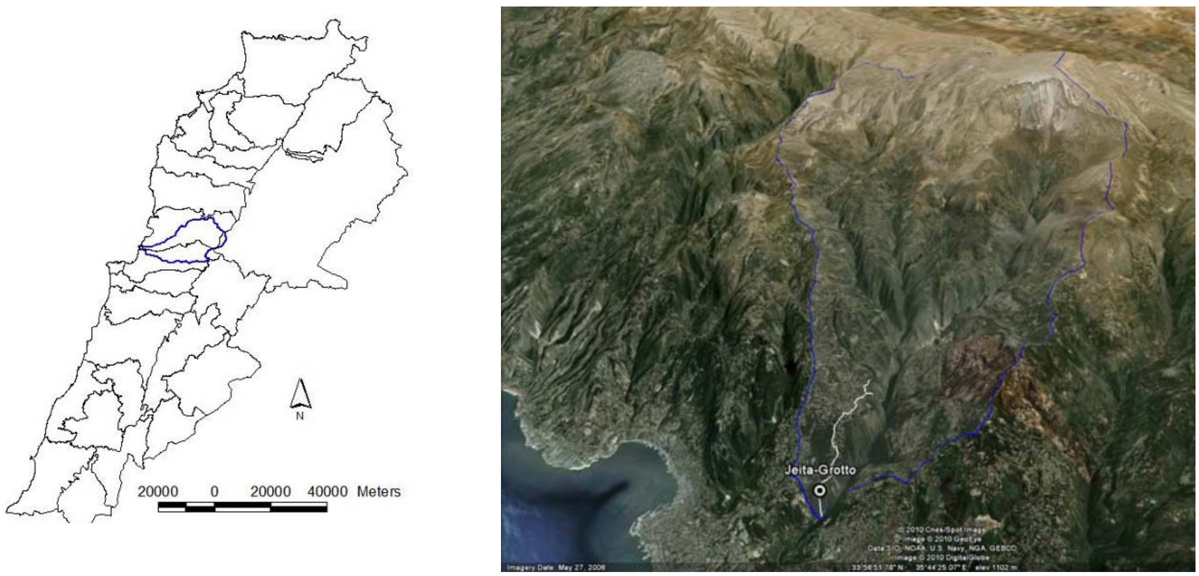


Figure 1-1 Location of Jeita Spring and Catchment in Lebanon (GoogleMaps)

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 the impact of the construction of a WWTP on the Jeita catchment area. The tests were applied to

- Identify a potential hydrogeological connection between the injection site (potential waste water treatment plant location and the potential wastewater release point) and the Jeita spring and eventually other springs existing on the catchment
- Characterize hydrodynamic flow and transport parameters of the Jeita Aquifer system (flow velocities; mean and maximum, transit times, longitudinal dispersivities, mass restitution, etc…)

An additional tracer test was 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 on 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 ($C_{25}H_{26}N_2O_7Na$; Figure 2-1) were selected as they are considered non toxic. Both tracers can be measured simultaneously on-site with low detection limits. 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. However for the purpose of this tracer test, Amidorhodamin G will also be regarded as a conservative tracer.

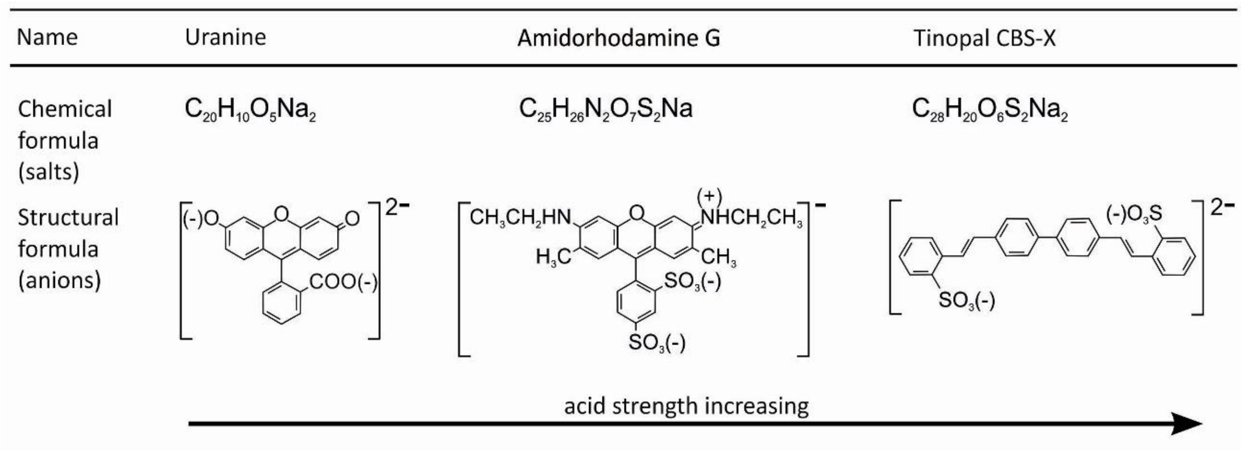


Figure 2-1 Chemical structures of the selected tracers (from Geyer et al. 2007).

Concentration of tracer was monitored in the springs and stream with field fluorometers (GGUN-FL30 serial numbers 524, 525, 526, 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 and Amidorhodamin G. 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. 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 tracers, the lamps are calibrated for both dyes; therefore, based on a system of two linear equations, the electrical signal is transformed into two 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 detection of tracer in water samples taken manually or with the automatic sampler was performed at a later stage using the field fluorometer GGUN-FL30 (serial number 524) activated for both Fluorescein and Amidorhodamin G at a sampling rate of 10 sec). 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

A tracer test was undertaken on the 19th of April (at 12:11) under relative low flow conditions. Five kilograms of the fluorescent dye Fluorescein were injected in the vicinity of the location of the PWWT into an artificially 10-m dug hole. The tracer, injected directly into a bucket was flushed with a total volume of 40 m^3 of water (from water tanks for about two hours; Figure 2-1). The pit hole was flushed with additional 20 m^3 on the next day (20th April 2010 at 8:11 am) 20 hours after the first flushing. On the 22nd of April 2010, five kilograms of Amidorhodamin G (AG) were injected in Abou Mizane in a drilled hole (of about 3-m diameter) during a rain event, and flushed with a total volume of 20 m^3 over about 1 hour. The favorable weather conditions and difficult accessibility of the tanks to the Injection pit hindered the appropriate flushing. Therefore, the pit was flushed only 15 hours after the first injection with additional 40 m^3. However it is to be noted that the infiltration rate was relatively low, which did not allow a good percolation of the AG. On the 28th of April 2010, 424 grams of fluorescein were released in the Jeita underground river at the "siphon terminal" of the Daraya Tunnel.

Table 2-1 Injections Points

INJECTION POINT	X,Y,Z (LAMBERT, m)	INJECTION TIME	FLUSHING VOLUME (m^3)	COMMENTS
Injection Point (1) Deir Chemra	149387 224042 555	19.04.2010 (12:11) 19.04.2010 (8:11)	40 20	Infiltration rate was relatively favorable to ensure good percolation of the tracer
Injection Point (2) Abu Mizane	148115 223315 450	22.04.2010 (15:59) 22.04.2010 (08:00)	20 40	During heavy rain event Infiltration rate was relatively low to ensure good percolation of the tracer
Daraya Tunnel (3)	146135 223503 140	28.04.2010	In flowing water	Turbidity rose after injection to about 48 NTU

Figure 2-1 Fluorescein Injection and Flushing in Deir Chemra pit hole on April 19th, 2010 (12:11)

Figure 2-2 Amidorhodamin G Injection and Flushing in Abu Mizane pit hole on April 22nd, 2010 (15:59)


Figure 2-3 Fluorescein Injection in the Jeita Underground River on April 28th, 2010 (11:42)

2.1.2.2 Observation points

Field spectrofluorometer with dataloggers were installed in the Jeita spring 500 m inside the cave and in the Siphon terminal (4800 m from the cave touristic entrance) and in the Qachqouch Spring for automatic sampling. Manual samples were collected from Jeita and Qachqouch springs and Nahr El Kalb River every hour (**Error! Reference source not found.** and Figure 2-4).

Table 2-2 Observations Points

OBSERVATIONS POINTS	X,Y,Z (LAMBERT, m)	SAMPLING	TIME TIME SPAN	SAMPLING INTERVAL	COMMENTS
Jeita Grotto (+500m)	142603 223385 95	Automatic	17.04.2010-11.05.2010	2 min	GGUN-FL30 serial number 525
Jeita Grotto Beginning of the Touristic Section (+0m)	142233 223115 90	Manual	19.04.2010-27.04.2010 (13:00)	1 hour	Analyzed on the 28.04.2010 with GGUN-FL30 serial number 524
Jeita Grotto Daraya Tunnel	146135 223503 140	Automatic	15.04.2010-12.05.2010	2 min	GGUN-FL30 serial number 526
Qachqouch Spring	141946 223006 60	Automatic	19.04.2010-04.05.2010	2 min	GGUN-FL30 serial number 524

OBSERVATIONS POINTS	X,Y,Z (LAMBERT, m)	SAMPLING	TIME TIME SPAN	SAMPLING INTERVAL	COMMENTS
Qachqouch Spring	141946 223006 60	Manual	19.04.2010-27.04.2010 (13:00)	1 hour	Analyzed on the 28.04.2010 with GGUN-FL30 serial number 524
Nahr El Kalb	142115 222989 50	Manual	19.04.2010-27.04.2010 (13:00)	1 hour	Analyzed on the 28.04.2010 with GGUN-FL30 serial numbers 524

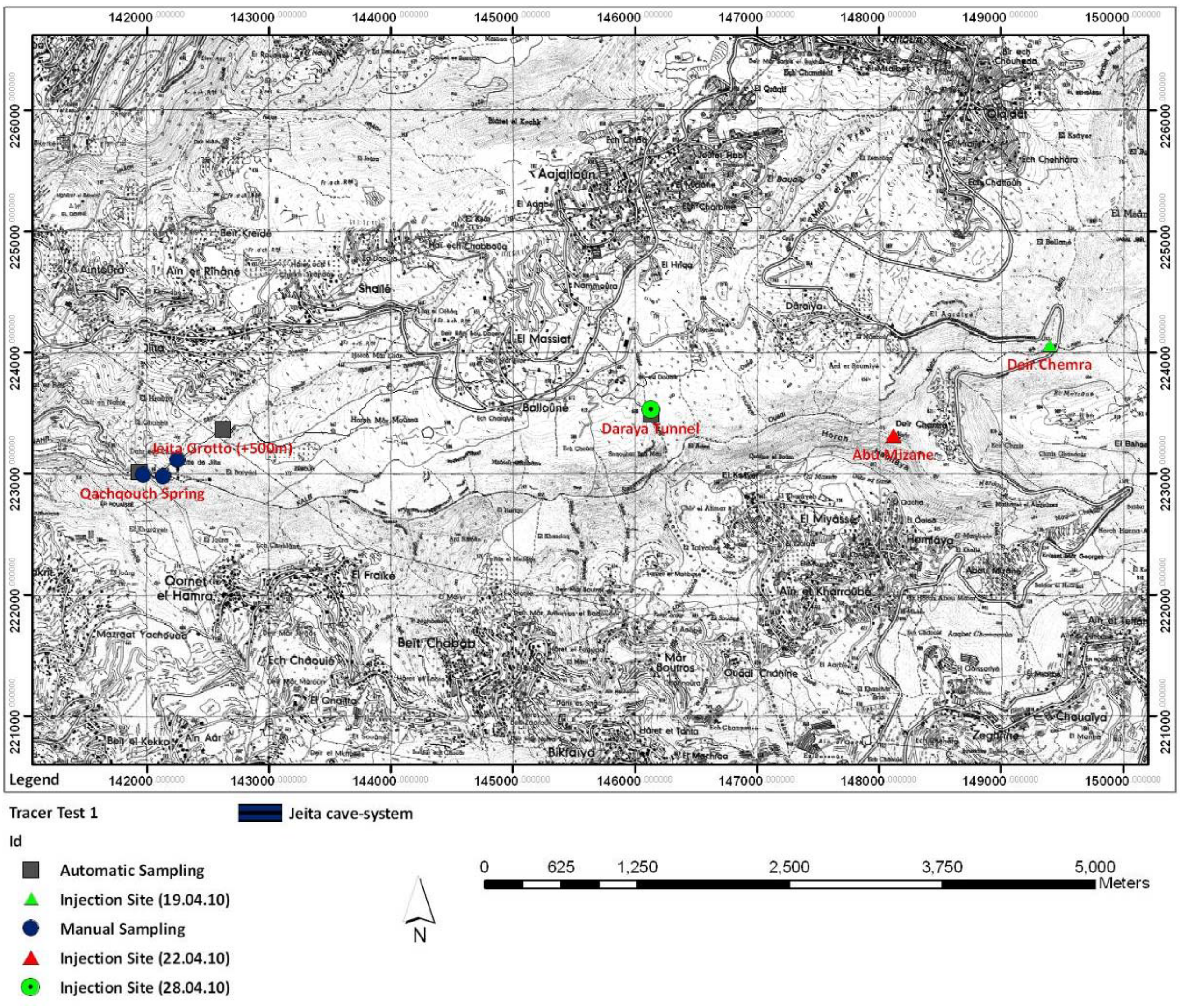


Figure 2-4 Location of Observation Points downstream to the Injection points during the tracer test undertaken in April 2010

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 and Qachqouch Springs 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. It was measured only once in the Jeita Cave to avoid interference with the large scale tracer tests. 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 0.4 m^3/sec due sometimes to incomplete dilution and short distance tests during discharge measurements using the dilution methods.

The discharge flow rates were measured during tracer tests at the various observation points namely, Jeita Spring at 500m inside the cave and in Daraya Tunnel as well as Qachqouch spring and Nahr El Kalb River.

Table 2-2 Discharge Rates Measured at the Observations Points

OBSERVATION POINT	METHOD	DATE	DISCHARGE RATE	COMMENTS
Jeita Grotto (+500m)	Dilution with fluorescein	17.04.2010	5.6 m^3/sec ±0.4 m^3/sec	
Jeita Grotto Daraya Tunnel	Dilution with fluorescein and salt (velocity estimation)	15.04.2010 23.04.2010 25.04.2010 28.04.2010	3.2-3.6 m^3/sec ±0.4 m^3/sec	Fluorescein dilution was not successful due to relatively short distance (14 m) and consequent incomplete dilution
Qachqouch Spring	Dilution with fluorescein and salt	20.04.2010 24.04.2010 25.04.2010 04.05.2010	1.4-1.5 m^3/sec ±0.1 m^3/sec	Salt dilution method was not successful due to the short distance (20 m) Fluorescein dilution was performed on a distance of 166.5 m
Nahr El Kalb	Dilution with fluorescein	04.05.2010		

2.2 EVALUATION AND MODELING

2.2.1 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.

2.2.1.1 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.

2.2.1.2 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)

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

2.2.1.3 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.

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

D_L being the longitudinal dispersion coefficient [L^2/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) [L^2/T]

2.2.2 Modeling

2.2.2.1 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 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)*).

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.

2.2.2.2 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 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.

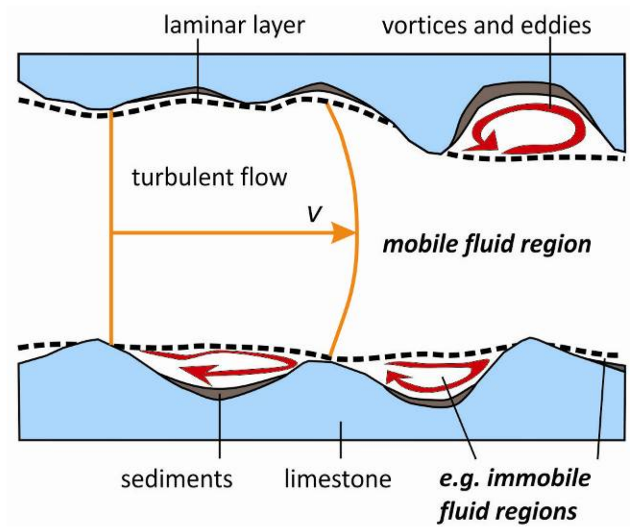


Figure 2-5 Conceptual model of flow within a karst conduit (from Geyer et al. 2007).

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.

3. RESULTS OF THE TRACER TEST

The first tracer test undertaken on April 19th, 2010 was positive as fluorescein was detected in the Jeita spring at various points, as well as in the Nahr El Kalb River. The tracer test undertaken on April 22nd, 2010 was negative, as amidorhodamine G was not detected in any of the observation points. The tracer test within the cave performed on April 28th, 2010 was also successful.

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:

- The distance between the Injection point and the Daraya tunnel was a straight line distance of about 2700m.
- The distance between the Injection point and the Jeita spring (+ 500 m) is about 7500 m accounting for 2700 m until the Daraya tunnel and additional 4800 m within the cave between the Daraya siphon terminal and the observation point.
- The distance between Injection point and the Jeita spring (at the touristic entrance) is about 8000 m.
- The distance within the cave was calculated based on the cave trace and accounts for turtuosity.

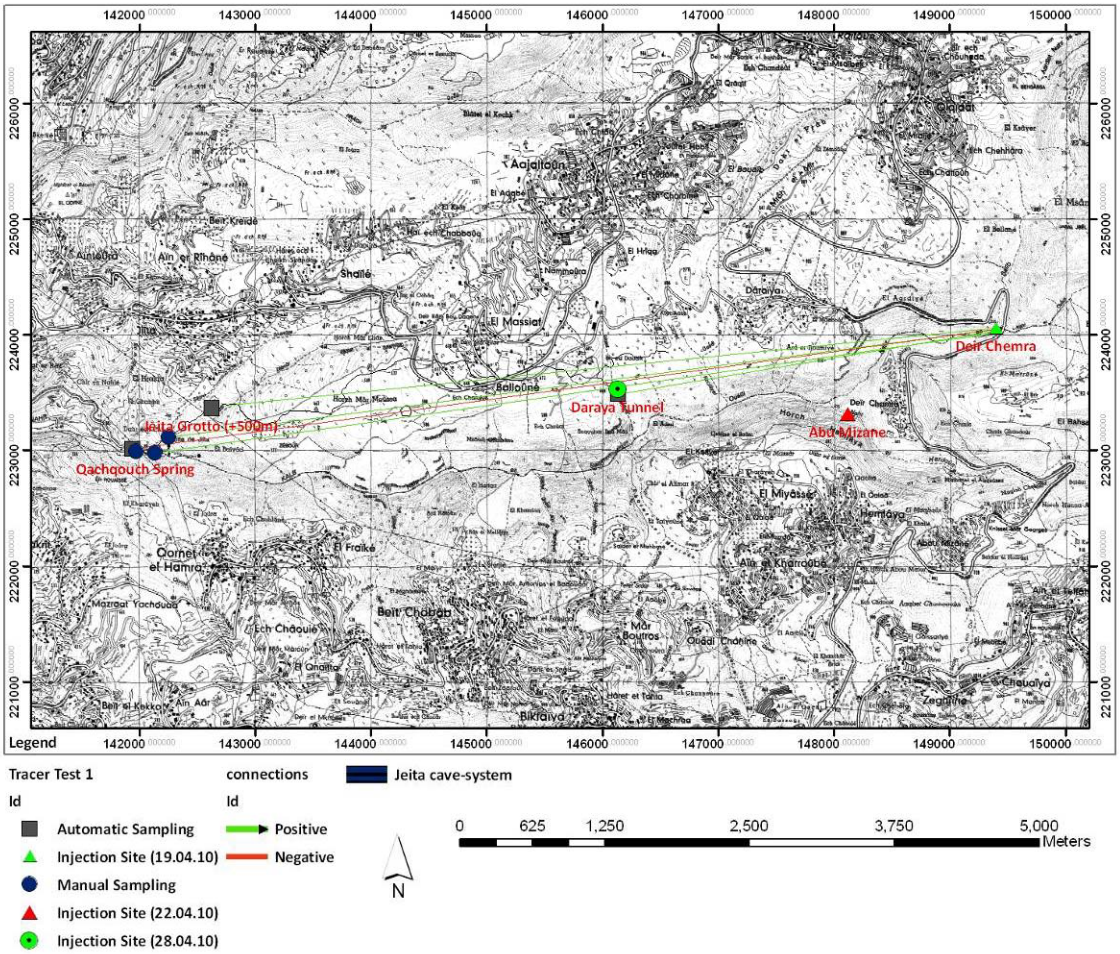


Figure 3-1 Connections between the observation and injection points

3.1 TRACER BREAKTHROUGH CURVES- TRACER TEST 1 (FLUORESCEIN)

Fluorescein was detected in the Jeita spring at the Daraya Tunnel, and at both locations within the cave, as well as in Nahr El Kalb River. However, no tracer was detected in Qachqouch Spring. Therefore a hydrogeological connection exists between the injection site at Deir Chemra and the Jeita Spring.

The following section discusses the fluorescein Breakthrough curves retrieved at the Jeita Spring. Connections between Injection point and observation points are shown in Figure 3-1.

3.1.1 Jeita Cave: Siphon Terminal- Daraya Tunnel

The tracer was detected in the Jeita Spring at daraya locality about 46 hours after the injection. The peak concentration reached 1.8 µg/L 57 hours after injection (Figure 3-2). The shape of the restitution curve is rather irregular, since it shows two peaks. The first peak being a result of the first injection, the second peak reaching 0.88 µg/L is believed to result from the flushing undertaken 20 hours after the first injection. As a matter of fact, the difference between the first and second peak is about 20 hours. The tailing started 100 hours and persisted 140 hours after injection. Tailing extended consequently for about 40 hours from the end of fluorescein recession.

Based on discharge rate under prevailing flow conditions (3.6 m^3/sec), approximately 650g of fluorescein were restituted in the Jeita Spring at the Daraya Tunnel, which represents 13% of the total injected mass of fluorescein.

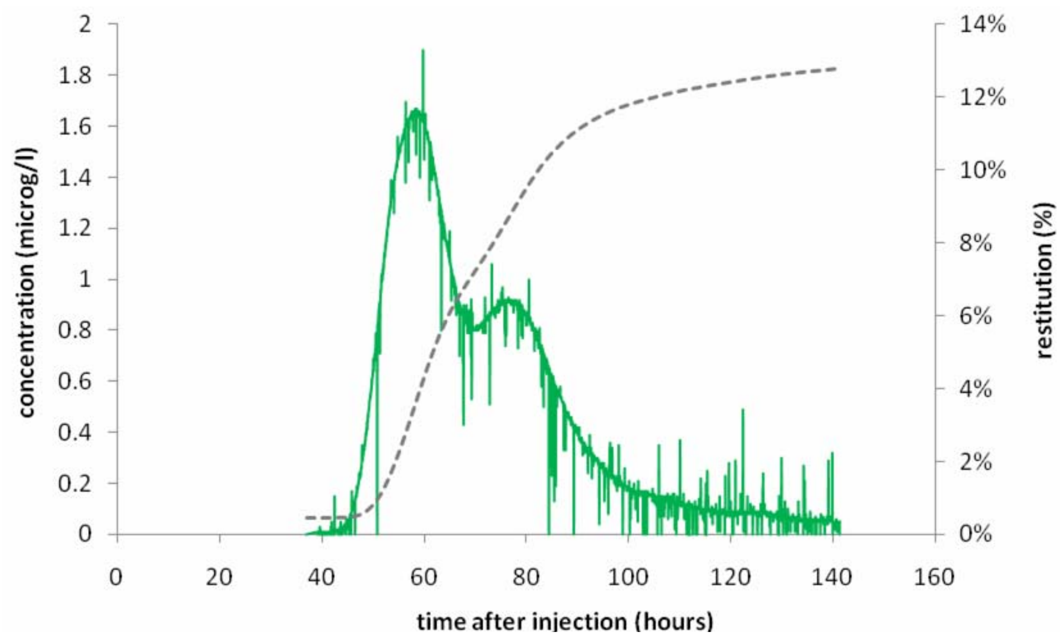


Figure 3-2 Fluorescein restitution curve (TBC) in Jeita cave at the siphon terminal (Daraya Tunnel) showing an extensive tailing, a peak of about 1.8 µg/L, and a recovery of about 13%. The second peak is due to the flushing occurred 20 hours after the first injection.

3.1.2 Jeita Cave: 500 m Inside the Cave from Entrance of Touristic Section

The tracer was detected in the Jeita Spring 500 m inside the cave from the entrance of the touristic section about 50 hours after the injection. Due to a malfunctioning of the field fluorometer the rest of the curve was not saved on the datalogger, as a result of which, the shape of the restitution curve is not complete. The tracer arrived about 50 hours after the injection. The recorded peak reached 1.2 µg/L appeared 63 hours after injection. Restitution cannot be calculated from the incomplete curve. It is worth noting that the tracer started to appear at the Jeita cave (+500m) 6 hours after its first detection in the Daraya section.

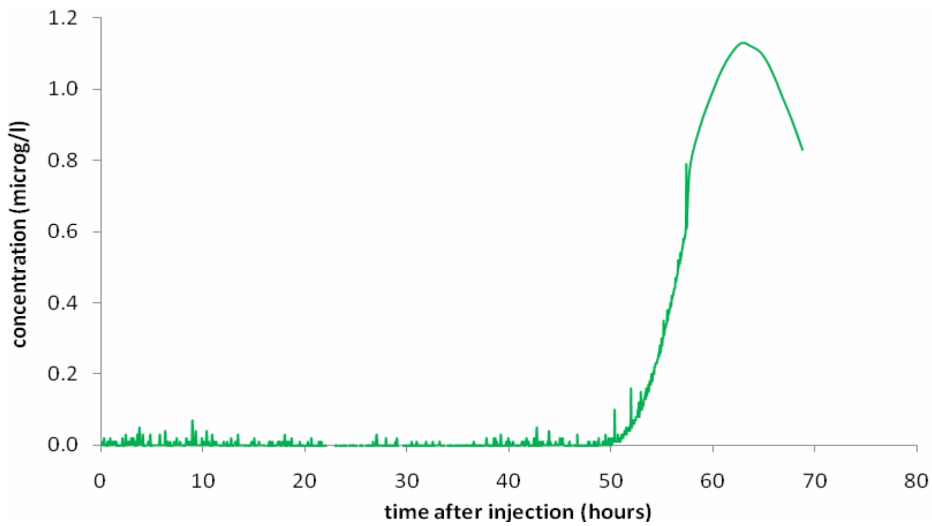


Figure 3-3 Fluorescein restitution curve (TBC) in Jeita cave 500 m inside the cave from the tourist entrance, a peak of about 1.2 µg/L. the curve is incomplete because of a malfunctioning of the fluorometer

3.1.3 Jeita Cave: Tourist Entrance

The tracer was detected in the Jeita Spring at the spring outlet at the touristic entrance about 50 hours after the injection. The peak concentration reached 1.2 µg/L 57 hours after injection (Figure 3-2). Like in the Jeita spring at the Daraya Tunnel, the TBC shows two peaks. The first peak being a result of the first injection, the second peak reaching about 0.75 µg/L is believed to have resulted from the second flushing undertaken 20 hours after the first injection. Conclusions about tailing could not be given in the case of the TBC reconstructed from manual sampling because of insufficient sampling period.

Retardation and decay were neglected in calculation as fluorescein is considered a relatively conservative non degradable tracer. Based on discharge rate under prevailing flow conditions, approximately 700g of fluorescein were restituted in the Jeita Spring outlet at the touristic entrance, which represents 14% of the total injected mass of fluorescein.

Fluorescein was detected in the samples collected hourly from the Nahr El Kalb River at the water authority pumping station (Figure 3-5). Measured concentrations reached about 1 µg/L. It is suspected that there are various inflow points into the Nahr El Kalb River, including inflow from the Jeita spring. Therefore restitution rates cannot be calculated from the TBC. On the other hand, fluorescein was not detected in the Qachqouch spring, neither in the samples collected manually nor by the field fluorometer.

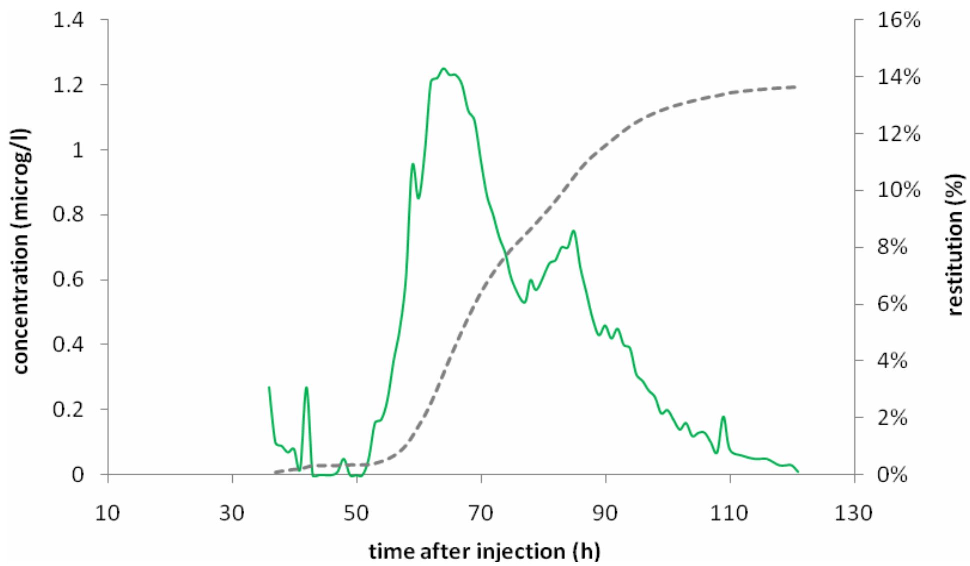


Figure 3-4 **Fluorescein Restitution Curve (TBC) in Jeita cave at the entrance of the tourist section based on manual collected samples. The second peak is due to the flushing occurred 20 hours after the first injection**

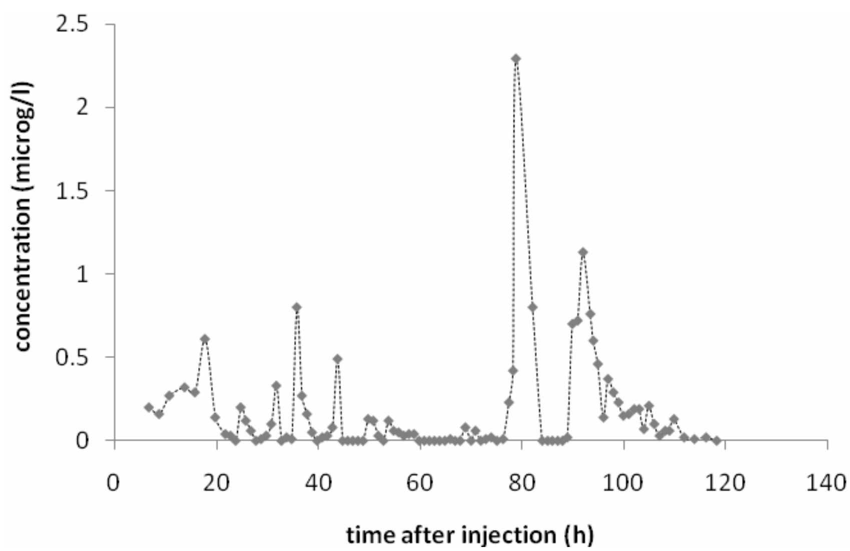


Figure 3-5 **Fluorescein Concentrations detected in the Samples collected in Nahr El Kalb River**

3.2 TRACER BREAKTHROUGH CURVES- TRACER TEST 1-B (FLUORESCEIN)

During the tracer test undertaken within the cave fluorescein was detected at the Jeita Spring 500 m inside the cave about 5.37 hours after the injection. The peak concentration reached about 11 µg/L 6 hours after injection (Figure 3-6).

Based on discharge rate under prevailing flow conditions (5.6 m^3/s), approximately 216 g of fluorescein were restituted in the Jeita Spring outlet at the touristic entrance, which represents about 51% of the total injected mass of fluorescein. Such low restitution rates within the cave between Daraya and the Jeita Spring are contradictory with the results of the first tracer test, which shows no losses within cave.

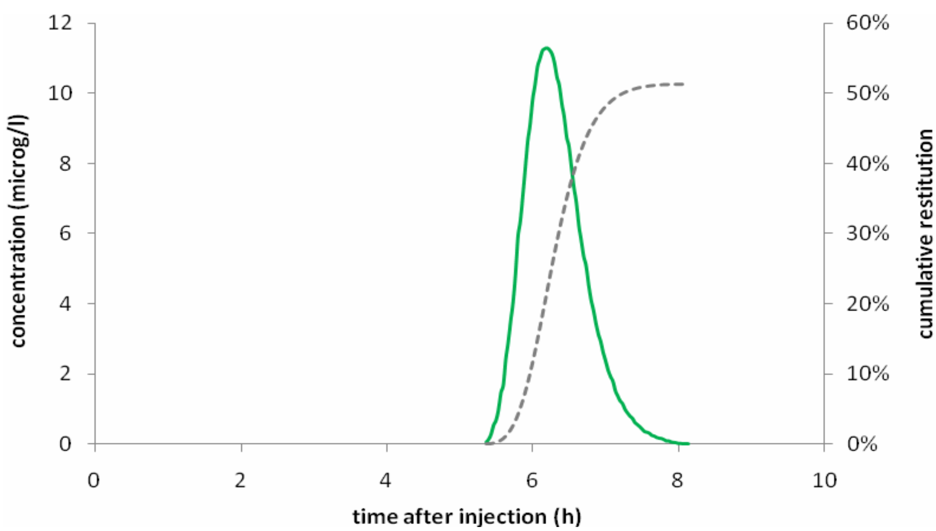


Figure 3-6 **Fluorescein Breakthrough Curve (TBC) resulting from the Injection in the Jeita cave at the daraya Tunnel recovered at the Jeita Spring (500 m inside the cave)**

3.3 COMPARISON OF RESULTS AND SYNOPSIS

The first tracer arrivals are detected 43, 48.8 and 49.8 hours after the tracer injection respectively in the Jeita spring at the Daraya Tunnel, at 500m inside the cave and at the cave outlet. Variance of the three TBC is relatively similar, which implies a similar dispersion coefficient of the three TBC.

Based on peak times of detection of 57.2, 63.8 and 64.8 hours in the Jeita spring at the Daraya Tunnel, at 500m inside the cave and at the cave outlet, the peak flow velocity of groundwater is considered to be 47 m/hour between injection point and Daraya System and about 120 m/hour under low flow conditions between the injection point and the Jeita spring including the Daraya tunnel. Velocities and restitution rates interpreted graphically from the TBC are shown in Table 3-1.

Velocities within the cave appear to be very high. Based on tracer first arrival time, the maximum velocity reaches about 900 m/d, whereas peak velocity calculated based on the time of peak concentration is about 786 m/d.

Table 3-1 Velocities and Restitution Rates deduced graphically from the TBC

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 (FLUORESCEIN) - 19. APRIL 2010- DEIR CHEMRA					
Jeita Grotto (+500m) 7500m	48.8	153	63.8	117.5	-
Jeita Grotto Beginning of the Touristic Section (+0m) 8000m	49.8	160.6	64.8	123.5	13
Jeita Grotto Daraya Tunnel 2700m	43	62.7	57.2	47.2	13
Qachqouch Spring					**NEGATIVE**
Nahr El Kalb	Suspected to be 75	Various peak tracer detected however no conclusions about velocities or restitution rates can be given			
TRACER TEST (AMIDORHODAMINE) – 22 APRIL 2010 – ABU MIZANE					**NEGATIVE**
TRACER TEST (FLUORESCEIN) – 28 APRIL 2010 – WITHIN THE CAVE					
Jeita Grotto (+500m) 4800m	5.3	905	6.1	786	51

4. MODELING RESULTS

A summary of all modeling results of the tracer tests performed in Deir Chamra and within the cave is presented in Table 4-1 . The quality of the model fits was assessed by estimation of the coefficient of correlation (R^2) and the mean square error (MSE). All fitting were achieved with coefficients of correlation exceeding 0.95 and a mean square error generally not exceeding 10^{-3} micrograms per liters, as portrayed in Table 4-1.

Table 4-1 Summary of the Modeling Results of the Positive Tracer Tests Undertaken in April 2010 (Deir Chemra and Jeita Cave)

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO DARAYA TUNNEL		JEITA GROTTO (+500M)	JEITA GROTTO BEGINNING OF THE TOURISTIC SECTION (+0M)	
TRACER TEST (FLUORESCEIN) - 19. APRIL 2010- DEIR CHEMRA							
Distance	D	m	2700		7500	8000	
Discharge	Q	m^3/sec	3.6		5.6	5.6	
ADVECTION DISPERSION METHOD (ADM)							
Mean Velocity	v	m/hour	45.1	43.8	**116**	**120**	**121**
Mean transient time	t_m	hours	60	62	66	66	67
Dispersion	D	m^2/hour	851	1230	**3410**	**5070**	**783**
Dispersivity	A	m	18.9	28	44.5	41.9	6.5
Peclet number	P_D	-	143.1	95.9	169	191	1230
Massive Flux	M	µg•h/l	29	16.8	17.3	21.5	11.5
Restitution Rate	R	%	11.9		6.98	13.32	
Statistical parameters							
Coefficient of Correlation	R^2	-	0.974	0.943	0.992	0.966	0.890
Mean Square Error	MSE	µg/l	6.98E-03	4.20E-03	4.82E-04	7.96E-03	4.45E-03
TWO REGION NON EQUILIBRIUM MODEL (2NREM)							
Mean Velocity	v	m/hour	**45.6**	**36.4**	**114**	**109**	**118**
Mean transient time	t_m	hours	59	74	65.8	73.4	67.8
Dispersion	D	m^2/hour	722.0	614.0	**5040**	**2900**	**916**

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO DARAYA TUNNEL		JEITA GROTTO (+500M)	JEITA GROTTO BEGINNING OF THE TOURISTIC SECTION (+0M)	
Partition coefficient	β	-	0.8	0.804	0.93	0.869	0.903
Mass transfer coefficient	ω	1/hour	2.39E-01	2.39E-01	1.7E-01	1.12E-04	1.97E-04
Dispersivity	α	m	15.8	16.9	44.2	26.6	7.8
Peclet number	P_D	-	170	160	170	301	1030
Massive Flux	M	µg•h/l	27.0	21.4	21.5	28.3	5
Restitution Rate	R	%	12.5%		8.68%	13.44%	
Statistical parameters							
Coefficient of Correlation	R^2	-	0.984	0.985	0.967	0.973	0.925
Root mean Square Error	RMSE	µg/l	4.80E-03	1.13E-03	1.87E-03	6.86E-03	1.19E-03

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO- DARAYA TUNNEL
TRACER TEST (FLUORESCEIN) – 28 APRIL 2010 – WITHIN THE CAVE			
Distance	d	m	4800
Discharge	Q	m^3/sec	5.6
ADVECTION DISPERSION METHOD (ADM)			
Mean Velocity	v	m/hour	**766**

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO-DARAYA TUNNEL
Mean transient time	t_m	hours	6
Dispersion	D	m^2/hour	6970
Dispersivity	α	m	9.1
Peclet number	P_D	-	528
Massive Flux	M	µg•h/l	10.81
Restitution Rate	R	%	51.44
Statistical parameters			
Coefficient of Correlation	R^2	-	0.9897
Mean Square Error	MSE	µg/l	1.62E-01
Degree of uncertainty	U	µg/l	
TWO REGION NON EQUILIBRIUM MODEL (2NREM)			
Mean Velocity	v	m/hour	760.0
Mean transient time	t_m	hours	6.3
Dispersion	D	m^2/hour	2380
Partition coefficient	β	-	0.92
Mass transfer coefficient	ω	1/hour	3.11
Dispersivity	α	M	3.1
Peclet number	P_D	-	1530
Massive Flux	M	µg•h/l	
Restitution Rate	R	%	51.44

PARAMETERS	SYMBOL	UNITS	JEITA GROTTO- DARAYA TUNNEL
Statistical parameters			
Coefficient of Correlation	R^2	-	1.0
Root mean Square Error	RMSE	µg/l	6.17E-03

4.1 TRACER BREAKTHROUGH CURVES- TRACER TEST 1 (FLUORESCEIN)

4.1.1 Jeita Cave: Siphon Terminal- Daraya Tunnel

The TBC recovered at the Jeita cave in the Daraya section was modeled using both the Advection Dispersion Model (ADM) and the Two Non Equilibrium Model (2RNEM). For modeling purposes the two peaks were regarded as results of two injections and peaks were modeled separately. According to both models mean flow velocities ranged between **43 and 45 m/day**. As a result of different infiltration rates triggered with the second flushing, variance in the second peak is greater, showing a more important dispersive component. Dispersion values vary between **850 and 1530 m^2/hour** respectively for the first and second peak.

Mean transit time between the Injection point and Daraya Tunnel (a total distance of 2700m and an altitude difference of about 400 m) resulted to be about 60 hours.

Since tailing is relatively pronounced in the second peak, it was modeled using the 2NREM model (Figure 4-1). The mobile phase proportion is estimated to be 80%. Mean velocity calculated with the 2NREM model is about 36 m/h accounting for the large observed tailing.

The summation of the two modeled peaks with both models is shown in Figure 4-2. It is to be noted that tailing is best fitted with the 2NREM.

Peclet numbers ranges between 160 and 170, reflecting the prevailing advective component of the transport through the karst system. Recovery rates reaching not more than 13% obtained with the CXTFIT fall in the same range of that calculated by manual integration.

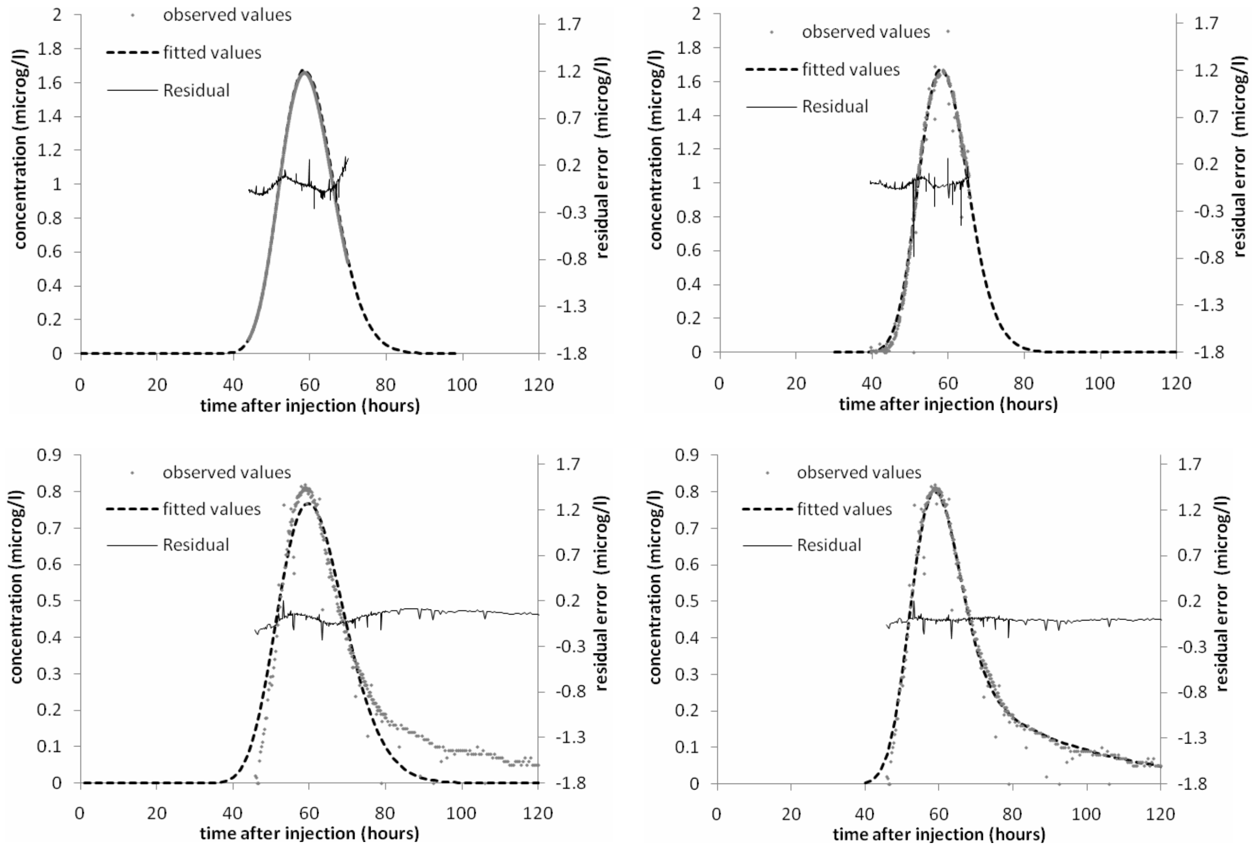


Figure 4-1 First and second peak of the Daraya TBC modeled respectively with ADM and 2NREM

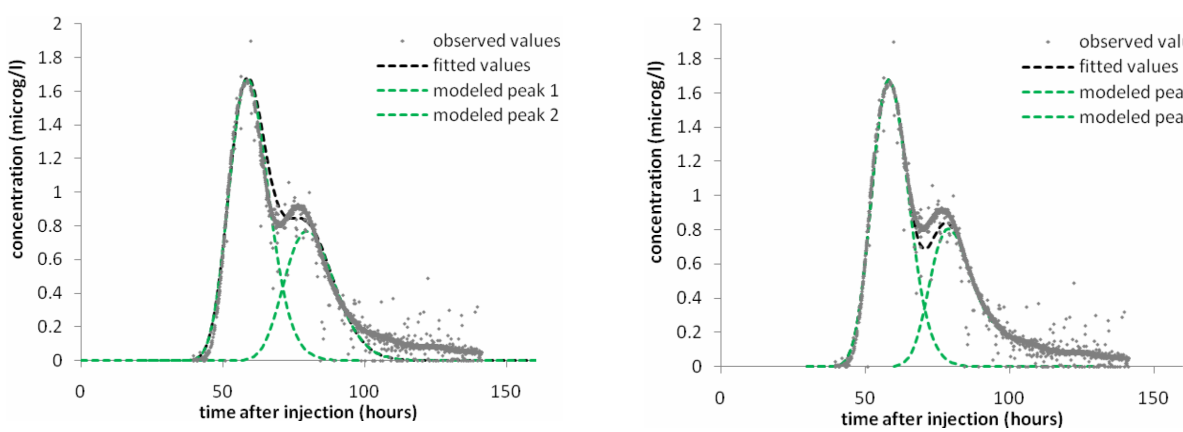
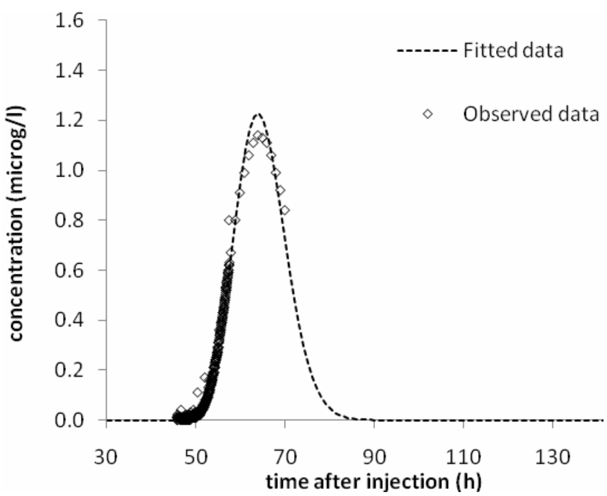


Figure 4-2 Summation of the first and second peaks of the Daraya TBC modeled respectively with ADM and 2NREM

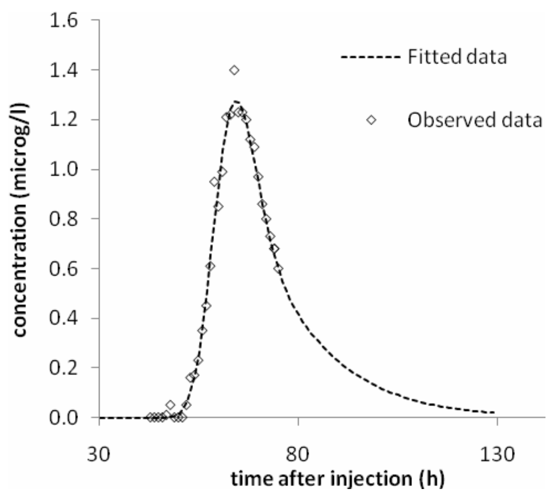
4.1.2 Jeita Cave: + 500m

The incomplete curve TBC restituted at the Jeita Spring 500m inside the cave by the fluorometer was simulated with the Advection Dispersion Model (ADM) and the Two Non Equilibrium Model (2RNEM; Figure 4-3). Since the curve is not complete on the tracer recession limb, the 2NREM modeled parameters are not fully reliable, especially that the tailing is missing. According to the ADM mean velocity is **114 m/day**. The calibrated value for dispersion is **5040 m^2/hour**. The mean transit time over a total distance of 7500 m was calculated to be about 66 hours.

Peclet numbers are higher than 100, reflecting the prevailing advective component of the transport. Recovery rate obtained with the CXTFIT are not representative of the total recovery rate. The massive flux was regarded in this case as a fitting parameter.



a



b

Figure 4-3 Fitted data of the Jeita (+500m) TBC modeled with ADM (a) and 2NREM (b)

4.1.3 Jeita Cave: Touristic Entrance

The TBC reconstructed from manual samples collected at the cave entrance was modeled using both the Advection Dispersion Model (ADM) and the Two Non Equilibrium Model (2RNEM). Like for Daraya TBC, for modeling purposes the two peaks were regarded as results of two injections. Therefore, during modeling every peak was modeled separately, the second injection being performed 20 hours after the first Injection. According to the ADM model, mean velocities ranged between **120 and 121 m/h**. Dispersion values vary between **5070 and 7830 m^2/h** respectively for the first and second peak. As a result of different infiltration rates triggered with the second flushing, variance in the second peak is greater, showing a more important dispersive component.

Mean transit time between the Injection point and this observation point (a total distance of 8000 m and an altitude difference of about 500 m) resulted to be about 66-67 hours.

In order to account for the tailing, the TBC was modeled using the 2NREM. In the latter case, modeled mean velocities ranged between **109 and 118 m/hour**. Modeled dispersion values ranging between **916 and 2900 m^2/hour** appears to be lower than the values obtained with the ADM model. The fitted mobile phase proportion ranges between **87% and 90%**. Peclet numbers are higher than 100, reflecting the prevailing advective component of the transport. Recovery rates obtained with the CXTFIT fall in the same range of that calculated by manual integration. The total restituted mass was considered as a fixed parameter, whereas the massive flux for each of the peaks was regarded as a fitting parameter.

Figure 4-4 and Figure 4-5 show the summation of the two peaks in an attempt to reproduce the entire observed TBC. As depicted in Figure 4-5, with the 2NREM model tailing is best accounted for and fitted values match to a good extent the observed values.

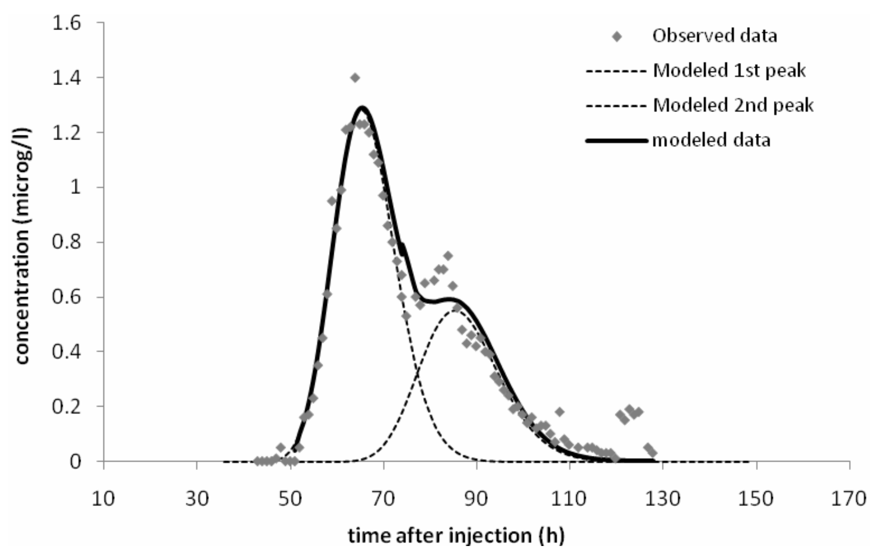


Figure 4-4 **Fitted data modeled with ADM for the Jeita (+0m) TBC. The modeled curve is the sum of the modeled first and second peaks**

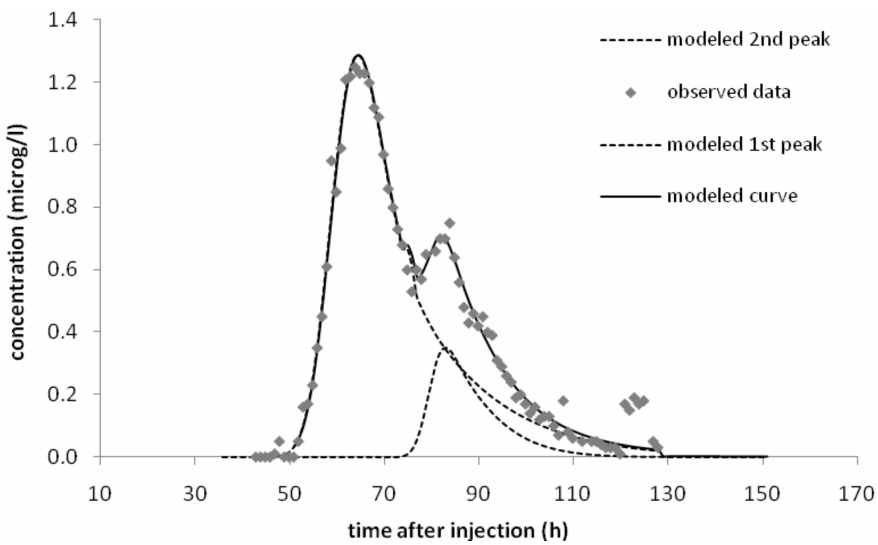


Figure 4-5 Fitted data modeled with 2NREM for the Jeita (+0m) TBC. The modeled curve is the sum of the modeled first and second peaks

4.2 TRACER TEST 1-B (FLUORESCEIN)

The TBC resulting from the tracer test undertaken within the cave was modeled using both the Advection Dispersion Model (ADM) and the Two Non Equilibrium Model (2RNEM, Figure 4-6). According to the ADM model, mean velocity was about **766 m/hour**. Dispersion reached **7000 m^2/hour**, which results in longitudinal dispersivity of about **9 m**. Such high values for dispersion obtained in the ADM model are due to the attempt of the model to account for the tailing. Mean transit time between the Injection point and this observation point (a total distance of 4800 m) resulted to be about **6.3 hours.**

The modeled mean velocity with the 2NREM Model is about **760 m/hour**, whereas the modeled Dispersion value reaches about **2380 m^2/h** yielding a longitudinal dispersivity of about **3.1 m**. The mobile phase proportion is about **92%**.

Peclet numbers are higher than 100, ranging between 528 (ADM) and 1530 (2NREM) reflecting the prevailing advective nature of the transport. Recovery rates obtained with the CXTFIT fall in the same range of that calculated by manual integration. The total restituted mass was regarded as a fixed parameter during modeling.

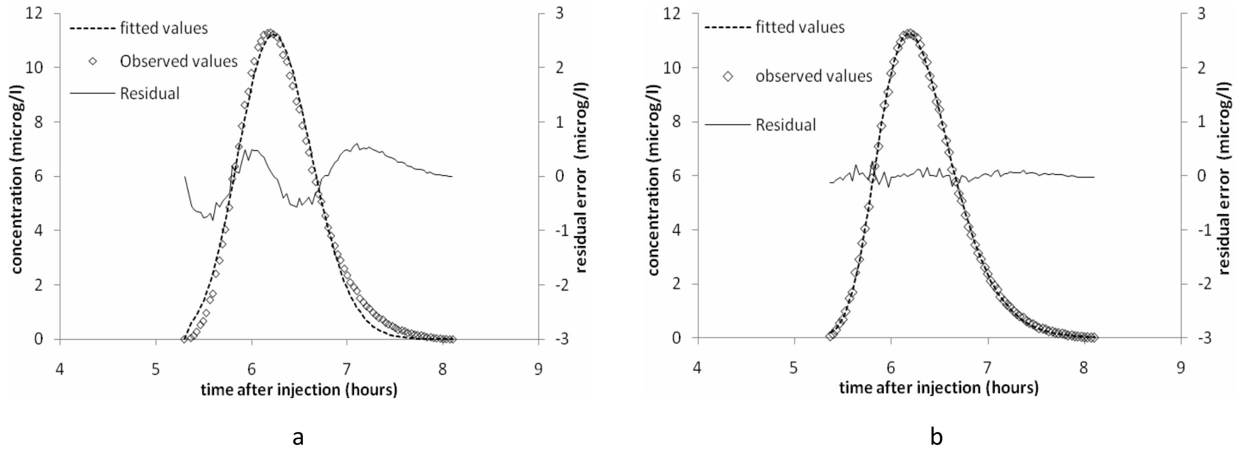


Figure 4-6 Fitted data modeled with ADM (a) and 2NREM (b) for the TBC resulting for the tracer test 1b

5. DISCUSSION AND CONCLUSIONS

Based on the tracer test undertaken on April 19th, 2010, a hydrogeological connection was established between an injection point in Deir Chemra at the potential location of the waste water treatment plant and the Jeita Spring at various points within the cave and at the outlet. Furthermore, tracer was also detected in the Nahr El Kalb River. The detected tracer in the River might have been channeled into the River through springs existing along the river, or an overflow from the Jeita cave itself.

Velocities within unsaturated zone depicted from the tracer behavior between the injection point and the Daraya tunnel ranges between 43 and 45 m/hour, yielding mean transient times of 60 hours. The mean transit time of the tracer between the injection point and the Jeita cave is about 66 hours, which imply a transit time of 6 hours within the cave, or a velocity of about 800 m/hour.

Velocities within the cave range between 760 and 766 m/hour, which are in accordance with the velocities calculated from the first tracer test. These velocities are considered relatively high but physically common velocities in karst systems. Longitudinal dispersivity within the cave ranges between 3m and 9 m depending on the adopted model.

Restitution rates in the first tracer test did not exceed 14 % in all the observation points namely, the Daraya tunnel and the Jeita Spring. Conclusions cannot be given about the remaining tracer quantity, which is probably trapped in the unsaturated zone, and released at very low rates.

The fluorescein concentrations observed in the TBC retrieved at the Jeita spring are lower than the ones observed in the Daraya TBC, due to dilution processes occurring in the cave because of additional $2m^3/s$ inflow at some location within the cave.

No tracer loss was detected between Daraya and Jeita outlet, as in both observation points tracer restitution was about 13-14 %. However the tracer test performed within the cave shows a loss of 49% in the tracer mass. This discrepancy can be explained either by inaccuracy in the input mass, high turbidities, or the tracer behavior. A portion of fluorescein might have remained stuck at the beginning of the Daraya section, and was not released with time. It is also worth mentioning that turbidity values at the time of tracer restitution were relatively high, exceeding 48 NTU, which might have hindered the fluorescein fluorescence. It is therefore advised to repeat the tracer test within the cave to rule out any possible losses.

Even though AG was 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 AG test 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.
- Orth J.P., Netter R., and Merkl, G. 1997. Bacterial and chemical contaminant transport in a karstic aquifer (Danube Valley, Swabian Jura, Germany). Karst water and environmental impacts. Ed. Gunay and Johnson. 173-179 pp
- 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.