Conceptualization of flow in a snow-governed groundwater catchment in Lebanon: A science-based approach for future guidelines for sustainable water management.

REPORT II: ARTIFICIAL TRACER EXPERIMENT

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1. INTRODUCTION

The American University of Beirut (AUB) was awarded a Grant by UNICEF to conduct a project titled: "Conceptualization of flow in a snow-governed groundwater catchment in Lebanon: A science- based approach for future guidelines for sustainable water management", in collaboration with the Saint Joseph University in Beirut (USJ). The study consists of undertaking a monitoring campaign on poorly investigated springs in the area of Kfarzebbiane in Mount Lebanon to quantify flow at a high resolution and the current **available quantities for supply** for decision makers. In addition, it includes a geological reconnaissance, mapping, as well as tracer experiments to allow the **characterization of the catchment area** of the investigated springs for a better understanding of the system in terms of flow preferential paths, velocities of transport in case of contamination and delineation of contribution zones. The processing of collected high resolution data and mapping outcomes aims at a better **conceptualization of the system** and of the expected quantities. The latter can be implemented in **advanced vulnerability and protection maps** and in the evaluation of **spring responses to climate change** scenarios or snow melt. All of these results will be disseminated via informative maps, flyers, and workshops to local stakeholders and decision makers to help them make science based decisions in the future to address water deficit issues that are yet to arise under climate change conditions. This report (Report II) details the activities and results of the tracer experiment undertaken on July 15, 2020. Following the description of the study area in section 2, the methods for tracer tests evaluation along with the modeling tools are exposed in section 3. Section 4 presents the results of the analysis of the Tracer Breakthrough Curves (TBC) retrieved at the respective springs. The latter mainly tackles aquifer dynamics and behavior as depicted during the experiment and gives insights into the velocities and dispersivities in the catchment area from injection to recovery. Finally section 5 presents some conclusions and recommendations.

1.1 GENERAL

The two investigated springs (Laban and Assal; Figure 1-1) and respective catchments are located in the area of Faraya (Kfardebbiane); Nabaa El Assal (35.828263° E, 33.995265°N) at an altitude of 1540 m above sea level (asl) and Nabaa el Laban (35.838420° E and 34.009919°N) at an altitude of 1643 m above. Nabaa El Assal mean yearly volumetric discharge amounts to about 22 Mm^3 (Doummar et al., 2018b. The catchment area of El Assal was delineated based on preliminary tracer experiments undertaken in 2014-2016 (Doummar et al., 2018b). However the catchments of both springs need further delineations based on extensive tracer experiments and water balance calculations and potentially numerical modelling. The Laban and Assal spring were monitored between 2010-2012, in the framework of a project on the Jeita spring located downstream by the German Federal Institute for Geological Sciences (BGR; Margane et al., 2018). The Afqa spring is not included in the project for the moment, however it was monitored to rule out any connection between the studied catchment and the spring.

1.2 ARTIFICIAL TRACER EXPERIMENTS: AN OVERVIEW

Artificial tracer tests are field experiments that count on tracking and identifying substances at one site after they were introduced at another (Kaess, 1998). Fluorescent dye is one type of artificial tracers. It is a colored substance that dissolves in water or aqueous solutions and could be identified using specific equipment. In hydrogeology, artificial tracer tests are applied to identify a connection between a tracer origin and observation sites (Morales et. al, 2007; Smart, 1988).

Different tracer experiments techniques are used depending on the geology, climate, and water system in the region. In the case of karst regions, among others, tracer injections are performed where water can infiltrate continuously into the subsurface conduits (Kaess, 1998). Thus, a doline is chosen as the tracer origin for this experiment because it allows for quick flow from the surface into the groundwater system. Observation sites are water outlets, such as springs or wells, where monitoring instruments are installed for the purpose of identifying and measuring the concentration of the injected substances.

A positive connection between the tracer origin and the observation site is determined upon detecting the tracer even in limited quantities at the observation site. In the latter case, the injection point is said to contribute to the catchment area of the said spring. However, the uses of the artificial tracer tests are not limited to that. The groundwater flow and transport with respect to hydrogeological significance is evaluated and interpreted using tracer tests (Morales et al., 2007). The number of tracer breakthrough curves (peaks) reflects the number of conduits between the source and the outlet. A mean transit time, flow velocity, and tracer recovery are some of the parameters that could be estimated using numerical and statistical analysis. Determining tracer recovery and comparing it to the injected mass may reflect the storage capacity in the groundwater system where the material may have been lost in channels which do not allow for exchange (Goldscheider & Drew, 2007). Moreover, it may also suggest that the tracer origin may be connected to other water outlets which were not considered as observation sites. As a conclusion, the delineation of the catchment area and the understanding of flow, transport, and dispersion processes within karst systems are important applications of the artificial tracer test (Doummar et al., 2018a; Morales et al., 2007).

Figure 1-1 Location of observation points (Aassal, Laban, and Afqa) with respect to the injection point

1.3 OBJECTIVES OF THE TRACER TEST

The main goal of the artificial tracer tests was to investigate hydrological connections between a rapid infiltration point source such as a doline in the upstream catchment area/ sub catchment areas suspected to contribute to the total recharge of the investigated springs.

The Objectives of the tracer test were mainly to:

- Identify a potential hydrogeological connection between the injection site (on the upstream Catchment) and the three springs Assal, Laban, and Afqa;
- Delineate the boundary of the catchment area.
- Characterize hydrodynamic flow and transport parameters of the Cretaceous Aquifer system (flow velocities; mean and maximum, transit times, longitudinal dispersivities, mass restitution, etc…) following the end of the snow melt event.

2. FIELD WORK AND METHODOLOGY

2.1 MATERIALS

The tracer uranine (Sodium fluorescein, acid yellow 73, BASF, CAS 518-47-8, $C_{20}H_{10}O_5Na_2$), was selected as it is considered nontoxic. Uranine can be measured automatically on-site with low detection limits using a field fluorometer. Uranine is sensible to photochemical decay and is only highly adsorptive under increasing acidity (Ford and Williams, 2007) and can be considered as conservative tracer in carbonate aquifers

Concentration of tracer was monitored in the springs with field fluorometers (GGUN-FL30 serial numbers 526 and 718; Schnegg 2002). The equipment measures continuously dye concentration at the monitoring site at specific intervals with two 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, are planned to be calibrated for uranine at the end of the experiment supposed to be in mid- September after the complete retrieval of the tracer. Uranine has a spectrum of luminescence ranging between 490 nm and 524 nm. In the presence of one tracer, the calibration file allows a direct conversion of electrical signal into concentration in micrograms per liter (Schnegg, 2002). The limit of detection of the field fluorometer is dye at a concentration of 0.02 µg/l for uranine. Correction for the presence of background tracer concentration was also taken into account.

2.2 FIELDWORK

2.2.1 Injections

The tracer experiment was undertaken on the under-snow melt conditions. The sites are located on the upper Cretaceous rock units in the upper part of the catchment. The tests were undertaken during snowmelt periods, where rapid snowmelt due to rapid rise of temperatures helped in flushing the tracer into the subsurface (Figure 2-1).

Two thousand and four hundred and eight (2408) grams of Sodium fluorescein (Uranine) dissolved in water were injected in the Jabal El Dib site (33.981320N, 35.857270E) on the July 15, 2020 (Figure 2-2), and the characteristics of the injection points are provided in Table 2-1. The injection point was characterized by a level of infiltration, where 50 liters of water were infiltrated in the subsurface in less than 5 minutes. Therefore, the experiment could be considered as an instantaneous injection at the time of injection, however the flow of the tracer in the subsurface depends greatly on the snowmelt and subsurface flushing rates. A lake composed of melting snow water was discharging at relatively low rates into the injection point ensuring a continuous flushing of the tracer in the subsurface

Figure 2-1 Jabal El dib Doline characterized by a lake resulting from snowmelt with a low lying point of high infiltration

Figure 2-2 Injection of the 2408 grams of uranine in the fast infiltration point located in the JED doline on July 15, 2020 at 11:43 AM.

Table 2-1 Location of tracer injection points for tracer test JED- Jabal El Dib- Test 1

INJECTION POINT	COORDINATES (ALTITUDE) (m)	INJECTION TIME	FLUSHING VOLUME (m^3)	COMMENTS
Test 1 (JED)	33.981320N, 35.857270E 2243 m asl	15.07.2020 (11:43 am)	50 liter bucket	2408 g of Sodium Fluorescein (infiltration rate was relatively favorable to ensure good percolation of the tracer)

2.2.2 Observation points

Two field spectro-fluorometers (718 and 526) with data loggers (F666 and F1667; Figure 2-3) were deployed respectively in the Laban and Assal springs while activated charcoal capable to detect qualitatively the fluorescence, was mounted every week into the Afqa Spring to check for potential arrival to this spring. A detailed description of the observation points is provided in

Table 2-2

a

b

Figure 2-3 Field fluorometers deployed at Laban (a) and Assal (b) springs. The dataloggers (b) were purchased from the UNICEF grant, while the measuring field fluorometers (a) are property of AUB.

Table 2-2 Observations Points Tracer Test JED-1 (Coordinate system; WGS, 1984)

AQUIFER	OBSERVATIONS POINTS	LATITUDE LONGITUDE Z (m asl)	LINEAR DISTANCE TO INJECTION (m)	SAMPLING	SAMPLING INTERVAL	COMMENTS
Cretaceous	Laban Spring	35.828263° E 33.995265°N 1664	3,060 m	Automatic	15 min	GGUN-FL30 serial number 718/666
	Assal Spring	35.838420° E 34.009919°N 1540	3,580 m	Automatic	15 min	GGUN-FL30 serial number 525/1667
	Afqa Spring	34.066575E 35.892335N 1170	10,160 m	Manual	weekly	Activated charcoal

2.3 DISCHARGE MEASUREMENTS

Flow rate measurements were mainly performed based on rating curves and measurement of water height in the spring at 30- min interval during the duration of the tracer restitution. The rating curves was established for the Assal spring in a previous project (Doummar et al., 2018b), while the discharge at Laban was estimated based on a rating curve established during the duration of this project. The rating curve was established based on weekly measurements with an electromagnetic flow meter and a measurement of water height (Ref. Report I). A pressure transducer was installed in the Laban spring starting July 2020 for the continuous monitoring of water height (30-

min) and corresponding discharge based on the established rating curve. Variable discharge rates as observed in

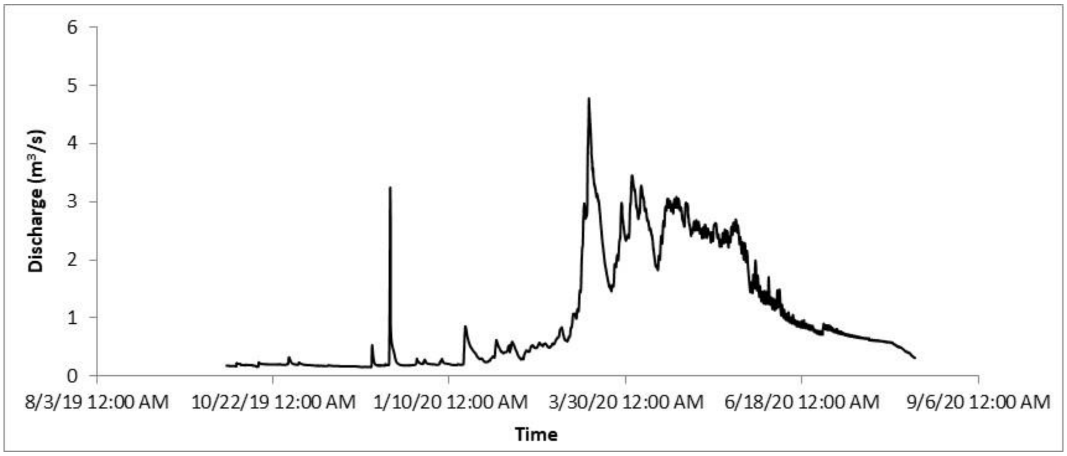

Figure 2-4 and

Figure 2-5 were adopted for the calculations of tracer mass restitution.

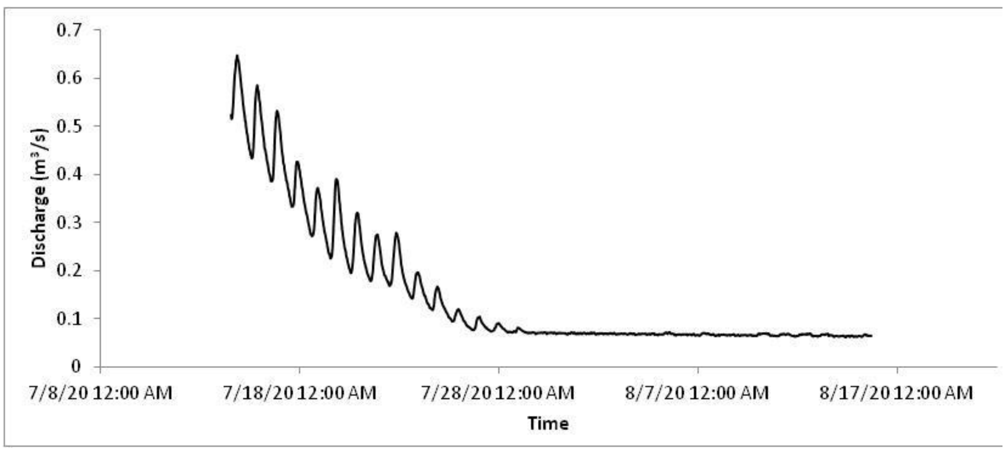

Figure 2-4 Discharge rates measured at the Observations Point: Laban

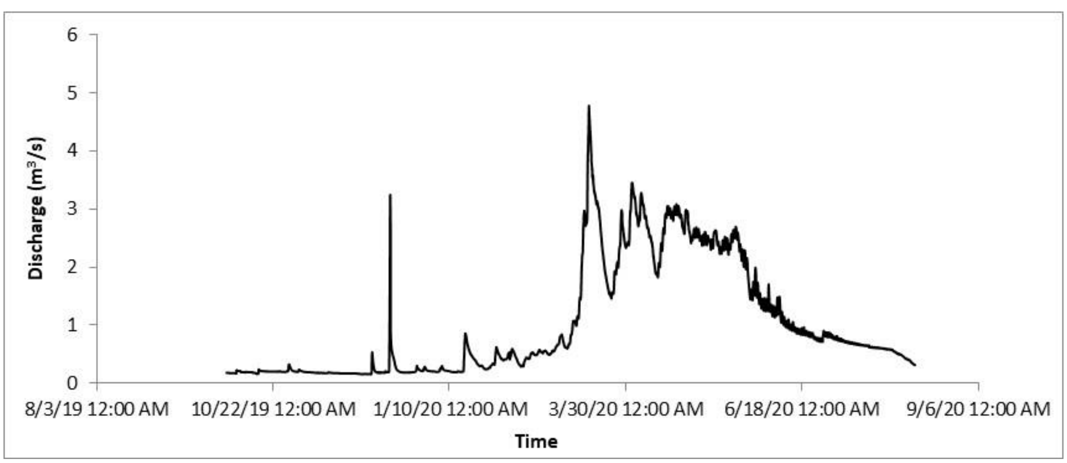

Figure 2-5 Discharge rates measured at the observations Point: Assal (2019-2020)

3. EVALUATION AND MODELING

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

3.1 PARAMETERS

3.1.1 Tracer recovery

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

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

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

3.1.2 Flow velocities

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

$$t_d = \int_{t=0}^{\infty} \frac{c(t) Q(t) t dt}{c(t) Q(t) dt} \qquad (2)$$

The sectional area of phreatic conduit was calculated based on the ratio of the volume of water elapsed during the restitution of the tracer and the transport distance between injection and observation point. The radius is calculated based on the cross sectional area. This estimated radius represents the dimensions of the phreatic conduit through which the tracer is transported and yields more information about the subsurface geometry between the doline and the point of restitution.

3.1.3 Longitudinal dispersivity and dispersion

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

$$D_L = \alpha_L \cdot v_m + D^* \qquad (3)$$

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 (1-D ADVECTION-DISPERSION MODEL (ADM))

The ADM was used to analyze the Tracer Breakthrough Curves (TBC) resulting from the tracer test undertaken on July 15, 2020. The ADM, governed by Equation 4, 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).

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

The software Stanmod (CXTFIT) was used for the modeling of TBCs resulting from a conservative tracer Dirac pulse test using the Advection-Dispersion Model (ADM). The latter does perform automatic runs. Initial estimates for

fitting parameters have to be introduced in the model. Observed values are input as concentration in micrograms per liter (µg/l) as a function of time in hours. At the beginning of the modeling, the maximum and minimum ranges were significantly high. With an iteration number often set to 50, the system returns a best fit for the observed values. Upon refinement of the curve, range between maxima and minima was reduced to a one final set of dispersion and mean velocity. The *massive flux* required by the model is the integral of the concentration as a function of time (*∫C(dt)*).

4. RESULTS OF THE TRACER TEST

Tracer breakthrough curves (TBC) were retrieved only in the Laban Spring (fluorometer 718-f666). The tracer was not restituted in any of the other observation points (Figure 4-1). The tracer test undertaken on July 15th, 2020 was therefore positive delineating a connection between the injection point and the Laban Spring. The results show that Jabal El Dib Doline does not contribute to (and are not located on the catchment areas of) the Afqa or Assal springs. A graphical interpretation of the TBC is presented in Table 4-1.

Even though true distances are usually more sinuous and therefore greater (Field and Nash 1997; Göppert and Goldscheider, 2007), linear distances between the injection point and the observation point are usually considered for velocity calculations, i.e. the calculated flow velocity is a lower bound of the average flow velocity. The distance adopted for the calculation of velocities between the Laban Spring and injection point JED is considered to be 3060 m.

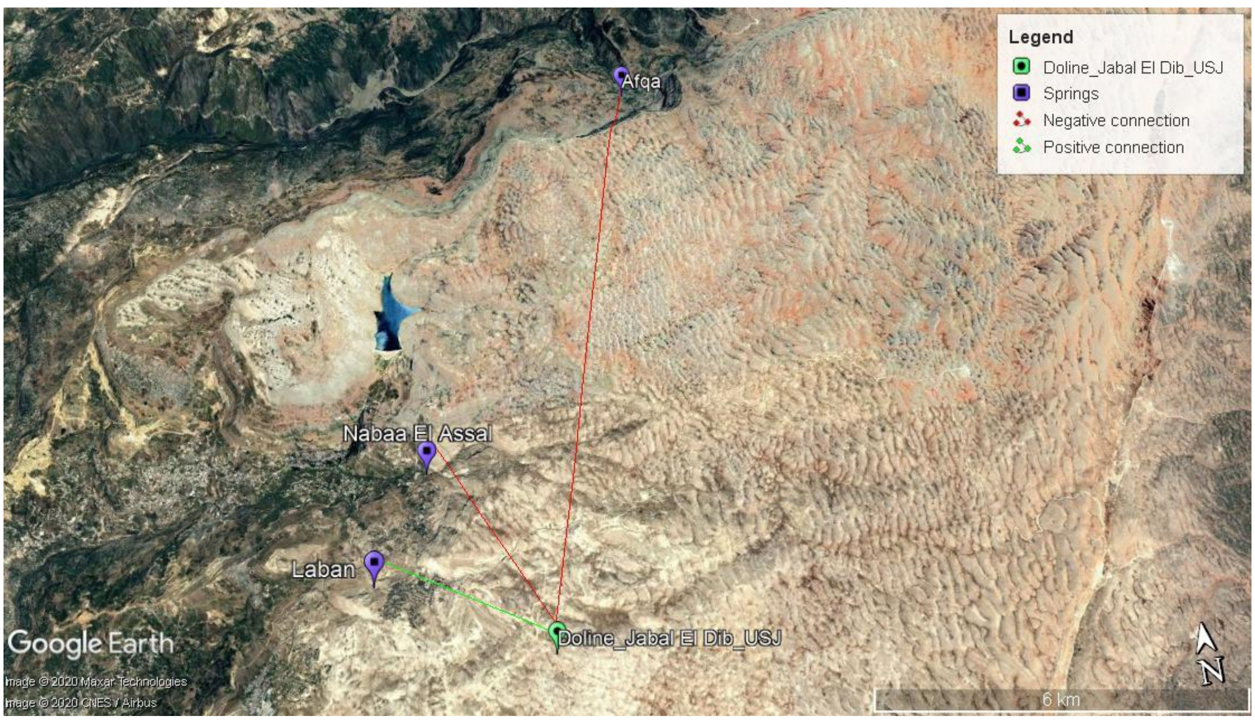

Figure 4-1 Results of the tracer test JED-1 (Green lines showing positive connection and red lines showing negative connection between the Injection point and the Observation point; Google Earth)

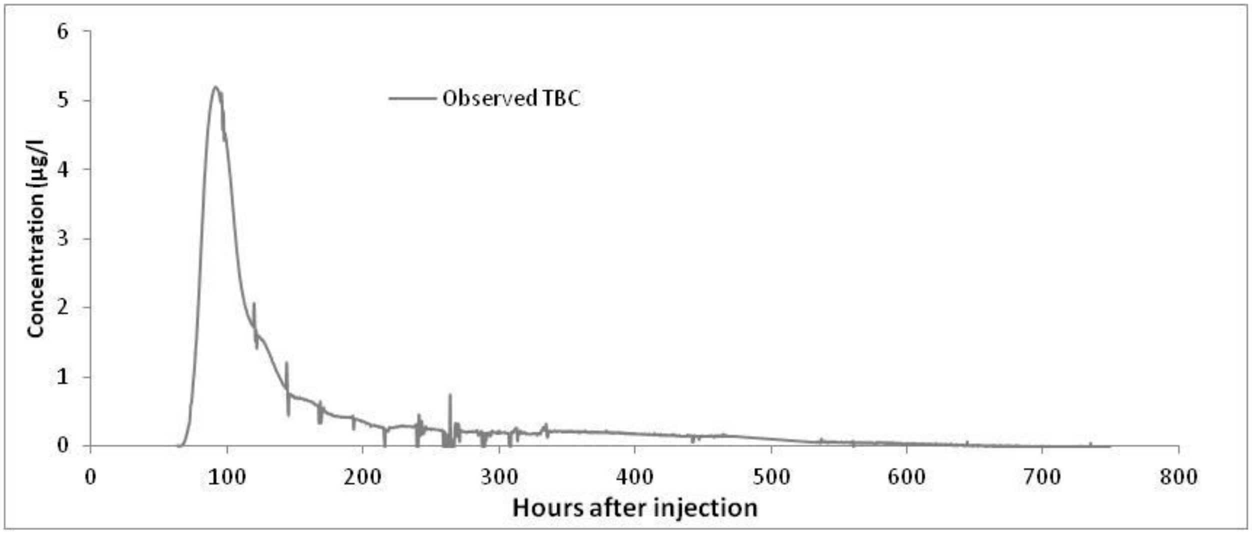

Figure 4-2 **Observed TBCs restituted in Laban Spring from injection point (JED)**

Table 4-1 **Graphical Interpretation of the TBC´s resulting from the Tracer Test (July 2020)**

OBSERVATION POINT	PEAK (µg/l)	TRACER FIRST ARRIVAL (hours)	MAXIMUM VELOCITY (m/hours)	PEAK CONCENTRATION TIME (hours)	VELOCITY TO VELOCITY OF PEAK CONCENTRATION (m/hour)	RESTITUTION (g; %)
Tracer 1 JED	5.07	66.28	46.5	90.28	33.9	231 g (9.6%)

4.1 TRACER BREAKTHROUGH CURVE (LABAN)

Uranine was first detected in fluorometer 718 in the in the Laban Spring about 66.28 hours after injection (equivalent to 2.8 days). The maximum velocity as calculated in both TBC is 46.5 m/hour. The maximum peak observed is 5.07 µg/L, yielding respective velocities to peak concentration (v_p) of 33.9 m/hour. The TBC is characterized by an irregular shape. Furthermore, snowmelt events are clearly depicted in the curve (Figure 4-3). Daily snowmelt events and resulting snow melt water infiltrating to the subsurface seem to activate the tracer in the unsaturated and saturated zone yielding multiple peaks. Based on a variable discharge rate (0.07-0.39 m^3/s) measured under prevailing flow conditions, a recovery of approximately not more than 9.6 % of uranine was achieved, probably due to injection conditions with little flushing and potential stagnation of the tracer because of fully saturated zone. The tracer concentration dropped to background concentrations (0.01 micrograms per liters) about 27 days after injection; however, the field fluorometer will remain installed in the spring, for any potential arrival of the uranine from the unsaturated zone, in the first rainy flushing events.

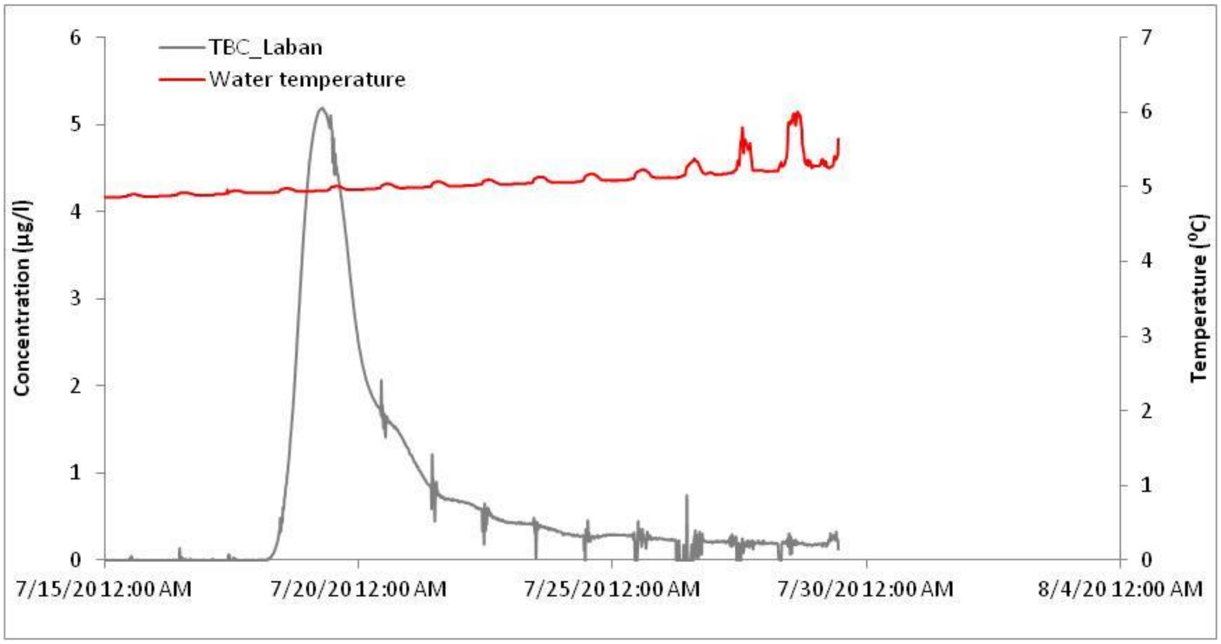

Figure 4-3 Water temperature at Laban Spring showing the snowmelt event, also reflected in the tracer breakthrough curve (TBC)

For modeling purposes using the advection dispersion model, the first peak of the tracer breakthrough curve was assessed for transport parameters. It is assumed that any subsequent peaks and tailing are due to snowmelt events, and have therefore similar transport parameters. The TBC is a convolution of multiple peaks from tracer transport with multiple snow melt events.

Based on the modeling of the first peak of the TBCs using the ADM model with CXTFIT (Table 4-2), the mean velocity over a distance of 3060 m between the injection point and the spring at the Laban Spring is about 33.10 m/hour. Longitudinal dispersion is estimated to be 592 m^2/h, yielding a longitudinal dispersion of 17.88 m; a value typical of karst systems. The coefficient of correlation between observed and modeled values is 0.997, considered highly acceptable, with a Mean Square Error of 0.011 micrograms/liters. The radius (R) of the phreatic conduit was calculated based on the volume of water during the transit time of the first peak was estimated at 2 m.

Table 4-2 Summary of the Modeling Results of the first peak of the tracer breakthrough curve retrieved at the Laban spring; Tracer experiment (JED-1) undertaken on July 15, 2020

PARAMETERS	SYMBOL	UNITS	JED I URANINE (LABAN SPRING) (F666) 1ST PEAK
Distance	D	m	3060
Discharge	Q	m^3/sec	Variable (0.24-0.38)
Mean Velocity	v	m/hour	**33.10**

PARAMETERS	**SYMBOL**	**UNITS**	**JED I URANINE (LABAN SPRING) (F666) 1ST PEAK**
Mean transient time	t_m	hours	92.44
Dispersion	D	m^2/hour	592
Dispersivity	A	M	17.88
Massive Flux	M	g	132
Coefficient of Correlation	R^2	-	0.997
Mean Square Error (MSE)	MSE	µg/l	0.011

5. CONCLUSIONS

Based on the tracer test undertaken on July 15, 2020, the following conclusions can be reached:

- **A hydrogeological connection was established between the injection point (JED-1) and the Laban Spring with a restitution rate of 9.6% of uranine.** The connection was not established with any other spring based on the negative results from both the monitoring of El Assal Spring with a field fluorometer, and activated charcoal in Afqa Spring. The latter, however, does not rule out any other possible ***direct connection*** with any other springs of the Cretaceous formation. The low rate of restitution will be further confirmed after a thorough calibration of the equipment upon finalization of the tracer experiment end of September 2020. The field fluorometer will be still deployed in the Laban and Assal springs until the level of uranine in Laban spring decreases back to 0 µg/ l.
- The tracer breakthrough curve displays one main initial peak, indicative of the arrival of the first pulse, while subsequent smaller peaks are indicative of daily snowmelt event and reactivation of the tracer into the saturated zone. Therefore, the analysis of transport parameter was done for the first peak, while the other peaks are believed to have similar transport characteristics. Further analysis will be performed in Q3 (third quarter) for the final reporting.
- Transport parameters can be deduced from the TBC for the specific pathway from the injection point till the Laban spring, notably with regards to mean velocity (about **33.10 m/hour**) which are considered typical of the cretaceous sequence characterized by a homogeneous fracturing and fissuring and thin limestone/ dolostones interbeds, which do not allow the formation of large conduits. Furthermore, the average longitudinal dispersivity indicative of the spreading of the tracer along its flow path, is about **17.9 m**, with longitudinal dispersion of 592 m^2/h, also typical of fissured karst aquifers.
- **In conclusion, the JED doline is located on the catchment area of Laban, and is currently discarded from the catchment areas of both Afqa and Assal spring based on the results of tracer experiment. The transport velocities are considered important, as any conservative contaminant can reach the Laban**

spring is less than 3 days and can last for a duration exceeding 650 hours (27 days) in different concentrations, because of snowmelt events during the experiment flow conditions. The information is also relevant for the purpose of delineation of protection areas. Further analysis related to snow melt and spring responses will be further elaborated in the final quarter of the project (correlative analysis).

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