Conceptualization of Flow in a Snow-Governed Groundwater Catchment in Lebanon: A Science-Based Approach for Future Guidelines for Sustainable Water Management

PROGRESS REPORT 6: Correlative analysis

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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 currently available quantities for supply for decision-makers. Besides, it includes 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 aim at a better conceptualization of the system and the expected quantities. The latter can be implemented in advanced vulnerability and protection maps and the evaluation of spring responses to climate change scenarios or snowmelt. 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 VI) presents the Correlative Analysis of high-resolution time series and the classifications of both springs in terms of storage, dynamic volumes and response to snowmelt.

1.1 GENERAL

The investigated area, Faraya (Kfardebbiane), in Mount Lebanon includes both Assal spring (35.828263° E, 33.995265° N) and Laban spring (35.838420° E and 34.009919° N; Figure 1).

1.2 OBJECTIVES

The objective of this activity is to analyze the collected time series; notably data of flow, temperature, in addition to climatic data to obtain information of spring water management application:

1. Classify the flow rates to identify flow rates of high occurrence and extremes of lower likelihood to occur,
2. Calculate the recession coefficient (s) of both springs' hydrographs to understand the rate at which the spring discharge declines with snow melt. The latter provides information about the flow dynamics occurring in the subsurface and allows predicting the spring water depletion during low flow,
3. Estimate the dynamic and static volume of the spring during different years: wet, intermediate, and dry ones.
4. Highlight a relationship and dependence between climatic parameters and the discharge at the spring to provide an insight into the influence that climatic changes may have on spring discharge in the future

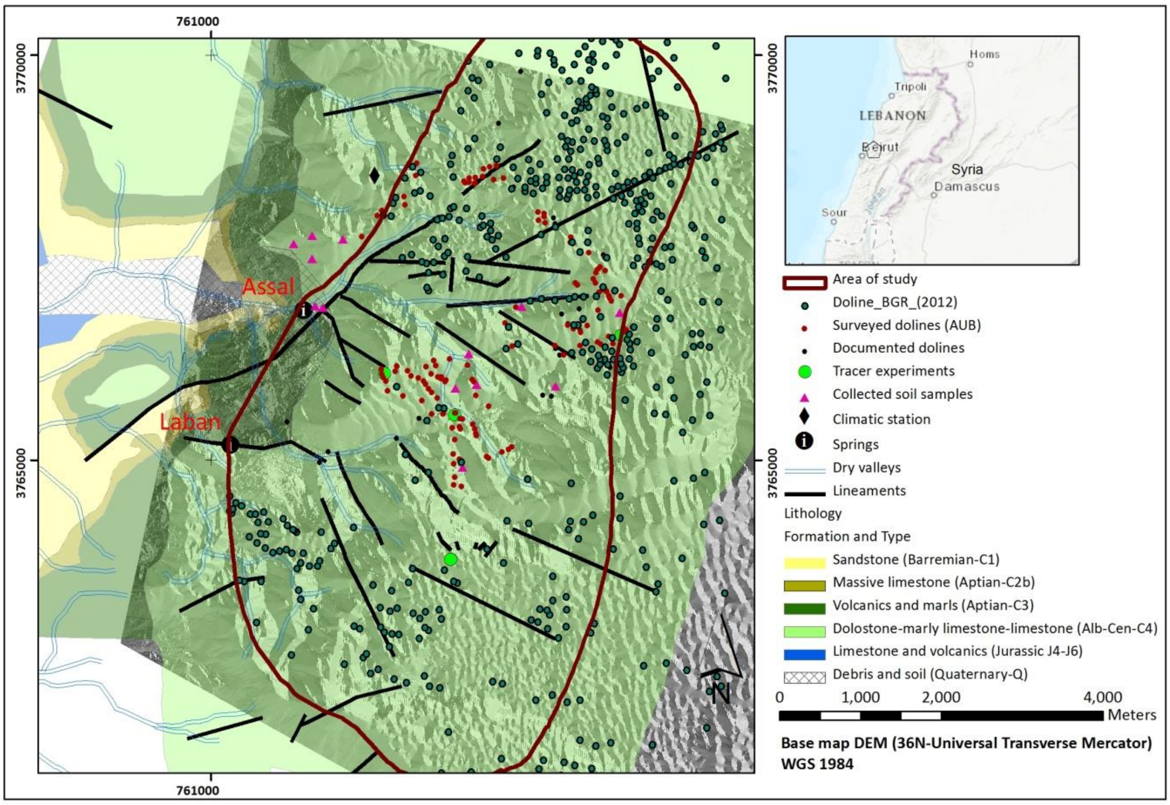


Figure 1 Geologic map for the study area encompassing the Laban and Assal springs (Report IV)

2. METHODOLOGY

The methodology consists of a statistical analysis of collected data timeseries from Activities 1.1 (set up of monitoring instruments) and 1.3 (monthly collection of data). Table 1 shows the different statistical analysis undertaken on the set of data (2015-2019) with a validation of the data for a complete data set for year 2020-21. The time series are Flow rate, equivalent rainfall (at the time of snowfall), Air temperature and spring temperature (Figure 2, Figure 3, Figure 4)

Table 1 Summary of the correlative and statistical analysis methods used to classify the spring responses of Laban and Assal.

Analysis method	Governing equation	Application and significance
Classified Flow Rates: Frequency Analysis	Ranking of discharge rates and assessment of the cumulative probability of occurrence of a ranked discharge.	Allows depicting the variation of discharge per time and the shape of the curve is indicative of different compartments in the system
Calculation of Dynamic Volume	$V_{DYN} = c.{Q_i}/{\alpha}$ (ref to Figure 5)	Calculation of dynamic volumes with respect to the total volume.
Simple recession analysis	$Q = Q_{R0}.e^{-\alpha t}$ (ref to Figure 5)	
Recession Analysis	$q = q_0.\frac{1-\eta.t}{1-\varepsilon.t}$ (ref to Figure 5)	Recession coefficients allows to understand the rate at which the spring reservoir gets depleted

Analysis method	Governing equation	Application and significance
		during low flow periods
Correlative Analysis (Autocorrelation)	$r(k) = \frac{C(k)}{C(o)}$ and $C(k) = \frac{1}{n} \cdot \sum_{t=1}^{n-k} (x_t - \bar{x})(x_{t+k} - \bar{x})$ Where k: the time lag (k = 0 to m); n: the length of the time series; x: a single event; $\bar{x}$: the mean of the events; m: the cutting point which determines the interval in which the analysis is carried out and is usually chosen to circumscribe a given behavior like annual or long-term effects.	Allows the understanding of the memory effect in the spring. In other terms how is a value of discharge at a certain time related to previous and later values of discharge.
Correlative Analysis (cross correlation)	$r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x . \sigma_y}$ and $C_{xy}(k) = \frac{1}{n} . \sum_{t=1}^{n-k} (x_t - \bar{x})(y_{t+k} - \bar{y})$ With: Cxy(k): the cross-correlogram; σx and σy: the standard deviations of the time series	A correlation among temperature, rain, discharge Laban and discharge at Assal allows to highlight the relationship between rain, temperature as predictor to the predictand (discharge). This allows

2.1 DATA TIME SERIES

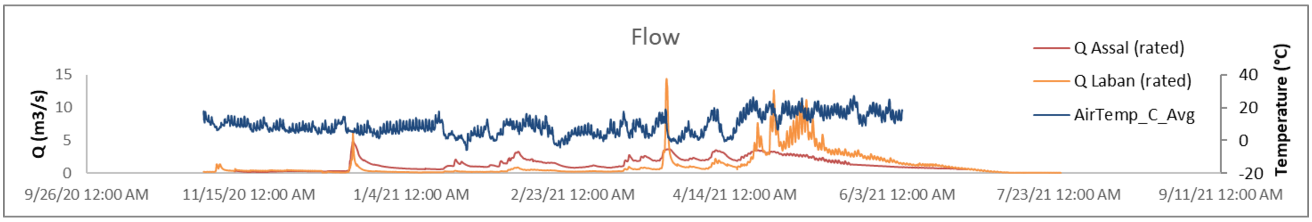


Figure 2 Flow collected from Laban and Assal spring (2020-2021) and ambient temperature from Chabrouh Station (AUB)

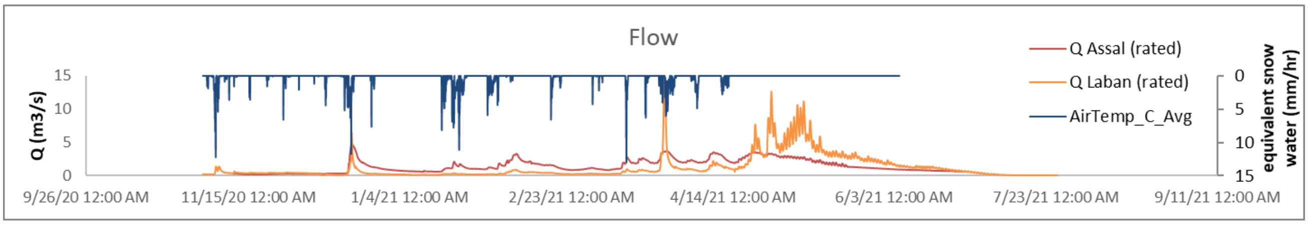


Figure 3 Flow collected from Laban and Assal spring (2020-2021) and equivalent water from the heated gauge from Chabrouh Station (AUB)

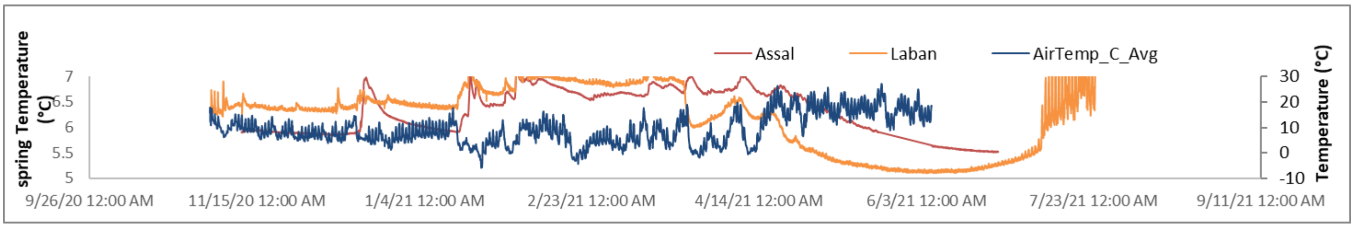


Figure 4 Temperature collected from Laban and Assal spring (2020-2021) and ambient temperature from Chabrouh Station (AUB)

2.2 Classified Flow Rates: Frequency Analysis

The sorting and classification of flow rates into groups allows the identification of a specific behavior of a karstic system Mangin, 1971; and Doertfliger et al., 2010. Flowrates and frequency of measurement are assessed using a normal log law to detect abnormal values and outliers. Such classification depicts the activation of an over-flow, the storage of a part of a flood, or the release of storage.

2.3 Mangin method: recession coefficient

In this report, we use a method to estimate the dynamic volume available in the aquifer during the depletion flow (Mangin (1971). This method separates the recession part of the hydrograph from the depletion part. It is the equivalent of considering two reservoirs, one for the vadose zone that is drained by the phreatic zone. As such, the flow rates can be simulated separately as shown in Figure 5.

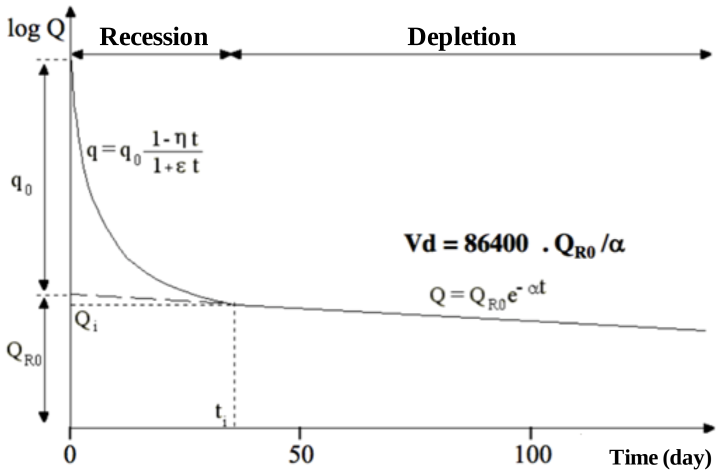
During the recession part, the flow rate is due to the emptying of the phreatic zone and the infiltration function (q).	During the depleting part, the flow rate (Q) is due to the emptying of the reservoir.	The dynamic volume (V_{DYN}) contained in the reservoir depends on its depleting coefficient.
$q = q_0 . \frac{1-\eta . t}{1-\varepsilon . t}$	$Q = Q_{R0} . e^{-\alpha t}$	$V_{DYN} = c . Q_i / \alpha$
q_o : the infiltrating flow at t_0, the beginning of the flood event (m^3/s) ; η : infiltrating velocity coefficient ($=1/t_i$ – d^{-1}) ; ε : Flow heterogeneity coefficient (d^{-1}) ; **t** : the time since the beginning of the flood event (d) ; **Q_{Ro}** : the fictional flow rate of the depleting curve at the maximum of the flood event (m^3/s) ; α : the depleting coefficient (d^{-1}) ; **Q_i** : the flow rate at the time t_i where the depleting begins (m^3/s) ; **c** : time constant = 86 400 (for Q_i in m^3/s and α in d^{-1}) ;	 	

Figure 5 Decomposition of the recession curve in Mangin (1971) *in* (Dubois, 2017)

Additionally, the nature of the catchment area can be characterized with two empirical values i and k (Mangin, 1971; Doertfliger et al., 2010, Dubois et al., 2020):

- The i parameter is the regulation power of the karstic system, meaning its process of storing and discharging the infiltrated rainfall.
- The k parameter is the delay of infiltration and is equal to the value of q (t = 2 days). K is between 0 and 1. The closer the value to 1, the slower and more complex the infiltration

3. RESULTS AND DISCUSSIONS

3.1 SPRING CLASSIFICATION AND TYPOLOGY AND RECESSION ANALYSIS

The classification of Laban and Assal flowrates provided in Figure 6 shows that the Laban is characterized by at least two level of storage, while Assal is characterized by a more homogeneous storage component over the entire range of classified discharge rates. On the one hand, Assal classifies as Type B; i.e., the input during flood periods comes from outside the system, which could be related to overflow occurring during intense snowmelt. On the other hand, Laban classifies as Type C, where storage input component is due to a precedent cycle (Figure 6).

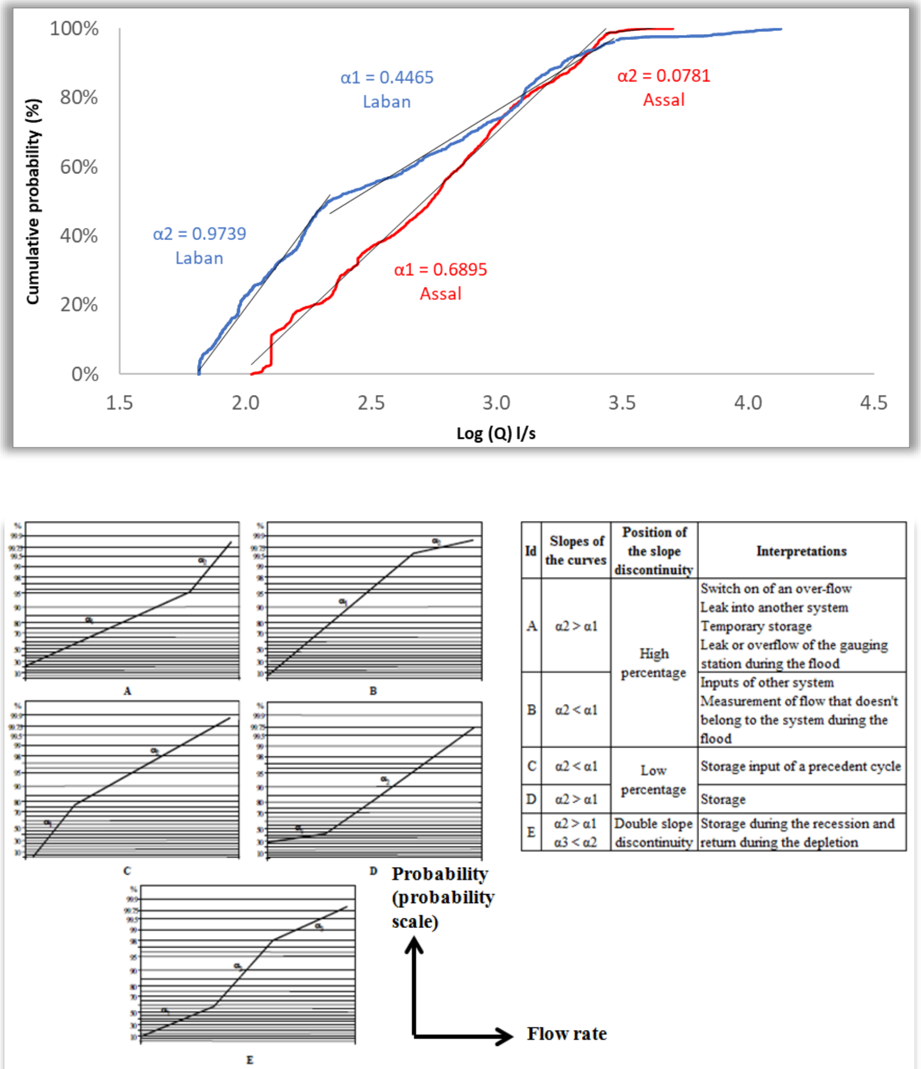


Figure 6 Flow classification curves of Assal and Laban compared to the slope discontinuities and their interpretation (modified from Doertfliger et al., 2010)

The Mangin classification for both springs based on daily discharge data from years 2016-2020 yielded the following for each of Laban and Assal (Doummar et al., 2021, *in review;* Figure 7*).*

1) Assal Spring (k= 0.48 and i=0.43) classifies as type 2, defined as a karstic system that is more karstified upstream than down-catchment either because of less developed karst systems (in that case the presence of dolomitic limestone) or/and because of a lingering snow melt effect.
2) Laban Spring (k= 0.10 and i=0.24) classifies as type 3, defined as a system that is very karstified in the downstream part of the catchment with developed karstic systems.

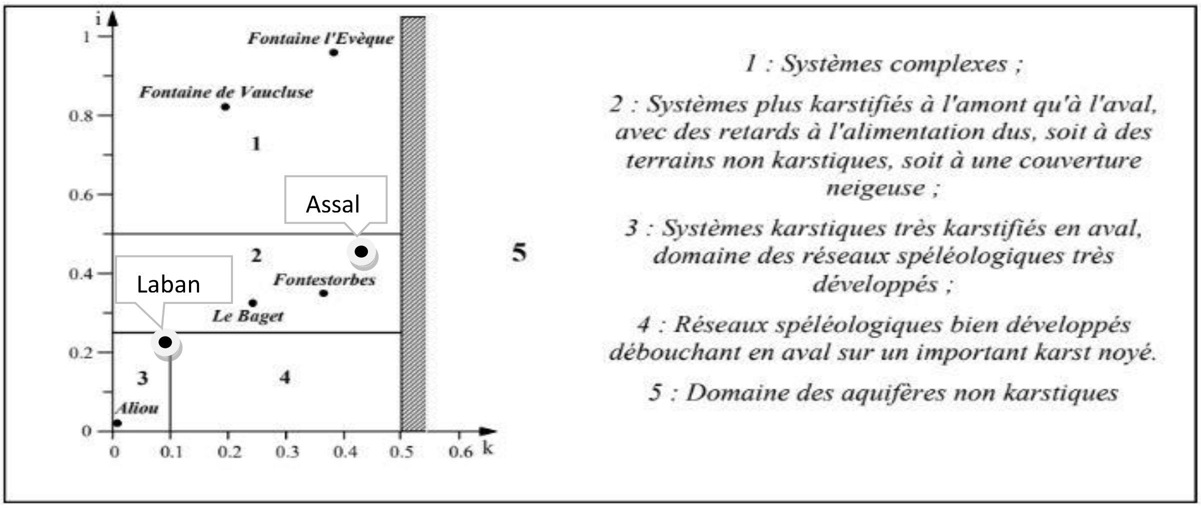


Figure 7 Spring classification according to Mangin (1970)

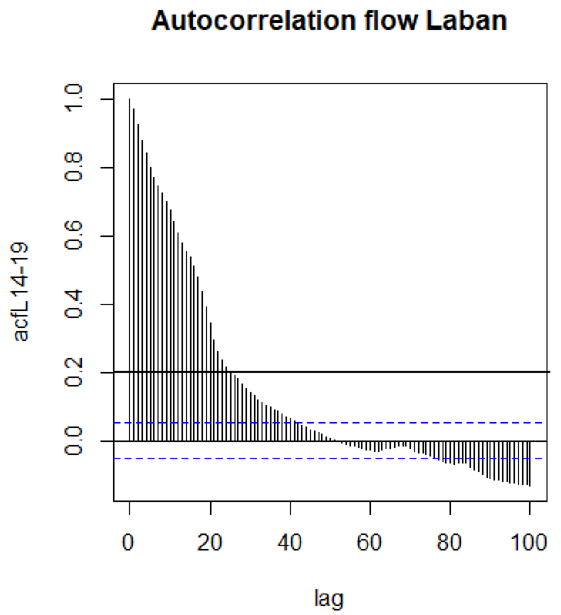
3.2 CORRELATIVE ANALYSIS

The simple correlation analysis allows to estimate the linear dependency of successive values over a time period. The correlogram, C(k), outlines the memory of the system. A slowly decreasing slope of the auto-correlation r(k), function is also indicative of whether a certain event has a long-term influence on the time series (Laroque, 1998). The maximum lag time is defined at r(k)=0.2.

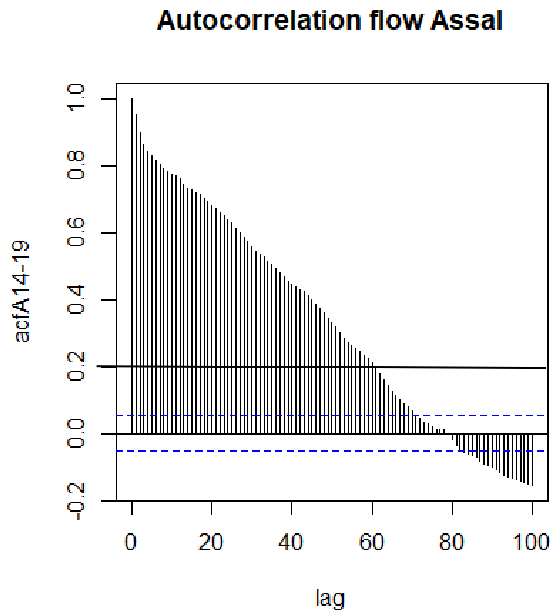
The autocorrelative analysis was done on the Assal and Laban dataset for 2015-19 and 2020-21 to estimate the memory of a dynamic variable (flow rate). The Assal spring has the highest correlations (0.2-1) at time lags varying between 48-61 days, while Laban flowrates have the highest autocorrelation (0.2-1) at a time lag varying between 25 and 35 days. The slope of the r(k) of Assal is gentler than that of Laban, indicating a longer-term influence of the recession event in Assal spring. In other words, in Assal, the discharge at point t=+60 is still dependent (influenced by) on the discharge at time t=0, while for Laban, the discharge at beyond t=+35 is no longer dependent on a previous discharge. The autocorrelation allows defining the inertia of the system and the dependence of discharge on time and its predictability based on past data, and its sustainability especially during recession.

The cross-correlative analysis allows to detect a relationship between a predictor (ambient temperature and Rain, on a predictand (the discharge rate of either Laban or Assal). A cross correlation was also undertaken between the flow rates of Laban and Assal to test the relationship between the two springs. The results are highlighted in Table 2.

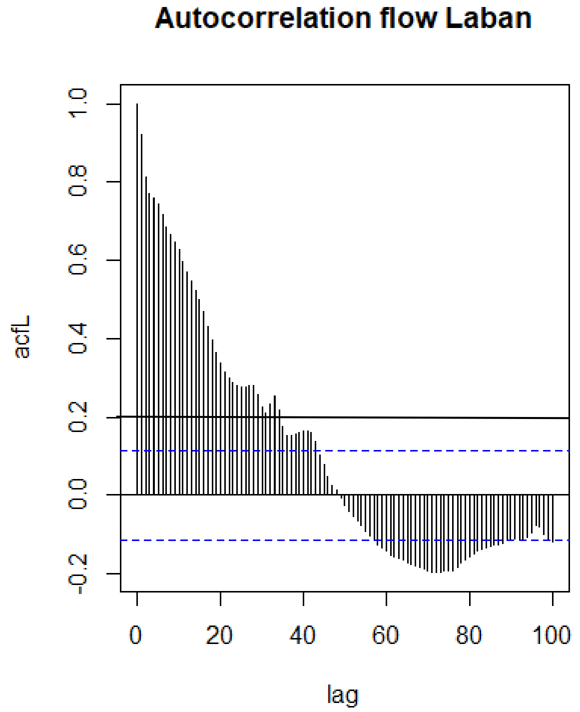
Table 2 Results of the Autocorrelation (ACF) and Cross Correlation (CCF) analysis between predictand (discharge rate at the spring) and predictors such as air temperature and rain. The analysis was done for two complete data sets (2015-2019) and 2020-21.



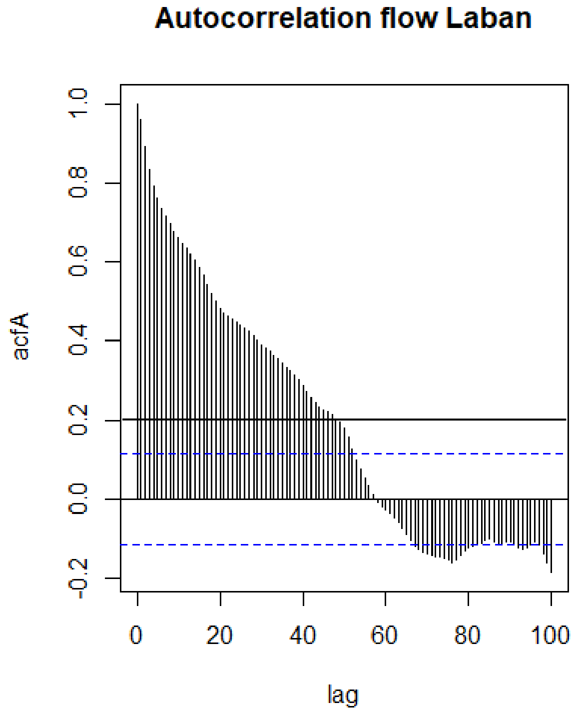
Autocorrelation (Laban flowrates)/ memory of 25 days (2015-19)



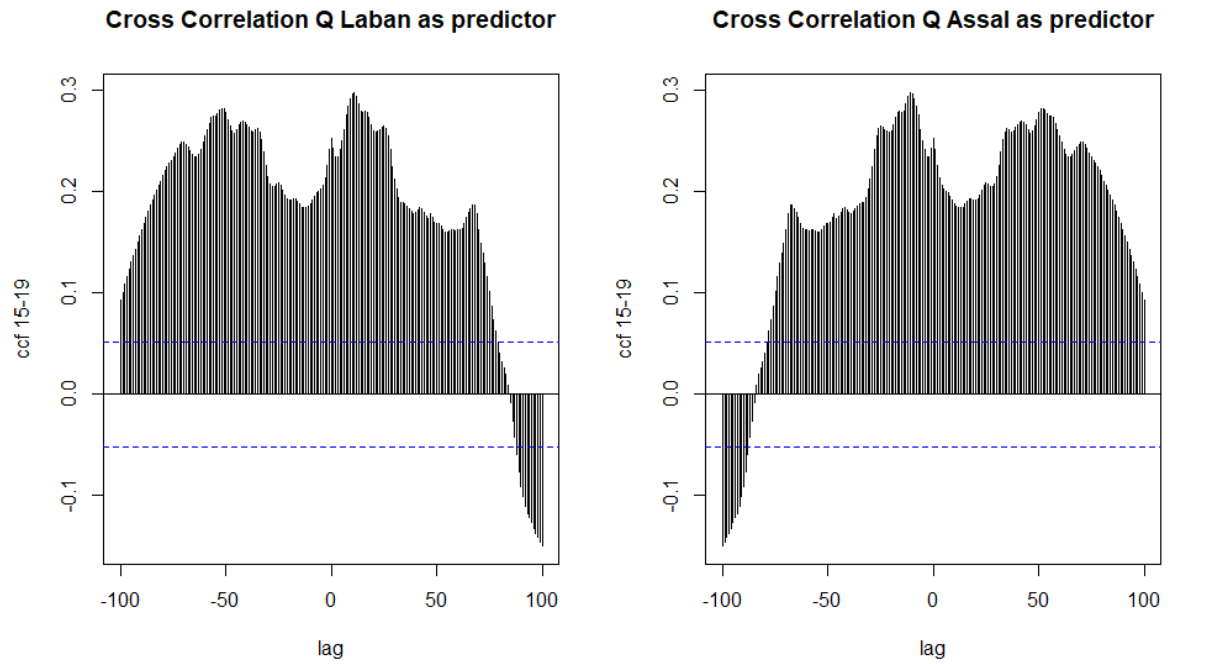
Autocorrelation (Assal flowrates)/ memory of 60.5 days (2015-19)



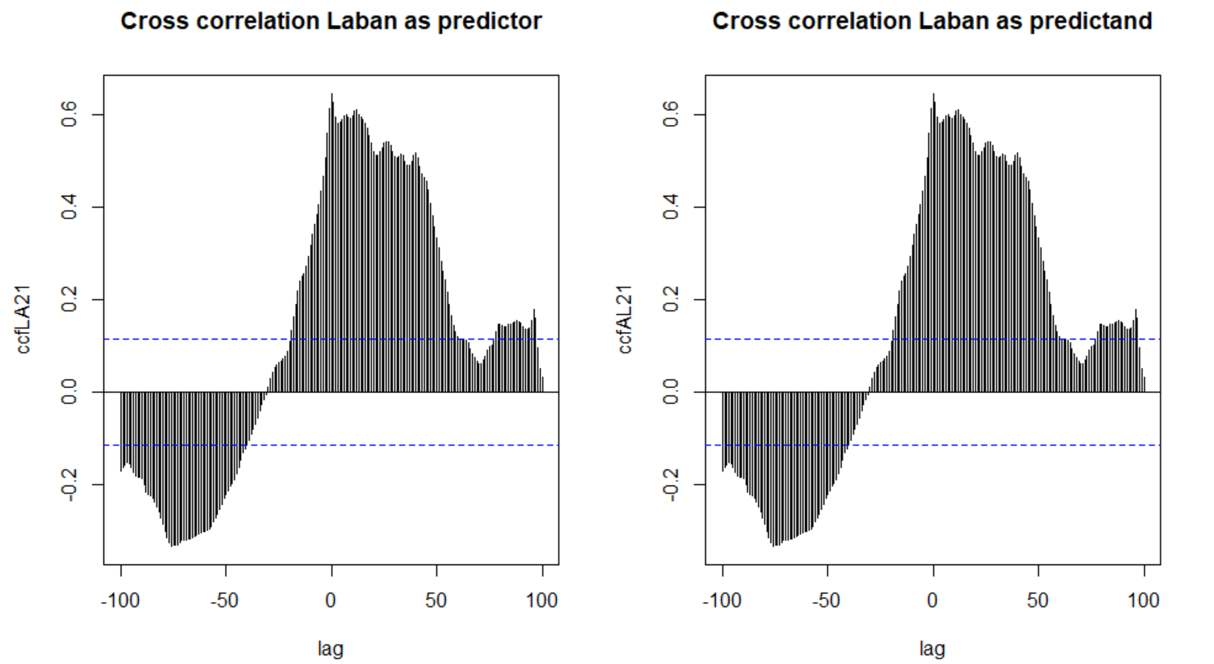
Autocorrelation (Laban flowrates)/ memory of 35 days in 2021



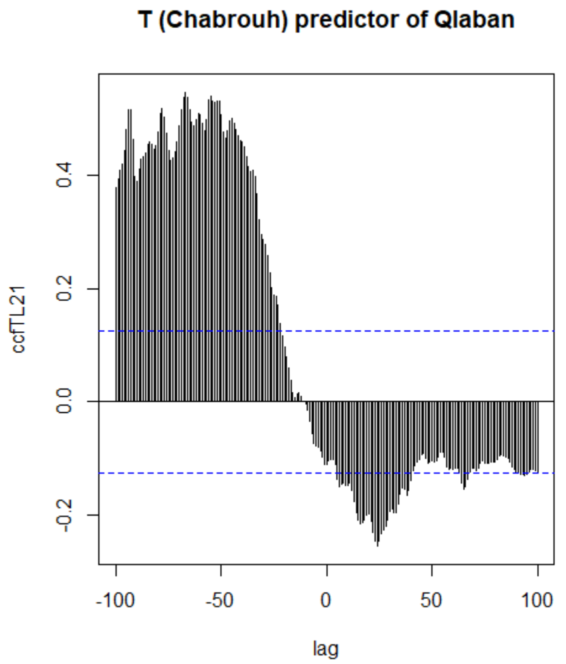
Autocorrelation (Assal flowrates)/ memory of 48 days in 2021

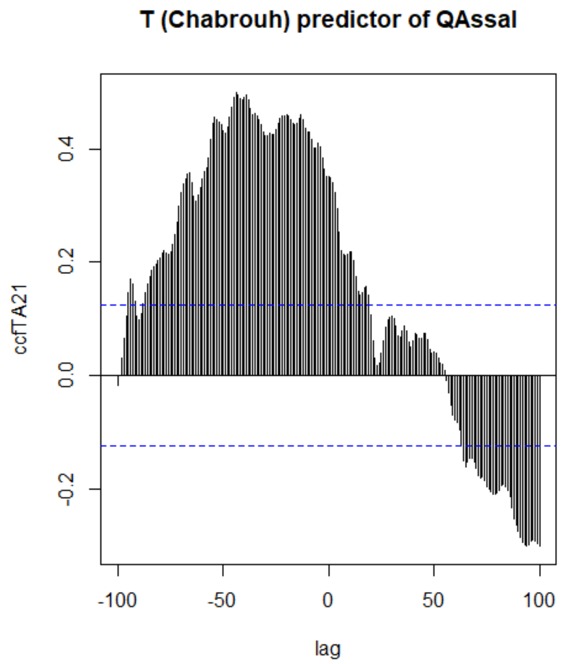


Cross- correlation discharge Laban (x) and Assal (y) (maximum lag= 100); Laban lags Assal by 11 days; (r(k)=0.3). The discharge rates at Laban are associated with the value of discharge at Assal with a delay of 11 days (2015-2019)



The discharge Laban and Assal are highly correlated (r(k)=0.6) at time t=0. There is a declining correlation until 60 days. (2020-21). The highest positive correlation with positive lag time indicate that Laban lags Assal.

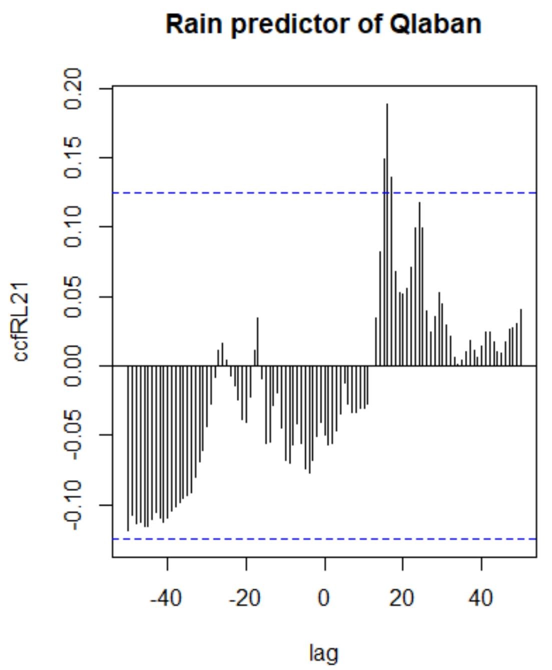


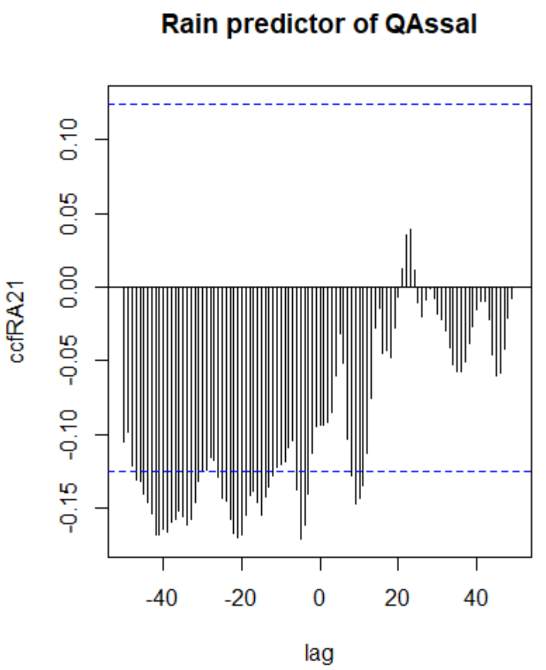


Cross correlation between temperature at Chabrouh and Q at Laban. Temperature lags the discharge at a peak of k=-67. An increase of temperature yields a change in discharge after about 67 days. The cross correlation is variable implying the snowmelt pattern and the dependance of discharge on multiple melting events.

Cross correlation between temperature at Chabrouh and Q at Assal. Temperature lags the discharge at a peak of k=-44

An increase of temperature yields a change in discharge after about 44 days. Dependance of Assal flowrates on the increase of air temperature is less prominent than that of Laban.





Cross correlation between Discharge Laban and Rain at Chabrouh (max lag=40)→Very low correlation with laban and a higher correlation with Assal around t=20 days

3.3 Synopsis: Spring classification and important parameters

The dynamic volumes and recession coefficient were calculated for both springs to reveal characteristics of Assal and Laban that can be used for the conceptualization of both systems. Some indicator parameters of the reservoir and the flow characteristics are identified from Mangin recession analysis and are further explained in Table 3.

Table 3 Indicator parameters of flow, heterogeneity, recession duration and dynamic volumes for both Assal and Laban spring based on a detailed analysis of hydrographs (2016-2020; Mangin, 1970)

Parameter	Assal	Laban	Significance
Recession/ depletion coefficient (α; 1/d)	0.004-0.008	0.013-0.17	The steeper the recession, the faster is the decay of flowrates to minimum value, meaning that the spring will experience water deficit much faster than with a less steep α
Dynamic volumes at depletion (Mm^3)	6.5	1.5	The faster the recession the lower is the available dynamic volume for exploitation during low flow period
Duration of recession (d)	50-83	22-73	The longer the recession and depletion the higher the likelihood for water deficit The duration of depletion is indicative of times of baseflow
Duration of depletion (d)	42-91	65-119	
Duration of recession and depletion (d)	92-174	87-192	
Heterogeneity coefficient (ε ; 1/d)	0.005-0.016	0.01-0.024	The higher this coefficient the higher the degree of heterogeneity in the system
Infiltration Velocity coefficient (η ; 1/d)	0.012-0.02	0.014-0.045	The higher the coefficient of infiltration the higher the response of the spring to infiltration and recharge.

4. Conclusions

The correlative analysis of high-resolution time series reveals information about the behavior of the investigated springs and their responses and allows to classify their typology. The following conclusions were reached:

1) The time series of discharge show that the Laban Spring peak flow arrives after that of Assal indicating a response to snowmelt at higher altitudes. Therefore, this can confirm that the catchment of Laban Spring extends to higher elevations than that of Assal.

2) The spring temperature data show that the increase of temperature in spring water is achieved in Laban prior to Assal indicating that the snowmelt response at Laban elapses quicker than in Assal. Additionally, the temperature of Assal is lower than that of Laban indicating deeper circulations or a higher transit time in the Assal system. The latter concurs with the conceptual model, where transit times in Assal are observed to be greater than that of Laban

3) Based on Mangin classification, Assal is defined as a karstic system that is more karstified upstream than down-catchment either because of less developed karst systems (in that case the presence of dolomitic limestone) or/and because of a lingering snow melt effect. On the other hand, Laban Spring is defined as a system that is very karstified in the downstream part of the catchment with developed karstic systems. This difference in degree of karstification allows to explain the discrepancies in the spring responses of Laban and Assal.

4) The recession coefficient of Assal is gentler than that of Laban due to the characteristics of the reservoir and porosity. The latter implies that Assal is more sustainable than Laban during recession and low flow periods and reacts less rapidly to snow melt, because it relies on a more important capacity of storage in its entire reservoir.

5) The cross-correlative analysis confirms the conceptual understanding of spring responses in relation to their reservoir characteristics and means of recharge. Additionally, the knowledge of the dependence of flowrate on air temperature or rain allows to predict conceptually the effect a varying temperature or rainfall on spring discharge. However, the later case would require a more robust model that can be validated on a longer time series.

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