LAG AND TRANSFER TIME INFERRED FROM MELTING CYCLES RECORD IN THE COULOMP KARST SPRING (ALPES DE HAUTE-PROVENCE, FRANCE)

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A 11-days long period of snowmelt cycles was selected from the discharge and temperature data collected at Coulomp spring (Alpes de Haute-Provence, France), which is the largest of French Southern Alps with a discharge of 1 m^3/s. Its catchment is 30–50 km^2-large and mainly composed of marly limestones and poorly permeable covers, responsible of a combined diffuse and concentrated recharge. From Q data we extracted snowmelt discharge (Snowmelt Q = oscillating part of the discharge) and Basal Q. The contribution of Snowmelt Q is 30–50 % of Q. Amplitude of spring temperature (T_{spring}) is about 2 °C due to alternation of cold snowmelt water with low residence time and "warm" phreatic water with longer residence time. The lag between the peak of air temperature (T_{air}) corresponding to the maximum of snow melting and the peaks of Q, corresponding to the transfer time between surface and spring, is less than 10 h. This 10 h transfer time combines about 7 h of vertical transfer through the vadose zone and 3 h of horizontal transfer through the drain.

1. Introduction

Snowmelt recharges karst aquifer through diffuse and slow seepage or through sudden contribution when abrupt melting combines with air warming and huge down pouring. Sudden melting is quickly transferred through high-velocity conduits, with limited storage. On the contrary, part of seepage uses low-velocity routes mainly through tiny fissures and contributes to storage in epikarst, vadose zone, and epiphreatic zone. As a consequence, snowmelt contributes to the deferred runoff during low-water periods at the end of summer, where the amount or scarcity of discharge depends on the thickness of the snow mantle accumulated during winter and on the rhythms of the snowmelt during spring. Otherwise, snowmelt daily cycles give rhythm to the input, which is transformed and transferred at the spring, and which allows making detailed analysis of the transfer function, namely transit routes, transfer time and lag, and storage time and capacity (Vigna and Suozzi 2009).

In this paper, we study the Coulomp spring in Alpes de Haute-Provence (France), which is the largest karst spring of the Southern French Alps. Recharge conditions are complex and are determined by diverse type of rock outcrops in the catchment where diffuse recharge is predominant. The monitoring of the spring, with a record of discharge and temperature during 4 yearly cycles, gives the possibility to focus on different kind of recharge period, namely long recessions, flash floods (Audra and Nobécourt 2012), long flooding periods, or snow melting, which is the topic of this paper. We analyze the recorded data combined with observations of the spring activity. The aim of this study is to understand the snowmelt cycles and their role in the spring activity, and the transfer times in the different karst zones (seepage fissures vs. conduits). Moreover, the understanding of transfer times is an important challenge to allow cave exploration. Indeed, the underground river is the largest of France (average Q = 1 m^3/s), which exploration represents a caving and scientific challenge and the access of the underground system is controlled by 3 sumps at the entrance which require pumping and which can close when flooding occurs.

2. Context and dynamic of the Coulomp spring

The Coulomp spring (commune of Castellet-lès-Sausses, Department of Alpes-de-Haute-Provence, France) pours out at 1,300 m a.s.l. with a scenery 65 m-high waterfall. The underground river has been explored along 1.7 km upstream to the spring (Audra et al. 2009). The spring is fed by a 30–50 km^2-large catchment, which encompasses the Baussebérard and Grand Coyer (2,693 m) Mountains (Fig. 1). The mean annual discharge is 1 m^3/s, making this spring the largest of the Southern French Alps. Most of the seepage occurs through Upper Cretaceous marly limestones, which thickness is several hundreds of meters and which in turn are covered uncomformably by the Nummulitic Trilogy (Nummulitic limestones, Priabonian blue clay, and Annot sandstones). The thickness and extension of these poorly permeable covers makes a particular recharge, which combine both diffuse seepage through marly limestones and concentrated input in sinkholes originating from surface runoff on marls and clays. Extreme discharges (30 m^3/s; 250 L/s) reveal a typical karst dynamic, influenced by fast transfer through conduits and long recessions kept on going by storage in sandstone covers and in the thick marly-limestone infiltration zone.

3. Material and methods

The spring pool level is recorded each 30 mn, and transformed in discharge (Q) through a rating curve, constructed with chemical gauging at different discharge. For the concerned discharges (200–2,000 L/s), the rating curve quality is fair (R^2 = 0.976). We recorded spring temperature (T_{spring}) and air temperature (T_{air}) with the same frequency. T_{air} is overestimated in the middle of the day, since the data logger was exposed to direct solar insulation.

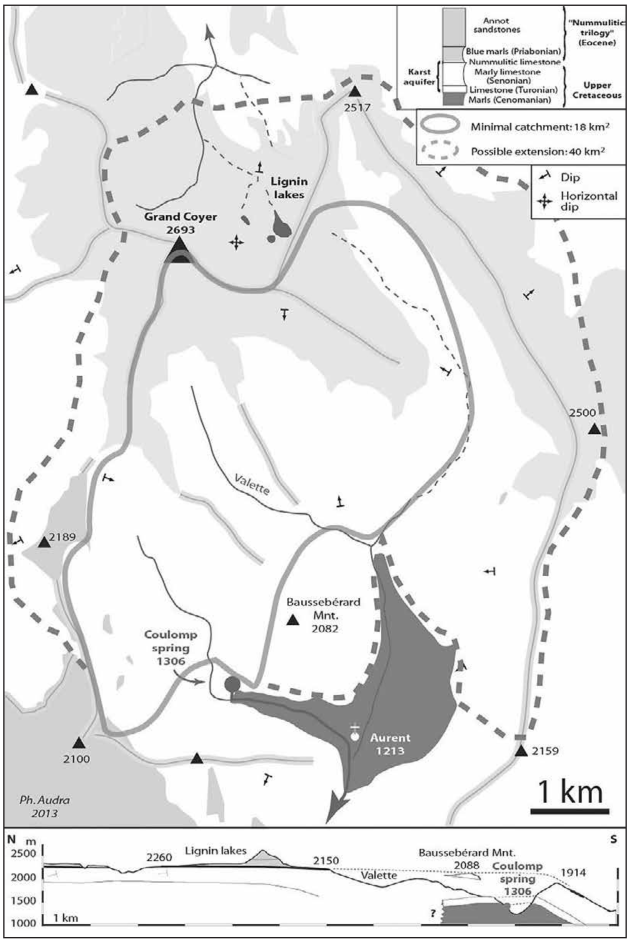

Figure 1. The catchment of the Coulomp spring is about 30–50 km². It stretches from 1,300 m a.s.l. at the spring to 2,693 m a.s.l. at the Grand Coyer. Mainly Cretaceous marly limestones crop out, covered with clay and sandstones.

However, we assume a reasonable validity for the air temperature regarding the relative trend and periods without direct solar heating (i.e. from 4 p.m. to 10 a.m.). Finally, data from the next meteorological station of Méailles (6 km distance, 1,090 m a.s.l.) provide minimal daily temperature and weather.

The chosen study period of 11-days in March 2009 corresponds to a typical stable wintertime "fine weather" (Fig. 2). At that time, most of the snow already melted at the altitude of the spring and up to 2,000 m on the south-exposed slopes of the mountain above the spring, but a thick mantle still remained in northern slopes and in the remote highest parts of the catchment above 2,000 m. At the beginning of the period, snowmelt increases as a consequence of a significant warming: night temperature minima at the spring rise from 0 to 5 °C but remain negative in the high catchment, whereas during the day maxima may overpass 20 °C on the southern slopes. No rain or snow fall occurred during the period, the melting cycle being only influenced by the daily thermal cycles. Weather remains sunny during most of the period, with only 2 partly cloudy days. A cooling with snowfalls ends this period.

The discharge curve (Q) displays daily cycles resulting from snowmelt (Fig. 2). The total discharge corresponds to the combination of a basal discharge (Basal Q) resulting from the slow recharge of the previous days and of snowmelt peak discharge (Snowmelt Q) directly resulting from the melting transfer.

In order to separate the Basal Q and the Snowmelt Q, we made the following treatment: (i) identification of daily discharge minima, (ii) interpolation between each minimum and construction of a curve with 30 mn timing corresponding to Basal Q, (iii) subtraction of Basal Q to Q and extraction of the cyclic Snowmelt Q.

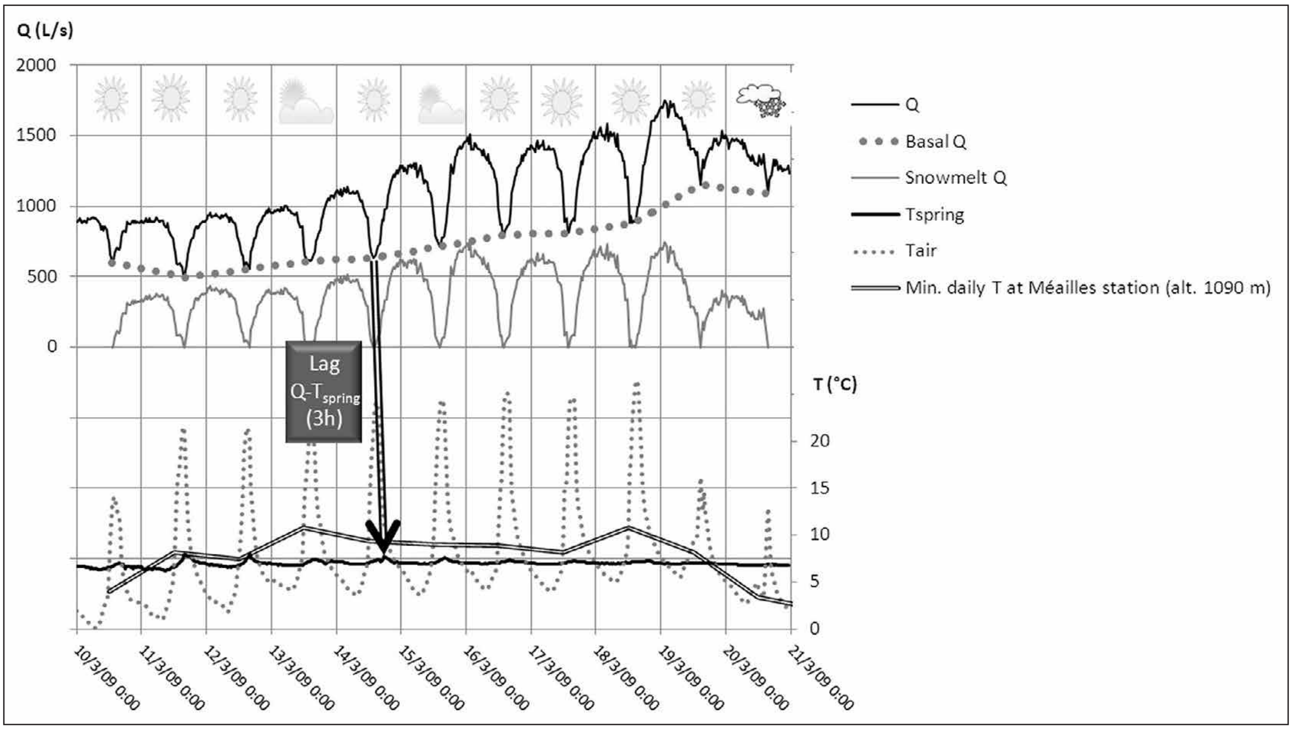

Figure 2. Snowmelt influence on the Coulomp spring in March 2009. The upper curve corresponds to the raw discharge (Q), the middle curve to the basal discharge (Basal Q), and the lower curve to the snowmelt discharge (Snowmelt Q) (see text for explanation). Additionally, the temperature of the spring (T_{spring}) and the temperature minima at the closest meteorological station (Méailles) are shown, with daily weather trend. X axis corresponds to winter time.

4. Results (Tab. 1)

Q: during the period, discharge was about 1m^3/s, however with an extreme daily variability due to snowmelt, with constant oscillation between 500–800 L/s and 900–1,700 L/s.

Basal Q and Snowmelt Q: the Basal Q corresponds to the lowest daily discharges corresponding to the cessation of daily snowmelt influence. Through the period, it gradually increases from 600 to 1,200 L/s. The Snowmelt Q strictly corresponds to the daily melting, with a mean value of 400 L/s, oscillation from 0 (snowmelt stop at night) to a maximum of 760 L/s. The relative contribution of Snowmelt Q to the total discharge (Q) evolves from 0 when snowmelt recharges stops at night to a maximum of 50% of Q, with a mean value of 30% of Q.

Table 1. Characteristic values of the daily snowmelt cycles at the Coulomp spring in March 2009.

Values	Min.	Aver.	Max.	Date of min.	Date of max.
Q (L/s)	497	1123	1754	11/03/2009 16:00	19/03/2009 01:30
Snowmelt Q (L/s)	0	374	760	N/A	16/03/2009 01:30
Snowmelt Q / Q (%)	0%	29%	50%	N/A	16/03/2009 01:00
Tspring (°C)	6,23	6,94	7,99	11/03/2009 08:30	12/03/2009 16:00
Lag min Tair to min Q (h)	6	7 (±1)	8,5	10/03/2009	20/03/2009
Lag max Tair to max Q (h)	8	12 (±2,3)	16	19/03/2009	10/03/2009

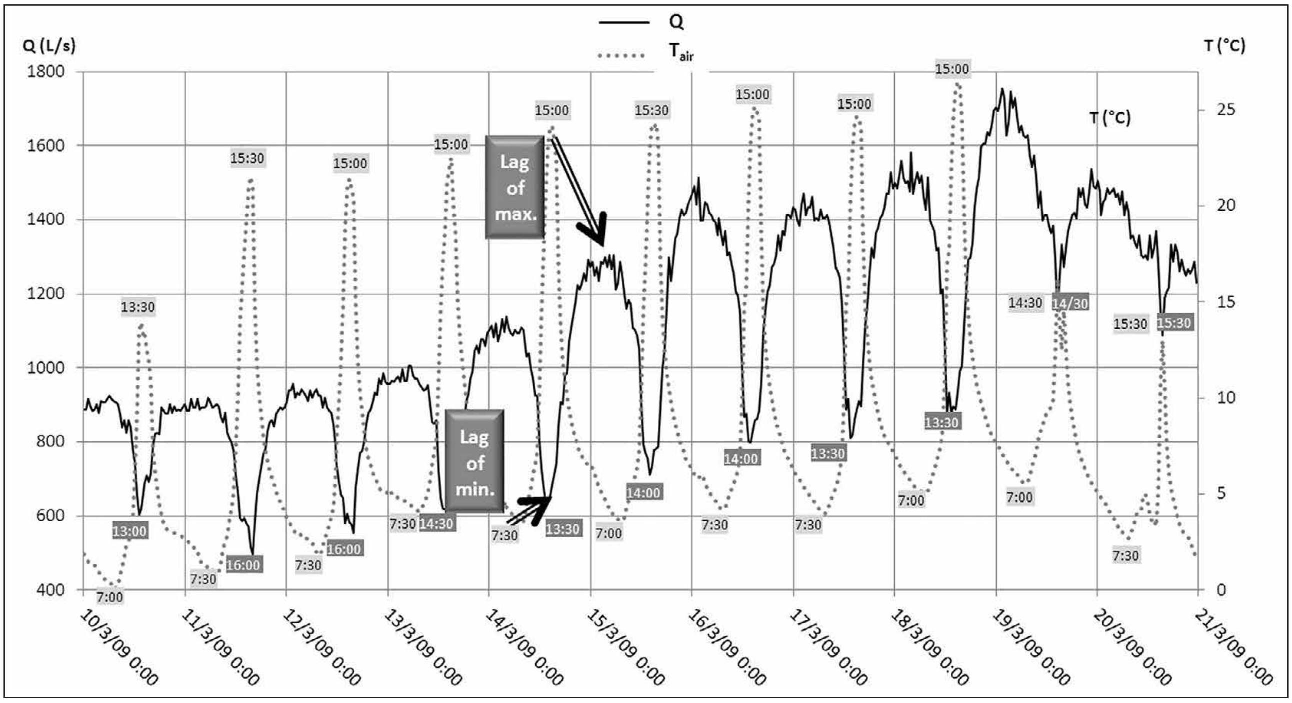

Figure 3. Lag between the air temperature (Tair) and the discharge (Q), for both minima and maxima.

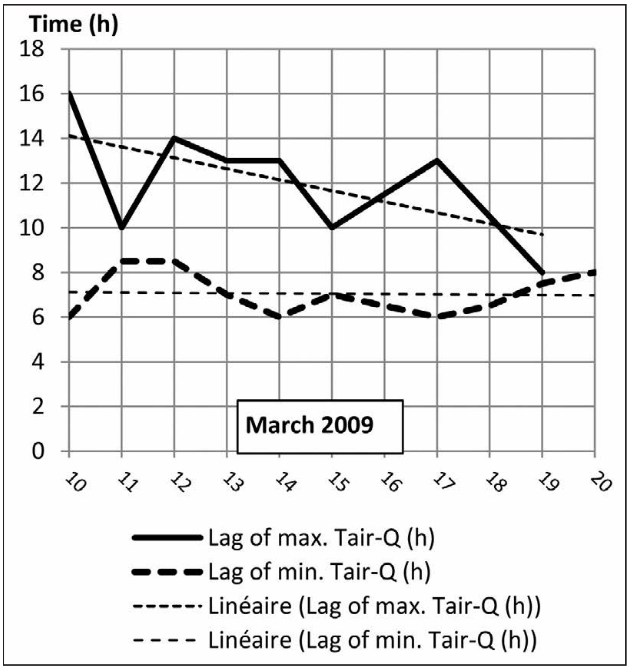

Figure 4. Evolution of the Tair-Q lag for both minima and maxima.

Evolution of Q: Q increase during the period results from the increase of the air temperature and the maintenance of high values during the day, whereas night frost occurring on most part of the catchment stops melting at night. A snowfall occurring at the end of the period stops the cycle.

Min-max Q lag: the daily minimum of Q is at about 14:30, the daily maximum of Q is at about 03:00 (Fig. 3). There is a lag of 7 h between snowmelt start on the surface at sunrise, given by the air temperature minima (T_{air}) and the beginning of restitution of infiltrated meltwater at the spring at the beginning of the afternoon. The lag between the T_{air} maxima and Q maxima (lag of T_{air}-Q maxima) is less defined, because of the presence of several secondary peaks of Q, however it is about 12 h. The lag of T_{air}-Q minima is stable during the period, whereas the lag of T_{air}-Q maxima shortens from 14 to 10 h during the same period (Fig. 4).

T_{spring}: the Q peaks correspond to T_{spring} minima and conversely. T_{spring} and Q are in phase inversion (Fig. 2). The thermal amplitude is up to 1.8°C (extreme T_{spring} are 6.2 and 8 °C). At the daily scale, the thermal amplitude is between 0.3 and 1.5 °C. Largest amplitudes are at the beginning of the period. Amplitudes gradually reduce till a quasi thermal stability at the end of the period. The lag between Q and Spring T_{spring} is about 3 h.

5. Discussion

Evolution of Basal Q (Fig. 2). The increase of basal Q (500 to 1,100 L/s) results of the infiltration of previous days melting: fast infiltration is transferred within half a day, whereas slow infiltration is spread in the course of the following days and cumulative contributes to the gradual increase of basal Q.

Secondary peaks. Snowmelt cycles are similar throughout the period. However peaks are systematically made of the merging of several secondary peaks (Fig. 3). Several hypotheses are possible: (i) zones of recharge may use different routes, with slightly different velocities. Such a reason would produce rather similar secondary peaks; (ii) the snow stock evolves according to the melting and each zone contribution may evolve through time; (iii) sun exposure may somehow change with the presence of clouds, producing jumps in the melting, with no similitude of secondary peaks across the period. Since secondary peaks do not display any evident similitude, we would favor this last hypothesis.

Snowmelt Q. The gradual increase of daily temperature results in the increase of Snowmelt Q. The instantaneous variations of Snowmelt Q range from 34 L/s in 30 mn in average up to 176 L/s in 30 mn. The highest variations occur during both Q rise and Q lowering. At the end of the period, Snowmelt Q represents halt of the total discharge. The relative lowering of temperature in the middle of the period does not affects snowmelt since day temperatures remain high. On the other hand, the significant temperature increase at the beginning of the period and the 17–18 March provokes a clear and lasting Q increase, for both Q and Snowmelt Q.

Lag. The lag between the snowmelt cycles, directly connected to the air temperature (T_{air}), and the restitution at the spring (Q) gives information about transfer velocity (Fig. 3). The snowmelt water arrives at the spring in 7 h (lag of minima), whereas lag of maxima is 12 h. It does not completely corresponds to water transfer, which is slightly longer, but to the succession of transfer in the vadose zone then to the arriving in the horizontal transfer zone, with both full pipe and open-channel flow, which quickly increases the discharge by piston-flow effect in the phreatic zones (see below). Concerning lags evolution during the period (Fig. 4), the stability of the lags of minima corresponds to the invariant time of infiltration through the vadose zone in recession condition (7 h), whereas the shortening of the lags of maxima reveals the gradual saturation of the vadose zone under the effect of repeated melting cycles and the simultaneous gradual increase of transfer velocity. Such a lag of 7 h, corresponding to the time between the beginning of infiltration and the restitution at the spring is similar to those observed during floods associated to rainy events while the infiltration zone is saturated. However, this lag can be shorter (< 3 h) in case of intense storm producing a preliminary concentration by surface runoff before introduction in sinkholes (Audra and Nobécourt 2012).

Thermal changes at the spring. The 2 °C amplitude of T_{spring} of is significant (Fig. 2). It corresponds to a relative proximity of the recharge zone and to the combination of Basal Q and Snowmelt Q. At the end of the period, T_{spring} amplitude gradually decreases till almost homogenization. It corresponds to the increase of the contribution of water with short residence time, i.e. the "cold" meltwater, which gradually dilutes and replaces the "warm" water having a longer residence time. Together with homogenization, T_{spring} gradually decreases. More precisely, there are 2 successive phases: (i) 10–11 March achieves a cycle of low T_{spring} corresponding to a low contribution of Basal Q; (ii) 11–21 March, strong snowmelt start first expels the "warm" water stored in the phreatic zone, which is gradually replaced by snowmelt water giving a thermal trend of slow decrease and homogenization.

Q-T_{spring} hysteresis curve. Plotting of Q and T_{spring} allows a deeper understanding of the transfer (Fig. 5). The phase

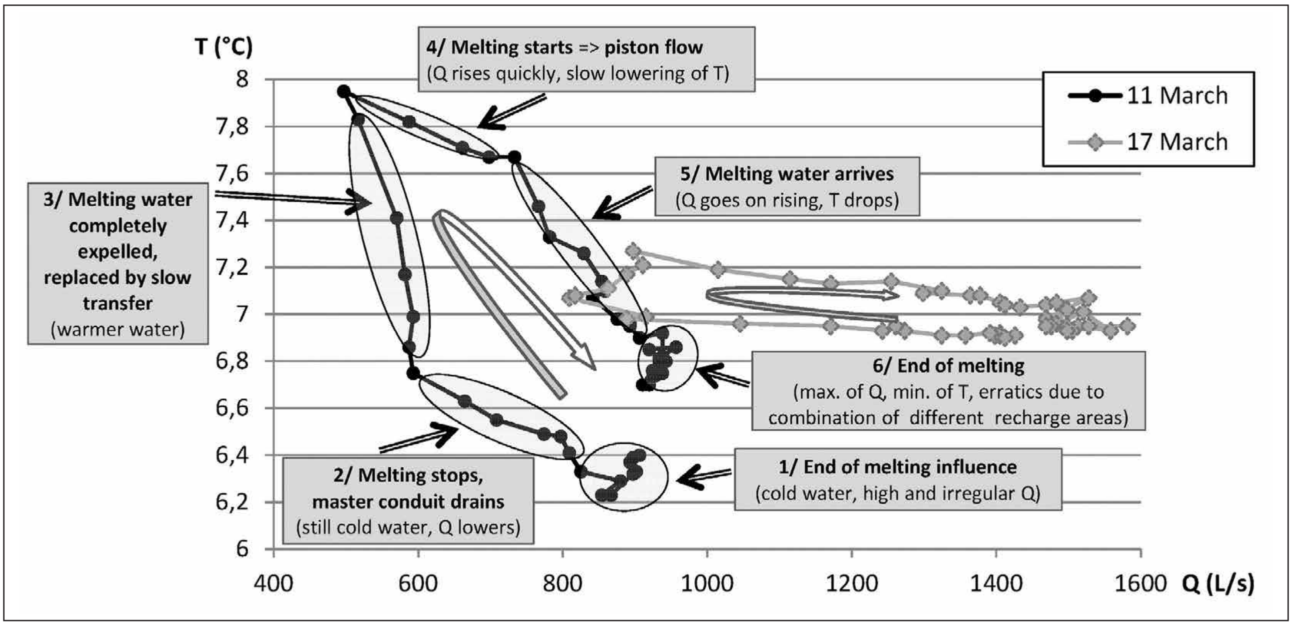

Figure 5. Hysteresis curves characteristic of daily snowmelt cycles (circles correspond to a cycle at the beginning of melting cycles; diamonds to a cycle after several days of intense snowmelt).

inversion between Q and T is easily explained by the contribution of snowmelt water which simultaneously increases Q and lowers T_{spring}. Conversely, during recession without influence of snow melting, contribution of water with longer residence time in the phreatic zone gives warmer T_{spring} and lower Q. The most interesting corresponds to the 3 h lag, where "warm" water is expelled whereas Snowmelt Q starts to rise (Fig. 2). It results from the "piston flow": "warm" water stored in the drain is contributing to the Basal Q, whereas arrival of snowmelt water in the phreatic zone makes a pressure rise, which quickly transfers to the spring. While Snowmelt Q starts to increase, the contributing water is still the "warm" water, progressively expelled of the drain. And conversely, after the end of Snowmelt Q contribution, the draining of the drain still provides cold snowmelt water.

Hysteresis curve represents the pathway of Q and T_{spring} during snowmelt cycles (Fig. 5). It displays 2 significant daily snowmelt cycles at the beginning and at the end of the period. Both pathways are similar even so at the end of the period thermal amplitude is less pronounced. This shows the increasing contribution of meltwater with short residence time, which gradually dilutes and expels the water having longer residence time. This was already visible in the thermal variations of the spring. The Q-T_{spring} 3h-lag corresponds to the transfer time of meltwater in the drain between its arrival in the phreatic zone and the spring (plus the time of transfer of piston-flow, assumed to be short). Or more probably, this time represents the average time of several point contributions of infiltrated water. Let's assume 7 h as the time including the transfer in the vadose zone (plus the transfer of piston-flow) and 3 h in the drain (which also includes the time of transfer of piston-flow). Accordingly, the transfer time from the surface to the spring would be a little less than about 10 h.

6. Conclusion

We studied an 11 days period of snowmelt influence on Coulomp karst spring dynamic. The discharge (Q) regularly oscillates between 500 and 1,700 L/s. The contribution of snowmelt discharge (Snowmelt Q) is 30–50 % of Q. Amplitude of spring temperature (T_{spring}) is about 2 °C due to alternation of cold snowmelt water with low residence time and "warm" phreatic water with longer residence time. The lag between the peak of air temperature (T_{air}) corresponding to the maximum of snow melting and the peaks of Q, corresponding to the transfer time between surface and spring, is less than 10 h. This 10 h transfer time combines about 7 h of vertical transfer through the vadose zone and 3 h of horizontal transfer through the drain. The time of transfer of piston flow is assumed to be short and would not affect significantly the estimation of both vertical and horizontal transfer times. In the future, we will use dye for an assessment of the velocity in the drain, which is know along 1.7 km, including 32 % in siphon (full-pipe flow), 50 % in pools (uniform flow), and 17 % in torrential flow. For similar Q and assuming a 3h time for horizontal transfer, we might obtain an estimation of the average distance of the location of vertical flow arriving in the horizontal transfer zone. Currently, this place, located beyond the upstream sump, remains unknown.

Acknowledgments

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