Groundwater response to precipitation extremes: the case of the “Vaia” storm (Eastern Italian Alps)

La risposta delle acque sotterranee a precipitazioni estreme: il caso della tempesta “Vaia” (Alpi Orientali)

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Abstract: Extreme precipitation events are expected to increase in intensity in Alpine regions due to climate change. While many studies have analyzed the impact of these phenomena on flooding risk, very few deal with their effect on groundwater. This work analyzes the hydrograph response of three springs to an extreme storm, which occurred in Northern Italy in October 2018. We observed that the newly infiltrated storm water contributed to feeding the winter baseflow, increasing its volume up to 85% compared to normal conditions. It was also found that the response of groundwater to heavy precipitation seems to be influenced by the type of media. A high-altitude spring belonging to the fractured carbonate aquifer shows a quick response to the storm input, while springs outflowing at the base of the mountain slopes (mixed fractured carbonate and porous deposits) exhibit a delayed response. Results are important when analyzing future water availability and to better understand the impact of extreme events on groundwater flow.

Introduction

Global warming is expected to produce several effects on the European Alpine climate, producing snow recession at low elevation (Beniston 2012) and a greater portion of liquid to solid precipitation (Confortola et al. 2013). While regional climatic models agree with a reduction of summer precipitation and thus increased drought stress in the future (Calanca 2007; Gobiet et al. 2014), precipitation extremes, such as those events with a 10-year return period, are expected to increase in intensity (Brönnimann et al. 2018; Asadieh and Krakauer 2015). Extreme weather events in the Alpine region are responsible for flooding and landslides, and have direct social and economic impact. For this reason, studies on precipitation extremes frequently deal with natural hazards, especially landslides and flooding risk (Yang et al. 2016; Dankers et al. 2014; Kron et al. 2019). Therefore, while knowledge on surface runoff is good, studies on the groundwater response to precipitation extremes are rare (Zhangh et al. 2016). The aim of this work, is to contribute to fill this gap by analyzing data from an exceptional storm (“Vaia”), thanks to a daily discharge dataset recorded from a spring monitoring network. The exceptional event occurred during the no-recharge period of the alpine aquifers, therefore the alteration of the spring recession curves was analyzed in order to achieve new knowledge on the drainage processes. Recession analysis is a fundamental tool in hydrogeology and has been used successfully to study the behavior of karst aquifers and to describe flow components (Bonacci 1993; Padilla et al. 1994; Baedke and Krothe 2001; Baedke and Krothe 2001; Fiorillo 2009).
Also, the comparison of different recession curves in the same spring allows understanding which recession parameters represent inherited aquifer characteristics (Amit et al. 2002). In the studied area, the three studied springs are utilized for drinking water supply. Hence, quantification of extreme events and understanding their effect on groundwater storage is fundamental for ensuring suitable a sustainable water management planning.

**Study area**

The study area is located in the Dolomites Mountains (Eastern Italian Alps). The elevation ranges between 1000 m a.s.l. at the valley floor and over 2900 m a.s.l. at the highest peaks, respectively the Pala di San Martino and the Canali Peak. The geology of the area consists in a thick sequence of Middle Triassic dolomites, forming the main fractured and karst aquifer (Fig. 1). Below, clay-rich evaporitic and terrigenous formations act as the regional aquiclude (Lucianetti et al. 2019). Rockfall deposits cover the mountain slopes, creating a transition between the vertical rock faces and the valley-fill deposits, mainly glacial morains and alluvial deposits. Water outflowing from the carbonate aquifer is transferred to the valley-fill deposits, which host multilayer porous aquifers. The Pradidali stream originates at the Pradidali springs (1456 m a.s.l.) and it flows until the confluence with the Canali stream. The Pradidali springs group drains water exclusively from the carbonate aquifer and comprises several seepages and a main emergence point (Pra in Fig.1). The Acque Nere springs (1150 m a.s.l.) emerge in the Canali valley at the base of a large debris cone below Mt. Feltraio, in correspondence with clay layers of the moraine deposit. Two spring houses, Acq1 and Acq2 feed the local water supply. Groundwater emerges also diffusively along the riverbed as gaining reaches along the streams. From a climatic point of view, the mean annual temperature for the 2014-2018 period is 7.9 °C and the mean annual precipitation is approximately 1480 mm at the Tonadico station (1045 m a.s.l.), while it is respectively 7.1 °C and 1735 mm at the Cereda station (1322 m a.s.l.) for the same time period.

**The storm Vaia**

Between October 27th and 29th of 2018, an extreme meteorological event known as storm "Vaia" hit the study area. The 72 hours rainfall quantity was exceptional, with peaks above 600 mm in two stations of the Trento Province, including one station, the Cereda station, located close to the study area (Trenti 2018). In the Tonadico station, the 72 hours cumulative amount was 361 mm, corresponding to 25% of the yearly average amount. The storm caused flood waves in several streams, landslides and intense forest damage due to the wind gusts exceeding 200 km h⁻¹ (http://www.meteotrentino.it). In the North of Italy the loss of standing trees was estimated to be 8.5 million cubic meters (Chirici et al. 2019). In the study area the damage was concentrated in the Canali valley, both in the upper part of the valley and near the confluence with the Pradidali stream, where the Canali stream overflowed its banks destroying the main road. The storm followed a dry and exceptionally warm period, which was characterized by Foehn winds and fires (http://www.nimbus.it/eventi/2018/181024CaldoRecord2.htm). After the storm and until the following April 2019 the precipitation amount was very low, with only one small event in February. These peculiar weather conditions allowed to clearly distinguish in the spring recession phase the part of the discharge volume attributed to the storm.

**Methods**

**Hydrological monitoring**

The monitoring network consists of three springs equipped with water level sensors: Pradidali spring and Acque Nere springs (Pra, Acq1, Acq2 in Fig. 1). Monthly discharge measurements were carried out using a magnetic current meter (OTT Nautilus) to extrapolate the stage-discharge relationships. The rating curves were used to convert level data into discharge time series (hydrographs). Data presented in the paper refer to the period between September 2017 and May 2019. Precipitation and temperature for the same time interval were derived from the official weather service (meteotrentino.it) at the Tonadico station.

**Data analysis**

The shape of the hydrographs was compared to climatic data to understand the general response of the groundwater to recharge inputs. The discharge regime of all springs was characterized by the spring coefficient of variation parameter (CV) (Buczyński 2018)

\[
CV = \frac{\sigma}{\theta} \times 100
\]

where \(\sigma\) is the standard deviation and \(\theta\) is the arithmetical mean of spring discharge values. Springs with lower values of CVs tend to be more stable. Then, the master recession curves (MRCs) for each spring were constructed using recession periods characterized by more or less unaffected conditions (i.e. without recharge impulses that could interrupt the recession signal). Individual recession sets were assembled together by moving them individually on the horizontal axis to find the most representative MRC, following the approach of Malik and Vojtkova (2012). In this step, the storm recession curve was discarded to obtain MRCs in normal weather conditions. Being aware that more years are usually required to build representative MRCs, we were limited by the availability of a two-year dataset. However, the pre-storm period reflects acceptable conditions to allow us to build average MRCs with sufficient accuracy. Based on the MRCs, the recession parameters of each spring were defined and attributed to the different flow components of the groundwater system (Kresic and Bonacci 2010, Malik 2015). The several phases of the recession period were described both with exponential equations and with linear equations. Recession parameters of the different springs were compared with each other to verify...
Fig. 1 - Hydrogeological setting of the study area (modified after Lucianetti et al. 2019) and location of the monitoring network. The pink color represents the carbonate complex, which is formed mainly by middle Triassic dolomites and represents the main fractured and karst aquifer, while the grey color represents the terrigenous and evaporitic complex forming the main regional aquiclade. The porous valley-fill deposits consist of interdigitated rockfall, alluvial and glacial deposits. Blue dots and blue triangles refer respectively to the main point springs and to submerged springs (i.e. gaining streams).

Based on an in-house Matlab script the “unaffected baseflow volume” ($V_{b\text{u}}$) and the “baseflow volume after the storm” ($V_{b\text{a}}$ after storm) were calculated for each spring.

The Matlab function computes the numerical integration of the discharge and was applied first to the unaffected discharge time series (i.e. to the MRC joined to the recession phase in September 2018). It was then interrupted by the storm arrival in order to show how the recession curve would have continued without the storm influence. This allowed to compare the two recession curves: the real post-storm recession and the presumed “unaffected” recession curve.

If they were affected by the different geological features of the springs. Then, to show if the recession parameters change during wet years or remain constant, the storm recession curve which lasted until the following April 2019 was analyzed. The previously built MRC for each spring was joined to the recession phase which started in September 2018 (interrupted by the storm arrival) in order to show how the recession curve would have continued without the storm influence. This allowed to compare the two recession curves: the real post-storm recession and the presumed “unaffected” recession curve.
winter recession phase (31 days before the first recharge input) was chosen for the calculations. For instance, for the Acq2 spring the first recharge input was observed on 05/04/2019, therefore the baseflow volumes were calculated considering the discharge between 04/03/2019 and 04/04/2019. To compute the baseflow volume variations ("extra V_b with storm") the unaffected V_b was subtracted from the V_b after storm.

**Results and discussion**

**Spring regime and general characteristics**

The daily discharge recorded for the monitored springs is represented in Fig. 2a. During the period under observation, some analogies can be recognized between the spring hydrographs. All the springs appear to be strongly influenced by snow, as high-flow starts in correspondence of the melting season (April and May), when the temperature rises above 0 °C (Fig. 2b). This causes a sudden increase in discharge. In late summer, when all the snow cover is melted the spring discharge starts to decrease towards the winter months. In autumn (September, October and November) the hydrograph is affected mainly by rain, as the temperature is usually above 0 °C.

![Fig. 2 - a) Daily hydrographs of the monitored springs b) climatic data at the Tonadico station. See Fig. 1 for the location.](image)

Low-flow periods occur during the winter months (January, February and March), when recharge is prevented by the snow cover and frozen soil. Average spring characteristics are reported in Tab.1. Among the monitored springs, Pra spring shows the highest mean discharge (152 L/s) and the greatest discharge variation (CV 64%) as well as a fast and steep response to precipitation. Acq2 and Acq1 springs show a delayed reaction to recharge inputs and a more buffered curve. Acq2 is characterized by the lowest average discharge (55 L/s) and a more stable regime (CV 39%).

| Spring code | Official name | Elevation [m a.s.l.] | Mean Q [L/s] | Min Q [L/s] | Max Q [L/s] | CV (%) |
|-------------|---------------|----------------------|--------------|-------------|-------------|-------|
| Pra         | Pradidali     | 1456                 | 152          | 19          | 317          | 64%   |
| Acq1        | Acque Nere    | 1154                 | 107          | 25          | 185          | 48%   |
| Acq2        | Acque Nere    | 1150                 | 55           | 19          | 90           | 39%   |

**Recession analysis in normal conditions**

The MRCs allowed identifying the different flow components of the springs (Fig. 3). In all cases, a single recession coefficient value seems unable to explain all the draining processes.

![Fig. 3 - Master recession curves of the monitored springs represented in a normal plot (a) and in a semilogarithmic plot (b).](image)

Three different regimes have been identified for the Pra and Acq1 springs as the recession curve can be approximated by two exponential functions and one linear function, with three recession coefficients (α_1 and α_2 for the exponential regimes and β_1 for the linear regime). Only two exponential regimes have been recognized for the Acq2 recession curve. As suggested by Milanovic (1976) and following literature, the coefficients can be interpreted as flow from three types of porosity, represented by the three recession coefficients of successive orders of magnitude. β_1 is a reflection of rapid outflow karst conduit and open fractures, α_2 is interpreted as mixed flow in well connected fissures and α_1 can be considered to be a response to the drainage of water from pores and narrow fissures. This last exponential term with the smallest recession coefficient corresponds to the baseflow no more fed by the meteoric recharge. The springs show similar baseflow parameters, with α_1 between 0.004 and
0.005 indicating a common hydraulic property attributed to the same basal regional aquifer (the carbonate aquifer). The contrast between the MRCs is highest during the first stage of the recession limb which is characterized by the rapid flow component ($\beta_1$) and is representative of the local properties of each spring. Pradidali spring is dominated by the quickflow for the first 63 days after the beginning of the recession. On the contrary, in the Acq2 spring, the rapid flow stage is absent. Acq1 displays an intermediate behavior, with a small volume of quickflow, which is rapidly released after the first 26 days from the beginning of the recession. Likely, the quickflow component is present also in the carbonate aquifer draining the Acque Nere springs, but it is progressively buffered by the slope deposits, which transfer the groundwater flow from the carbonate aquifer to the valley-fill porous aquifers. Springs influenced by the porous deposits are therefore progressively more stable (CV 64%, 48% and 39% for the Pra, Acq1 and Acq2 respectively). A summary of the recession parameters can be found in Tab.2.

**Hydrograph response to extreme precipitation**

All the springs show a clear spike related to the rapid infiltration of storm water produced by Vaia (Fig. 4). Pradidali spring shows the fastest recovery to pre-event discharge (55 days) (Tab. 3). Recovery of the discharge to pre-event values takes 88 days for the Acq1 spring and 116 days for the Acq2 spring. This difference in recovery time can be explained with the fact that the storm occurred during the quickflow recession stage for the Pra spring, during mixed flow for the Acq1 spring and during the slow flow recession stage for the Acq2 spring (Fig. 4), therefore producing a faster or slower release of the storm wave. This hypothesis is supported also by the delayed response of the springs to the storm flood wave. A very fast discharge response to the storm peak is manifested in the Pradidali hydrograph, contrary to the other springs that show a delayed peak after 8 days.

| Spring code | Flow type | Equation type | MRC Recession curve parameters [1/day] | MRC Q₀ at the beginning of recession [L/s] | Storm Recession curve parameters [1/day] | Q₀ at the beginning of storm recession [L/s] |
|-------------|-----------|---------------|----------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| Pra         | Quickflow (conduit flow) | $Q_t= Q_0(1-\beta_1 t)$ | $\beta_1 = 0.012$ | 262 | $\beta_1 = 0.012$ | 274 |
|             | Mixed flow | $Q_t= Q_0 e^{-\alpha_2 t}$ | $\alpha_2 = 0.012$ | 68 | $\alpha_2 = 0.011$ | 76 |
|             | Baseflow (diffuse flow) | $Q_t= Q_0 e^{-\alpha_1 t}$ | $\alpha_1 = 0.004$ | 30 | $\alpha_1 = 0.003$ | 32 |
| Acq1        | Quickflow (conduit flow) | $Q_t= Q_0(1-\beta_1 t)$ | $\beta_1 = 0.016$ | 139 | $\beta_1 = 0.012$ | 185 |
|             | Mixed flow | $Q_t= Q_0 e^{-\alpha_2 t}$ | $\alpha_2 = 0.010$ | 81 | $\alpha_2 = 0.010$ | 82 |
|             | Baseflow (diffuse flow) | $Q_t= Q_0 e^{-\alpha_1 t}$ | $\alpha_1 = 0.005$ | 52 | $\alpha_1 = 0.005$ | 44 |
| Acq2        | Mixed flow | $Q_t= Q_0 e^{-\alpha_2 t}$ | $\alpha_2 = 0.011$ | 61 | $\alpha_2 = 0.010$ | 87 |
|             | Baseflow (diffuse flow) | $Q_t= Q_0 e^{-\alpha_1 t}$ | $\alpha_1 = 0.005$ | 34 | $\alpha_1 = 0.004$ | 32 |

Tab. 2 - Recession parameters and flow components identified for the monitored springs.

Tab. 2 - Parametri di recessione e componenti del flusso identificati per le sorgenti monitorate.

Fig. 4 - Hydrographs of the monitored springs. The master curves previously build for each spring (Fig.3) were joined to the recession phase which started in September 2018 (interrupted by the storm arrival) in order to show how the 2018-2019 winter recession curve would have continued without the storm influence.

Fig. 4 - Idrogrammi delle sorgenti monitorate. Le curve di master precedentemente costruite (Fig.3) sono state giunte alla recessione iniziata a Settembre 2018 (interrotta dall’arrivo della tempesta) per confrontare come sarebbe prosseguita la recessione durante l’inverno 2018-2019 senza l’influsso della tempesta.
suggest that extreme events will maintain their seasonality. If for water resources management. Also, climate change models predicted to intensify in the alpine region, so understanding conditions. With climate change, precipitation extremes are interesting to investigate the effect of precipitation extremes even in the following recession (2019-2020). It could also be this additional recharge input will contribute to baseflow in the following dry season and thus is crucial both for water resources utilization and for ecological purposes.

The recession analysis performed after storm shows that the recession coefficients of the springs remain more or less unaltered compared to the average parameters found with the MRCs, therefore the recession coefficients reflect inherited aquifer characteristics. The effect of the storm is manifested in a shifting of time of several months of the recession stages. For instance, the Pradidali spring, in normal conditions would have reached baseflow in the middle of January, whereas the baseflow beginning is shifted to the end of March. For Acq1, baseflow would have started in the end of November and is moved further to March. Compared to unaffected conditions, all the springs show a rising of the baseflow (Fig. 4) indicating that the storm water is able to reach the saturated zone of the aquifer. The volume difference between the baseflow in normal conditions and the baseflow after the storm can be considered as a measure of the impact of the storm on the groundwater reserves. The baseflow volume increase is similar (Tab. 3) and is comprised between 32100 m$^3$ at the Pra spring and 36641 m$^3$ at the Acq2 spring. Considering the percentage increase compared to normal conditions, an average baseflow increase of 61% was found for the monitored springs, with the highest increase in the Acq2 spring (85%).

Conclusions

Exceptional storm events can be interesting because they can significantly affect the groundwater system allowing to gain insights into the aquifers characteristics. Results from this work show that the “Vaia” storm recharged the groundwater system for several months, causing a delay of the spring hydrograph recession. This additional recharge sustains baseflow in the following dry season and thus is crucial both for water resources utilization and for ecological purposes. The results of this work should be intended as a preliminary approach: climate models versus observations. Hydrology and Earth System Sciences 21:5863-5874

Tab. 3 - Parameters that reflect the passage and release of the storm water. *The volume refers to the last month (31 days) of baseflow before the new recharge input.

| Spring code | Lag time from precipitation peak [days] | Peak Q [L/s] | Pre-event Q [L/s] | Recovery to pre-event Q [days] | Unaffected baseflow volume* [m$^3$] | Baseflow volume after storm [m$^3$] | Extra baseflow volume [m$^3$] | Baseflow volume increase % |
|-------------|----------------------------------------|--------------|------------------|-------------------------------|---------------------------------|-------------------------------|-----------------------------|--------------------------|
| Pra         | < 1                                    | 317          | 101              | 55                            | 58468                           | 90568                         | 32100                       | 55%                      |
| Acq1        | 8                                      | 185          | 64               | 88                            | 76863                           | 109770                        | 32907                       | 43%                      |
| Acq2        | 8                                      | 87           | 33               | 116                           | 43042                           | 79683                         | 36641                       | 85%                      |

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