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COMPREHENDING MOUNTAIN SPRINGS' HYDROGEOLOGICAL PERSPECTIVES UNDER CLIMATE CHANGE IN AOSTA VALLEY (NORTHWESTERN ITALY): NEW AUTOMATED TOOLS AND SIMPLIFIED APPROACHES

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EXTENDED ABSTRACT

I meccanismi di ricarica delle sorgenti montane hanno subito cambiamenti significativi a causa dei cambiamenti climatici e dell'uso del suolo, nonché dei modelli e delle politiche di consumo idrico attuati nel corso degli ultimi anni. In particolare, le mutate condizioni metereologiche hanno influenzato i volumi di deflusso delle portate sorgive, i tassi di evapotraspirazione, i rapporti neve-pioggia, causando nuovi regimi di precipitazione, anche associati all'aumento delle temperature medie dell'aria alle diverse quote. Di conseguenza, esaminare come i meccanismi di stoccaggio delle acque sotterranee stiano cambiando in risposta agli agenti climatici e antropici è diventato cruciale per comprendere ed elaborare scenari futuri associati alla disponibilità di acqua potabile in area montana. Per fare ciò, è necessario sviluppare e rendere applicabili strumenti automatizzati e approcci semplificati per monitorare continuamente le variabili idrogeologiche che influenzano il sistema di ricarica delle sorgenti, comprendendo correttamente le dinamiche di esaurimento delle risorse idriche sotterranee. SOURCE (a semi-automatic tool for Spring mOnitoring data analysis and aqUifeR CharactErization) è un avanzato strumento di analisi, scritto in linguaggio Python, che automatizza il processo di caratterizzazione idrogeologica di una sorgente.

Le sue funzionalità sono state testate in questo lavoro attraverso l'analisi delle sorgenti montane denominate Promise (Comune di La Thuile) e Alpe Perrot (Comune di Champdepraz) e delle relative stazioni meteorologiche (La Thuile-Villaret e Champdepraz-Chevrère), site all'interno del territorio della Regione Valle d'Aosta (Italia nordoccidentale). I dati di input (portata, temperatura, conducibilità elettrica e precipitazioni) sono elaborati rapidamente, ottenendo output grafici, nonché valori relativi ai principali parametri idrodinamici dell'acquifero (coefficienti di auto e di correlazione incrociata). Inoltre, per comprendere la relazione tra i cambiamenti delle condizioni meteorologiche locali e la disponibilità idrica, sono stati presi in considerazione i trend di precipitazione e portata sorgiva relativi ad un arco temporale di 7 anni. Nonostante i trend definiti crescenti di portata, considerati i limitati valori di vulnerabilità ottenuti per la Sorgente Alpe Perrot è possibile ipotizzare un impatto ritardato dei cambiamenti climatici sul sistema di ricarica risorgiva. Tale impatto si suppone possa essere più veloce per la Sorgente Promise. Tuttavia, la natura geologica e le dimensioni dell'acquifero sono tali da rendere il sistema più resiliente all'aumento della temperatura dell'acqua.

Riuscire a monitorare e definire in maniera automatizzata gli effetti indotti sulle riserve idriche, attraverso approcci di analisi semplificati come quelli presentati in questo lavoro, è sempre più necessario, soprattutto per gli enti gestori dei servizi acquedottistici e le autorità locali. Un unico strumento software come SOURCE che raccoglie i principali metodi di caratterizzazione sorgiva ha il potenziale per ridurre sensibilmente i tempi di analisi. Inoltre, l'interfaccia intuitiva di SOURCE consente, non solo a ricercatori e idrogeologi ma anche ad utenti non esperti, di testare il software e utilizzare correttamente le sue funzionalità per l'analisi delle sorgenti montane.

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ABSTRACT

Mountain springs' recharging mechanisms have undergone significant changes due to climate change, as well as altered water consumption patterns and policies. Specifically, climate change has influenced the characteristics of spring discharges, evapotranspiration, snow-rainfall ratios, and snow seasonality, bringing new rainfall patterns associated with increased average air temperatures. Consequently, examining how groundwater storage mechanisms are changing in response to climate-driven has become crucial for understanding the future scenarios associated with water availability in such areas. Therefore, increasingly automated tools and simplified approaches need to be applied to continuously monitor hydrogeological variables affecting the spring recharge system.

SOURCE (a semi-automatic tool for Spring mOnitoring data analysis and aqUifeR CharactErization) is an advanced semi-automatic Python tool that automates the hydrogeological characterization of the springs' aquifers. Its functionalities were tested through the analysis of the Promise and Alpe Perrot mountain springs and the related meteorological stations (La Thuile-Villaret and Champdepraz-Chevrère) located in the Aosta Valley region (NW Italy). Input data (flow rate, temperature, electrical conductivity, and rainfall) can be rapidly processed, providing graphical outputs, as well as values for the main hydrodynamic parameters (e.g. auto and cross-correlation coefficients) for an aquifer. Besides, to comprehend the relationship between changes in weather conditions and water availability in the Aosta Valley Region (Northwestern Italy), 7-year precipitation and discharge trends were considered. Despite the increasing trends in flow rate, considering the limited vulnerability values obtained for Alpe Perrot, it is possible to hypothesize a delayed impact of climatic changes on the spring system. The impact of climatic changes on Promise spring is supposed to be faster. However, the nature and dimensions of the aquifer are such as to be resilience to increasing water temperature. Being able to continuously monitor and define the effects induced on water reserves through simplified analysis approaches, such as those presented in this paper, is increasingly necessary, especially for local authorities. A single software package such as SOURCE that contains all the main methods of water spring analysis has the potential to significantly reduce any analysis times.

***Keywords**: mountain springs, hydrogeology, hydrology, Python App, spring vulnerability*

INTRODUCTION

The impacts of climate change are readily observable in the Alpine regions. Mountainous areas and the species that inhabit them are dependent on and defined by climatic conditions that vary along elevation gradients. As a result, changes in climatic parameters have a strong impact on both the physical environment and the living world. Since the beginning of the 21st century, new record temperature highs are accumulating, signaling global warming. At the scale of the European Alps, over the 20th century, temperatures have risen by 2°C (Begert & Frei, 2018; Kuhn & Olefs, 2020; Kotlarski *et alii*, 2022). The warming phenomenon is amplified in mountain environments due to the increase in temperatures leading to a variation in the zones' size covered with ice and snow reflecting the sun's rays. These zones are replaced by areas of dark rock and vegetation, which instead absorb the sun's heat, increase ground temperature and contribute to the melting. Among the negative impacts recorded, the increase in temperature, combined with the decrease in summer rainfall, has led to summer droughts and groundwater shortages. This phenomenon is aggravated by the reduction of the snow cover and can cause a decrease in the available water amount (Laigle *et alii*, 2022).

Since mountain areas are characterized by high spatial variability of climate and surface features and steep vertical gradients, a reliable future projection of the climate change impacts on groundwater is challenging. The resulting patterns of climate change are often highly complex, small-scale, and demanding in terms of monitoring, modeling, and analysis. As reported by Cantonati *et alii*, 2022, the underground water's residence time characterizes the spring system's retention. If the water stays in the groundwater body for an extended period, a delayed impact of climatic changes on the spring habitat is expected. Correspondingly, groundwater bodies with a larger volume have higher resilience to increasing temperatures than smaller ones with the same flow velocity. Therefore, springs that drain small groundwater bodies are likely to be affected more quickly by climate change. In addition, the factor of the elevation of the springs' recharging area is also of importance. With increasing altitude, snow depth, and snow cover duration increase while the type of precipitation input varies. As the snow cover acts as a source of water for the mountain springs, the cool meltwater leads to increased discharge. Changes in the quantity and seasonality of precipitation strongly impact the spring system (Gizzi *et alii*, 2020; Cerino Abdin *et alii*, 2021; Gizzi *et alii*, 2022; Mondani *et alii*, 2022). However, the effects of small-scale weather extremes on springs have so far received little attention in the literature (Segadelli *et alii*, 2020). In addition, changes in spring habitat can be expected due to surface runoff after heavy rains, which can bring increased amounts of fresh rainwater. These influences of microclimatic conditions on the spring system must be understood and observed in the long-term period, to define the climate change effects and be able to assess them differently depending on the spring's location and altitude.

Considering the above, optimizing the current and future management of mountain groundwater resources and understanding their recharging systems from a hydrogeological perspective is increasingly necessary for developing adequate resource management strategies. In addition, groundwater resources must be correctly quantified to provide information for the assessment of the effects of climate change on water resources. In this context, new automated techniques and tools need to be applied to the analysis of aquifer hydrogeological parameters, fully understanding the dynamics of exhausting available groundwater resources. Over the decades, a large number of methodologies have been developed to derive hydrogeological information about mountain spring recharging systems. As reported by Leone *et alii*, 2020, the trends of the leading climate variables (i.e., rainfall, snow, and temperature) have direct control over groundwater storage conditions as well as spring discharge amounts. Therefore, long-term spring discharge time series, combined with available climate variables trend analyses, can facilitate the investigation of the possible effects of climate change on groundwater recharge mechanisms in different regions. Gizzi *et alii*, 2022 focused their analysis on the variations in groundwater discharge and recharge (i.e., precipitation) in the Aosta Valley (Northwestern Italy), defining how their trends have changed over the past years. 7-year discharge series of different Aosta Valley springs (Promise, Alpe Perrot, Promiod, Cheserod), rainfall data, and measured snow heights from selected meteorological stations were analyzed. Flow rate and precipitation trends were defined and validated for all case studies using the Mann–Kendall and Sen's slope trend detection tests applied to the entire series of data. Moreover, recent studies have highlighted the potentialities of using autocorrelation and cross-correlation methods for analyzing mountain spring monitoring datasets. In detail, the univariate (autocorrelation) method has been used to define the characteristics and structure of individual time series while the bivariate (cross-correlation) one has been used to investigate the connection between input and output time series, preliminarily defining the spring's vulnerability (Amanzio *et alii*, 2015; Lo Russo *et alii*, 2015; Lo Russo *et alii*, 2021).

In this paper, the tool SOURCE (a semi-automatic tool for Spring mOnitoring data analysis and aqUifeR CharactErization), developed by the applied geology-research group of the Politecnico di Torino, within the framework of the INTERREG ITALY-SWITZERLAND RESERVAQUA, project and described in Lo Russo *et alii* 2021, was applied to perform autocorrelation and cross-correlation analyses. Continuous datasets of input data (flow rate, temperature, electrical conductivity, and rainfall) from springs (Promise spring and Alpe Perrot spring) and meteorological stations (La Thuile - Villaret and Champdepraz – Chevrère), respectively, were used. The potentialities connected with the use of SOURCE were underlined. Besides, the results obtained were then compared with those described in Cantonati *et alii*, 2022, and Gizzi *et alii*, 2022, allowing for a hydrogeological characterization of Promise and Alpe Perrot springs aquifers under climate change.

MATERIAL AND METHODS

Case Studies: Promise and Alpe Perrot Springs

The Aosta Valley region is geographically located in the northwestern sector of the Italian peninsula (Fig. 1). From a geological point of view, the quaternary deposits of the Aosta Valley region cover the entire Quaternary period and are mainly related to the last Upper Pleistocene glacial episode and the post-glacial period (Holocene - present). Usually, quaternary deposits overlie the mountain slopes and constitute the aquifers supplying springs that are widespread over the entire region (Lo Russo *et alii*, 2015). In the proposed paper, Promise and Alpe Perrot mountain springs were explored. The selected springs, characterized by different aquifer types, are located in two minor tributary valleys. Besides, Promise and Alpe Perrot springs have been studied since 2010 through the activities carried out in the frameworks of several EU Cooperation and National projects.

The Promise spring is located at an elevation of 1580 m a.s.l. inside the La Thuile municipality territory. The Quaternary and recent formations comprise glacial deposits, deposits of gravitational origin, and eluvial-colluvial deposits. A series of gravitational structures and deposits are recognizable on the slope where the spring is located. In detail, the spring is hosted in an old argentiferous lead mine that reached its peak of production in the early 1900s. At present, the entire mine serves as the drainage of the spring, which has an intake spoil near the mine exit.

The Alpe Perrot spring is located at an elevation of 1280 m (Champdepraz municipality). The Quaternary cover that characterizes the slope that hosts the spring comprises Pleistocene glacial deposits (undifferentiated till, ablation or bottom deposits, landslide deposits with glacial transport, and scattered moraine skeletons) and glaciogenic deposits (glacial contact, glacial-lacustrine, and fluvioglacial). In addition, two other deposits are also present, namely, a glacial deposit consisting of poorly sorted pebbles and angular boulders mixed with eluvial-colluvial cover, present along the entire route leading to the spring, and a gravitational accumulation of large blocks that characterizes the entire area upstream of the spring at an altitude of approximately 1750 m a.s.l. (Gizzi *et alii*, 2022).

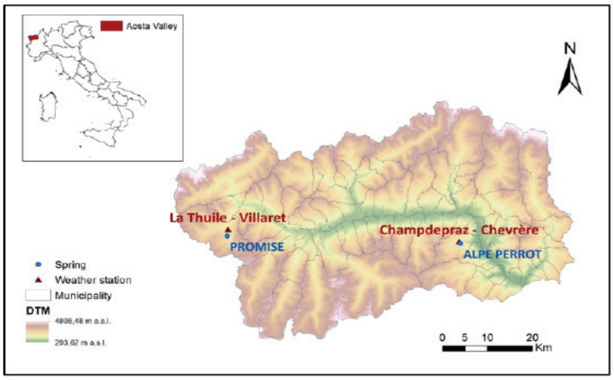

Fig. 1 - Promise and Alpe Perrot springs' geographical location

Source CODE

The dynamics of mountain groundwater resource depletion are heavily influenced by climate conditions. Annual variations in snow and rain precipitation inputs impact the hydrodynamic characteristics and exhaustion modalities of each spring. As such, it is necessary to propose to the scientific community new increasingly automated techniques that will allow researchers to estimate the main parameters of mountain aquifers quickly and accurately. For this purpose, SOURCE, a new, advanced, semi-automatic tool for spring characterization that uses available continuous datasets was developed by the applied geology-research group of the Politecnico di Torino and made freely available to the scientific community (Lo Russo *et alii*, 2021).

SOURCE is based on Python code, a high-level programming language with an object-oriented approach created by Guido van Rossum in 1991. The first version of the described Python code was developed in 2014 at Politecnico di Torino within the framework of the INTERREG ITALY-SWITZERLAND PROJECT. Over time, the tool was updated with the latest libraries of Python. To improve software performance, the number of libraries used has been limited, with preference given to common libraries over more experimental ones. In addition to the standard Python libraries, code for the proposed tool utilized the following:

- Numpy (https:// numpy. org/), the fundamental packagefor scientific computing;
- Matplotlib (https:// matpl otlib. org/), a comprehensive library for creating static, animated and interactive visualisations;
- Scipy (https:// www. scipy. org/), a Python-based ecosystem of open-source software for mathematics, science and engineering.

The script of the final version of the code was connected to a Postgres Database, where all input information is stored. The final program accepts tabulated data in an Excel spreadsheet and is usable in virtual environments on Linux, Mac and Windows OS. To correctly use SOURCE, Excel files must have a first sheet named "Spring-data" which contains the water spring's data, and a sheet named "Meteo-data" with associated meteorological data. Using the described format, it is possible to easily run the SOURCE script after setting parameters employing the proposed GUI interface (Fig. 2). The following information is also required:

- Filename: the file path of the Excel document, type string;
- Date start: the start date for the data, type string;
- Date stop: the stop date for the data, type string;
- Water spring name: name of the spring to be analyzed, type string;
- Select type of analysis: a choice of 'All', 'Recession curves', 'VESPA vulnerability index', 'Plot data' or 'Auto & Cross-correlation';
- Select method for recession curves: a choice of 'All', 'Maillet', 'Boussinesq' or 'none'.

Tool developed by Politecnico di Torino 2020 thanks to the project INTERREG RESERVAQUA.

Water spring name

Filename Open Excel File

Date Start 01/01/00

Date Stop 01/01/00

Select type of Analysis ○ All ○ Recession curves ○ Vespa Index ○ Plot Data ○ Cross Correlation

Select method for Recession curves: ○ All ○ Boussinesq ○ None ○ Maillet

Run application

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Fig. 2 - SOURCE code GUI (modified from Lo Russo et alii, 2021)

Autocorrelation and cross-correlation functions

Using the final version of the described Python code-SOURCE, graphical outputs and hydrodynamic parameter values for the analyzed springs can be obtained. In detail, spring hydrographs and recession curves analyses, VESPA index, autocorrelation and cross-correlation coefficient estimations can be performed, starting from continuous datasets of input data (i.e., flow rate, temperature, electrical conductivity, and rainfall).

Going into detail, the main potential of the code-SOURCE lies in the ability to rapidly execute time series data (autocorrelation and cross-correlation analyses) of flow rate (Q) and rainfall (P) data. Autocorrelation function (ACF) evaluates the linear dependency of successive values of a single parameter for a defined time series (e.g., flow rate). The method is univariate and gives information about the memory effect, corresponding to the temporal reciprocal influence on subsequent data of a single dataset. Statistically, the autocorrelation of a random process describes the correlation between values of the process at different points in time, as a function of the two times or the time difference. The autocorrelation coefficient (ACC) for a distance τ can be estimated by defining the covariance of all measurements xt and the ones with a time distance xτ+τ, according to the following equation (Eq. 1) (Lo Russo *et alii*, 2015):

$$cov\tau = \frac{1}{n-\tau}\sum_{t=1+\tau}^{n} x_t x_{t-\tau} - X_t X_{t-\tau} \tag{1}$$

where x is a time series, n is the number of measurements in the time series, τ is the time distance between two measurements, and X is the average value of the sample. The ACC ranges from 1 to 1. An ACC of 1 means that the compared time series are positively correlated.

Besides, to identify any instances of pronounced similarity or linear correlation between individual data, two different time series can be compared using the cross-correlation function (CCF; e.g., discharge versus rainfall parameters). Cross-correlation analysis is based on an equation similar to the autocorrelation function (ACF). If two-time series are marked as variables X and Y, and n is the number of pairs that are compared in one step (k) of the CCF, the cross-correlation coefficient can be obtained by the following (Box *et alii*, 1974) (Eq.2):

$$R_{xy}(K) = \frac{n\sum XY - \sum X \sum Y}{\sqrt{[n\sum X^2 - (\sum X)^2] \times [n\sum Y^2 - (\sum Y)^2]}} \qquad (2)$$

Values can range between -1 (perfect negative correlation) and +1 (perfect positive correlation); a value of 0 indicates no correlation.

As with the ACF, the CCF is an established technique that is usually applied to Q and P datasets. However, the CCF can also assess T and EC datasets, and such analyses could be used to validate hydrogeological considerations of the time lag response and maximum Rxy(K) values. Furthermore, the vulnerability index of different springs can be estimated using the lag time derived from cross-correlation analysis. This statistical method can be applied to explore the relationship between discharge and rainfall, as well as the relation between electrical conductivity and rainfall (Lo Russo *et alii*, 2021).

RESULTS

As reported in the introductory chapter, the tool SOURCE can be applied to obtain autocorrelation and cross-correlation coefficients. Continuous datasets of input data (flow rate, temperature, electrical conductivity, and rainfall) from springs (Promise spring and Alpe Perrot spring) and meteorological stations (La Thuile - Villaret and Champdepraz – Chevrère), respectively, were used to elaborate graphics outputs and properly perform springs analysis. Available input data were continuously recorded by the multiparametric probes installed in the Promise and Alpe Perrot springs and meteorological stations. Specific time intervals for both springs were selected, and the data for this period were processed using the final version of the described Python code (Tab.1). The monitoring datasets for the hydrogeological years 2018–2019 were selected and the outputs below were obtained and presented:

- spring hydrograph;
- autocorrelation and cross-correlation coefficients.

	2018–2019			
	Hydrogeological year		Recession period	
Promise spring	30/10/2018	16/10/2019	28/05/2019	16/10/2019
Alpe Perrot spring	28/10/2018	07/10/2019	22/06/2019	07/10/2019

Tab. 1 - Promise and Alpe Perrot springs hydrogeological year analyzed

Spring hydrograph

The first graphical output that can be obtained is spring hydrographs. As reported in Figs.3 and 4, the Promise spring and Alpe Perrot spring hydrographs were obtained by analyzing data from the selected time range (Tab.1), showing variation in quick flow at the end of the winter period. Pronounced discharge fluctuations in the fast-flow regime of the springs were due to contributions from snowmelt and the infiltration of precipitation during the autumn season. Abundant rainfall occurred during the autumn period of the selected hydrographic years, causing the formation of a new peak and a decrease in the recorded values of T and EC.

Autocorrelation and cross-correlation coefficient

The correlogram analysis is a commonly used tool for checking the randomness of datasets. If they are random, autocorrelations should be near zero for any time-lag separations considered. For Promise and Alpe Perrot springs correlation analysis was first performed on flow rate (Q) data. The distribution trend of the correlation coefficient reported in Fig.5a – 5b can be identified as a Gaussian curve; the correlation coefficient values are concentrated in a narrow range of values, and so the maximum autocorrelation

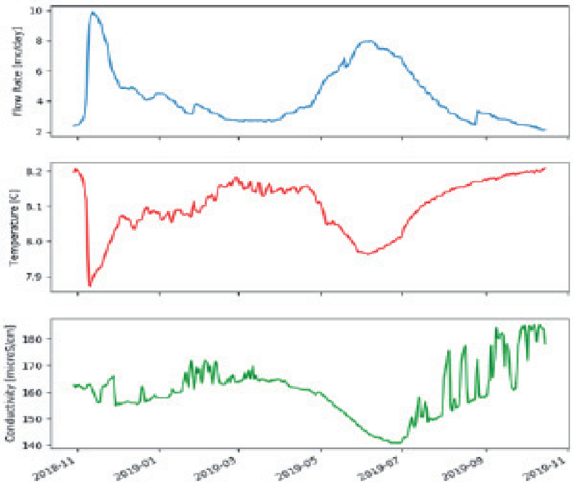
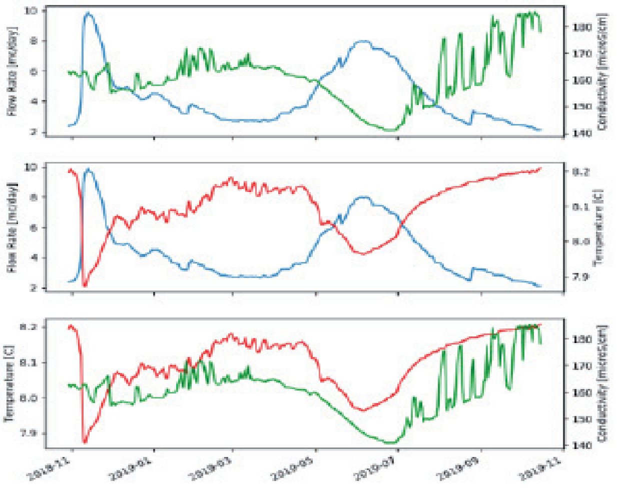


Fig. 3 - Promise spring's hydrograph: Q in blue, T in red, EC in green



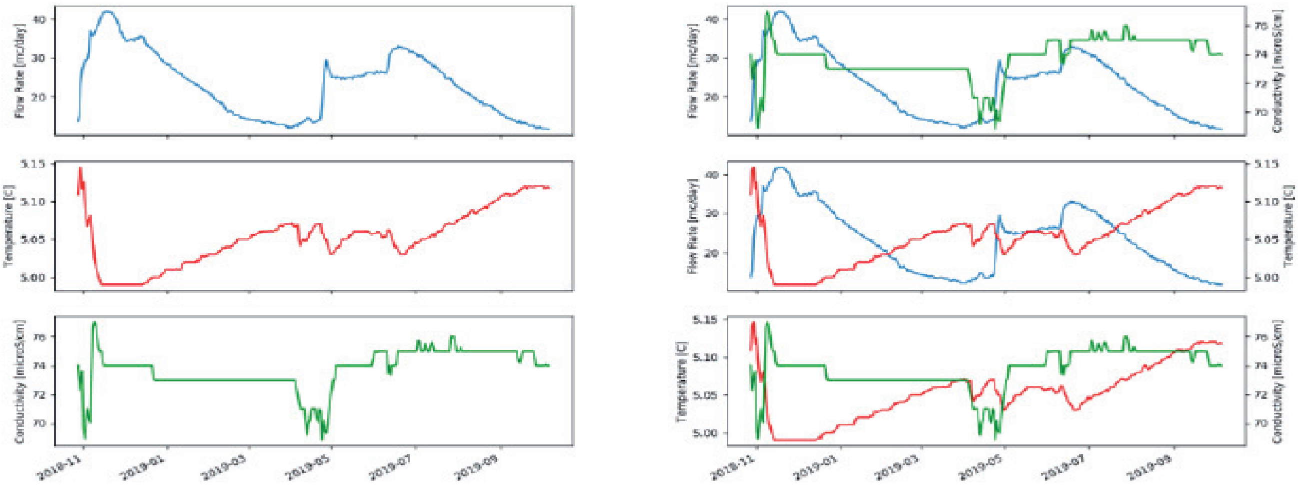


Fig. 4 - Alpe Perrot spring's hydrograph: Q in blue, T in red, EC in green

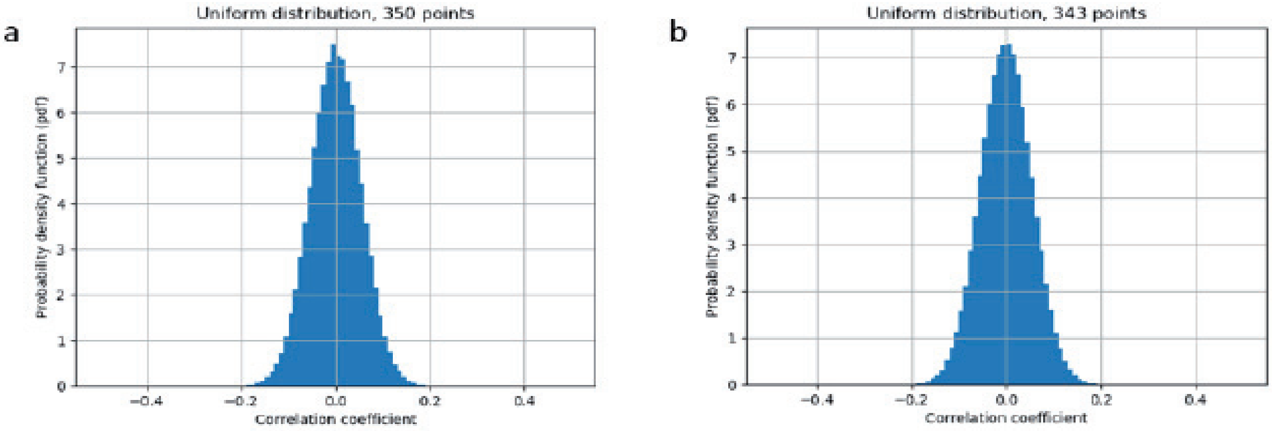


Fig. 5 - PDF of the estimated correlation coefficients a. Promise spring b. Alpe Perrot spring

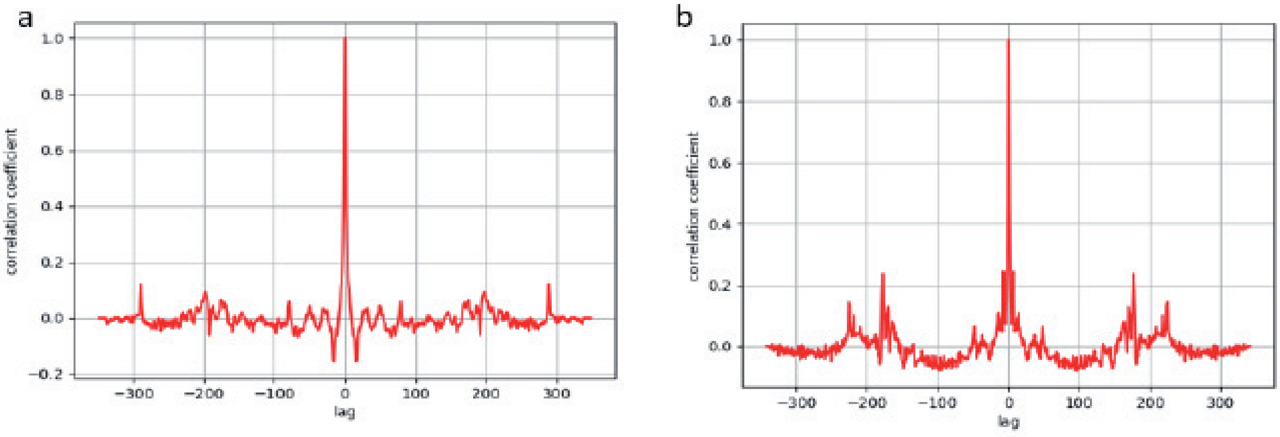


Fig. 6 - Estimated correlation coefficients, considering different time lags a. Promise spring b. Alpe Perrot spring

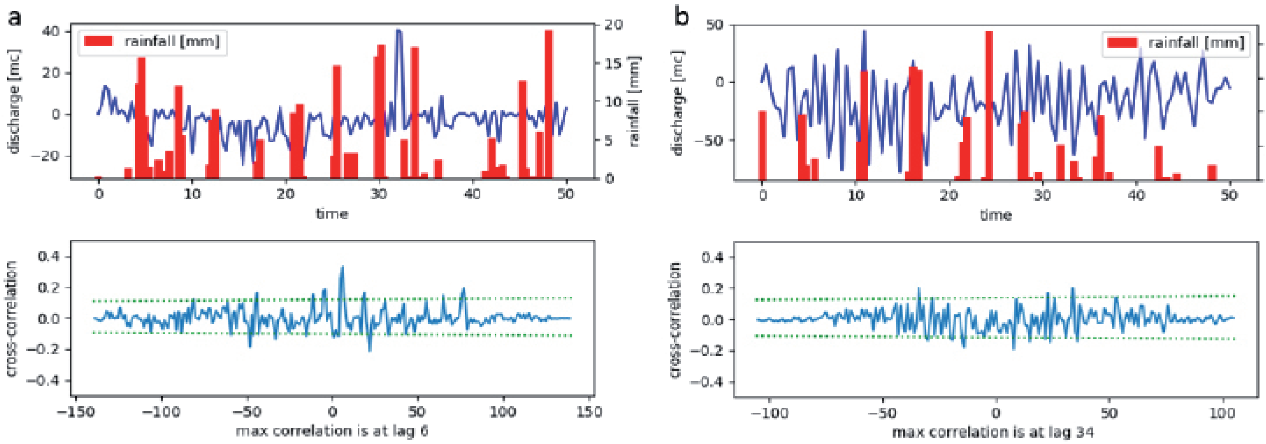


Fig. 7 - Cross-correlation between rainfall and flow rate a. Promise spring b. Alpe Perrot spring

is obtained with a very short lag time (Figs.6a – 6b).

In order to properly understand the correlation period between precipitation (P) and spring response (Q) has been neglected the influence of the winter recharge (solid precipitation) period until the maximum flow rate value (melting period). Therefore, the beginning of the period selected for cross-correlation analysis was considered coincident with the beginning of the exhaustion period (See Tab.1). Considering the selected period of analysis, it is possible to see how the lag time between rainfall and discharge tends to differ between the two springs. As shown in Figs.7a - 7b, the considered lag time was 6 days for promise spring and 34 days for Alpe Perrot spring.

DISCUSSION

The Aosta Valley territory includes several aquifer systems with different recharge rates and mechanisms. From the analysis of the results obtained, the Promise and Alpe Perrot recharge mechanisms turned out to be strictly connected with the geological nature of the aquifers. Their intrinsic features influence the extent of the correlation between different springs' physical variables. Due to their hydrogeological characteristics and the storage capacity of the drainage network system, the porous aquifer of the Alpe Perrot appears to be less vulnerable. Differently, Promise springs' fractured aquifer, is characterized by flow regimes with higher velocity and therefore vulnerability index. The results from cross-correlation analyses confirm this consideration.

Following what was described by Cantonati *et alii*, 2022, the underground water's residence time characterizes the spring system's retention. If the water stays in the groundwater body for an extended period, a delayed impact of climatic changes on the spring habitat is expected. In the same way, groundwater bodies with a larger volume have higher resilience to increasing temperatures than smaller ones with the same flow velocity. Therefore, springs that drain small groundwater bodies are likely to be affected more quickly by climate change. In addition, Gizzi *et alii*, 2022 focused their analysis on the variations in groundwater discharge and recharge (i.e., precipitation) in the Aosta Valley, defining among others how Promise and Alpe Perrot trends have changed over the past years. 7-year series of discharge, rainfall data, and measured snow heights from the associated meteorological stations (La Thuile - Villaret and Champdepraz – Chevrère) were analyzed in their work using the Mann–Kendall and Sen's slope trend detection tests. La Thuile-Villaret and Champdepraz– Chevrère meteorological stations revealed an overall decreasing trend in annual rainfall (mm), with a slight increase in intensity (mm/day) as a result of the reduction in rainfall events (number of rainy days). Nonetheless, based on the analysis of flow rate data relating to the associated springs, Promise and Alpe Perrot show an overall increasing trend of discharge over time. Considering the above, despite the defined increasing trends in flow rate, considering the limited vulnerability values obtained for Alpe Perrot it is possible to hypothesize a delayed impact of climatic changes on the spring habitat. However, the limited size of the aquifer's basin does not protect the groundwater resource from any changes in the water temperature parameter. Conversely, the impact of climatic changes on Promise spring is supposed to be immediate. However, the nature and dimensions of the aquifer are such as to be resilience to increasing water temperature.

CONCLUSIONS

Analyzing the impact of climatic variations on the water resources in mountain area is becoming increasingly important to develop future management strategies for drinkable water resources. In doing that, increasingly automated tools and simplified approaches need to be applied to continuously monitor hydrogeological variables affecting the spring recharge system and to punctually understand the dynamics of exhausting the available groundwater. The described code SOURCE (a semi-automatic tool for Spring mOnitoring data analysis and aqUifeR CharactErization) is an advanced semi-automatic Python tool that allows automating the hydrogeological characterization of the aquifers' behavior such as the Promise and Alpe Perrot springs ones. Input data were processed, providing graphical outputs, as well as values for the main hydrodynamic parameters (e.g. auto and cross-correlation coefficients) for an aquifer: a delayed impact of climatic changes can be hypothesized for the Alpe Perrot's spring system. As the opposite, considering the geological structure of the aquifer, the impact of climatic changes on Promise spring is supposed to be faster.

Being able to continuously monitor and define the present and future effects induced by climatic change on water reserves through simplified approaches such as those presented in this paper is important, especially for local authorities. The software package SOURCE contains all the main methods of water spring analysis; it has the potential to significantly reduce any analysis times. Besides, the SOURCE intuitive interface allows not only researchers and hydrogeologists, but also non-expert users to correctly use its functionalities for mountain spring analysis. The authors are open to all comments and advice from users that could help to further implement the code and improve the performance.

Code availability

SOURCE is an open-source software tool. The code is available for free download at https://www.diati.polito.it/ricerca/aree/geologia_applicata_geografia_fisica_e_geomorfologia

REFERENCES

Amanzio G., Bertolo D., De Maio M., Lodi L.P., Pitet L. & Suozzi E. (2015) - *Global warming in the alps: Vulnerability and climatic dependency of alpine springs in italy, regione valle d'aosta and switzerland, canton valais.* Eng. Geol. Soc. Territ. - Vol. 5 Urban Geol. Sustain. Plan. Landsc. Exploit. 1375–1378. https://doi.org/10.1007/978-3-319-09048-1_263

Begert M. & Frei C. (2018) - *Long-term area-mean temperature series for Switzerland—Combining homogenized station data and high resolution grid data.* Int. J. Climatol., **38**: 2792–2807. https://doi.org/10.1002/joc.5460

Box G.E.P., Jenkins G.M. & MacGregor J.F. (1974) - *Some Recent Advances in Forecasting and Control*. J. R. Stat. Soc. Ser. C., Applied Stat., **23**: 158–179.

Cantonati M., Lichtenwöhrer K., Leonhardt G., Seifert L., Mustoni A., Hotzy R., Schubert E., Blattner L., Bilous O., Lotz A., Poschlod B. & Gerecke R. (2022) - *Using Springs as Sentinels of Climate Change in Nature Parks North and South of the Alps: A Critical Evaluation of Methodological Aspects and Recommendations for Long-Term Monitoring.* Water, **14**. https://doi.org/10.3390/w14182843

Cerino Abdin E., Taddia G., Gizzi M. & Lo Russo S. (2021) - *Reliability of spring recession curve analysis as a function of the temporal resolution of the monitoring dataset*. Environ. Earth Sci., **80**: 1–12. https://doi.org/10.1007/s12665-021-09529-2

Gizzi M., Lo Russo S., Forno M.G., Cerino Abdin E. & Taddia G. (2020) - *Geological and Hydrogeological Characterization of Springs in a DSGSD Context (Rodoretto Valley – NW Italian Alps).* Appl. Geol.: 3–19. https://doi.org/10.1007/978-3-030-43953-8_1

Gizzi M., Mondani M., Taddia G., Suozzi E. & Lo Russo S. (2022) - *Aosta Valley Mountain Springs: A Preliminary Analysis for Understanding Variations in Water Resource Availability under Climate Change.* Water, **14**. https://doi.org/10.3390/w14071004

Kotlarski S., Gobiet A., Morin S., Olefs M., Rajczak J. & Samacoïts R. (2022) - *21st Century alpine climate change.* Clim. Dyn. **60**: 65–86. https://doi.org/10.1007/s00382-022-06303-3

Kuhn M., Olefs M. (2020) - *Elevation-Dependent Climate Change in the European Alps.* Oxford Res. Encycl. Clim. Sci.

Laigle I., Carlson B.Z., Delestrade A., Bison M., Van Reeth C. & Yoccoz N.G. (2022) - *In-situ Temperature Stations Elucidate Species' Phenological Responses to Climate in the Alps, but Meteorological and Snow Reanalysis Facilitates Broad Scale and Long-Term Studies*. Front. Earth Sci., **10**: 1–15. https://doi.org/10.3389/feart.2022.912048

Leone G., Pagnozzi M., Catani V., Ventafridda G., Esposito L. & Fiorillo F. (2020) - *A hundred years of Caposele spring discharge measurements: trends and statistics for understanding water resource availability under climate change.* Stoch. Environ. Res. Risk Assess. https://doi.org/10.1007/s00477-020-01908-8

Lo Russo S., Amanzio G., Ghione R. & De Maio M. (2015) - *Recession hydrographs and time series analysis of springs monitoring data: application on porous and shallow aquifers in mou ntain areas (Aosta Valley).* Environ. Earth Sci. **73**: 7415–7434. https://doi.org/10.1007/s12665-014-3916-z

Lo Russo S., Suozzi E., Gizzi M. & Taddia G. (2021) - *Source*: *a semi-automatic tool for spring-monitoring data analysis and aquifer characterisation.* Environ. Earth Sci., **80**: 1–13. https://doi.org/10.1007/s12665-021-10027-8

Mondani M., Gizzi M. & Taddia G. (2022) - *Role Of Snowpack-Hydrometeorological Sensors For Hydrogeological System Comprehension Inside An Alpine Closed-Basin*. Sensors, **22**. https://Doi.Org/10.3390/S22197130

Segadelli S., Grazzini F., Adorni M., De Nardo M.T., Fornasiero A., Chelli A. & Cantonati M. (2020). *Predicting Extreme-Precipitation Effects On The Geomorphology Of Small Mountain Catchments: Towards An Improved Understanding Of The Consequences For Freshwater Biodiversity And Ecosystems.* Water, **12**(1): 79 . https://doi.org/10.3390/w12010079

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