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Revealing spring discharge variability through Long-Term Hydrogeological Monitoring: insights from case studies in the Aosta Valley

Analisi della variabilità delle portate delle sorgenti mediante monitoraggio idrogeologico a lungo termine: risultati da casi di studio in Valle d'Aosta

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Abstract

Springs are key discharge points in groundwater systems and provide valuable insights into aquifer dynamics, particularly in Alpine regions, where they often represent the primary expression of subsurface flow. In the Aosta Valley (northwestern Italian Alps), a long-term monitoring network has been operating since 2010 to record water levels, temperatures, and electrical conductivity at representative springs across different geological and climatic settings.

By applying site-specific weir equations to continuous water-level data, discharge values were derived for multiple sites over a 14-year period (2010–2024). The results reveal differences in behaviour among the monitored springs. Cheserod, Mascognaz and, to a lesser extent, Entrebin show relatively buffered discharge regimes, whereas Gabiet and Promise display stronger interannual variability. Promise shows a marked increase in discharge in recent years, suggesting changes in recharge dynamics or hydrological functioning.

Comparative analyses highlight heterogeneous responses to climatic variability, confirming that Alpine groundwater systems are site-dependent. Graphical tools such as heatmaps, bubble charts and Olympic-pool equivalents were used to facilitate the communication of hydrogeological results to non-specialist audiences. The findings underscore the importance of continuous spring monitoring for both scientific understanding and the sustainable management of drinking-water supplies under changing climatic conditions.

Riassunto

Le sorgenti montane sono indicatori fondamentali del comportamento idrodinamico degli acquiferi, in particolare nelle regioni alpine, dove spesso rappresentano la principale manifestazione del deflusso sotterraneo. In Valle d'Aosta (Alpi nordoccidentali italiane) è attiva dal 2010 una rete di monitoraggio a lungo termine che registra in continuo il livello idrico, la temperatura e la conducibilità elettrica in sorgenti distribuite in diversi contesti geologici e climatici.

Mediante l'analisi di dati orari di livello idrico, disponibili per ciascun sito monitorato, sono stati derivati i valori giornalieri di portata e il volume annuale defluito per il periodo 2010–2024. I risultati evidenziano differenze significative nel comportamento idrodinamico tra le sorgenti monitorate. Cheserod, Mascognaz e, in misura minore, Entrebin mostrano regimi di portata relativamente stabili, mentre Gabiet e Promise evidenziano una maggiore variabilità interannuale. Promise registra un marcato aumento della portata negli ultimi anni, suggerendo possibili cambiamenti nelle dinamiche di ricarica o nel funzionamento idrologico del sistema.

Oltre alla prospettiva idrogeologica, il lavoro ha anche una finalità comunicativa. L'impiego di strumenti grafici, quali mappe di calore (*heatmap*), diagrammi a bolle e volumi espressi in equivalenti di vasche olimpioniche, è stato utilizzato per facilitare la comunicazione dei risultati idrogeologici a un pubblico non specialista. I risultati confermano l'importanza di un monitoraggio sorgivo continuo, al fine di sviluppare le conoscenze scientifiche e garantire una gestione sostenibile delle risorse idropotabili in un contesto climatico in evoluzione.

Introduction

Springs serve as key discharge points of groundwater systems and are vital indicators of the hydrodynamic behaviour of aquifers. In mountainous regions, especially in the Alps, they often represent the primary expression of groundwater flow, providing crucial information for both hydrogeological characterisation and water resource management. However, spring discharge variability is influenced by multiple factors, including aquifer lithology, geometry, recharge regime, and climate conditions, making the interpretation of discharge data a challenging but revealing task (Fiorillo et al., 2021; Mondani et al., 2022; De Filippi et al., 2024; Casati et al., 2024).

In the Aosta Valley (northwestern Italian Alps), groundwater circulation is strongly influenced by the region's complex geology and geomorphology. The territory is characterised by narrow valleys, steep hydraulic gradients, and a heterogeneous distribution of lithotypes ranging from fractured crystalline rocks to glacial and alluvial deposits. These features result in a wide variety of spring typologies, from perennial sources with significant baseflow components to highly variable, climate-driven springs. Despite their hydrogeological importance, systematic long-term monitoring of spring behaviour in the region has historically been limited (Grappein et al., 2021; Santillán-Quiroga et al., 2023).

Since 2019, within the framework of the RESERVAQUA project (Interreg V-A Italy–Switzerland Cooperation Programme), the Applied Geology Research Group at Politecnico di Torino has been conducting extensive spring monitoring in the Aosta Valley. Data collected from multiparametric water probes that record water levels hourly enable estimation of discharge volumes in selected Alpine springs over multiple hydrogeological years.

These recent activities build on the groundwork established between 2010 and 2013 through the STRADA and STRADA 2.0 projects, which focused on vulnerability assessments of monitored springs, the definition of protection areas, and the development of a regional spring monitoring network by installing weirs and multiparametric probes. Together, these efforts have created one of the most continuous and detailed spring datasets available for the Alpine region, offering a unique opportunity to investigate discharge variability across diverse hydrogeological and climatic settings.

In 2021, a new software tool called SOURCE (Spring mOnitoring data analysis and aqUifeR Characterisation) was developed and used to improve the efficiency and reproducibility of hydrogeological analyses. SOURCE enables semi-automatic processing of monitoring data to characterise spring aquifers by combining discharge, temperature, electrical conductivity, and meteorological data. Input data, arranged in standardised Excel templates, are processed to produce graphical outputs and calculate key hydrodynamic parameters, such as auto- and cross-correlation coefficients. The tool was first implemented for the Mascognaz spring (Lo Russo et al., 2021) and the Alpe Perrot and Promise springs in the Aosta Valley (Gizzi et al., 2023), where its features were tested using meteorological data from La Thuile–Villaret and Champdepraz-Chevrère stations. The analysis revealed different responses of the two aquifers to climatic forcing: climate variability had a delayed effect on the Alpe Perrot spring, whereas the Promise spring showed a quicker response.

Further regional-scale analyses were presented by Gizzi et al. (2022) to explore the relationship between changes in weather conditions and water availability in the Aosta Valley, as well as the evolution of these trends over the past decade. A seven-year discharge series from multiple monitored springs (Promise, Alpe Perrot, Promiod, and Cheserod) was analysed together with precipitation data from nearby meteorological stations (Saint-Vincent, Aymavilles-Viayes, La Thuile-Villaret, and Champdepraz). Mann–Kendall and Sen's slope tests were applied to detect trends in both precipitation and flow rates. The findings suggest that spring systems in the Aosta Valley may exhibit heterogeneous responses to climate variability depending on aquifer type, geometry, and recharge mechanisms. The most recent results were obtained by Gizzi & Biamino (2025), who focused on the Promise Spring between October 2011 and July 2024 and employed innovative methodologies, including Fourier transform analysis, to characterise spring hydrograph signals and their relationships with atmospheric temperature, snow depth, and rainfall data. Additionally, isotopic analyses of water samples were conducted to better understand the origin of the recharge waters that feed the spring. The study revealed a strong correlation between environmental variables and discharge dynamics, with the main discharge peaks coinciding with the completion of snowmelt (April–May). This confirms that snowmelt represents a primary source of recharge for the spring. Recent increases in discharge and the temporal shift of recession minima towards autumn and winter were attributed to altered meteorological conditions that have modified snow-accumulation regimes at higher elevations. The isotopic composition of Promise Spring waters indicated the absence of glacial water and a predominantly meteoric origin derived from snowmelt and precipitation.

Building on this long-term monitoring experience and the methodological advances developed through SOURCE and subsequent investigations, this work investigates the temporal variability of daily spring discharge across the Aosta Valley. The study's main contribution lies in the comparative analysis of long-term discharge records from multiple springs located in different hydrogeological and climatic settings, coupled with the estimation of annual discharge volumes for each hydrogeological year. This approach enables the identification of differences in the hydrodynamic behaviour of spring systems spread across different valleys of the region, supporting a comparative interpretation of how spring discharge and water availability have changed over time.

Beyond the strictly hydrogeological perspective, this study also functions as a means of communication. The results are presented in a way that is understandable not only to specialists but also to local authorities, stakeholders, and citizens who rely on these groundwater resources.

Within the environmental domain, effective communication has become increasingly central to addressing climate-related challenges and supporting informed decision-making (Cox, 2013). Previous studies have increasingly emphasised the importance of making groundwater and hydrogeological information more accessible to non-specialised audiences. For example, Linton & Budds (2014), within the framework of the hydro-social cycle, highlight the need to contextualise water knowledge within social and political dimensions, thereby broadening its interpretative accessibility beyond technical experts. Similarly, Gleeson et al. (2020) stress the importance of transparent communication of groundwater sustainability indicators in order to support informed policy decisions at multiple governance levels. Scientific knowledge gains practical value only when it is both credible and accessible to the broader public. In this sense, disseminating monitoring results and hydrological interpretations contributes not only to scientific progress but also to informed water governance and adaptive management strategies (Haasnoot et al., 2013; Castelli et al., 2025).

In this study, simplification consists of identifying key hydrogeological indicators that synthetically represent system behaviour and translating complex quantitative results into more intuitive, relatable graphs. More precisely, discharge volumes, expressed in litres, have been converted into more familiar reference units - such as the equivalent number of Olympic-sized swimming pools - to facilitate intuitive understanding among non-specialised audiences.

Materials and methods

Study area

The Aosta Valley Region (northwestern Italy) is an Alpine area characterised by complex geological, geomorphological, and climatic conditions that significantly influence groundwater movement. The region extends from Mont Blanc in the west to the Monte Rosa massif in the east, with elevations ranging from about 300 m above sea level in the central valley to over 4,000 m along the surrounding peaks. The geological framework primarily consists of crystalline and metamorphic rocks from the Penninic and Austroalpine domains, supplemented by glacial and alluvial deposits along the main valley floor (Bonetto et al., 2010; D'Amico et al., 2020; Arienti et al., 2024).

This structural and lithological diversity generates numerous springs, which serve as primary indicators of the regional groundwater flow system. Springs in the Aosta Valley exhibit significant differences in discharge patterns, recharge processes, and aquifer types, ranging from perennial, deep-fractured systems to shallow, snowmelt-driven sources (Lo Russo et al., 2015).

Climatic conditions are generally Alpine, with yearly precipitation ranging from 800 to 1,200 mm, mostly falling in spring and autumn, and showing significant spatial variability related to valley orientation and altitude. Snow accumulation and melting processes are essential for the annual recharge of aquifers, influencing both the volume and timing of spring discharge (Cremonese et al., 2019; Avanzi et al., 2022).

Spring monitoring network and data acquisition

Since 2010, a spring monitoring network has been gradually developed and expanded in the Aosta Valley through various regional and cross-border projects (STRADA, STRADA 2.0, RESERVAQUA). The network encompasses representative springs situated in different valleys and hydrogeological contexts: Cheserod, Promiod, Promise, Entrebin, Mascognaz, and Gabiet. These sites were chosen to represent a variety of elevations, lithologies, and hydrological behaviours that reflect regional variability. Each spring is fitted with multiparametric probes that record water level, temperature, and electrical conductivity at hourly intervals (Fig. 1).

Among the monitored sites, the Cheserod, Entrebin, Mascognaz, and Gabiet springs are equipped with intake structures for municipal water supply, whereas the remaining springs (Promiod and Promise) are either unexploited or used for local monitoring and research.

Water level data are recorded continuously and stored in dataloggers, with regular maintenance and data retrieval performed by the Applied Geology Research Group of the Politecnico di Torino. The measurement period considered in this work spans from October 2010 to September 2024, covering up to 14 hydrogeological years depending on data availability at each site.

For the purpose of this study, water-level time series were converted to spring discharge using standard weir equations specific to each monitored site and based on the known geometry of the installed weirs. Discharge values were expressed in litres per second (L/s) for analytical consistency.

Data Processing and Analysis

Water-level data from OTT CTD multiparametric probes constitute the primary dataset for the analysis. These data, expressed as water head (H, in meters) above the crest of the measurement structure, were collected at hourly intervals in correspondence with spring intake weirs. Each weir is characterised by specific geometric parameters that control the hydraulic relationship between water level and discharge.

Each monitored spring is equipped with a calibrated weir whose geometry was surveyed during the STRADA project. The main geometric and hydraulic parameters adopted for level–discharge conversion are summarised in Table 1.

The discharge (Q) associated with each recorded water level (H) was calculated using the classical weir equation in its general rectangular or triangular form, as reported in Eqs. 1 and 2, respectively (Henderson, 1966):

$$Q = \frac{2}{3} C_d b \sqrt{2g} H^{3/2} \qquad 1)$$

$$Q = \frac{8}{15} C_d \sqrt{2g} \tan\left(\frac{\theta}{2}\right) H^{5/2} \qquad 2)$$

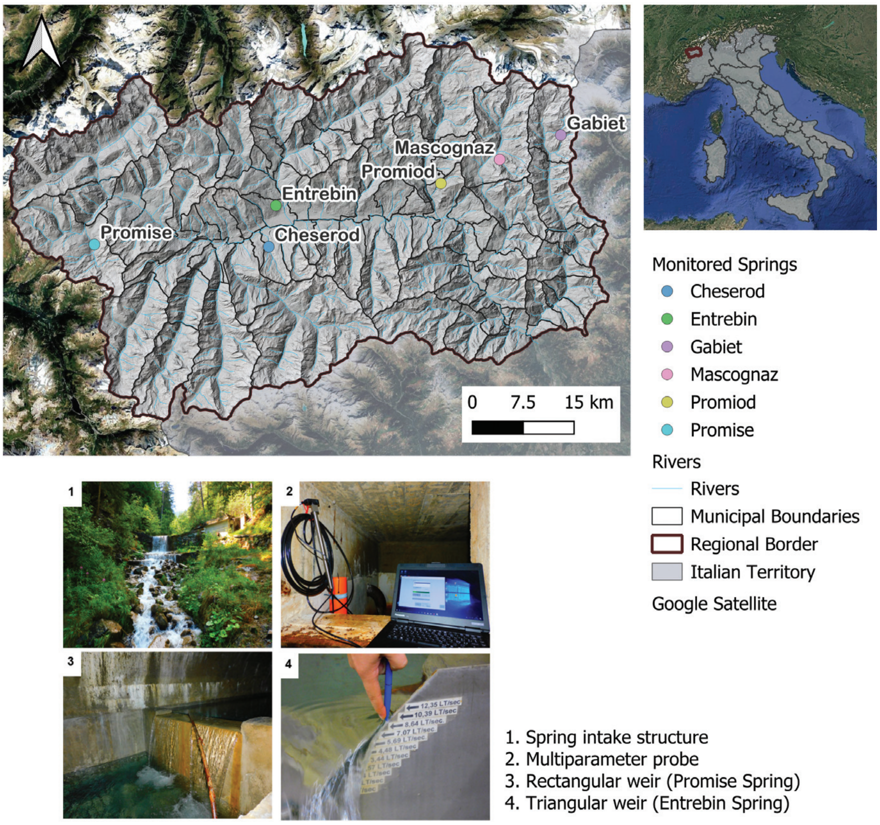

Fig. 1 - Map showing the location of the six monitored springs-Cheserod, Entrebin, Gabiet, Mascognaz, Promiod, and Promise-within the Aosta Valley (northwestern Italian Alps).
Photographs illustrate: (1) a typical spring intake structure, (2) a multiparameter probe installed inside the intake chamber, (3) a rectangular weir at Promise Spring, and (4) a triangular weir at Entrebin Spring.

Fig. 1 - Mappa che mostra l'ubicazione delle sei sorgenti monitorate - Cheserod, Entrebin, Gabiet, Mascognaz, Promiod e Promise - all'interno della Valle d'Aosta (Alpi italiane nord-occidentali).
Le fotografie illustrano: (1) una tipica opera di captazione, (2) una sonda multiparametrica installata all'interno della captazione, (3) lo stramazzo rettangolare presso la sorgente Promise e (4) lo stramazzo triangolare presso la sorgente Entrebin.

Tab. 1 - Summary of the main characteristics of the monitored springs in the Aosta Valley, including weir type, geometric parameters, discharge coefficient, reference elevation, and monitoring start date.

Tab. 1 - Sintesi delle principali caratteristiche delle sorgenti monitorate in Valle d'Aosta, comprendente il tipo di stramazzo, i parametri geometrici, il coefficiente di deflusso, la quota di riferimento e la data di inizio del monitoraggio.

Spring name	Valley/ Location	Weir type	Crest width *b* (m)	Crest angle (θ°)	Discharge coefficient *Cd*	Spring elevation (m a.s.l.)	Monitoring start
Cheserod	Gressan	Triangular		90	0.60	1095	December 2010
Promiod	Chatillon	Rectangular	0.52		0.60	1650	October 2010
Promise	La Thuile	Rectangular	1.4		0.60	1580	July 2012
Entrebin	Aosta	Triangular		90	0.60	981	October 2010
Mascognaz	Ayas	Rectangular	1.01		0.60	1850	February 2011
Gabiet	Gressoney	Rectangular	1.20		0.60	2340	October 2011

where C_d is the discharge coefficient (dimensionless), b is the effective crest width (m), g is the acceleration of gravity (9.81 m/s²), θ is the vertex angle (in radians or degrees), and H is the measured head over the crest (m). The coefficient C_d and geometric parameters were determined for each installation based on the specific weir type (rectangular, triangular, or compound) as recorded during the STRADA survey activities. The resulting level–discharge relationships were subsequently verified against manual discharge measurements collected during the STRADA project, confirming the overall reliability of the adopted rating curves.

For each monitored spring, the hourly discharge series was then aggregated into daily mean values, representing the average outflow for each day of record. These daily mean discharge values were subsequently used to calculate the total annual discharge volume for each hydrogeological year (1 October – 30 September) through numerical integration as Eq.3:

$$V_y = \sum_{i=1}^{n} Q_{avg,i}\Delta t \qquad 3)$$

where Δt = 86,400 seconds (one day). This yields the total discharged volume (V) which is subsequently expressed in Liters (L).

The resulting dataset, therefore, consists of:

1. Continuous daily discharge series for each monitored spring,

2. Cumulative annual volumes (hydrogeological years 2010–2024, depending on data availability).

The workflow, from data import to volume computation, was implemented using custom scripts developed in Python (van Rossum, 1995). These scripts ensure reproducibility of calculations and consistency among different sites. The results provide a quantitative foundation for analysing temporal variations in spring discharge and comparing the hydrodynamic behaviour of springs across different geological and climatic contexts within the Aosta Valley.

Data cleaning and outlier detection

Daily discharge data can contain measurement errors, gaps, or abrupt variations unrelated to hydrological processes (e.g., sensor malfunctions, data-logging errors, or short-term freezing).

To ensure data consistency and reliability, a moving-window statistical filter was applied to identify and correct anomalous values. For each day t, a rolling mean and rolling standard deviation were computed over a symmetric time window of N=30 days (Eqs. 4 and 5):

$$\mu_t = \frac{1}{N}\sum_{i=t-\frac{N}{2}}^{t+\frac{N}{2}} Q_i \qquad 4)$$

$$\sigma_t = \sqrt{\frac{1}{N-1}\sum_{i=t-\frac{N}{2}}^{t+\frac{N}{2}} \left(Q_i - \mu_t\right)^2} \qquad 5)$$

where Q_i represents the daily mean discharge. A value Q_t was classified as an ***outlier*** when it exceeded the range:

$$\mu_t \pm k\sigma_t \qquad 6)$$

with k=3.5 defining the sensitivity of the filter (following a 3–4 σ rule commonly adopted in environmental time-series analysis).

This approach enables the detection of both abnormally high and low values while accommodating seasonal variability in discharge. Detected outliers were replaced by *NaN* values and subsequently corrected through time-based linear interpolation, preserving the continuity and temporal resolution of the daily series. No filtering or smoothing was applied beyond this step, ensuring that natural discharge variability, including seasonal peaks, remained unaffected.

The proportion of corrected records was very limited across all monitored springs. A total of 23 values (0.48%) were identified as outliers at Gabiet, 8 (0.15%) at Entrebin, 8 (0.15%) at Promiod, and 1 (0.02%) at Promise, while no outliers were detected at Mascognaz. Given the very low percentage of corrected observations relative to the total length of each time series, the influence of the interpolation procedure on annual discharge volumes and anomaly patterns is considered negligible.

The above-described method was implemented in Python 3.12, using the pandas library for time-series processing and matplotlib for visualising the corrected daily discharge time series (see supplementary files).

Results

Analysis of annual discharge volumes from the monitored springs (Cheserod, Entrebin, Gabiet, Mascognaz, Promiod, and Promise) reveals spatial and temporal variations across the 2011-2024 hydrological years.

The grouped bar chart (Fig. 2) illustrates that Cheserod consistently generated the highest volumes, ranging from approximately 1.0 × 10^9 to 1.75 × 10^9 L per year. Gabiet and Mascognaz showed intermediate yields, while Entrebin and Promiod contributed smaller and more stable volumes. Besides, Promise Spring, initially among the least productive springs, showed a gradual increase in discharge after 2018, becoming a significant part of the total volume in recent years.

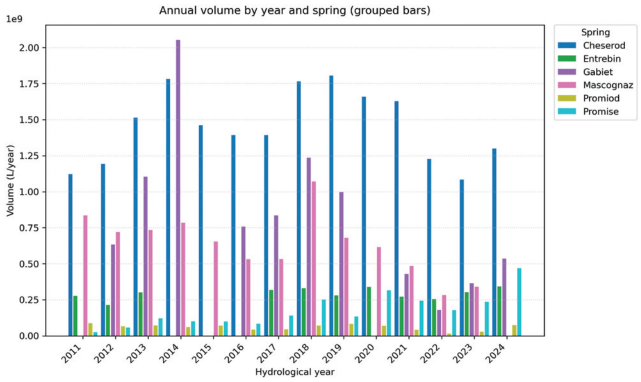

Fig. 2 - Annual discharge volumes (L) by spring and hydrological year (2011–2024).

Fig. 2 - Volumi annui di portata (L) per ciascuna sorgente e anno idrologico (2011–2024).

The bubble chart (Fig. 3) highlights the springs' dynamics by showing the relative interannual variations in a compact visual form. High-discharge years are concentrated around 2013-2019, with nearly all springs showing larger bubbles, while smaller bubbles dominate 2021-2023, indicating a phase of reduced overall discharge.

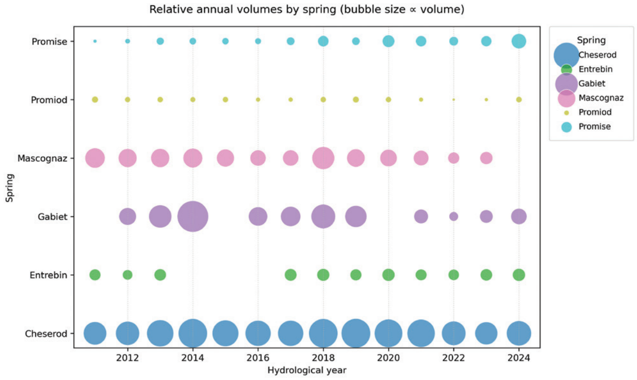

Fig. 3 - Relative annual discharge volumes by spring (2011–2024; bubble size proportional to volume).

Fig. 3 - Volumi annui relativi per ciascuna sorgente (2011–2024; dimensione delle bolle proporzionale al volume).

The multi-annual mean distribution of total volumes (Fig. 4) shows that Cheserod alone accounted for about 42% of the total discharge, followed by Gabiet (24%) and Mascognaz (18%). The remaining springs-Entrebin, Promise, and Promiod-collectively contributed less than 15%. This uneven distribution underscores the spatial concentration of discharge within a few dominant sources and highlights the contrasting behaviour between stable and more variable springs.

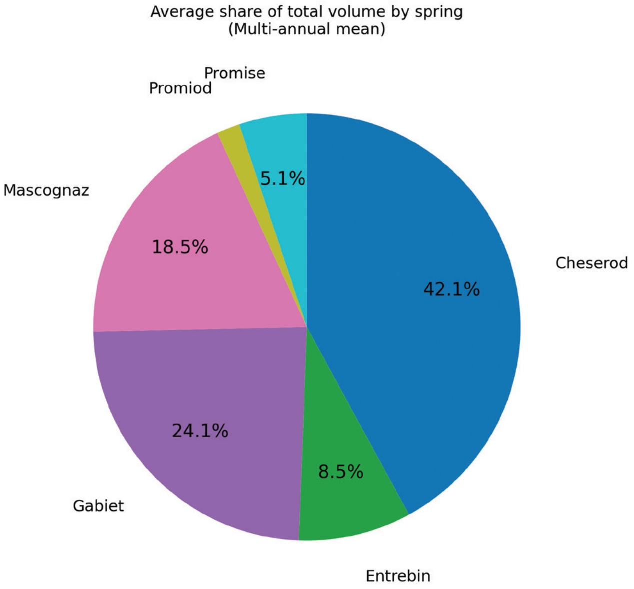

Fig. 4 - Average share of total discharge volume by spring, calculated using only the hydrological years common to all monitored springs (2011–2024).

Fig. 4 - Contributo medio di ciascuna sorgente al volume totale di portata, calcolato sugli anni idrologici comuni a tutte le sorgenti monitorate (2011–2024).

Finally, the discharge anomaly heatmap (Fig. 5), using a blue–red colour ramp, highlights coherent temporal clusters of positive and negative deviations across the monitored springs. The periods 2013-2015 and 2018-2020 are characterised by predominantly positive anomalies, often exceeding +50% at several sites. Notably, Gabiet shows a peak of +150% in 2014, while Mascognaz reaches +70% in 2018. Conversely, the interval 2021-2023 stands out as markedly dry, with widespread negative anomalies frequently below −50%, particularly at Gabiet and Promise.

Cheserod, despite being the major contributor in terms of absolute discharge, exhibits only moderate interannual variability, generally remaining within ±20% of the mean, indicating a relatively stable regime. In contrast, Gabiet and Promise display the largest anomaly amplitudes, reflecting a more sensitive hydrological response. Promise, in particular, shows a marked transition from persistent negative anomalies before 2018 to strongly positive ones after 2020, culminating in a +160% anomaly in 2024. This shift indicates a substantial change in recharge dynamics or in the spring's hydrological functioning.

Communication and outreach perspective

To improve the communication of discharge amounts to non-specialist audiences, annual water volumes were also expressed as the equivalent number of Olympic-size swimming pools (approximately 2.5 × 10^6 litres each). This conversion provides an intuitive way to understand the amount of water released by each spring over time. Figure 6 illustrates these results, showing that the Cheserod spring alone can fill between approximately 400 and 800 Olympic-size swimming pools per year, depending on hydrological conditions. Gabiet shows values ranging from 200 to 500 pools, while Mascognaz displays relatively steady outputs of around 200-300 pools annually. Entrebin and Promiod contribute more modestly (<100 pools), whereas Promise shows a gradual increase in recent years, reaching about 200 pools in 2024.

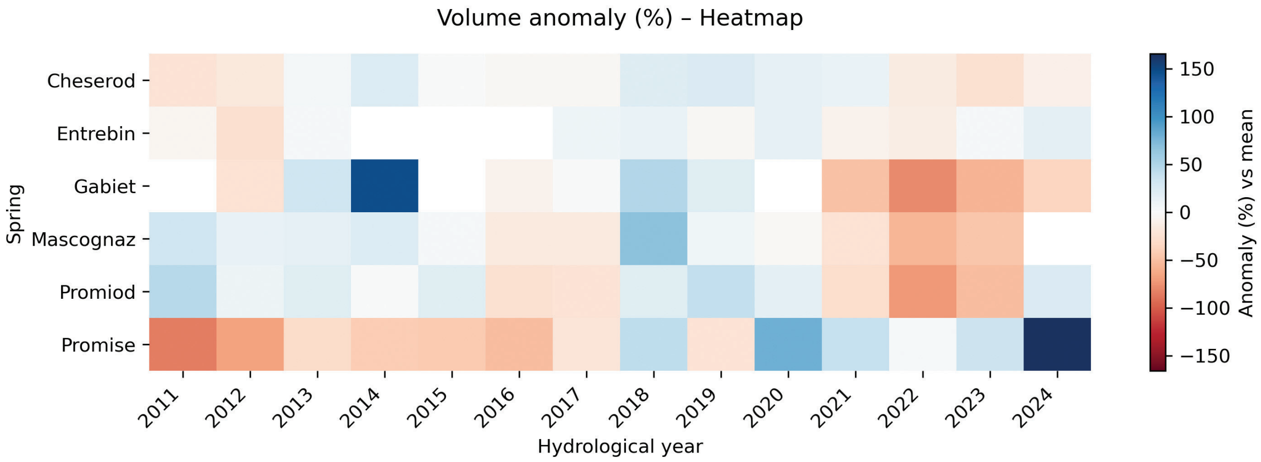

Fig. 5 - Heatmap of annual discharge anomalies (% vs. mean) for monitored springs (2011–2024).

Fig. 5 - Mappa delle anomalie annuali di portata (% rispetto alla media) delle sorgenti monitorate (2011–2024).

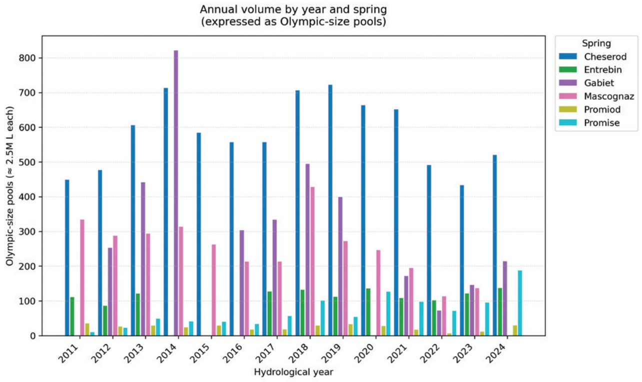

Fig. 6 - Annual discharge volumes expressed as Olympic-size swimming pool equivalents.

Fig. 6 - Volumi annui di acqua erogata, espressi come numero equivalente di piscine olimpioniche.

Discussion

Cheserod, Gabiet, and Mascognaz Springs together account for more than 80% of the total system discharge, highlighting the uneven spatial distribution of available groundwater resources.

Cheserod demonstrates relatively stable discharge over time, indicating an aquifer characterised by high storage capacity, which buffers and attenuates the hydrological response to climatic variability. In contrast, Gabiet and Promise exhibit the highest interannual variability, as shown by the large positive and negative anomalies in the heatmap. These springs likely respond quickly to fluctuations in recharge, possibly due to shallow flow paths or limited reservoir volumes. As already discussed in Gizzi et al. (2025), the recent increase in discharge observed at the Promise spring, located in the La Thuile Valley, may reflect a change in its hydrological behaviour. Possible explanations include altered infiltration dynamics associated with reduced snowpack persistence and/or permafrost degradation, although these mechanisms are not directly investigated in the present study. Springs with lower discharge (Entrebin and Promiod) exhibit smaller anomalies and limited long-term trends, suggesting relatively steady hydrological behaviour under variable climatic conditions.

Besides, the temporal coherence of positive and negative anomalies across multiple springs suggests a potential influence of regional-scale climatic controls rather than exclusively local processes. In particular, periods of widespread positive anomalies (e.g., 2014, 2018, 2020) appear consistent with wet or snow-rich conditions previously reported for the region, while the 2021–2023 deficit may reflect the dry and warm conditions documented across large sectors of the Alpine domain (Cabina di Regia dei Ghiacciai Valdostani, 2022; Avanzi et al., 2023). These patterns are consistent with regional climatic anomalies reported in previous studies, although a quantitative attribution would require direct integration of meteorological, snow cover, and temperature data.

Apart from the scientific explanation, expressing water volumes in terms of equivalent Olympic-size swimming pools creates a communicative link between technical analysis and public perception. By converting large numerical values into familiar, tangible units, this method helps non-expert audiences understand the importance of hydrological variability and the scale of water resources. Besides enhancing outreach, it supports awareness initiatives related to water scarcity and climate resilience, showcasing how scientific monitoring can inform both management and education.

Conclusions

This study offers an integrated assessment of long-term hydrogeological monitoring data from multiple springs in the Aosta Valley, emphasising variations in discharge behaviour and their connections to geological and climatic factors. The analysis of annual discharge volumes demonstrated that springs in different valleys respond differently to climatic influences, depending on aquifer type, recharge processes, and the degree of hydraulic buffering.

Notably, Cheserod, Entrebin, Mascognaz, and Gabiet springs, all vital for drinking-water supply, represent key strategic resources for local communities. Monitoring these springs for more than a decade has been crucial to ensuring the reliability and sustainability of water abstraction. However, the monitored springs do not exhibit a uniform hydrodynamic behaviour. Cheserod, Mascognaz and Entrebin show relatively buffered discharge regimes, whereas Gabiet and Promise display stronger interannual variability. This contrast highlights the need for spring-specific management strategies rather than a uniform interpretation of monitoring data from Alpine springs. The observed interannual fluctuations also underscore the importance of accounting for climate-induced variability in long-term water resource management.

The combined use of quantitative analyses and graphical representations (heatmaps, bubble plots, and “Olympic-pool equivalents”) improved both the scientific interpretation and the clarity of results. As discussed in the Introduction, disseminating hydrogeological data in accessible formats supports informed water governance and raises awareness among decision-makers and citizens about the vulnerability of mountain water resources.

Overall, this work shows that ongoing spring monitoring is a crucial tool not only for scientific research but also for protecting drinking-water supplies in Alpine regions facing increasing climatic stress. The strong interannual variability and spatial heterogeneity identified in this study highlight the need for adaptive management strategies that account for the differing response times and sensitivities of each spring.

Future efforts should focus on maintaining and broadening the monitoring network, integrating meteorological, isotopic, and socio-hydrological data to support adaptive management and long-term resource resilience.

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Competing interest

The authors declare no competing interest.

AI use declaration statement

The authors used ChatGPT EDU during the writing process to improve readability and grammar in some parts of the paper. All AI-generated suggestions were verified for factual accuracy by the authors. The authors confirm that the AI tool is not listed as a co-author.

Author contributions

Collection of data, MG, FB, ES; data processing, MG; interpretation of results, MG; writing-original draft preparation, MG; writing-review and editing, MG, ES, GT, AF; visualisation, MG; supervision, GT, AF; project administration, GT. All authors have read and agreed to the final version of the manuscript.

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Supplementary Materials

Supplementary materials can be downloaded at:
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