Spring trends in slow-moving landslide displacement: is it a reliable way to predict their movements? Two case studies in the Susa Valley (NW Italy)

Landslides
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Spring trends in slow-moving landslide displacement: is it a reliable way to predict their movements? Two case studies in the Susa Valley (NW Italy)

Abstract Mountainous regions are highly susceptible to ground instabilities due to their geomorphological features and the climate events. Slow-moving landslides are influenced by multiple interacting predisposing factors, complicating the prediction of acceleration patterns. Rising groundwater levels, closely linked to net precipitation and snowmelt, are the main drivers of slope movements. Thus, reconstructing ground instability scenarios requires analysing groundwater dynamics. In this context, the present study focuses on the methodological development and validation of an alternative approach for landslide monitoring, rather than on the direct cause-effect relationship between groundwater variation and slope movements. The proposed method aims to assess the reliability of using spring water levels as a proxy for predicting slope displacements, and to compare this approach with the use of piezometric data, which are typically employed in conventional monitoring system. This is particularly relevant in mountainous environments, where the number of in situ instruments is often limited. The methodology combines statistical tools and Fourier spectral analysis to investigate the coherence between hydrogeological and kinematic time series. The analysis was applied to two large slow-moving landslides in the Western Italian Alps (Champlas du Col and Thures). Results show that when springs and inclinometers are in proximity and belong to the same landslide dynamics, as in Thures landslide, the spring trend can effectively predict conditions triggering movement. Conversely, at Champlas du Col landslide, discrepancy between spring and displacement trends suggests the presence of a sub-landslide within the main body. This is likely related to local geological settings, as confirmed by the strong correlation between piezometric data and displacement rates. Overall, this research highlights the methodological potential of integrating spring monitoring into landslide observation frameworks, providing a cost-effective and scalable tool for areas with limited instrumentation. This approach lays the groundwork for the development of generalised criteria to identify suitable springs and to support the forecasting of slope accelerations in similar geological contexts.

Keywords Slow-moving landslides · Groundwater level · Fourier spectral analysis · Displacement rates · Alps

Introduction

Large deep-seated, slow-moving landslides pose significant challenges due to their complex hydrogeological dynamics and the potential stages of movement acceleration and catastrophic failure (Chen et al. 2024; Cruden and Varnes 1996; Liu et al. 2025). Understanding the mechanisms that cause these deformations is crucial for the development of effective monitoring and mitigation strategies, especially in areas where buildings and infrastructure are at risk.

The kinematics and long-lasting evolution of these phenomena are driven by several predisposing factors. Lithology, structural settings and regional tectonic stresses strongly control the slope stability over time. A common example is mechanically anisotropic rocks, such as foliated metamorphic schists, which provide planes of weakness that localize shear (Agliardi et al. 2001; Crosta et al. 2013).

In mountain regions, deglaciation is one of the most impactful processes on slow-moving landslides deformations, as it causes a stress redistribution on slopes, thereby contributing to rock damage. Consequently, changes in loading conditions on the valley bottom and on its flanks can interact with fracture opening, thereby affecting hydraulic conductivity and groundwater circulation. This process is often observed in the European Alps, particularly in glacial valleys such as the Chisone and Susa Valleys (Italian Western Alps) with a high density of Deep-Seated Gravitational Slope Deformation (DSGSD). In addition to these factors, acceleration phases in slow-moving landslides are typically triggered by groundwater forcing, which is commonly linked to prolonged infiltration from intense rainfall or snowmelt. This leads to elevated pore-water pressures, reduced effective stress on discontinuities and increased deformation. These dynamics may develop gradually across seasons or episodically during anomalously wet years (Toločka 2025).

Given the amount of available meteorological data, groundwater depth measurements and continuous time series of monitored displacements, the definition of a data-driven model capable of statistically estimating the deformation response to changes in the main triggering factors may be useful.

Several authors have conducted researches to assess the effects of precipitation and groundwater flow regime on landslide reactivations. Lacroix et al. (2020) and Bordoni et al. (2023) reviewed the environmental conditions of landslide-prone regions and the forcing factors such as precipitation, earthquakes and human activities that drive movements, and discussed the circumstances under which slow-moving landslides can accelerate rapidly or fail catastrophically. In this framework, the impact of climate change on precipitation patterns and its implications on changes in water source availability (Leone et al. 2021; Gizzi et al. 2022; Ruigar and Golian 2015) and in turn on landslide activity (Mo et al. 2019) plays an important role. Moreover, a continuous groundwater

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monitoring in terms of storage and chemical-physical characteristics provides detailed insight into the influence of the DSGSD morphostructure on infiltration dynamics and deep-water circulation (Gizzi et al. 2020), explored through statistical methods, hydrochemical analysis and field surveys (De Luca et al. 2019).

Bernardie et al. (2015) introduced a statistical-mechanical approach to predict changes in landslide displacement as a function of pore water pressure, which influences soil shear strength along the sliding surface (Conte and Troncone 2011). Indeed, the positive pore pressure due to the rising groundwater level is considered the main mechanism leading to failure in hydrologically induced deep-seated landslides, implying that water content controls the behaviour of slow-moving landslides (Prokešová et al. 2013; Van Asch et al. 2007). Matsuura et al. (2008) investigated the relationship between rainfall, snowmelt and pore water pressure increases over time and correlating them with landslide displacements.

Similarly, the Fourier spectral analysis has been effectively applied in numerous research fields, for monitoring environmental seismic noise datasets (Colombero et al. 2018), to quantify groundwater level fluctuations in terms of frequency (Joelson et al. 2016), in landslide susceptibility mapping (Bao et al. 2022; Hoseinzade et al. 2022) and hydrology, demonstrating its potential for modelling and predicting precipitation patterns (Laguardia 2011). The hydrogeological and geomechanical properties of slopes under rainfall conditions have been extensively investigated, with important contributions by Huang et al. (2012) and Pecoraro and Calvello (2021) in the monitoring of pore pressures and the development of warning systems. The role of thresholds in supporting these systems has been emphasized by Segoni et al. (2015) and Berti et al. (2012) who developed probabilistic methods to assess rainfall thresholds for landslide occurrence, providing more accurate and statistically rigorous prediction models.

What is still missing, at least to the best of the authors' knowledge, is the ability to use spring water level, an important indicator of aquifer dynamics (Kresic and Stevanovic 2010), as a powerful tool for detecting slow-moving landslide displacements and establishing thresholds useful for early warning or risk reduction (Pecoraro et al. 2019). In this framework, by collecting groundwater level and landslide displacement time series, this work aims to improve understanding of the hydrogeological factors influencing slow-moving landslides, focusing on two sites in the Susa Valley (NW of Piedmont Region). As precipitation is often the main preparatory factor, it is important to quantify the recharge mechanisms and consequently the effects on displacement trends. Using this approach, the displacements trend could be described from the groundwater level, bypassing the precipitation input data.

Given these assumptions, the performed analysis follows these main steps: (i) understanding the dynamics of aquifer by detecting spring hydrometric data with autocorrelation function and assessing the system response to rainfall through cross-correlation analysis; (ii) application of the Fourier Transform to water level and displacement data to detect possible periodicity of signals and clarify whether the spring can reasonably represent the effects of groundwater fluctuations on landslide acceleration; (iii) detection of anomalies in the landslide acceleration patterns in the meaning of significant groundwater level rising.

Geological and hydrogeological settings of the study areas

The investigated sites of Champlas du Col and Thures landslides are located in the Susa Valley, in the Western Alps of Piedmont region (Italy) (Fig. 1a).

From a geological point of view, the whole area is predominantly covered by Lago Nero oceanic units (LCS), consisting of calcschists and serpentinites belonging to ophiolitic units, with intercalations of serpentinites and serpentine schists from the Cerogne-Ciantiplagna unit (CNR) (Fig. 1b). A few outcrops of continental margin dolomite have been identified in the Thures area.

The widespread formations of the Quaternary succession consist of continental deposits of glacial origin, developed during the Last Glacial Maximum and subsequent glacial retreat, and are irregularly distributed along the slopes. In contrast, alluvial deposits are located along the main valley bottoms and are sometimes connected with DSGSD and large active landslides that affect extensive areas of the valley (Fioraso 2017). Typical morpho-structural features related to the evolution of these deformations, such as main scarps, are shown in Fig. 2.

Among the predisposing factors contributing to slope instability in the area, tectonic features strongly influenced the drainage network and landscape morphology, as testified by the Dora Riparia and Chisone rivers and tributaries pattern, which is controlled by NE-SW and NNW-SSE fault systems. Moreover, glacial morphodynamics have played a dominant role, reshaping the past and actual slope setting (Cignetti et al. 2019). Evidence from drilling surveys conducted on various landslides in this area have revealed that the evolution of gravitational phenomena has completely modified the original post-glacial morphology of valley bottoms (Fioraso et al. 2011).

The two sites analysed are characterised by intense fracturing of the rock mass, which allows the development of a complex network of water outlets, with supply sectors in the highest areas of the slopes. The presence of intense and widespread water circulation within the rock mass is manifested on the surface by numerous springs (S1 and S2 blue dots in Fig. 1a), mainly distributed in the lower-middle part of the contact between landslides or glacial deposits and the bedrock or rock mass. These springs are generally characterised by modest flow rates (< 0.5 l/s) and, in some cases, are subjected to significant variations in flow rate due to the seasonality of the inflow from the recharge zone. S1 and S2 are actually spring intakes, where groundwater is collected into a chamber with a cement basin, as shown in Fig. 2c. The water is not under pressure, and the hydrochemical analyses performed indicate that it originates from a shallow flow system (Bonomo 2023), directly influenced by meteorological precipitation, as discussed later in the paper.

The two case studies are noted as: (i) Champlas du Col landslide and (ii) Thures landslide, whose simplified cross-sections are shown in Fig. 1c-d.

Champlas du Col landslide

The Champlas du Col landslide is located in the Sestriere municipality, in Champlas du Col locality (1768 m a.s.l.), along to SP23R road connecting the Susa and Chisone valleys. The landslide has

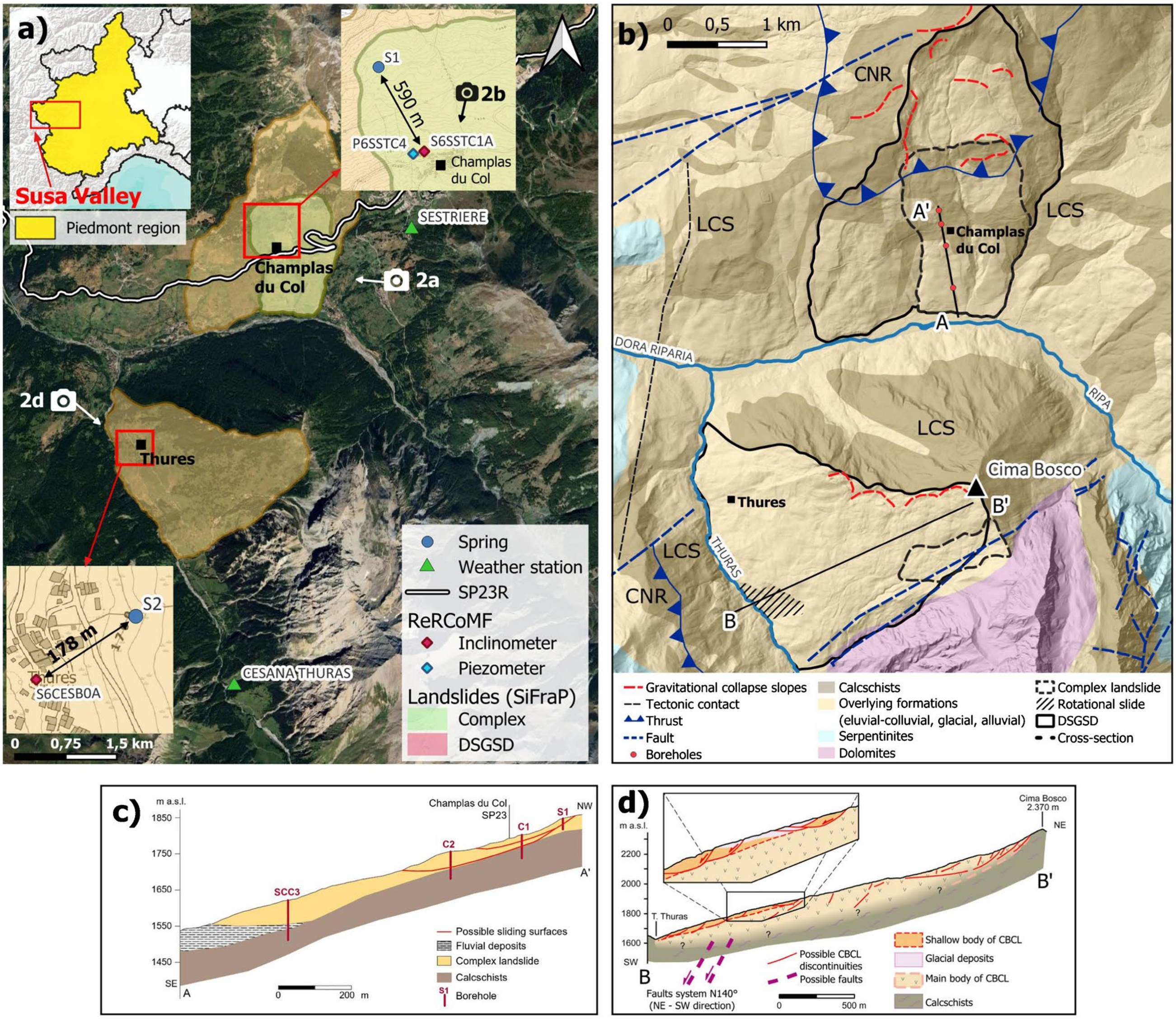

Fig. 1 **a** Study area and location of (i) Champlas du Col and (ii) Thures landslides. Camera icons indicate the shooting locations and directions of pictures shown in Fig. 2a-b-d; **b** Geological map (modified by FOGLIO 171, Servizio Geologico d'Italia 2014); **c** Simplified cross-section of the Champlas du Col landslide (created using AutoCAD® 2024); **d** Geological cross-section of the Thures landslide site (modified after Alberto et al. 2008)

been classified as complex phenomenon in the Regional Landslide Inventory (Sistema informativo fenomeni Franosi Piemonte—SiFraP) and covers an area of 2 km², extending from 2080 m a.s.l. down to the Ripa Valley floor at about 1500 m a.s.l. (Fig. 1a). The phenomenon is the superficial expression of a larger DSGSD that extends from the top to the bottom of the relief (Narcisi et al. 2024). Surface movements, such as flows and rotational slides are very active and periodically cause damage the SP23R road.

A geological section (Fig. 1c) of the landslide was defined using available borehole data and geological documents provided by the Regional Agency for the Protection of Environment (ARPA Piemonte—Banca Dati Geotecnica) to reconstruct the stratigraphy. Previous analyses have recognized a complex system with several sliding surfaces, attributed to the presence of a highly fractured and disjointed rock mass, a factor that contributes to the infiltration of meteoric water inputs. Moreover, the existing borehole C1, used to install the S6SSTC1A inclinometer, intercepts two sliding surfaces at 18 and 31 m depth respectively.

As evidenced by the SCC3 borehole, in the lower part of the slope, the presence of fluvial deposits at a depth of 79–89 m indicates that the landslide advanced along a sliding surface below the existing valley floor. Upstream of SP23R, movement occurs along horizons of different permeability due to the presence of gravel alternating with silt and sand. Given the shallow depth of the boreholes (maximum 100 m), the thickness of these incoherent soils along the slope was roughly estimated. From a

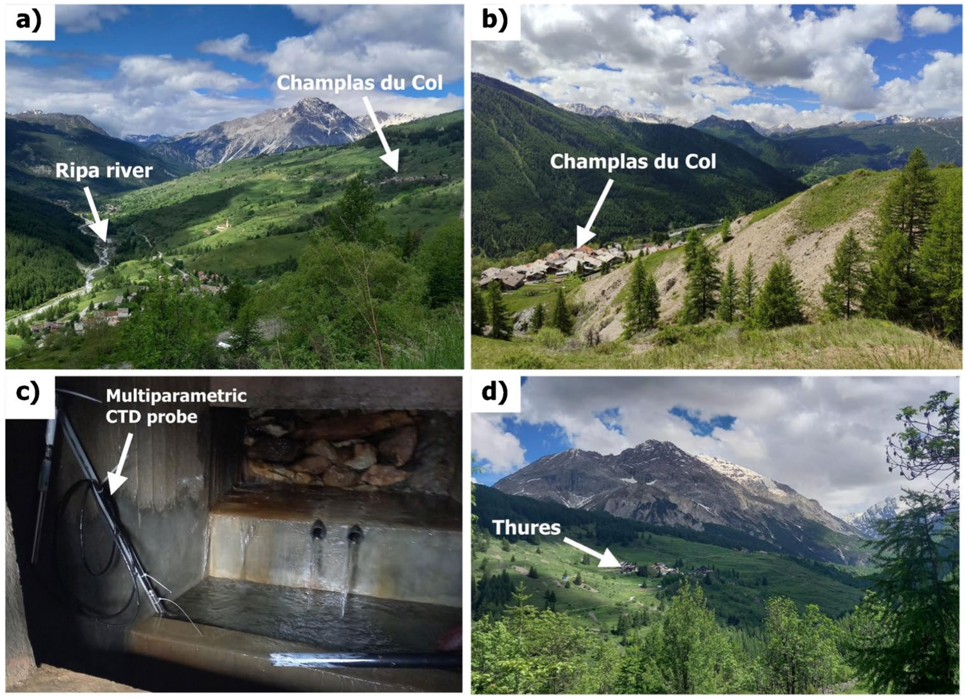

Fig. 2 **a** Champlas du Col slope from the eastern side **b** Counterscarp on Champlas du Col landslide body **c** Spring cement basin with multiparametric CTD probe d View of Thures from the opposite slope (see Fig. 1a for pictures location)

hydrogeological point of view, the landslide body hosts an aquifer characterised by the prevalence of glacial deposits which, subject to consolidation phenomenon, reduces the overall permeability (Comune di Sestriere 2022).

Most of the monitoring points are distributed near the buildings of Champlas du Col and along the SP23R, due to the recurrent damages observed (ARPA Piemonte 2024a).

In the context of the DSGSD, the specific case of the Champlas du Col reveals the typical characteristics of rock flows. Here, the slope collapse is dominated by a visco-plastic deformation component, with creep movements distributed over a large part of the rock mass. This results in a dominant sliding component along different planes on structural discontinuities (Fioraso et al. 2014).

Thures landslide

The Cima Bosco Complex Landslide (CBCL), so called because it extends on the hydrographical right slope of the Thuràs Valley from the top of Cima Bosco (2350 m a.s.l.), is located in the municipality of Cesana Torinese, in the Thures locality (1670 m a.s.l.). The entire west-oriented slope of the Cima Bosco mountain is affected by a DSGSD covering an area of 4.27 km^2. The deformation is mainly concentrated along well-defined discontinuities, which cause the movement of rock masses towards the valley floor (Fioraso et al. 2014). Within this area, it is possible to distinguish a main shallow landslide body (Fig. 1d) from a deeper bedrock layer (first 10–20 m), consisting of overlying formations such as eluvial-colluvial products, glacial deposits and alluvial deposits in flat conoids. The CBCL has a well-developed surface hydrographic network in its distal sector, associated with the groundwater table. This hydrographic system is sustained by the main landslide body, which, despite its loosened and disarticulated structure, is characterized by a low permeability due to the presence of the abundant silt–clay matrix. Based on all available evidence, the aquifer supply is primarily superficial (Alberto et al. 2008; ARPA Piemonte 2024b). Field observations and monitoring (using inclinometers and SAR-PS techniques) show slow and non-homogeneous movements (about 10 mm/year), which have caused some damages to the buildings in Thures.

Data collection and methodology

The water springs (blue dots in Fig. 1a) were monitored by ARPA Piemonte in collaboration with the Applied Geology research group at the Department of the Environment, Land and Infrastructures Engineering (DIATI) of the Politecnico di Torino. Multiparameter CTD probes were installed at the S1 (since 2020) and S2 (since 2017). Both springs, which are actually spring intakes, are collected within small cement basins (Fig. 2c) to measure electrical conductivity (EC), temperature (T) and water depth (D), hereafter referred to as water level, with an hourly time step (Bonomo 2023). The analysed dataset is updated to the last measurement campaign conducted in December 2024 (Table 1).

The water level time series were compared with precipitation data to investigate possible impacts on groundwater springs. Precipitation data were obtained by selecting available weather stations from the official ARPA Piemonte regional network. The

Table 1 Landslide sites monitoring network

Site	Spring	Elevation (m a.s.l.)	Weather station	Elevation (m a.s.l.)	Distance (km) spring – weather station	ReRCoMF		
						ID code	Instrument	Period
(i) Champlas du Col	S1 (17/10/2020–09/12/2024)	1960	Sestriere (since 1996)	2016	2.2	S6SSTC1A	Inclinometer	2013/09—2024/11
						P6SSTC4	Piezometer	2004/09—present
(ii) Thures	S2 (19/10/2017–09/12/2024)	1700	Cesana Thuras (since 2002)	1902	3.7	S6CESB0A	Inclinometer	2012/10—present

choice of these weather station was based on the following criteria: i) proximity to the investigated site, ii) comparable topographical altitude, iii) same exposure and iv) continuity of the time series. The Sestriere and Cesana Torinese weather stations met these criteria (Fig. 1a and Table 1). To ensure consistency between spring and weather datasets, the hourly water level data were transformed into average daily values.

Spring and precipitation data were compared in order to analyse the groundwater level variations and available deep displacements dataset from the already installed monitoring system to detect any correlation with acceleration phases in the landslide deformation trends. As described in the previous section, the two sites (Fig. 1a and Table 1) have been equipped with traditional and automatic fixed inclinometers and piezometers by the ARPA Piemonte through the Regional Landslide Control Network (Rete Regionale Controllo Movimenti Franosi–ReRCoMF). These data with related technical reports have been provided from ARPA Piemonte upon request. Analogous to the choice of weather stations, only useful instruments with large and continuous datasets. Therefore, inclinometers without automatic acquisition were excluded, and only fixed probe inclinometers, which provide daily cumulative displacement values from the installation date, were considered. The S6SSTC1A and S6CESB0A inclinometer probes intercept the main sliding surface at depths of 18 m and 22.5 m respectively.

Both sites have more than 10 years of available data, with the exception of the S6SSTC1A inclinometer, whose fixed probe was removed in November 2024 due to pipe damage caused by high movement rates of the landslide body during the previous spring season. For the following analyses, data recorded after 10 June 2024, for the Champlas du Col landslides, were neglected in the comparison with other considered parameters.

The piezometers record daily depth to groundwater levels, reflecting changes in the hydraulic head of the aquifer, and therefore can be useful in supplementing the spring measurements to detect groundwater fluctuations. For the Champlas du Col site, piezometric data were included in the analysis of landslide accelerations due to the proximity of the instrument to the inclinometer (Fig. 1a). Conversely, at the Thures site, the piezometric dataset was neglected, both due to its limited length, as the existing piezometer was installed in 2019, and because the spring is located very close to the inclinometer considered in this study.

For all datasets, a correction of time series and filling of short gaps using interpolation (Brockwell and Davis 2006) was applied where necessary, as shown in Fig. 3.

Autocorrelation and cross-correlation analysis of spring hydrometric data

Statistical analyses (Shumway and Stoffer 2006) were carried out to describe the spring system behaviour over the hydrological years, a crucial step for the comprehension of possible effects on changes in landslide displacement trends. The proposed approach aims to reproduce the preliminary analysis steps that can be implemented

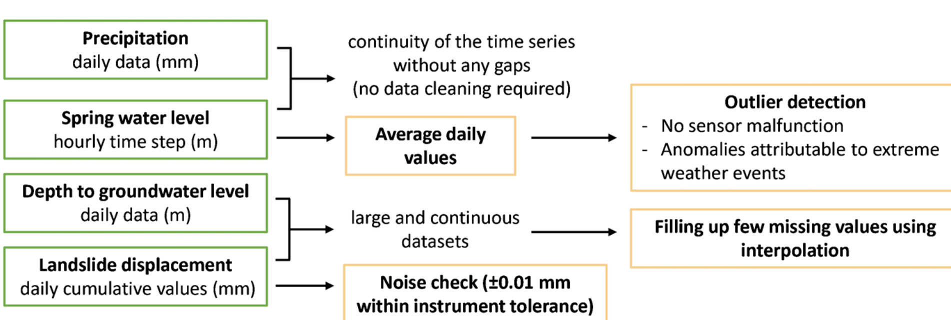

Fig. 3 Schematic framework of data pre-processing

within the SOURCE tool (Gizzi et al. 2023; Lo Russo et al. 2021), which is useful for a semi-automatic hydrogeological characterisation of aquifers supplying the monitored springs. In this work, the SOURCE methodology has been customized to the analysis purposes and improved for assessing the structure of time series and the presence of cyclical components.

For both springs, the AutoCorrelation Function (ACF) applied to the water level values was evaluated to determine the possible existence of memory in the recorded signal and to identify potential stationarity (Sapone 2023), as well as the vulnerability of the aquifer system under dry and wet conditions. The ACF is a statistical measure that quantifies the relationship between a given time series value and its preceding values. In practice, it assesses the correlation between observations of a time series at two points in time, separated by a specific lag time (τ). The ACF for a lag τ corresponds to the covariance of all measurements x_t and measurements with a time distance $x_{t+\tau}$, according to the following equation (Lo Russo et al. 2021):

$$\text{cov}\ \tau = \frac{1}{n-\tau}\sum\nolimits_{t-\tau}^{n} x_{t-\tau} - X_t X_{t-\tau} \tag{1}$$

where x is the time series, n is the number of measurements in the time series, t is the time (days), τ is the time distance between two measurements, and X is the average value of the sample. The ACF function always assumes values between −1 and 1, and particularly for $\tau = 0$, ACF = 1, which indicates a perfect linear correlation with itself. Therefore, the graph of the ACF always has a value of 1 at the origin (i.e. at lag = 0). When using the ACF on hydrological data, a slow decline indicates an aquifer characterised by poor draining properties, low permeability or significant groundwater storage. Conversely, a fast decline indicates a more rapid flow of water through the aquifer or limited storage capacity, which could be characteristic of a karst aquifer (Lo Russo et al. 2021).

Subsequently, to identify any pronounced similarity between individual data, two different time series can be compared in order to obtain information about the degree of the correlation between them and the time delay at points of maximum similarity. For this purpose, the cross-correlation analysis was performed to investigate the connection between input (e.g., daily rainfall) and output time series (e.g., daily spring water level) (Kresic and Stevanovic 2010; Lo Russo et al. 2015).

The Cross-Correlation Function (CCF) is a key indicator of the degree of linear relationship between two time series, which can be expressed by the Pearson coefficient (r) (Pearson 1895). Cross-correlation analysis is based on an equation similar to the autocorrelation function (ACF) (Eq. 1) as it depends on the time interval k between the individual values in the series. 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 (Gizzi et al. 2023), the cross-correlation coefficient can be obtained by (Box and Jenkis 1974):

$$\text{r(k)} = \frac{n\sum XY - \sum X \sum Y}{\sqrt{\left[n\sum X^2 - \left(\sum X\right)^2\right] \times \left[n\sum Y^2 - \left(\sum Y\right)^2\right]}} \tag{2}$$

The coefficient $r(k)$ can range between −1 (perfect negative correlation) and + 1 (perfect positive correlation); a value of 0 indicates no correlation.

Power spectral density

The trend and magnitude of landslide movements in relation to the recharge regime of the groundwater system was examined.

The evaluation of the periodogram was carried out to identify possible dominant periodicities in the groundwater level and displacement time series. Before this step, a preliminary analysis of the inclinometer data was required because the cumulative displacements recorded since the installation date of the instrument are plotted as a monotonically increasing curve, which does not provide comprehensive information on variations in landslide displacements over time. Given the typical long-term evolution of slow-moving landslides, the daily displacement for both sites is very low (< 0.05 mm), but conversely, more significant displacement rates can be observed over a larger time window. Therefore, the cumulative values were processed by considering the displacement rates over a 30-days moving time window, using the following expression:

$$\text{vt} = \frac{d_t - d_{t-30}}{30} \tag{3}$$

$$\text{t} = 1, 2, \ldots, \text{N}$$

where d_t is the displacement value on day t, N is the total number of daily displacements, v_t is the displacement rate.

This approach enables the comparison of daily water levels with displacement values, providing a preliminary overview of any potential correlation between the rise in water levels and the landslide accelerations.

A periodogram is an estimate of the Power Spectral Density (PSD) of a signal and it is mathematically related to the autocorrelation sequence r_{xx} by the discrete-time Fourier transform (Oppenheim and Schafer 1989). This function provides a representation of the spectral components of the parameters in terms of frequency:

$$\text{Pk}(\omega) = \frac{1}{2\pi}\sum\nolimits_{m=-\infty}^{+\infty} r_{xx}(m)e^{-j\omega m} \tag{4}$$

where ω is $2\varpi f/f_s$, f is the physical frequency and f_s the sampling frequency (Fiorillo and Doglioni 2010).

Fourier analysis assumes signal stationarity, which can limit its performance when time series are affected by extreme or transient events, such as the spring water level, groundwater level and displacement signal analysed here. However, the PSD provides an averaged representation of the spectral content, which is suitable for identifying dominant periodicities in the dataset, even though it does not fully capture transient or evolving frequency responses associated with short-term disturbances. In this sense, the PSD allows the identification of recurrences in the analysed datasets, from which e of the coupling between slope deformations and groundwater fluctuations can be inferred (Priestley 1981).

Detection of landslide acceleration anomalies

A meaningful step in this work aims to evaluate the acceleration of the landslide body using the following expression:

$$a_t = \frac{v_t - v_{t-30}}{30} \quad (5)$$

where v_t is the displacement rate on day t (Eq. 3) and a_t quantify the variation of displacement rates over a 30-days moving time window.

Given the acceleration time series for both sites, potential anomalies were identified using the Interquartile Range (IQR) method (Barbato et al. 2011). The IQR method uses statistical descriptors provided by the quartiles of the data distribution, specifically the first (Q1) and third (Q3) quartiles, to calculate the interquartile range (IQR = Q3—Q1). Data outside the range defined by Q1-1.5 × IQR and Q3 + 1.5I × QR are considered outliers, which could be linked to extreme scenarios, such as heavy rainfall or groundwater recharge due to significant snow accumulation. It was then checked whether these anomalies are consistent with pronounced fluctuations in groundwater levels.

Results

Groundwater springs investigations

The daily water levels of the springs were processed from the available hourly dataset and compared with precipitation dataset. As shown in Fig. 4, the two investigated spring regimes exhibit different behaviours.

For the S1 spring (Fig. 4a), it is rather difficult to identify regular components as the hydrometric level is fairly constant and ranges between 0.11 m to 0.13 m, with few peaks up to 0.17 m. The spring is strongly influenced by rapid flow contributions, characterised by water level peaks following intense rainfall events, which overlap with the base flow component driven by snowmelt process. A notable example is the highest peak ever recorded, immediately following the precipitation event of December 1, 2023 (60 mm/day). The overview is markedly different in the case of S2 spring (Fig. 4c) in which the hydrometric values exhibit a more regular and smoothed regime defined by clearly distinguishable snowmelt peaks and seasonal recessions, with variations ranging from 0.13 m to 0.15 m. On the other hand, for the S2, there appears to be no direct influence from a single rainfall event. The hydrograph shows a stronger dependence on the snowmelt process, with peaks clearly associated with the spring season. The hydrogeological years are easily distinguishable, as well as the summer recession rate is more pronounced. The autocorrelation analysis allowed to highlight precisely these differences, considering as demonstration cases the scenarios of a dry year (2021–2022) and wet year (2023–2024) affecting the Piedmont region, in order to assess their respective impacts on both sources. The winter 2021–2022 was the third warmest and driest in the last 65 years, a highly anomalous season, as such a combination of extreme drought and warm temperatures is rare during winter (ARPA Piemonte 2024c). On the other hand, the winter 2023–2024 was the warmest in the last 67 years and it was also characterised by abundant precipitation (ARPA Piemonte 2024d). The amount of spring rainfall was also meaningful: while the spring 2022 was one of the driest since 1958, the spring 2024 had a surplus 102% compared to the 1991–2020 climate reference normal (ARPA Piemonte 2024e, 2024f).

It is noteworthy that the evaluation of the ACF curves (Fig. 4b-d) is based on the analysis of water levels trend over the whole hydrogeological year (starting in October) without distinguishing between the corresponding effects of snow and rainfall on spring discharge variations.

The hypothesis of a dependent (autocorrelated) time series is tested by evaluating whether the ACF coefficients exceed the 95% confidence limits. An autocorrelation coefficient is considered

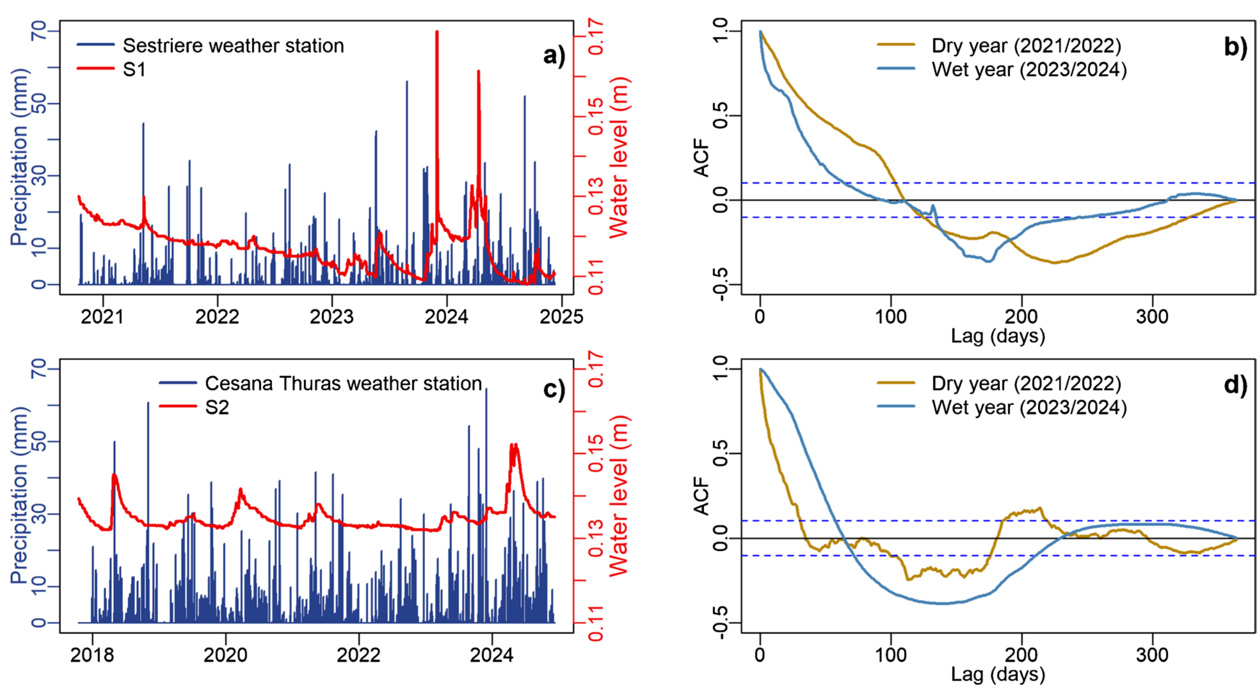

Fig. 4 Daily spring water levels compared with precipitation at Champlas du Col (**a**) and Thures (**c**) and autocorrelogram of S1 (**b**) and S2 (**d**)

statistically significant if it falls outside these bounds, which represent the threshold for the entire correlogram.

For S1 spring (Fig. 4b), the autocorrelation is higher and longer under dry conditions. A persistent exceeding of the confidence limits can be observed, indicating that the autocorrelation coefficients for this period are significantly different from zero. This suggests that the water level time series is characterized by low variability, making it highly autocorrelated. On the other hand, in 2023/2024, fluctuations in spring levels are more pronounced, suggesting that the system is more sensitive and responsive to atmospheric inputs. ACF curve decreases more rapidly over time because rainwater infiltrates quickly and is not retained in the system for long time.

S2 autocorrelogram (Fig. 4d) shows a more rapid decline during dry periods, with values mostly distributed within the confidence interval, indicating that changes in water levels are minimally influenced by previous values. The ACF curve tends to decrease more quickly because daily fluctuations in spring level are less attenuated by the constant recharging action. In contrast, the behaviour is reversed under conditions of heavy rainfall. The system appears to have a greater storage capacity with more gradual release times, as evidenced by the slower recession after annual snowmelt peaks compared to the S1 spring.

To determine the degree of influence of rainfall on the hydrometric levels of the springs -- a cross-correlation analysis (Eq. 2) was performed. This approach requires eliminating the influence of the winter recharge period up to the peak caused by snowmelt. Snow coverage is predominant from December to April, while rainfall is random throughout the year, with intense events occurring more frequently during summer and autumn season. Springs do not respond directly to winter precipitation as the water feeding the springs comes mainly from snowmelt, which is correlated with temperature fluctuations rather than precipitation (Lo Russo et al. 2021). However, the effect of rainfall on groundwater recharge remains unclear.

Based on these considerations, the cross-correlation between daily water level fluctuations and rainfall time series was evaluated for the period from April to November, under the assumption that no snow precipitation occurs during these months and by neglecting the snowmelt contribution. The analysis was performed for the dry year 2022 (Fig. 5a-c) and the wet year 2024 (Fig. 5b-d) of the available water level dataset, comparing the results obtained for both sites.

The graphs clearly show the strength and time of response of the two systems for the scenarios examined. According to the assumptions of the autocorrelation analysis, S1 is more reactive to rainfall inputs and shows marked fluctuations that are not found in the Thures system, which seems to react impassively to precipitation contribution. The strong contrast between the dry and wet years reveals the significant impact of heavy rainfall events.

As shown in Fig. 6, the low cross-correlation values for both springs suggest that the influence of the fast flow component is significantly attenuated by the presence of low-permeability soil, as discussed in the geological setting section. However, S1 appears to respond more quickly and noticeably to intense rainfall events, as shown by the maximum correlation peaks for short lags. On the other hand, water level fluctuations at the S2 are less pronounced and nearly negligible, as shown by the low cross-correlation coefficients over longer lags in particular for dry year, in which all CCF values are within the confidence interval. This suggests that the rise

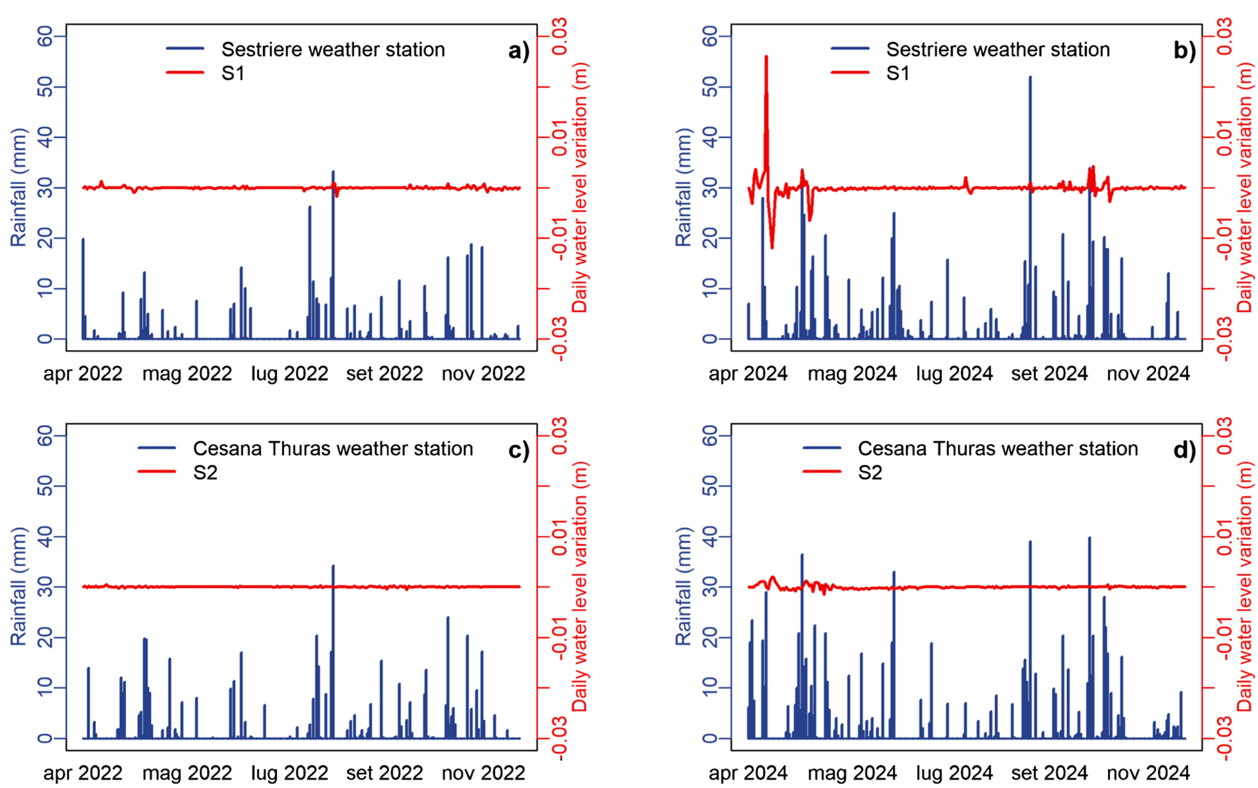

Fig. 5 Daily water level variations of S1 and S2 spring compared to rainfall in the dry (**a**, **c**) and wet year (**b**, **d**)

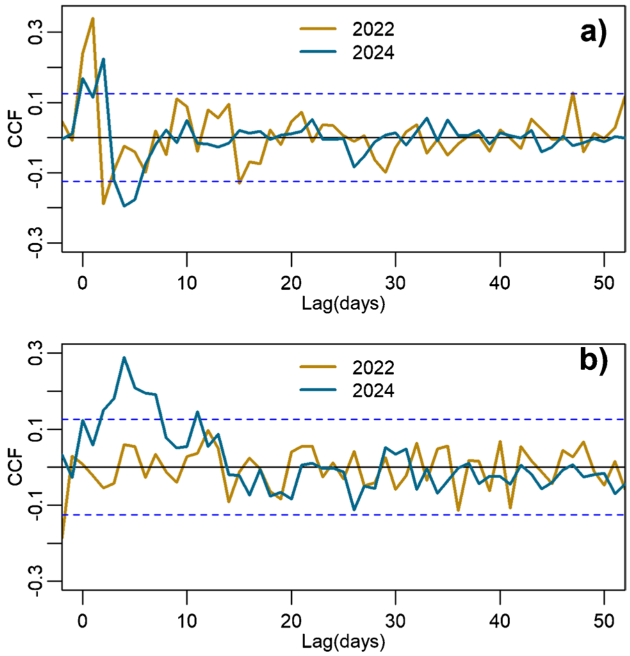

Fig. 6 Crosscorrelogram of (**a**) S1 and (**b**) S2 spring water levels

in water level is primarily associated to the snowmelt period and it reacts poorly and slowly to rainfall events, maybe regulated by a deeper or more regulated flow system.

Conversely, in 2024, S2 shows a more pronounced response, although with a longer lag than S1 spring, indicating a major influence from the prolonged recharge of rainfall.

Cause-effect relationships between groundwater fluctuations and landslide displacement trends

Daily time series of spring water level and inclinometer displacement were compared for both sites to understand if their trends are compliant. The graphs in Fig. 7 show how the processed inclinometer data (Eq. 3) accurately describes the evolution of landslide body movement over the year, suggesting a more direct dependence on variations in the groundwater level pattern.

In the first case, the supplementary dataset of piezometric values provided by P6SSTC4 was also exploited, as discussed in the Sect. 3, by considering the available displacements dataset (until 10 June 2024). Thus, knowing the date of installation of the S1 probe, the spring hydrometric level, the groundwater level and displacement trends from October 2020 to June 2024 were plotted (Fig. 7a).

In the case of Thures (Fig. 7c), on the other hand, it is possible to observe how spring data can capture the landslide displacement trend over hydrogeological years. The acceleration phase of the landslide body is clearly recognisable in the spring season in coincidence with the snowmelt period, which is precisely described by the spring recharge leading up to the snowmelt peak.

The power spectral density, described in Sect. 3.3, was applied to investigate the seasonal components of springs and displacements. Figure 7 shows the power spectrum in the frequency domain (1/day) and the frequencies associated with the most significant peaks are reported in the corresponding Table 2.

In both cases, a peak at approximately 365 days was detected (frequency 4 in Champlas and frequency 7 in Thures), indicating a complete annual variation of the signals, with water level peaking during spring season and then returning to their initial values, strictly affecting the displacements. This finding suggests

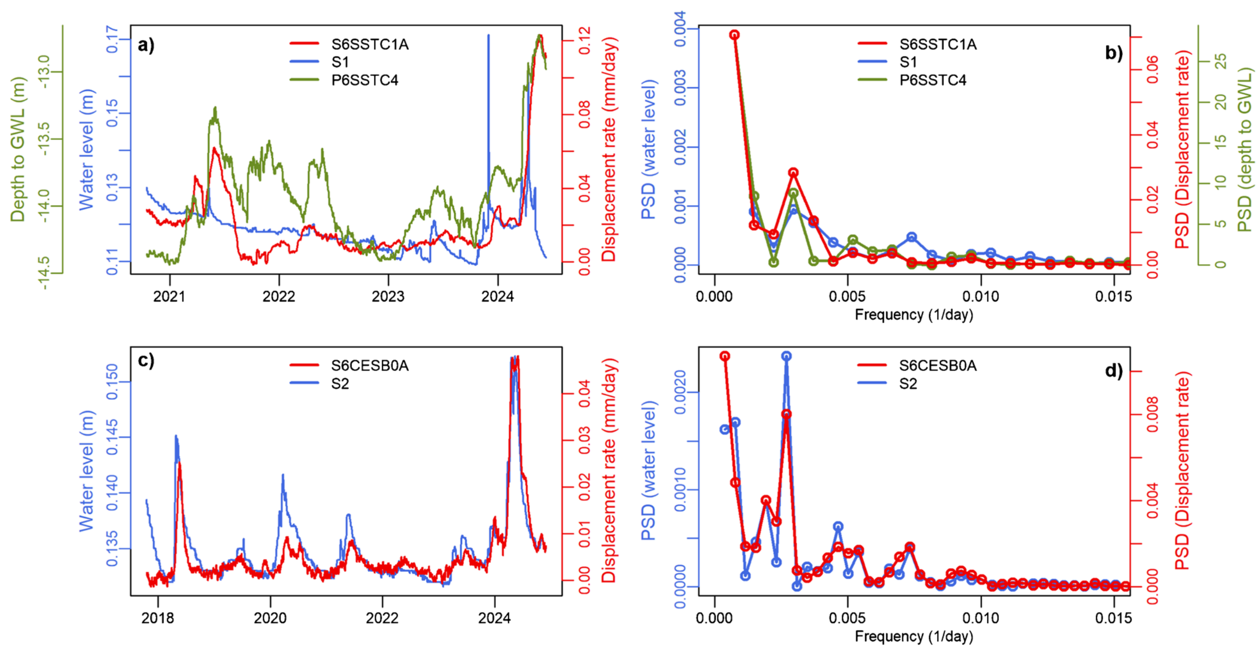

Fig. 7 Groundwater level patterns and displacement rates in (**a**) Champlas du Col and (**c**) Thures and related spectral analysis (**b**, **d**)

Table 2 Main components (indices in brackets) of PSD curve

Site	Frequency (1/day)			Days
(i) Champlas du Col	**S1**	**P6SSTC4**	**S6SSTC1A**	
	(1) 0.00074 (4) 0.00296	(1) 0.00074 (4) 0.00296	(1) 0.00074 (4) 0.00296	(1) 1350 (4) 338
(ii) Thures	**S2**	-	**S6CESB0A**	
	(2) 0.00077 (7) 0.00270	-	(1) 0.00038 (7) 0.00270	(1) 2592 (2) 1296 (7) 370

a relatively consistent pattern typical of spring discharge across hydrological years.

However, for both systems, the first dominant peak appears at lower frequencies (1 in Champlas du Col and 2 in Thures) indicating a non-cyclical component likely associated with an extreme event throughout the entire dataset. This phenomenon corresponds to the conditions occurred in the spring 2024, when heavy precipitation led to an unusual increase in both groundwater levels and landslide displacement rates. The spectral response suggests that this event had a significant impact on the landslide dynamics, inducing an acceleration phase that deviated from the typical displacements trend.

In this analysis, the difference between the performance of the spring and the piezometer in Fig. 7b in delineating displacement variations is quite imperceptible. Although they measure different parameters, both reflect the groundwater recharge regime, which intensifies during snowmelt. Consequently, the annual component is unequivocal in both spectra. The correlation analysis has highlighted the importance of piezometric data to describe displacement variations over time, as spring data alone do not adequately capture these variations, particularly in S1 spring. As discussed in detail in previous sections, the water levels of the S2 show a more pronounced regularity, suggesting a stronger annual cyclical pattern, as revealed by the higher PSD magnitude compared to the annual component of the S1.

These considerations are supported by correlation analysis between the variables in Fig. 7 using the pairs.panel() function provided by the psych() library (Revelle 2023). Each panel in the matrix provides complementary information on the relationships among the monitored variables. The plots below the diagonal show the bivariate scatterplots between each pair of variables, highlighting their degree of linear association (the red line represents the linear fit). The histograms in the diagonal panels show the distribution of the datasets and the Pearson correlation coefficients above the diagonal quantify the strength and direction of the linear relationships between variables (values close to 1 indicate a strong positive correlation).

The correlation matrix for the case (i) (Fig. 8a) shows a weak relationship between the spring data and the displacement data, indicating that the water level signal does not fully describe the landslide deformations. However, when the depth to groundwater level (gwl) is considered, the correlation with displacement increases substantially (r = 0.70), suggesting that the piezometric data effectively capture the hydromechanical response of the Champlas du Col system. Conversely, in the case (ii) (Fig. 8b) a much stronger correlation is observed, proving that spring water

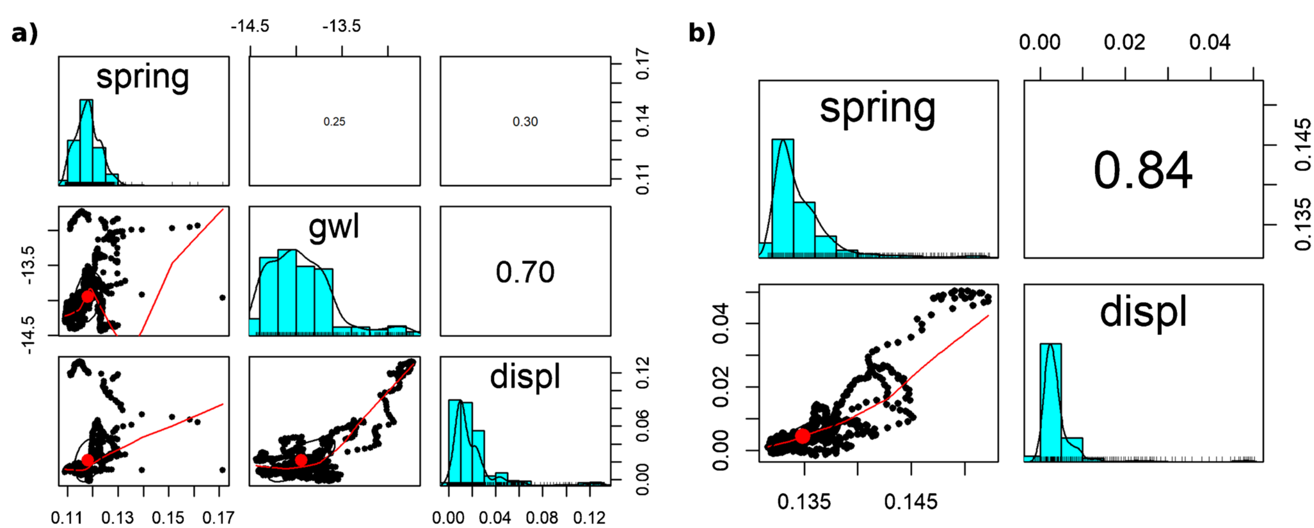

Fig. 8 Correlation matrix for the (**a**) Champlas du Col and (**b**) Thures case study

levels can adequately describes the deformation behaviour. These findings suggest that the linear correlation provides a reasonable first-order approximation of the proportional relationship between water level and displacement. Nevertheless, it assumes instantaneous responses between the variables, without accounting for potential lag effects.

In this final section, acceleration values were derived from displacement rates to identify potential anomalies under specific conditions. In addition to the already discussed scenario of spring 2024, similar patterns were also observed in spring 2018, affected by heavy and prolonged precipitation (ARPA Piemonte 2024g). Analysis of landslide accelerations (Fig. 9) related to snow cover height provides a more sensitive assessment of normalised displacement rates over time, particularly in capturing responses to triggering factors.

This approach allows the characterisation of anomalous accelerations of the landslide body based solely on spring level data for Thures and piezometric level data for Champlas, thus avoiding the analysis of precipitation pattern.

Since the Cesana Thuras weather station does not have a snow gauge, data from the Sestriere station were also adopted for the Thures site (Fig. 9b), assuming similar conditions.

The main landslide acceleration phases appear to be driven by meaningful fluctuations in piezometric levels for Champlas du Col system (Fig. 9a) which rise significantly following the groundwater recharge due to snowmelt. Noteworthy are the peaks in piezometric data observed during the spring season, which appear to be proportional to the amount of accumulated snow on the ground. Conversely, in Thures system (Fig. 9b), the anomalies are associated with abnormal increases in spring water levels occurring in the same season, likely due to similar hydrological processes.

In this context, the Interquartile Range (IQR) method was applied to identify significant outliers from the central distribution of the data. The insight of the data distributions (Fig. 8) indicates that the variables are non-normally distributed, although without significant skewness. Given this condition, the use of the IQR method is appropriate, as it is a non-parametric and robust approach that does not require normality (Helsel et al. 2020). The Table 3 summarizes the key statistical descriptors of the dataset, including mean and quartiles. It is noteworthy that the mean and median are almost identical for each variable, confirming that the deviation from normality is minimal. Based on the first (Q1) and third (Q3) quartiles, the lower and upper bounds of the central distribution were defined. In order to detect abnormal accelerations—potentially indicators of rapid displacement rate or sudden instabilities of the landslide body—only values exceeding the upper bound ($Q3 + 1.5 \times IQR$) were considered. Lower outliers are excluded, as they correspond to deceleration phases of the landslide, which are not relevant for risk assessment purposes. In both systems, the temporal ranges of acceleration outliers identified in the 2018 and 2024 scenarios exhibit a short lag of only a few days relative to the onset of anomalies in the groundwater level time series. This short lag suggests a rapid response of slope acceleration to hydrological forcing. However, in case (i), notable accelerations were recorded during spring 2024 despite the absence of corresponding outliers in the piezometric series. This discrepancy is attributed to unusually warm winter temperatures, which led to early snowmelt and early-season soil saturation. Under these conditions, the water table rise was low, as the water infiltrated during the prolonged rainfall did not migrate downwards as quickly as in the case of unsaturated soil. This process triggered a marked acceleration in both systems, approximately one month earlier than in 2018.

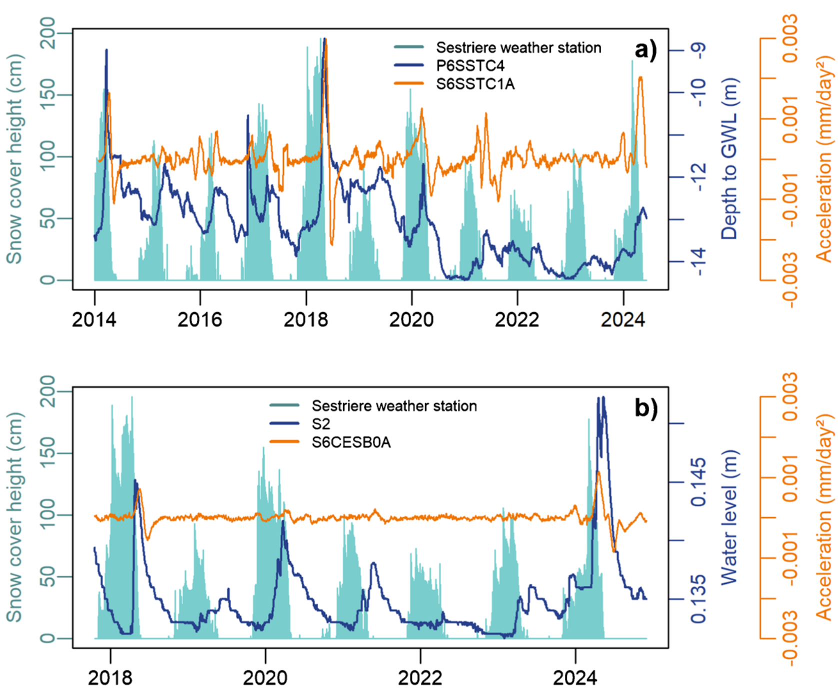

Fig. 9 Acceleration patterns of the (**a**) Champlas du Col and (**b**) Thures landslide

Table 3 Statistical descriptors and identified outliers in groundwater level (GWL) and acceleration patterns

	GWL (P6SSTC4)	Outliers (> Q3 + 1.5 × IQR)	Acceleration (S6SSTC1A)	Outliers (> Q3 + 1.5 × IQR)
(i) Champlas du Col	*Mean* −13.10	19/04–21/05/2018	*Mean* 2.68e-05	22/04–07/06/2018
	Median −13.15		*Median 1.24e-05*	
	Min −14.44	−8.71 (peak on 10/05/2018)	*Min* −2.13e-03	2.97e-03 (peak on 20/05/2018)
	Max −8.71		*Max* 2.97e-03	
	Q1 −13.87		*Q1* −1.22e-04	
	Q3 −12.41		*Q3* 1.11e-04	28/03–28/05/2024
	Q1-1.5 × IQR −16.06		*Q1-1.5 × IQR* −4.70e-04	2.04e-03 (peak on 05/05/2024)
	Q3 + 1.5 × IQR −10.22		*Q3 + 1.5 × IQR* 4.60e-04	
(ii)Thures	**GWL (S2)**	**Outliers (> Q3 + 1.5 × IQR)**	Acceleration (S6CESB0A)	**Outliers (> Q3 + 1.5 × IQR)**
	Mean 0.1349	22/04–30/05/2018	*Mean* 2.59e-06	24/04–04/06/2018
	Median 0.1340		*Median 1.96e-06*	
	Min −0.1316	0.1452 (peak on 27/04/2018)	*Min* −8.44e-04	7.22e-04 (peak on 17/05/2018)
	Max 0.1523		*Max* 1.14e-03	
	Q1 0.1330		*Q1* 4.44e-05	
	Q3 0.1359	22/03–27/06/2024	*Q3* 3.33e-05	23/03–13/05/2024
	Q1-1.5 × IQR 0.1286	0.1523 (peak on 17/04/2024)	*Q1-1.5 × IQR* −1.60e-04	1.14e-03 (peak on 19/04/2024)
	Q3 + 1.5 × IQR 0.1402		*Q3 + 1.5 × IQR* 1.50e-04	

Discussion

The purpose of this study was twofold: firstly, to clarify the relationship between groundwater regime and landslide displacements in the mountain context of Susa Valley and secondly, to explore the potential of using spring behaviour as an indicator to detect and forecast landslide acceleration. The two sites analysed, Champlas du Col and Thures, are affected by deep-seated landslides who hidden shallower landslides whose movements are strongly dependent on hydrogeological factors.

The presence of monitoring points in both sites enabled a comprehensive statistical analysis using groundwater level variations and displacement data. Each spring located on the landslide body play a crucial role, providing valuable insights into aquifer dynamics in response to precipitation and annual snowmelt cycles. The analysis of the water levels using piezometer also allowed for a better understanding of the infiltration process within these systems and whether they can influence the acceleration phases of landslide movements (Corominas et al. 2005). However, the limited spatial distribution of springs across large areas represents a constraint for this analysis. In the first case, the hydrometric levels of the spring are not representative of the groundwater fluctuations occurring at Champlas du Col, as the spring is located far from the SP23R road, where the main sliding surfaces responsible for continuous surface deformations are detected by the S6SSTC1A inclinometer. As demonstrated by the correlation analysis, in this case, piezometric data are more reliable than spring water levels for predicting changes in displacement rates.

Conversely, for Thures site the spring hydrometric data and displacement measurements from the S6CESB0A inclinometer can be spatially correlated and it provides a valuable case study for the development of forecasting models of landslide displacement trends based on spring dynamics.

Autocorrelation and spectral analysis applied to the spring water level data highlighted the influence of monitoring location on the hydrometric level patterns. The S1 spring is part of a shallower system, situated near the aquifer recharge area at the top of the landslide body, which makes it more sensitive to surface runoff from rainfall, as also confirmed by the cross-correlation results (Fig. 6a-b). In contrast, the S2 spring is fed by an aquifer primarily influenced by snowmelt, with rainfall contributing only minimally, though not insignificantly. In this context, extending the analysis to additional spring parameters, such as electrical conductivity, could provide valuable insights into seasonal responses to external inputs.

As discussed in previous work (Musbah et al. 2019), Fourier analysis has made it possible to identify cyclical components in the groundwater fluctuations, and to understand how these can lead to periodic variations in displacement (Conte et al. 2016; Vallet et al. 2016; Wang et al. 2023).

The power spectrum applied to the variables of interest revealed that the groundwater regime—monitored through spring hydrometric level and piezometric data—exhibits a clear annual pattern governed by snowmelt. This analysis also confirmed that the activity of most slow-moving landslides is seasonal, following the periodicity of groundwater fluctuations (Liu et al. 2022; Van Asch et al. 2009). If the water content in the slope is strongly correlated with snow accumulation, which governs the long-term hydrological balance of groundwater recharge in deep landslides, then short-term hydroclimatic conditions also play an important role in soil saturation (Prokešová et al. 2013).

Indeed, extreme weather events, such as those recorded in 2024, can cause sharp increases in groundwater levels, leading to significant acceleration phases. These are identified as rare events through spectral analysis of the available dataset and are also recognized as outliers within the overall dataset.

The rapid development of slope saturation occurred in spring 2024 undoubtedly affected the time lag in the landslide system's response. In this regard, the analyses could be expanded by assessing the water content responsible for the behaviour of deep-seated landslides, through appropriate numerical and hydromechanical models (Cappa et al. 2014; Conte and Troncone 2011; Yokoyama et al. 2022), which can simulate deformations under specific soil saturation conditions. This would allow to identify threshold values based on the contributions of precipitation as well as the role of temperature variations on snowmelt process.

This numerical approach could be adopted particularly in the case of Champlas du Col, since the analyses carried out have shown the strategic importance of the area in terms of possible protective measures to be planned for the presence of the SP23R road. As ARPA Piemonte reports, the greatest displacements occurred after the wettest winters. In the case of Champlas, cumulative precipitation above 100 mm in the winter season of the years 2014, 2018, 2020, 2024, with a peak of 206 mm in 2018, the snowiest winter, resulted in bimonthly displacements during the spring season with values between 3 and 6 mm, when the average value is 1.42 mm. In particular, the year 2024 was the most anomalous as April and May months were very rainy (ARPA Piemonte 2024h) that led to a significant increase in surface deformations (Città Metropolitana di Torino 2024), in this regard the S6SSTC1A inclinometer recorded the highest value so far (7.06 mm) on 5 June 2024. Given these considerations, a much more extensive monitoring network based on geophysical surveys could be designed to monitor the constant infiltrative inputs affecting the Champlas du Col landslide body.

In summary, the potential use of spring dynamics as an indicator of landslide displacement and acceleration is promising, as demonstrated in this study, but it also presents some limitations: i) the location and distribution of springs within the landslide body, depending on its geological setting and spatial extent; ii) the hydrodynamic characteristics of the water circulating within the landslide mass; iii) the availability of deep deformation measurements. Nevertheless, spring data offer a valuable alternative to the traditional monitoring approach based on piezometric data, also because spring probes are unaffected by deep slope movements which frequently damage piezometer pipe, thereby reducing intervention costs in the view of maintenance needs.

Conclusions

The Western Italian Alps are affected by extensive gravitational phenomena due to geomorphological features and intense postglacial erosion. In this paper, two deep-seated landslides in the Susa Valley are represented as clear example of gravitational phenomena influenced by variations groundwater levels. To investigate the effects of seasonal groundwater fluctuations on landslide displacement trends, a purely statistical analysis approach was developed. This approach provides a valuable tool for interpreting slope accelerations in relations to water level changes.

The results obtained through this statistical method demonstrate that the groundwater regime, when analysed using appropriate monitoring data, can be considered indicative of landslide behaviour. Specifically, the annual trend of displacement and groundwater levels, both governed by snow melting processes, show a close temporal and proportional correlation: displacement accelerations occur shortly after water level rises, with the same magnitude. The influence of periods of intense rainfall was also identified, contributing to a more accurate reconstruction of water level behaviour and, consequently, displacement increases.

Among the two case studies discussed, the Thures landslide appears to be the most suitable for predicting displacement variations based on the springtime groundwater data.

Nonetheless, the Champlas du Col site is also of significant interest due to the potential for additional surveys that could improve the assessment of surface movements and help mitigate ongoing damage to the SP23R road. Furthermore, a warning system could be implemented to alert authorities in the event of anomalous precipitation, which could lead to rock mass oversaturation and increase slope instability.

Software

The data were processed using the RStudio 2023.06.0 software based on the R programming language for statistical calculation and graphics. The maps and the related database were created with QGIS 3.34.5.

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Data availability

The data that support the findings of this study are available from the author upon request.

Declarations

Competing interests The authors declare that they have no competing interests.

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