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# Using ERA-5 LAND reanalysis rainfall data to better evaluate the performance of the regional shallow landslide early warning system of Piemonte (north-western Italy) in the context of climate change

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To correctly understand how and whether climate change has influenced the behavior of shallow landslide events over the last century, it is essential to carefully identify the historical series of phenomena and their respective triggering causes, as well as to accurately select the most appropriate analytical tools to minimize the degree of uncertainty in statistical correlation of causes and effects. Shallow landslide events occurring from 1960 to 2023 in Piemonte (NW Italy) are considered here, for which the primary triggering cause is represented by rainfall events, with a negligible contribution from antecedent precipitations. This paper is an update of a previous study, adding to the analysis recent widespread landslide events covering a wider time range with new precipitation data (additional 4 years). The primary difference lies in the use of a different method to analyze the rainfall responsible for the occurrence of shallow landslides. In particular, the results obtained for 24 and 48 h rainfall durations, when compared with the triggering thresholds of the R-SLEWS (previously employed the Optimal Interpolation Method), are verified using new and more flexible method for reconstructing triggering rainfall based on ERA5-Land hourly precipitation data. The new approach moderately improves the identification of actual triggering rainfall over 24 h but is less performant when it comes to identifying triggering shallow landslides over 48 h. Where no significant improvements in the detection of rainfall-inducing shallow landslide events are obtained, the method can still be effectively used in areas with a sparser rain gauge network, which can rely less on observed precipitation data.

KEYWORDS

**landslide event, global warming, rainfall threshold, Copernicus services, hilly environment, Alps**

# 1 Introduction

Shallow landslides occurrence directly depends on rainfall events and is not influenced by antecedent precipitations, including water contribution by snowmelt, as demonstrated by Tiranti and Rabuffetti (2010), Cremonini and Tiranti (2018) and Tiranti et al. (2019). For this reason, shallow landslide events in Piemonte are directly driven by rainfall regime characteristics at regional scale and related variations in intensity and spatiotemporal distribution (Stoffel et al., 2014; Tiranti and Ronchi, 2023).

When occurred, changes in shallow landslide events behavior are strictly dependent on alterations in precipitation patterns which, in some cases, can be attributed to climate changes at local scale, as reported in many recent scientific papers focused on shifting rainfall trends in Italy (Brunetti et al., 2004; Picarelli et al., 2015; Libertino et al., 2018; Gentilucci et al., 2019; Mazzoglio et al., 2020; Moccia et al., 2021).

However, the phenomena observed at national extension do not fully represent the dynamics occurring at regional scales, where substantial differences can be identified both in terms of changes in precipitation trends and, consequently, in the occurrence (intensity, seasonality and spatiotemporal distribution) of shallow landslide events (Borgatti and Soldati, 2010; Gariano et al., 2015; Gariano and Guzzetti, 2016; Gariano et al., 2018; Tonini et al., 2022; Tiranti and Ronchi, 2023).

In order to minimize the uncertainty associated with the attribution of triggering rainfall and to comprehensively understand the actual relationships between precipitation trends and shallow landslide events, as well as their interdependent variations over time, it is essential to accurately identify the best approach characterized by the least uncertainty to be employed in statistical analyses.

In a previous study, Tiranti and Ronchi (2023) examined the effectiveness of the triggering thresholds employed in the development of the Regional Shallow Landslide Early Warning System (R-SLEWS) for different geological and geomorphological environments (Alps, Apennines, Turin hill and Tertiary Piemonte Basin - TPB) in the Piemonte region. The analysis, considering the average landslide triggering threshold values for 24 and 48-h duration with respective reference values of 120 mm and 170 mm for the mountains (Alps), and 70 mm and 80 mm for the hills (Turin Hill, TPB and Apennines foothill), is derived from the R-SLEWS “Shallow Landslide Occurrence Prediction System” (SLOPS) operating in Piemonte since 2018 (Tiranti et al., 2019). The analysis compared 120 shallow landslide events recorded between 1960 and 2019 with daily precipitation data interpolated using the Optimal Interpolation (OI) method (Kalnay, 2003) over the same timeframe. The study reported a hit rate of 68%, indicating that the existing triggering thresholds used in the R-SLEWS are reliable to both mountainous and hilly areas throughout the entire study period.

However, a significant limitation of this research was the coarse temporal resolution of the precipitation dataset, which was limited to 24-h intervals (from 00:00 to 23:59 UTC). Consequently, this framework is inadequate for evaluating the validity of the triggering thresholds over shorter timeframes (e.g., 6 or 12 h) and does not facilitate the analysis of precipitation events occurring over two consecutive days that do not exceed the 48-h threshold.

In this study, we used ERA5-Land hourly precipitation data, applying daily quantile mapping to appropriately correct biases, and implement 24-h and 48-h moving windows to enhance temporal resolution. The primary objectives of this research are double: (1) to verify the effectiveness of the R-SLEWS triggering thresholds by specifically focusing of rainfall events exceeding the 24 h/48 h threshold but developing on two or more consecutive days, and (2) to evaluate the feasibility of employing large-scale satellite data for assessing and forecasting slope phenomena at regional and local scale.

TABLE 1 Shallow landslide event severity class adopted to quantify the landslide events’ intensity based on landslides’ range numbers occurred during a single rainfall event.

| Landslide event severity class | Landslides number range |
|---|---|
| 1 - Extremely Low | 1–50 |
| 2 - Very Low | >50–100 |
| 3 - Low | >100–200 |
| 4 - Moderate | >200–500 |
| 5 - High | >500–2,000 |
| 6 - Very High | >2,000–5,000 |
| 7 - Exceptionally High | >5,000–10,000 and upper |

# 2 Materials and methods

## 2.1 Updated shallow landslide events framework

To improve the results obtained by Tiranti and Ronchi (2023), we considered an updated and extended analysis that encompasses 123 widespread landslide events from 1960 to 2023 (collected from historical archive of national newspaper “La Stampa” - http://www.archiviolastampa.it - and from the regional technical reports archive - https://www.arpa.piemonte.it/ricerca/pubblicazioni?field_tema_target_id=18), distinguishing shallow landslide events through a classification into seven severity classes related to the number of landslides that occurred during a rainfall event (Table 1).

A weak upward trend is highlighted from 1960 to 2023, indicating that shallow landslide events are progressively becoming more intense in terms of the number of landslides occurring during a single rainfall event, considering landslide events having a severity class ≥4 (moderate or higher) (Figure 1A).

On the contrary, the number of shallow landslide events shows a decreasing trend in the same time interval divided into five-year periods, as illustrated in Figure 1B.

## 2.2 ERA5-land precipitation data preparation

We used ERA5-Land hourly precipitation data from 1 January 1960, to 31 December 2023, for Piemonte and neighboring areas

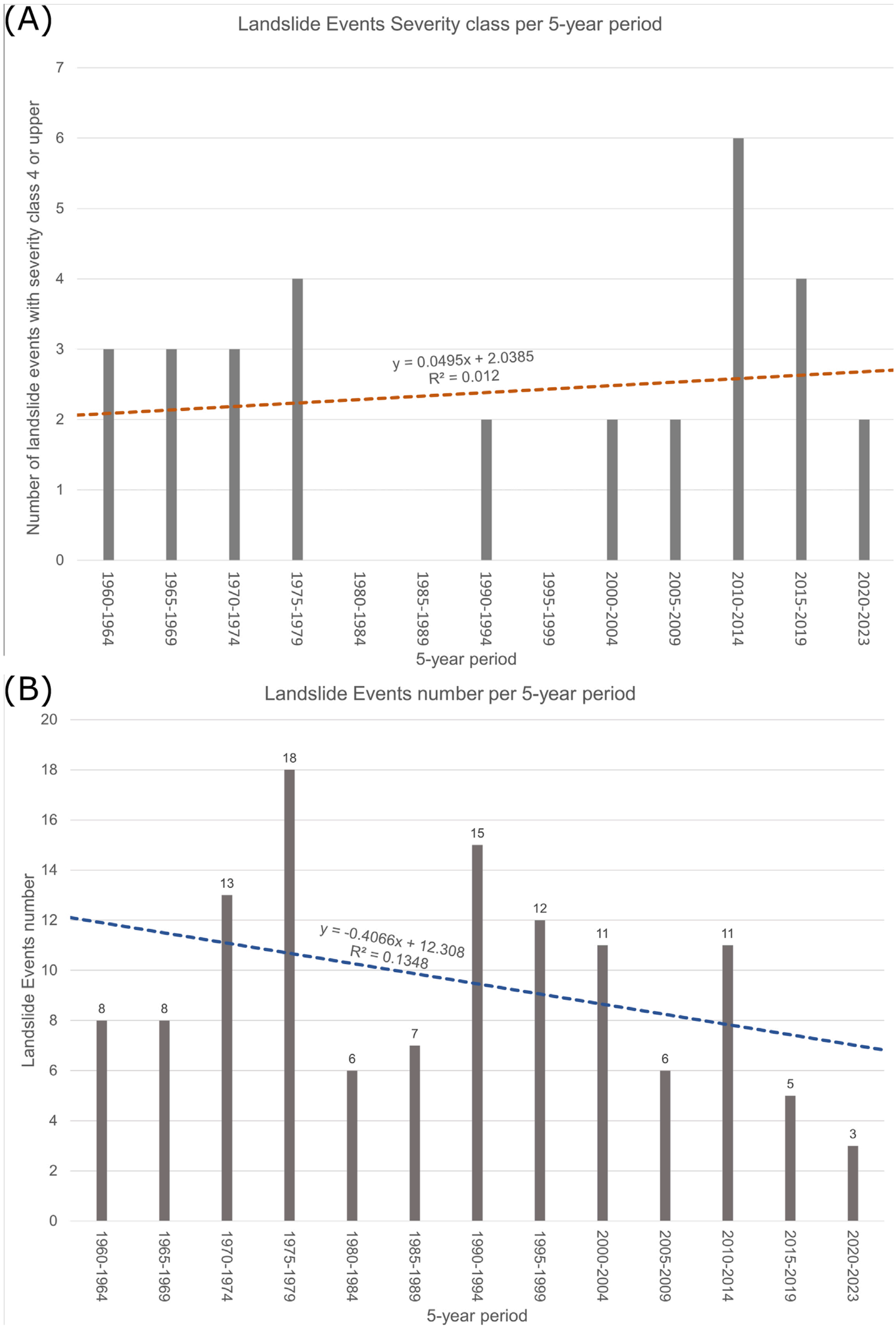


FIGURE 1
**(A)** Shallow landslide events temporal distribution (from 1960 to 2023) grouped by 5-year periods having a severity class ≥4 showing a weak increasing trend. **(B)** Shallow landslide events occurred from 1960 to 2023 grouped by 5-year periods showing a decreasing trend.

(longitude: 6.5°E to 9.5°E; latitude: 44°N to 46.5°N), sourced from the Copernicus Climate Data Store. For a preliminary validation of applied bias correction technique, the hourly data were aggregated into daily cumulative precipitation to match the temporal resolution of the regional dataset developed by the Regional Agency for Environmental Protection of Piemonte (ARPA Piemonte), which uses OI techniques. The OI dataset contains daily cumulative precipitation (along with maximum and minimum temperatures, not used in this study) from 1959 onwards, on a 0.125° grid (~15 km resolution) covering the Piemonte region. The ERA5-Land data were interpolated onto the OI grid points using the "remapcon" function provided by the Climate Data Operators toolset (Schulzweida, 2023).

To minimize biases in the ERA5-Land data, robust Quantile Mapping (QM) was applied daily, based on the 1991–2020 climatological reference period, using the fitQmapRQUANT function in the "qmap" package in R software (Gudmundsson et al., 2012). To evaluate the performance of QM we computed and plotted (see Figure 2A of Section 3) the average monthly precipitation over the entire study period. For further validation at a finer scale, we applied a geographical mask for the Piemonte region to both the ERA5-Land dataset and the adjusted dataset. For both, we calculated the mean daily regional precipitation for each day from 1 January 1960, to 31 December 2023. In order to test the performance of each dataset after QM bias correction in recognizing wet (≥1 mm rain) vs. dry (<1 mm rain) days, contingency tables were calculated, performance metrics were computed, and a performance diagram was plotted (see Figure 2B of Section 3) using the "verification" package in R software, with the OI dataset serving as the reference.

After checking the validity of daily QM for correcting biases in ERA5-Land data, 24-h rolling cumulative precipitation totals were calculated for all possible 24-h windows (e.g., 00:00–23:59; 01:00–00:59 D+1; 02:00–01:59 D+1, etc.), creating 24 distinct datasets. This step was decisive for testing the R-SLEWS of Piemonte, particularly for rainfall events that last for several days, where the total precipitation over a 24-h window might exceed the threshold, even if individual days do not. The rolling windows were essential to capture events where the cumulative precipitation exceeds the threshold outside of the standard 00:00–23:59 timeframe, ensuring that no significant events were overlooked due to the fixed daily boundary. These events, which might exceed landslide-triggering thresholds but go undetected by standard daily 00:00–23:59 UTC precipitation data, are now accounted for by this rolling approach. The QM-corrected coefficients were applied to each of 24-h datasets to align the ERA5-Land data with the observed OI precipitation, ensuring consistency across all datasets used for validation and modeling. The treatment of the climate datasets described in this paragraph was performed using the Climate Data Operators (Schulzweida, 2023).

## 2.3 Triggering threshold verification

Each of the 24 dataset was then analyzed to assess their ability to predict shallow landslide events triggered by rainfall. For each dataset, we identified the dates when the average 24-h cumulative precipitation exceeded the trigger thresholds defined by the R-SLEWS developed by Tiranti et al. (2019): 70 mm for hilly areas and 120 mm for mountainous areas. These dates were subsequently compared against a database of 120 shallow landslide events, collected from technical reports and newspaper archives. It is important to note that some of these landslide events were very widespread and affected both mountainous and hilly areas. For the purposes of this study, these widespread events were also divided into 179 sub-events (fragmenting a single event into sub-events based on the geographical environment involved) and analyzed individually.

In the updated study here presented, the dataset was composed of 185 sub-events derived from a total of 123 widespread events, adding to the previous 120 events those that occurred between 2020 and 2023:

- 2–3 October 2020: the landslide event involved both Alps and TPB environments with a range of shallow landslides between 500 and 1,000 (high severity class);
- 13 July 2021: the landslide event involved Alpine environment with a range of shallow landslides between 50 and 100 (very low severity class);
- 19–21 May 2023: the landslide event involved Alps, Turin Hill and TPB areas with a range of shallow landslides between 200 and 500 (moderate severity class).

For each 24-h dataset, we applied an elevation mask to extract precipitation data for areas at elevations between 400 and 700 m asl (designated as "hills") and higher than 700 m asl (designated as "mountains"). For each dataset, we generated a list of dates on which precipitation exceeded the triggering threshold (either 70 mm or 120 mm, depending on elevation and related geological features) within moving 24-h windows. These lists were then automatically cross-referenced with the dataset of shallow landslide events compiled for Piemonte to identify all matches within each 24-h window. We then refined the results by removing any duplicated dates.

To further explore the detection capabilities of our approach, we applied running sums to each of the 24 datasets. This allowed us to obtain cumulative sums over two consecutive timesteps, for each dataset. Such data were then used to compile 48 datasets, each covering a time window of 48 h (00:00 D – 23:59 D+1; 01:00 D + 00:59 D+2, and so on). From each dataset we then extracted list of dates on which precipitation exceeded the triggering threshold (either 80 mm or 170 mm, depending on elevation and geological features) within moving 48-h windows. After cross-referencing such lists with the shallow landslide dataset to identify all matches, the results were then refined by removing any duplicated dates.

The final output of our analyses, for both mountainous and hilly regions, was a list of dates on which bias-corrected precipitation surpassed the triggering thresholds, coinciding with an observed shallow landslide event. In this study, if a shallow landslide event was widespread and extended over multiple consecutive days, we considered it as successfully identified if the triggering threshold was exceeded on at least 1 day during the event duration.

# 3 Results

## 3.1 Quantile mapping evaluation

Mean monthly precipitation of the OI dataset, the ERA5-Land dataset and the QM-corrected dataset are represented in Figure 2A. Raw ERA5-Land data generally capture the observed precipitation patterns from the OI dataset, correctly identifying May, October, and November as the wettest months. However, ERA5-Land systematically overestimates average monthly precipitation (Pearson

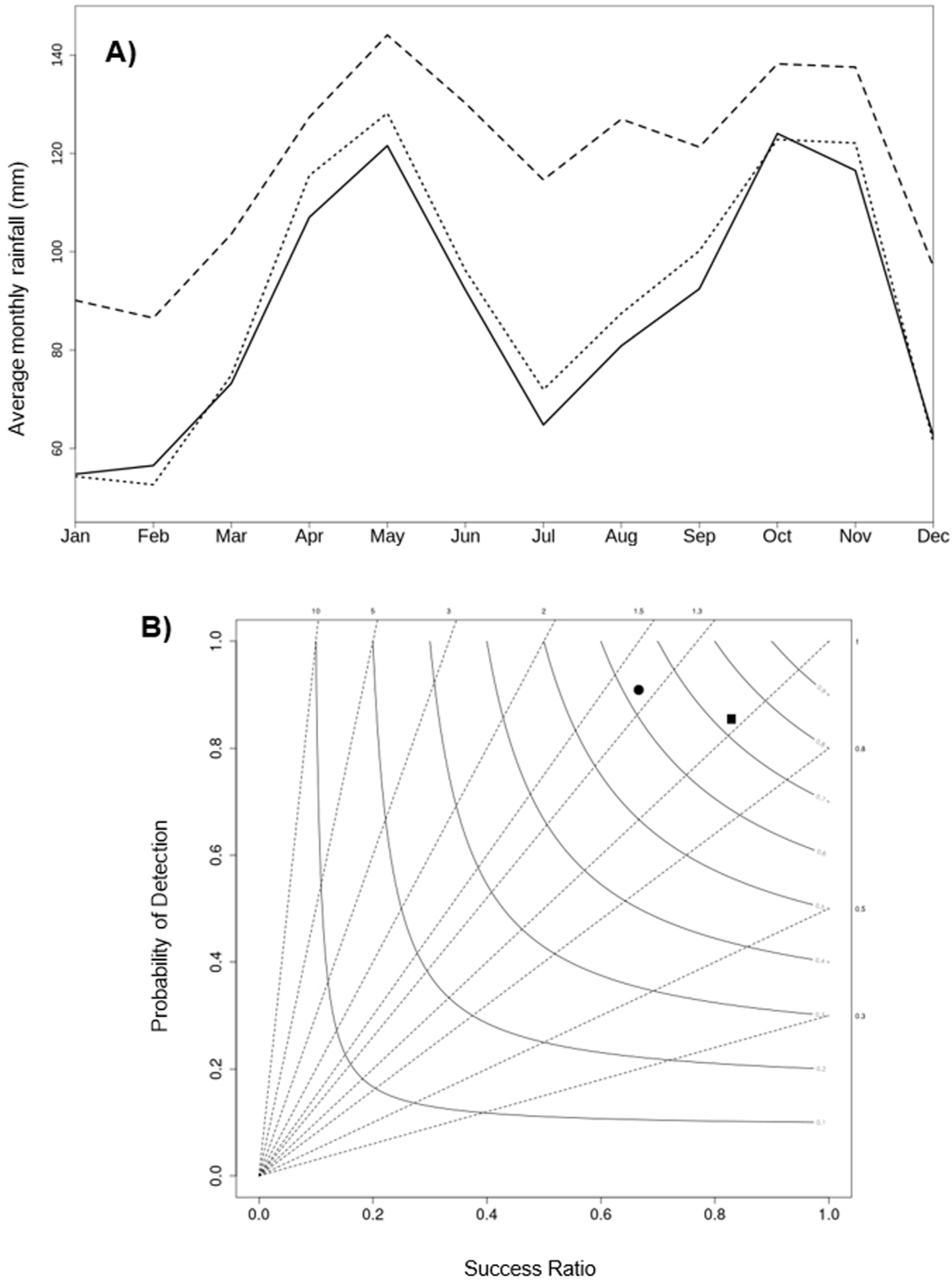


FIGURE 2
**(A)** Comparison of average monthly precipitation for the period 1960–2023 for the OI dataset derived from observed rainfall (solid line), the ERA5-Land dataset (dashed line) and the bias-corrected dataset used for shallow landslide detection (dotted line). **(B)** Performance diagram comparing the ability of detecting wet and dry days between different dataset (black dot: OI data vs. ERA5-Land data; black square: OI data vs. bias corrected data).

correlation coefficient: 0.88; RMSE: 33.82), with this overestimation being less pronounced in spring (MAM) and fall (SON) but markedly higher in summer (JJA) and winter (DJF). The application of QM to the ERA5-Land data noticeably reduces these biases and aligns with the trends and values observed in the OI dataset (Pearson correlation coefficient: 0.96, RMSE: 9.03).

The effectiveness of daily QM in reducing biases is confirmed when the analyses are repeated for the mean daily regional precipitation, in order to evaluate the ability to distinguish wet and dry days. The QM-corrected dataset, when compared to the observed data, exhibits a high correlation (Pearson correlation coefficient: 80%), with a RMSE of 4.43 mm and a SD of 6.98 mm. The performance diagram of the bias-corrected dataset in identifying wet vs. dry days is represented in Figure 2B. The statistical metrics (POD: 0.76; SR: 0.73; CSI 0.60; bias: 1.04) confirm that the bias-corrected dataset is reasonably accurate in detecting and forecasting precipitation; notably, the bias value indicates that the QM-corrected dataset does not significantly over-estimates or under-estimates the number of wet days (Roebber, 2009).

Based on these results, daily QM emerges as an acceptable approach for bias correction of ERA5-Land precipitation data over Piemonte, showing good skills in capturing the natural variability of rainfall events. Consequently, the QM indices calculated using daily QM were applied to obtain the 24-h rolling cumulative precipitation.

## 3.2 Triggering threshold identification and comparison with shallow landslide events database

Following the approach of Tiranti and Ronchi (2023), we categorized the landslide events based on their geographical setting into two groups: Alpine areas (mainly characterized by crystalline bedrocks) and Apennines/hilly areas (mainly characterized by sedimentary bedrocks). The latter group includes all shallow landslide events that occurred in the TPB, the Turin hills, and the Apennines foothill. Widespread shallow landslide events affecting multiple environments were divided into sub-events, which were then grouped based on the specific environment where each sub-event took place and treated accordingly. Final shallow landslide dataset included 123 events, that could further be subdivided in 87 sub-events in Alpine environments, and 84 sub-events in the hilly/Apennines environments (of which: 8 in the Apennines, 13 in the Turin hill, 77 in the TPB).

New approach allowed to correctly identify 61 shallow landslide events based on 24-h cumulated rainfall, out of the 123 collected in the landslide database of Piemonte. We correctly identified 33 shallow landslide events taking place in Alpine areas, and 49 taking place in the hills. Interestingly, the detection capability was only marginally increased by the application of sliding windows: daily cumulated rainfall between 00:00 and 23:59 UTC allowed to detect 59 events, while the analysis on different 24-h sliding windows provided only two additional events. Remarkably, such additional events were observed in the data regarding Alpine areas, triggered by heavy precipitations (exceeding 120 mm/24 h). The sliding window approach, on the other hand, had no appreciable effect on the detection of events taking place in hilly areas, which can be triggered by less intense rainfall (>70 mm/24 h).

When 48-h periods were considered, we successfully identified 68 events (of which 34 in the mountains and 54 in hilly areas). Once again, the application of sliding 48-h windows did not impact the detection of events in the hilly areas, while it sensibly improved the performance in Alpine areas (6 additional events). Only when 24-h periods and 48-h periods were pooled were we able to correctly identify 73 events, representing nearly 60% of the shallow land slide events recorded in our dataset. Table 2 shows in details the number of hits and misses alarms we obtained with our procedure.

TABLE 2 Performance metrics of hits and misses for Hills and Mountain subevents, as well as all events combined, analyzed over 24-h, 48-h, and combined timeframes.

| Duration | Hits | Misses |
|---|---|---|
| 24-h | | |
| Hills subevents | 49 (58.3%) | 35 (41.7%) |
| Mountain subevents | 33 (37.9%) | 54 (62.1%) |
| All events | 61 (49.6%) | 62 (50.4%) |
| 48-h | | |
| Hills subevents | 54 (64.3%) | 30 (35.7%) |
| Mountain subevents | 34 (39.1%) | 53 (60.9%) |
| All events | 68 (55.3%) | 55 (44.7%) |
| 24 + 48-h COMBINED | | |
| Hills subevents | 56 (63.7%) | 28 (33.3%) |
| Mountain subevents | 39 (44.8%) | 48 (55.2%) |
| All events | 73 (59.3%) | 50 (40.7%) |

# 4 Discussion

Annual and seasonal cumulative rainfall in Piemonte has remained relatively stable over recent decades. However, a slight decrease in the number of rainy days has been observed, suggesting that precipitation events have become less frequent but more intense (ARPA Piemonte, 2020). This trend aligns with the observed behavior of shallow landslides in the region, which have decreased in frequency but increased in severity between 1960 and 2023.

Shallow landslides are among the most hazardous natural phenomena, causing significant infrastructure damage and high casualty rates. A reliable R-SLEWS is therefore critical to predict such events and mitigate associated risks. Since 2019, ARPA Piemonte has adopted the R-SLEWS SLOPS (Tiranti et al., 2019) for this purpose. Recent back-analyses using optimally interpolated precipitation data revealed that SLOPS achieves a detection rate of 68% for 48-h rainfall thresholds but is less effective for 24-h thresholds (hit rate: 47.5%) (Tiranti and Ronchi, 2023).

This study extends previous research by incorporating a larger dataset of shallow landslides and utilizing modelled hourly precipitation data from the ERA5-Land database. To reduce biases and ensure comparability with observed precipitation measurements, we applied daily QM. This research represents the first use of bias-corrected ERA5-Land data for a regional back-analysis of shallow landslides, providing novel insights into the potential of reanalysis data for such applications.

The bias-corrected ERA5-Land dataset demonstrated hit rates of approximately 50% for 24-h windows and 55% for 48-h windows. Combining both timeframes improved the hit rate to around 60%. However, these results reveal significant variability based on the elevation of landslide detachment zones. For Alpine events, hit rates ranged from 38% to 45%, while for hilly regions, they were notably higher, between 58% and 64%. This disparity underscores the spatial and temporal variability of precipitation patterns and the challenges of accurately modeling such processes.

Compared to interpolated observational data used in the previous work, the ERA5-Land dataset, despite bias correction, exhibited lower detection capabilities. This discrepancy might be due to the fact that the regional rain gauge network is well developed and collects continuous data series since 1958. With approximately 250 rain gauges distributed across various sloped environments and altitudes, the rain gauge network provides detailed coverage of most rainfall events (although some very localized convective event may be missed), including interpolations for areas without direct measurements. Conversely, ERA5-Land, derived from a reanalysis of large-scale rainfall data, may incorporate uncertainties and biases, particularly in complex terrains like the Alps. Hence, while ERA5-Land provides hourly estimates of numerous variables at a 10 km spatial resolution, its numerical model-based nature cannot fully match the granularity of observational datasets in regions with dense station networks.

Validation studies of ERA5-Land precipitation data are still limited. A recent study in mainland China (Jintao et al., 2022) found that ERA5-Land accurately represents rainfall in temperate climates but underperforms in high-mountain regions. Similarly, validation over Spain (1951–2020) revealed that ERA5 and ERA5-Land data detect moderate precipitation events (≤20 mm/day) effectively but underestimate heavier precipitation (Gomis-Cebolla et al., 2023). These findings are consistent with our results, where ERA5-Land underrepresents landslides triggered by intense rainfall at higher elevations.

To align modeled data with local observations, we employed QM, which identifies quantile-dependent transformations to minimize biases in modeled variables (Gudmundsson et al., 2012). While QM is widely used to improve the representation of precipitation extremes (Tani and Gobiet, 2019), it faces limitations, especially for rare high-intensity events. These are poorly represented in calibration datasets, leading to underrepresentation in bias-corrected datasets (Feigenwinter et al., 2018). This limitation likely explains the lower detection capability for shallow landslides in Alpine regions.

Another limitation of QM lies in its spatial representativeness. In areas with complex topography, such as the Alps, the coarse resolution of climate models may fail to capture local-scale variability accurately (Feigenwinter et al., 2018). Additionally, adopted QM correction function was calibrated on data from the 1991–2020 period and applied to the 1960–2023 dataset, implicitly assuming that biases and correction functions remain temporally stationary, but in a changing climate this assumption might introduces uncertainties. Despite these challenges, we validated the QM implementation thoroughly and confirmed its overall effectiveness, though some inherent limitations might not have been entirely mitigated.

Finally, we adopted a sliding window approach to leverage the high temporal resolution of ERA5-Land data. By calculating cumulative 24-h and 48-h rainfall totals for each day, this method improved landslide detection in Alpine regions by 6% (24-h) and 17% (48-h) but had no impact on hilly areas. The sliding window approach effectively captures precipitation events spanning consecutive days, which is particularly advantageous in mountainous regions where rainfall patterns are more variable, and triggering thresholds are higher. By providing a more comprehensive representation of cumulative rainfall, the sliding window approach partially compensates for the limitations of QM in mountainous areas, enhancing landslide detection driven by aggregated precipitation events that might otherwise be missed by rigid daily boundaries.

## 5 Conclusion

Despite the higher temporal and spatial resolution, ERA5-Land rain data are less reliable than OI data derived from rain gauges in identifying rainfall events that trigger shallow landslides in Piemonte over the last 63 years. However, despite these limitations, the correction of ERA5-Land hourly rainfall data with QM remains a valuable tool, especially in regions with sparse instrumental networks. In such areas, it can provide an alternative means of evaluating precipitation fields, not only for identifying rainfall-induced shallow landslides but also for other applications that might benefit from the back-analysis of climatic data, including model validation and insurance evaluations following extreme weather events.

Furthermore, the potential of this approach could be enhanced by leveraging satellite-derived precipitation data (such as IMERG) or higher-resolution reanalysis datasets (e.g., the COSMO-CLM model with 0.02° resolution). These advancements would improve both the spatial and temporal accuracy of the input data, leading to more robust identification of shallow landslide events and offering significant opportunities for improving risk assessment and management in data-scarce regions.

## Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: The hourly precipitation dataset for this study can be found in the Copernicus Climate Data Store https://cds.climate.copernicus.eu/#!/home, accessed on 11/20/2024. Technical reports on landslide events in Piemonte are available at ARPA Piemonte website https://www.arpa.piemonte.it/ricerca/pubblicazioni?field_tema_target_id=18, accessed on 11/20/2024. Historical archive of national newspaper "La Stampa" archive - http://www.archiviolastampa.it, accessed on 11/20/2024.

## Author contributions

VB: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation,

Visualization, Writing–original draft, Writing–review and editing. DT: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. SB: Methodology, Resources, Validation, Writing–review and editing. CR: Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note



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