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Statistical Approaches for Regionalisation and Interpolation of Intense Precipitation for Climate Resilience in South Tyrol

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Abstract

Reliable design storms are indispensable for climate-resilient drainage in the Alpine province of South Tyrol, where steep orography produces sub-kilometre rainfall contrasts that existing atlases fail to capture. The present study proposes a comprehensive methodology for interpolating intense precipitation data in South Tyrol. Utilising advanced statistical techniques, including exponential distribution and Ordinary Kriging interpolation, the study offers a reproducible workflow that converts 5-minute gauge records from several stations in South Tyrol into a 1 x 1 km grid of Intensity-Duration-Frequency (IDF) curves. The objective of the study was to enhance hydrological modelling and flood risk assessment across various durations and return periods. After rigorous quality control, the annual maxima are fitted with the exponential distribution and the scale (u) and slope (w) parameters are then regionalised by 3D ordinary kriging within six homogeneous subregions. The approach was validated against observed station data, thereby confirming its robustness. The novel grid has demonstrated efficacy in reducing interpolation error whilst concomitantly enhancing the resolution of the valley-ridge gradient characteristic of convective Alpine storms. The released dataset provides the first kilometre-scale basis for urban drainage design, flood mapping and climate adaptation planning in South Tyrol and offers a transferable framework for other mountain regions.

Highlights

- A high-resolution (1x1 km) precipitation grid for South Tyrol capturing the spatial variability of rainfall across complex topography.
- Integration of statistical distribution fitting with three-dimensional ordinary kriging enables effective regionalisation of intense precipitation.
- The resulting precipitation intensity maps improve the performance of hydrological modelling and the reliability of flood risk assessments in the region.

Introduction

Understanding the spatial distribution and recurrence characteristics of extreme precipitation is essential for effective hydrological modelling, flood risk assessment, and climate resilience planning, especially in complex Alpine regions such as South Tyrol. The region's intricate topography, diverse microclimates, variable density of rainfall monitoring stations present unique challenges for accurately interpolating precipitation extremes. Traditional gauge networks often fail to capture the fine-scale spatial variability inherent in mountainous areas.

To address these limitations, various statistical and geostatistical interpolation methods have been developed, including deterministic approaches like Inverse Distance Weighting (IDW) and Splines, as

well as geostatistical techniques such as Ordinary Kriging (OK), Kriging with External Drift (KED), and CoKriging (Hassim et al., 2020). A broad body of literature compares interpolation methods and research consistently demonstrates that geostatistical techniques, particularly KED, outperform superior performance when incorporating auxiliary data, such as elevation or satellite-derived indices (e.g., NDVI, cloud properties) (Pellicone et al., 2018) (Caloiero et al., 2021).

Conventional interpolation techniques for precipitation data are frequently influenced by topographical features and other geographical variables. A substantial body of research has demonstrated that topography significantly influences precipitation distribution, with numerous studies indicating improvements in interpolation accuracy when integrating geographical variables (Kebaili Bargaoui and Chebbi, 2009) (Rogelis and Werner, 2013) (Bárdossy and Pegram, 2013). (Militino et al., 2015) utilised spatiotemporal patterns and clustering methodologies to facilitate the interpolation of daily precipitation data. The study emphasised the importance of incorporating temporal and spatial variability to achieve more precise estimates.

Advanced spatial and temporal interpolation approaches, like those utilized in Germany's MUNSTAR project ("Methodische Untersuchungen zur Novellierung der Starkregenstatistik für Deutschland (MUNSTAR)," n.d.), having integrated over 1,400 rain gauges and applied advanced regionalisation strategies to generate updated IDF statistics across Germany, and anomaly-based methods developed specifically for the Trentino–South Tyrol region (Crespi et al., 2021), that developed a high-resolution (250 m) gridded dataset of daily temperature and precipitation for Trentino–South Tyrol, provide robust frameworks and regionally validated climatological that have been validated for mountainous areas for hydrological modelling and spatial analysis in alpine environment.

Statistical methodologies for spatial interpolation, including linear and polynomial regression, are based on models that seek to elucidate data variability through functional relationships. (Chen et al., 2017) demonstrated that multiple linear regression (MLR) and a principal regression with residual correction (PCRR) approach outperformed traditional Kriging by reducing interpolation errors and improving correlation within hydrological simulations.

Alongside spatial interpolation, stochastic rainfall models, notably enhancements of Bartlett–Lewis point process models, have significantly enabling accurate simulation of rainfall events at sub-hourly resolutions (Cowpertwait et al., 2007). Recent implementations, such as the Python-based *pyBL* package, have been demonstrated to effectively capture extreme rainfall properties and provide solutions suitable for areas with sparse high-frequency data records (Onof and Wang, 2020) (Wei et al., 2025), enabling sub-hourly and daily simulations that preserve both standard and extreme statistical properties and supporting multi-timescale calibration, a particularly useful feature when long-term, high-frequency data are not uniformly available, a situation common in Alpine regions such as South Tyrol.

Complementing these statistical methodologies, machine learning algorithms and hybrid models, incorporating techniques such as random forests, support vector machines, XGBoost and neural network architectures for super-resolution, have demonstrated efficacy in enhancing the spatial and temporal resolution of rainfall estimates, particularly when complemented by statistical post-processing, remote sensing products and detailed orographic data (Zhu et al., 2023) (Xu et al., 2023) (Reddy et al., 2023) (Abdollahipour et al., 2021).

Building upon this extensive body of research, this study introduces an integrated methodological framework tailored to South Tyrol's specific geographic and climatic characteristics. By integrating data from a dense network of local weather stations and combining exponential distribution fitting with Ordinary Kriging, the research aims to produce a high-resolution (1×1 km) gridded dataset of precipitation intensities across multiple durations and return periods. The result is a comprehensive framework capable of capturing South Tyrol's intricate precipitation patterns: this dataset will provide an essential foundation for hydrological simulations, climate impact analyses, and strategies for disaster risk reduction in Alpine environments serving as a robust input for hydrological simulation, climate impact modelling, and disaster risk reduction strategies. This work contributes to bridging the gap between statistical theory and practical application in regions where terrain complexity, data sparsity, and climatic extremes intersect.

Methodology

South Tyrol is characterised by a diversified topography and significant precipitation variability, which poses considerable challenges to the accurate modelling of hydrological systems and the assessment of flood risk. Intense rainfall events in this Alpine region pose a threat to urban infrastructure and community resilience, necessitating accurate spatial representations of precipitation intensities. To address these challenges a robust methodology for regionalizing and interpolating precipitation data was developed, leveraging advanced statistical and geostatistical techniques to enhance urban drainage modeling and flood management. The present study builds on the methodological foundations laid down in recent research, extending the concept to three-dimensional space.

The methodology was structured in several key phases. Initially, pluviometric data were systematically collected from a dense network of meteorological stations across South Tyrol. In order to ensure reliability, rigorous quality control measures were applied: these included outlier detection and data normalisation. The annual maxima were extracted using a partial duration threshold of five events per year, in accordance with the provincial guidelines. The parameters of the exponential distribution (u and w) were estimated using L-moments, providing robust fits across station-duration combinations. Subsequently, South Tyrol was divided into six homogeneous regions. The basis for this division was the physiographic characteristics of the region, including such factors as altitude, land use, and proximity to water bodies. In addition to these characteristics, the division was also based on statistical similarities in observed precipitation data. This regionalisation enhanced the accuracy of subsequent interpolations.

Exploratory variogram analyses revealed distinct spatial correlation patterns within each region and duration level to quantify the spatial variability of precipitation measurements. Empirical variograms were then computed in three-dimensional space (longitude, latitude, altitude) and fitted with Gaussian, exponential, and spherical theoretical models using weighted least squares, selecting parameter sets with minimum root mean square error (RMSE) and residual sum of squares (RSS).

The variogram models facilitated the implementation of 3D Ordinary Kriging, interpolating precipitation intensities onto a finely resolved 1×1 km grid derived from the EU Digital Elevation Model (EU DEM). The interpolation process utilised the previously fitted variogram models to assign weights based on spatial correlation, thereby ensuring that measurements from nearby stations had a greater influence on the estimated precipitation intensities at unmeasured locations. PyKriging was utilised for the solution of Kriging equations, incorporating altitude as a third dimension. The implementation of a 10 km buffer zone around the interpolation grid served to mitigate the effects of boundaries.

The validation of interpolation performance was achieved through the implementation of leave-one-out cross-validation, a process which entailed the comparison of interpolated values against observed intensities for multiple return periods. The performance of the interpolation process was evaluated by the calculation of metrics such as the root mean square error (RMSE), the mean absolute error (MAE), the Nash-Sutcliffe efficiency index (NSE), and the coefficient of determination (R^2).

A comprehensive GIS-based grid was finally generated, integrating elevation data to accurately reflect topographical influences on rainfall patterns. This provided detailed and reliable spatial representations of intense precipitation across South Tyrol.

Case study

The methodology was applied to the autonomous province of South Tyrol, which is located in the northernmost part of Italy and is characterised by complex orography and varied climatic conditions, thus posing significant challenges for the accurate regionalisation of extreme precipitation. In order to effectively address these complexities, data from a dense network of meteorological stations distributed throughout the territory were utilised. Each station provided high-resolution rainfall data, the quality of which was checked using rigorous procedures.

Initially, precipitation intensities for various durations (e.g., 5, 15, 60 minutes, and 1 day) and return periods were computed using an exponential distribution fitted to partial duration series. The

parameters of the distribution $u_p(D)$ and $w_p(D)$ were calculated for each station and duration and were subsequently utilised to estimate precipitation heights via the following equation:

$$h_N(D, T_n) = u_p(D) + w_p(D) \log T_n$$

where h_N denotes rainfall height [mm] for a specific duration D [min] and return period T_n [years]. These parameters provided the foundation for the subsequent spatial interpolation and regionalisation phases.

In consideration of the pronounced terrain heterogeneity, which encompasses both deep Alpine valleys and high-altitude ridgelines, the study introduced a regionalisation step to improve spatial coherence and estimation accuracy.

The principles of the KOSTRA-DWD methodology were utilised to divide South Tyrol into six climatologically homogeneous regions (see Figure 1). This regionalisation took into account geographical attributes such as elevation, land use, and proximity to water bodies, as well as statistical similarities observed in intense rainfall patterns among neighbouring stations. Initial interpolation results across the province indicated distinct regional characteristics, thus validating the necessity of this segmentation. This regional segmentation was informed by preliminary spatial analyses, which revealed consistent structural patterns in the distribution of precipitation extremes throughout the province.

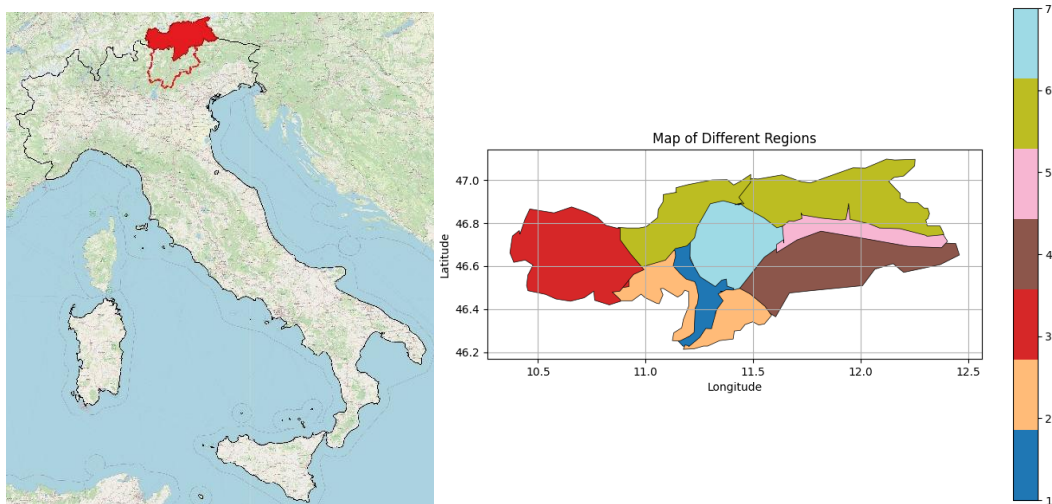


Figure 1. Homogeneous regions.

Results and discussion

Empirical semivariograms were computed in order to quantify the spatial dependence of model parameters within each homogeneous region. These semivariograms illustrated the increasing dissimilarity in precipitation parameters with distance between stations. For each duration and region, the mean squared differences between station pairs were plotted against separation distances. The resulting empirical curves were then fitted with theoretical models (Gaussian, exponential, or spherical). The selection of model was informed by the application of quality criteria, incorporating root mean square error (RMSE) and residual sum of squares (RSS). The variogram parameters, including nugget, sill, and range, were determined and stored accordingly (see Figure 2a).

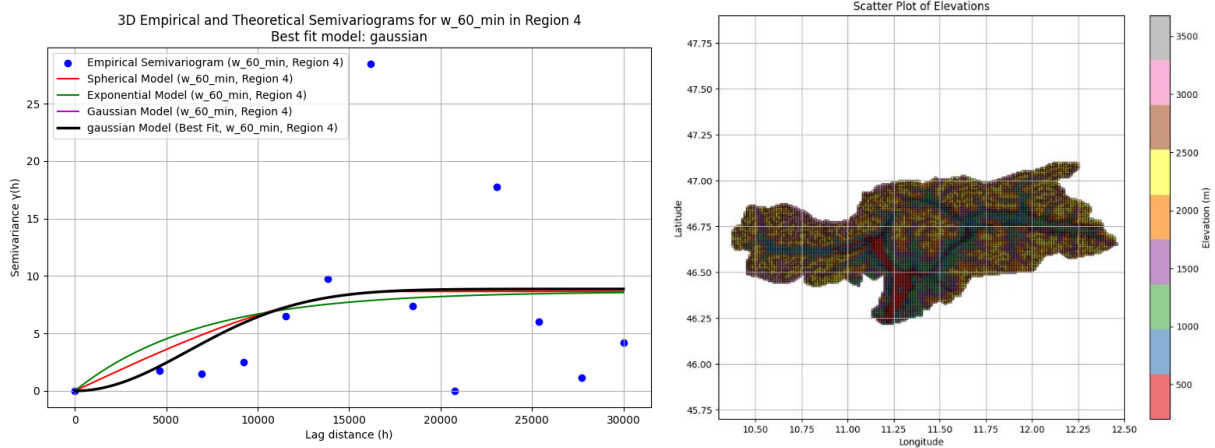


Figure 2. a) Theoretical and empirical semivariogram of the parameter w in region 4 Duration 60 minutes; b) The 1x1 km grid, with colour-coded altitude information.

With the variogram models established, three-dimensional Ordinary Kriging interpolation was performed, incorporating longitude, latitude, and elevation to adequately capture topographic influences. The interpolation, executed separately within each homogeneous region using the PyKriging library, estimated parameters $u_p(D)$ and $w_p(D)$ at a 1x1 km spatial resolution. Kriging weights were defined based on variogram-derived spatial correlation structures, ensuring greater influence from closer and topographically similar stations. The Kriging weights were defined on the basis of variogram-derived spatial correlation structures, thereby ensuring a greater influence from closer and topographically similar stations. The elevation data were sourced from the DEM digital elevation model, and each grid cell was assigned regional classifications and mean elevation data to facilitate interpolation (see Figure 2b)

Subsequently, interpolated parameters were utilised to calculate precipitation heights and intensities across the grid, encompassing return periods of 1, 2, 5, 10, 20, 50, and 100 years. The outputs were expressed in millimetres and litres per second per hectare and organised into datasets for each duration class. The final spatial maps presented visualised the intensity of rainfall across a range of return levels and durations. These maps were accompanied by scatter plots, which were used for the purpose of validation. These plots compared observed values with interpolated values (Figure 3).

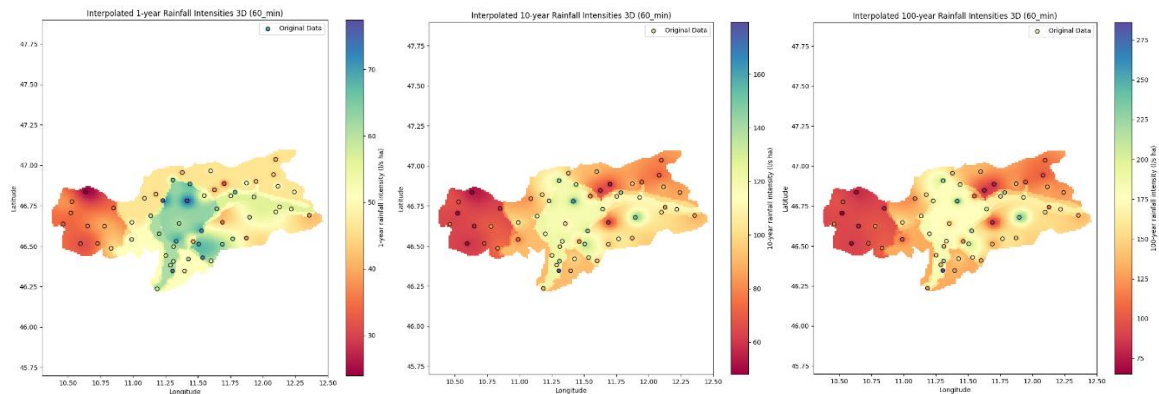


Figure 3. Precipitation intensity map of interpolated values with scatter plot of measured values for a duration of 60 minutes, return period: 1 year, 10 years, 100 years.

The validation phase involved a direct comparison of interpolated intensities with original station observations, presented visually through scatter diagrams and cartographic maps. The validation results indicated a strong overall agreement, although typical smoothing effects of Ordinary Kriging were apparent in areas of lower variability, consistent with observations documented in literature such as the MUNSTAR report. Special attention was given to the verification of altitude integration throughout the modelling chain.

Furthermore, altitudinal integration was verified through analyses of rainfall intensity as a function of elevation. These checks confirmed that the vertical dimension had been effectively incorporated into the interpolation process and that the influence of topography was adequately captured, despite minor smoothing artefacts occurring in certain regions. The observed concordance between measured and interpolated values across varying elevations served to reinforce the robustness and methodological accuracy of including topographic variables within the spatial interpolation framework (see Figure 4).

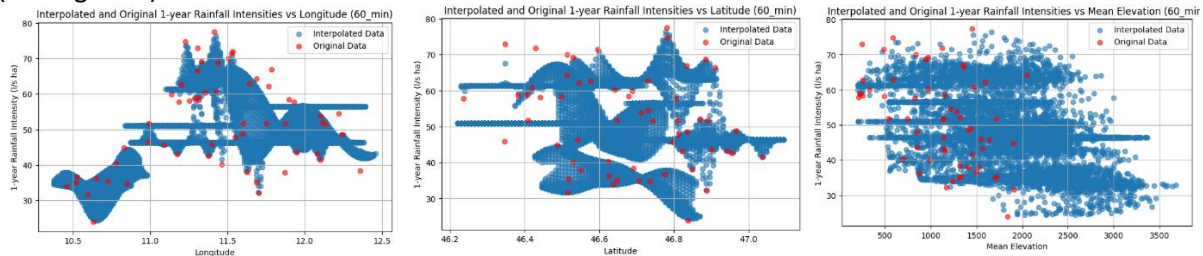


Figure 4. Precipitation intensities as a function of longitude, latitude and altitude of the measured values and interpolated values. Duration level: 60 minutes, return period: 1 year.

Conclusions and future work

This study successfully developed a robust methodological framework for regionalising and interpolating intense precipitation data in South Tyrol, effectively addressing hydrological modelling challenges posed by its complex alpine terrain. A high-resolution (1×1 km) precipitation grid representing precipitation intensities for various durations (5, 15, 60 minutes, and one day) and return periods (1, 2, 5, 10, 20, 50, and 100 years) was produced, thereby providing detailed and spatially consistent rainfall intensity information across various durations and return periods. This dataset significantly enhances flood risk assessment and urban infrastructure planning, facilitating informed decision-making in disaster management, filling the gap in current regional data products, offering more detailed and spatially consistent information on intense rainfall events.

A three-dimensional geostatistical approach tailored to complex alpine terrain, incorporating elevation directly into the interpolation process via Ordinary Kriging, effectively captured the region’s pronounced orographic influences and delivers kilometre-scale IDF information with validated error bounds. The validation process demonstrated the accuracy and reliability of the interpolated values and a strong predictive capacity, although some spatial smoothing was noted, with Nash–Sutcliffe Efficiency (NSE) values consistently exceeding 0.70, and lower Root Mean Square Error (RMSE) compared to national benchmarks, affirming the grid’s reliability for practical applications.

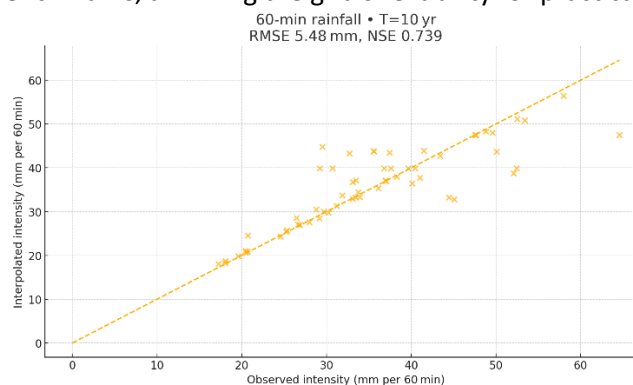


Figure 5. Comparison of observed and interpolated rainfall intensity for 60-minute duration events ($T = 10$ years). The dashed line represents the 1:1 straight line. The model shows good predictive ability (NSE = 0.739). See **Table 1** for an overview of all analysed durations.

The spatial patterns evident in the interpolated precipitation maps are clearly influenced by topography, providing crucial insights for the identification of flood-prone areas and the guidance of infrastructure development. Despite the presence of minor smoothing effects inherent to Ordinary

Kriging, particularly in regions exhibiting rapid variogram plateauing, the overall accuracy remains within acceptable design tolerances.

Duration	RMSE (mm)	MAE (mm)	NSE	R ²
1 day	8.59	6.14	0.82	0.842
10 min	2.08	1.37	0.784	0.785
120 min	5.78	3.55	0.775	0.775
15 min	2.95	1.93	0.751	0.751
180 min	5.41	3.25	0.799	0.8
2 day	9.69	6.51	0.882	0.889
30 min	4.03	2.73	0.735	0.735
5 min	1.3	0.86	0.781	0.782
60 min	5.48	3.24	0.739	0.739
90 min	5.37	3.18	0.792	0.792

Table 1: Validation metrics for T = 10 yr

This performance improvement is largely attributable to the three-dimensional formulation of the interpolation, which better captures orographic gradients than Cartesian kriging approaches like those used in the MUNSTAR prototype.

Looking ahead, the methodology provides a solid foundation. Future research directions include incorporating additional cross-border data, such as from neighbouring regions, including Trentino and Austria, to enhance boundary accuracy, applying non-stationary extreme value models to better account for climatic changes, and integrating hybrid workflows that combine deterministic spatial grids with stochastic rainfall generators for comprehensive temporal disaggregation and scenario-based simulations.

This approach, proven effective for South Tyrol, and the openly released grid underpins drainage design, flood mapping and adaptation planning across South Tyrol and offers a transferable template for other mountain regions, supporting broader climate resilience and sustainable water resource management strategies. In conclusion, the present study provides both a validated methodological framework and a transferable high-resolution data product. Beyond improving scientific understanding of local precipitation dynamics, the outcomes of this work significantly contribute to improving hydrological modelling capabilities, flood hazard mapping, and climate adaptation planning, ultimately strengthening regional resilience against extreme weather events in mountainous regions. In doing so, the study not only aligns with best practices in the field but also lays the groundwork for future policy-oriented and interdisciplinary research aimed at mitigating the impacts of extreme weather in the Alpine environment of South Tyrol.

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