

**Landslide25\_22****Exploring the Interplay Between Urbanization and Hydrogeological Disaster Impacts in Italy**

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**SUMMARY**

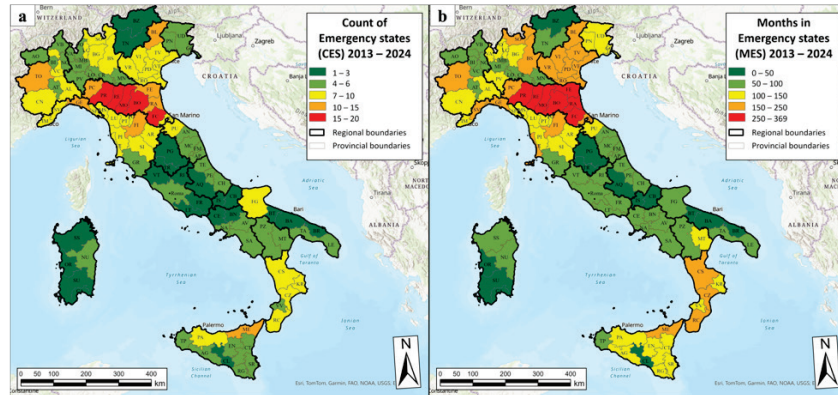
This study explores statistical correlations between the impact of hydrogeological disasters (HGDs) and 57 environmental and urban development indicators across Italian provinces. The analysis showed that the strongest relationships exist between HGD persistence and soil sealing in medium-hazard areas, particularly those exposed to medium flood and landslide risk. While strict development restrictions regulate high-hazard zones, medium-hazard areas remain more permissive, allowing continued urbanization. A dynamic analysis confirmed that in provinces hit by disasters, soil sealing in these zones increased by approximately 2% within three years after the event, mirroring pre-disaster trends. This suggests that high-impact events do not lead to significant policy shifts in land use. The findings reveal a mismatch between risk perception and actual planning strategies, indicating that medium-risk areas play a critical role in shaping disaster impacts. Current policies appear insufficient to mitigate long-term vulnerability, fostering a cycle where urban expansion in sensitive areas continues largely unaffected by disaster experience. The study underscores the need to re-evaluate land use policies to better account for the cumulative and persistent nature of HGD impacts.

## Introduction

Hydrogeological hazards, including floods and landslides, are responsible for widespread damage and loss of life across the globe. Empirical and statistical analyses have demonstrated that the frequency and intensity of extreme events are increasing, leading to a greater number and severity of disasters (Froude & Petley, 2018). Two primary drivers have been identified for this trend: climate change, marked by unprecedented global warming, and escalating human pressure on natural environments (Arnell & Gosling, 2016). The latter is largely due to economic development and population growth, which lead to the expansion of urban areas and infrastructure networks. Urban expansion plays a dual role in hydrogeological risk. On one hand, it increases the probability of hazardous events occurring, such as landslides triggered by road cuts on unstable slopes or floods exacerbated by buildings and infrastructures that reduce river channel capacity and increase surface runoff (Kumar Shrestha, 2021). On the other hand, development increasingly encroaches upon areas that are already prone to natural hazards, thereby raising the exposure of people, assets, and economies to these events. Hydrogeological risk is commonly defined as the combination of hazard (the probability of an event), exposure (the value of elements at risk), and vulnerability (the degree of potential loss). Urbanization can directly amplify both hazard and exposure, turning natural processes into disasters when territorial planning fails to properly account for them. In response, international institutions have introduced agendas and frameworks to reduce hydrogeological risk, and many national governments have adopted planning policies that recognize the link between urban growth and natural hazards (Papa et al., 2016). In the European Union, for example, member states are required to produce hazard and risk maps and implement mitigation plans, such as restricting activities in high-risk zones. Despite these measures, the impact on human settlements continues to rise, underscoring the complexity of the issue and the need for a stronger integration of scientific knowledge into policymaking and land use planning. This study addresses this need through a nationwide case study in Italy, exploring the relationship between urban features and hydrogeological disasters. A comprehensive dataset detailing the distribution of such disasters across the country (Gatto et al., 2023) was analyzed alongside 57 indicators derived from official sources and recent research. Statistical methods were applied to identify which indicators are most strongly associated with the occurrence of hydrogeological events. A dynamic analysis was also carried out to determine whether trends in the most relevant indicators change significantly after a province experiences a disaster. The results suggest that hydrogeological risk is often underestimated by decision-makers, and that even the most compelling empirical evidence is frequently overlooked in territorial planning processes.

## Methods

This study explores how hydrogeological disasters relate to environmental conditions and patterns of urban development in Italy, a country particularly prone to floods and landslides (Gatto et al., 2023; Segoni & Caleca, 2021). The choice of Italy as a test site is based on the availability of complete hazard mapping, well-documented disaster records, and numerous publicly accessible environmental datasets. The goal is to understand how specific environmental and urban indicators relate to the frequency and persistence of hydrogeological disasters and whether these indicators show significant changes after such events occur. The analysis is conducted at the provincial level and relies on two Impact Variables (IVs) and 57 Environmental Variables (EVs). The impact variables are designed to capture the recurrence and duration of hydrogeological disasters across local territories. The first, Count of Emergency States (CES), represents how many times a province experienced a disaster severe enough to trigger a national emergency declaration. The second, Months in Emergency State (MES), measures the cumulative duration of such emergency periods, serving as a proxy for the persistence of disaster impacts. Data were collected for the period 2013 to 2024, during which 158 emergency declarations were issued in response to extreme rainfall events accompanied by flooding and widespread landslides. The spatial distribution of CES and MES in Italian provinces is shown in figure 1a and b.



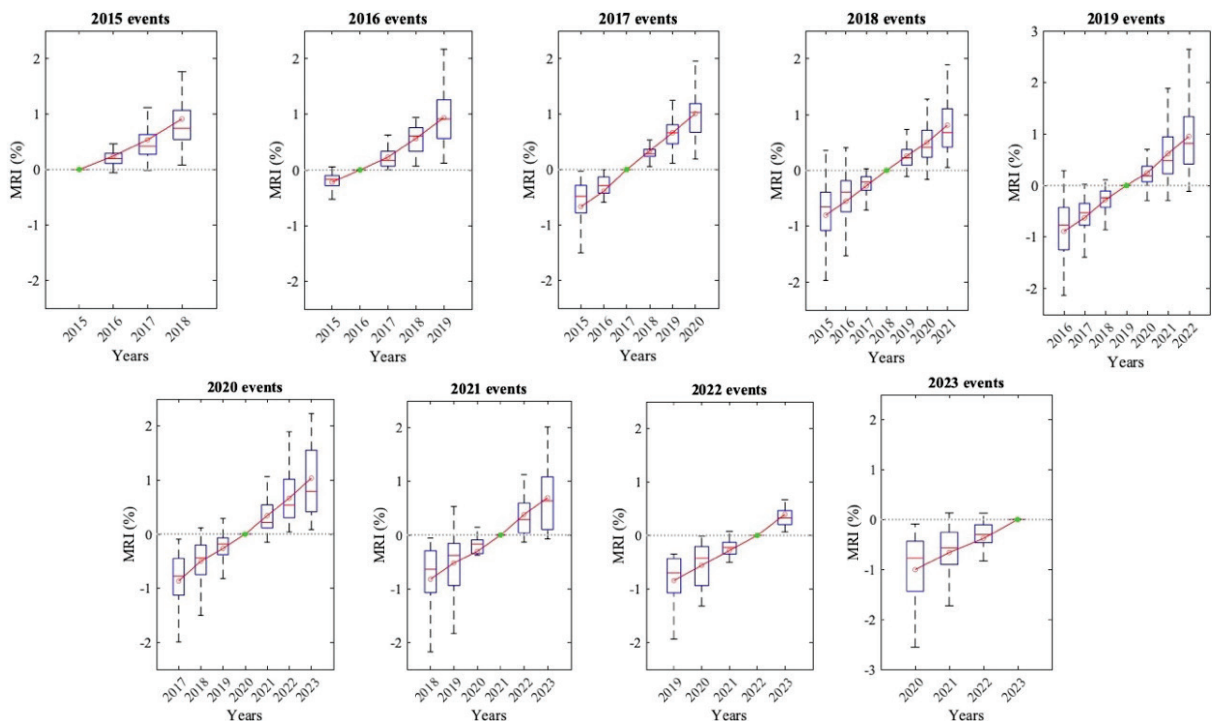
**Figure 1** Spatial distribution of CES (a) and MES (b) in Italian provinces over the period 2013 – 2024

EVs fall into three main categories: the first group consists of variables related to hydrogeological hazard and risk, including the extent of areas classified as flood- or landslide-prone and the number of exposed elements such as people, buildings, and cultural assets. These indicators are based on official hazard and risk maps developed by national authorities and integrated with demographic and land use data, updated until 2021 (Iadanza et al., 2021). From an initial pool of 124 variables, 33 were selected for their direct relevance to hydrogeological processes. The second group concerns soil sealing, or the permanent coverage of land by artificial surfaces (ISPRA (Istituto superiore per la protezione e la ricerca ambientale)), updated until 2023. Nineteen variables were chosen, offering insight into the intensity and spatial pattern of urbanization. The third group includes two synthetic indicators that combine aspects of hazard and urban pressure: the Severe-Risk Indicator (SRI), built by combining sealed soil within the highest risk zones for floods and landslides, and the Mild-Risk Indicator (MRI), which is the same but for moderate-risk areas. CES and MES were recalculated to match the most recent year available in the corresponding EV database. To evaluate the relationship between environmental and impact variables, three statistical approaches were used: the coefficient of determination  $R^2$  quantified the strength of correlation between each environmental indicator and IVs across provinces; the chi-square test assessed whether the spatial distribution patterns of environmental and impact variables were significantly aligned (provinces were divided into quartiles, yielding a theoretical  $\chi^2$  value of 16.919); finally, a Poisson Generalized Linear Model (GLM) was applied to estimate the strength and direction of influence and to determine statistical significance. Once these tests identified strong and statistically significant relationships between environmental conditions and disaster impact, a dynamic analysis was conducted to assess whether the most strongly correlated EV changed over time following a hydrogeological event. For this purpose, each year within the dataset was considered individually as a reference point. For every province affected by a disaster in the selected year, the change in this environmental indicator was measured within a six-year time window, spanning three years before and three years after the event. This temporal analysis aimed to detect whether critical events influence territorial or urban development trends, providing insight into whether disaster occurrence is followed by any measurable response in land management or environmental change. All analyses presented in this study are based on an updated dataset building upon the work by Gatto et al., 2024, which included data available up to the year 2021. For a comprehensive description of the methodological framework and data processing procedures, the reader is referred to the original work, Gatto et al., 2024.

## Results

The statistical analysis focused on evaluating the strength and significance of the relationship between hydrogeological IVs and various EVs. For each of the 57 EVs, an  $R^2$  value was calculated to estimate how much of the variation in disaster impact (measured as recurrence and persistence) could be explained by each environmental factor. In general, the results showed that correlations with the persistence of disasters (MES) were consistently stronger than those with their recurrence (CES). The highest  $R^2$  value was found

between MES and MRI (0.52), followed by soil sealing in medium hydraulic-risk areas (0.42), and the number of business units or buildings in those zones (both 0.42), suggesting that the observed relationship is primarily flood-driven rather than landslide-driven. However, these high correlations were influenced by a small number of provinces with extreme values; when top outliers were removed, the  $R^2$  values dropped considerably, indicating that while the relationship is strong in specific locations, it does not fully explain the national distribution of disasters. Nonetheless, the data suggest that provinces experiencing more severe and persistent impacts also tend to concentrate intense building activity in moderately risky areas. To complement the correlation analysis, a chi-square test was used to determine whether spatial patterns of environmental and impact variables aligned significantly. The results showed  $\chi^2$  values higher than the theoretical value for all EVs related to hydraulic risk, confirming a non-random spatial dependence between variables. In particular, the MES-MRI pair yielded a  $\chi^2$  of 26.869. Further validation was provided by Poisson GLM, which confirmed stronger associations with MES than CES. For the MRI-MES pair, the model showed a very low p-value of  $5.10 \times 10^{-316}$ , with a standard error of  $1.50 \times 10^{-6}$ , indicating a highly robust correlation. To avoid false positives due to multiple testing, a Bonferroni correction was applied, and the relationship remained statistically significant. On the other hand, the dynamic analysis investigated whether soil sealing trends changed following hydrogeological disasters, aiming to reveal potential shifts in land use or planning. Due to limited data availability, consistent annual soil sealing records were only accessible from 2015 onward, allowing a full  $\pm 3$  year window only for disasters that occurred in the years 2018, 2019 and 2020. Despite this constraint, the results revealed a consistent trend: In provinces affected by disasters, soil sealing in risk-prone areas continued to increase after the event at rates of approximately 2% over three years. Boxplots and yearly averages confirmed the trend, as shown in figure 2, suggesting that even high-impact disasters did not trigger measurable shifts in urban expansion or land management. Overall, the findings indicate that hydrogeological disasters did not alter land consumption dynamics; instead, urban development continued in already vulnerable areas, reflecting a lack of reactive policy.



**Figure 2** Yearly MRI variations affected by disasters ( $\pm 3$  years, conditional on data availability)

## Conclusions

The statistical analysis demonstrated that the indicator measuring the persistence of hydrogeological disaster impacts (MES) consistently shows higher correlation values than the indicator based on the number of disasters (CES). This outcome is particularly relevant, as risk analyses often rely on disaster frequency or extent, whereas MES incorporates both frequency and the duration of long-term socioeconomic consequences, offering a more comprehensive picture of impact severity. The analysis of environmental variables revealed a complex system of interactions. Variables describing the extent of hazardous areas, although statistically significant, had relatively low explanatory power, indicating that while the presence of dangerous zones is a prerequisite for disasters, it is not sufficient to predict their occurrence or severity. Instead, how the land is used appears to be the key variable. Indicators related to buildings and business units in hazard-prone areas displayed stronger correlations with disaster impacts, and among all variables analyzed, the amount of sealed soil in medium-risk areas (MRI) showed the strongest correlation with MES, supported by all statistical tests. This finding aligns with well-established disaster science, which highlights that extreme natural events become disasters only when they interact with vulnerable human environments. The analysis also showed that total soil sealing or soil sealing outside of risk zones is not strongly associated with hydrogeological disasters. Surprisingly, soil sealing in high-risk areas was not significantly correlated with disaster impacts either. The strongest correlations were observed in medium-risk areas, and this finding has two main explanations. First, regulations on high-risk zones are strict, with new construction largely prohibited except for exceptional cases, meaning that existing buildings are mostly legacy structures. In contrast, medium-risk areas are subject to more lenient rules, allowing new developments if basic mitigation measures are adopted or through regulatory exceptions. Second, climate change is altering the intensity and spatial distribution of extreme events, causing unexpected impacts even in areas previously considered moderately exposed. These conditions make medium-risk areas increasingly vulnerable, even though they are not always recognized as such in existing hazard maps.

## References

- Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387–401. <https://doi.org/10.1007/S10584-014-1084-5/FIGURES/3>
- Froude, M. J., & Petley, D. N. (2018). Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences*, *18*(8), 2161–2181. [doi.org/10.5194/NHESS-18-2161-2018](https://doi.org/10.5194/NHESS-18-2161-2018)
- Gatto, A., Clò, S., Martellozzo, F., & Segoni, S. (2023). Tracking a Decade of Hydrogeological Emergencies in Italian Municipalities. *Data* *2023*, Vol. 8, Page 151, 8(10), 151. <https://doi.org/10.3390/DATA8100151>
- Gatto, A., Martellozzo, F., Clò, S., Ciulla, L., & Segoni, S. (2024). The downward spiral entangling soil sealing and hydrogeological disasters. *Environmental Research Letters*, *19*(8), 084023. <https://doi.org/10.1088/1748-9326/ad5fa1>
- Iadanza, C., Trigila, A., Starace, P., Dragoni, A., Biondo, T., & Roccisano, M. (2021). IdroGEO: A Collaborative Web Mapping Application Based on REST API Services and Open Data on Landslides and Floods in Italy. *ISPRS International Journal of Geo-Information* *2021*, Vol. 10, Page 89, 10(2), 89. <https://doi.org/10.3390/IJGI10020089>
- ISPRA (Istituto superiore per la protezione e la ricerca ambientale). *Usa, copertura e consumo di suolo*. Retrieved June 29, 2023, from <https://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo>
- Kumar Shrestha, J. (2021). Impact of Road Cuts in slope stability in Hilly Regions of. *Nepal Journal of Advanced College of Engineering and Management*, *6*, 2021.
- Papa, R., Ali, M., De Kerckhove, D., Deakin, M., Kellerman, A., Levinson, D. M., Malanima, P., Nuzzolo, A., Battarra, R., Anna, R., Rocca, L., & Mazzeo, G. (2016). Cities at risk: status of Italian planning system in reducing seismic and hydrogeological risks. *TeMA - Journal of Land Use, Mobility and Environment*, *9*(1), 43–62. <https://doi.org/10.6092/1970-9870/3726>
- Segoni, S., & Caleca, F. (2021). Definition of environmental indicators for a fast estimation of landslide risk at national scale. *Land*, *10*(6). <https://doi.org/10.3390/land10060621>