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The downward spiral entangling soil sealing and hydrogeological disasters

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Abstract

The frequency of occurrence of hydrogeological disasters (HGDs), as well as the persistence of their impacts, are not evenly distributed. Hazardous areas, by definition, are more prone to extreme events, while in densely urbanized regions, the impacts of these events tend to be more severe. The objective of this study is to investigate statistical relationships between urban and natural environment features and HGD occurrences. Taking Italian provinces as a comprehensive case study, we assessed the coefficient of determination, the χ^2 test, and the p-value to determine the degree of statistical correlation between impact indicators and 57 hazard/risk/land management indicators, such as extension of at-risk areas or soil sealing. We discovered that HGDs persistence and frequency correlate best with an indicator describing the amount of soil sealing (i.e. urbanized soil) in medium-hazard areas. Building on that, a further dynamic analysis was carried out to investigate whether soil sealing trends changed significantly after the provinces were struck by HGDs. Our findings hold significant implications, challenging current policy norms. European directives and Italian national laws impose strict development restrictions in 'high-hazard' areas, but generally allow for urbanization in 'medium-hazard' areas, with only minor limitations. Moreover, a paradoxical positive urbanization trend is observed in the most sensitive areas, greater than in safer areas and generally unchanged after HGDs. This outcome highlights a critical gap in risk perception that reflects into territorial planning, decision-making processes, and existing policies.

1. Introduction

Hydrogeological hazards (such as floods and landslides) are responsible for casualties and damage worldwide [1–5]. Empirical and statistical evidence has demonstrated that the frequency and magnitude of extreme events have increased, thus causing a growing number of disasters of increasing severity [6–9]. Two main reasons have been identified for this trend: ongoing climate change, guided by a record-breaking rate of global warming [10–12], and growing human pressure on natural environments [13–17]. This last factor, driven by economic growth and increasing population, is characterized by the expansion of the urban environment and infrastructure networks, which plays a two-fold role. First, it may increase the hazard, intended as the probability of occurrence of a disaster with a given intensity: this is well documented for both landslides (e.g. for roadcuts on mountainsides or for slopes [18]) and floods (as buildings or infrastructures may reduce the hydraulic sections of rivers and seal the soil, thus increasing water runoff [19–21]). Second, urban development requires that building activities be expanded in areas with increasingly higher levels of hazards. Thus, the exposure of territories and local economies to natural hydrogeological processes increases [22–24]. Hydrogeological risk can be defined as the product of hazard (probability of occurrence), exposure (value of the exposed elements), and vulnerability (expected degree of loss in the impacted elements) [25, 26]. Accordingly, urban expansion may directly increase two of the aforementioned factors, turning natural hydro-geological processes into disasters because of incorrect or incautious territorial planning.

Consequently, international organizations have adopted agendas and frameworks to reduce hydrogeological risk [27–30], while many countries have implemented territorial planning regulations and policies to account for the interconnection between urban growth and hydrogeological risk. For instance, since directives 200/60/EC and 2007/60/EC, the European Union has imposed all member states to cope with hydrogeological hazards by defining hazard and risk maps and implementing plans for mitigation measures (e.g. restricting activities in the most dangerous areas) [31–33]. However, the toll paid by settlements worldwide is constantly increasing [34–36], highlighting that the phenomenon is complex and needs to be further investigated to provide stronger links between scientific evidence, policies, and territorial planning.

This work aims to address this gap on a nationwide case study (Italy), where the correlation between urban characteristics and hydrogeological disasters is investigated. A recently compiled dataset portraying the distribution of hydrogeological disasters (HGDs) across Italy [37] was compared with 57 indicators released by governmental authorities or recent studies. Statistical correlations were performed to identify the indicators most strongly correlated with the observed HGDs distribution. A dynamic analysis was also implemented, to investigate whether the trend of the most influential indicators significantly changes after a province is struck by HGDs. Results show that hydrogeological risk is generally underestimated by policymakers and that even the most severe empirical evidence is not properly accounted for in territorial planning.

2. Methods

The test site for this work was Italy, which can be considered relevant groundwork for the analyses due to its high susceptibility to floods and landslides [7, 37–39], the availability of established environmental indicators [40–42] and complete documentation of recent disasters [37].

To investigate the interplay between critical impacts and urban environment dynamics, we take into account 57 environmental indicators and we implement some simple statistical analyses to identify the indicators most correlated with the recurrence and persistence of HGDs in Italian provinces in the last decade. The analyses include the χ^2 test, the calculation of the coefficient of determination, and the estimation of a Poisson model. After identifying some key variables related to territorial planning, a dynamic analysis was carried out to investigate if their trends change after HGDs occurrence.

2.1. Impact variables (IVs)

To quantify the impact of hydrogeological disasters on Italian territory, two recently proposed variables were used [37], based on the documentation of HGDs that have been severe enough to force the Italian government to issue an urgent decree and declare a national-level emergency state.

Count of emergency states (CES) accounts for how many times in the reference period each province was hit by a hydrogeological event that required a national-level emergency state. CES was used as a proxy for HGD recurrence within each province.

Months in emergency state (MES) accounts for the cumulative duration of the emergency states. As an emergency state is officially closed only when 'the normal conditions of life are restored', MES was used as a proxy for the persistence of the negative impacts of HGDs in each province. Further details about these indicators and emergency states management in Italy can be found in [37].

Since most of the indicators introduced in the following section were updated until 2021, from the original dataset spanning from 2013 to 2022 [37], MES and CES data from 2013 to 2021 were extracted. During this timeframe, 112 emergency states were issued. They mainly refer to large storms that hit several neighboring provinces causing the flooding of rivers, flash floods of small streams, and widespread activation of landslides. Figure 1 shows that the spatial distribution of HGDs across the 107 Italian provinces is not random, thus justifying the research on environmental variables, investigating correlations that could contribute to explaining the observed spatial patterns.

2.2. Environmental variables (EVs)

We considered a wide list of environmental indicators describing the hydrogeological hazard and the urbanization of the Italian territory, using publicly available data released by ISTAT (National Institute of Statistics) and ISPRA (Higher Institute for Environmental Research and Protection). The indicators used in the analysis are aggregated at the province level to be consistent with IVs.

2.2.1. Hydro-geological risk-related variables

Hazard and risk indicators for landslides and floods were considered. According to European directives and national regulations, the Italian territory has been officially mapped by purposely instituted authorities (River Basin District Authorities), who identified areas at low, medium and high flood hazard and areas at low, medium, high and very high landslide hazard. This subdivision is based on the return time of floods and, regarding landslides, on assessments carried out by experts employing field surveys, ancillary data, and remote sensing. ISPRA supervised the mapping process, set homogeneous criteria, and collated

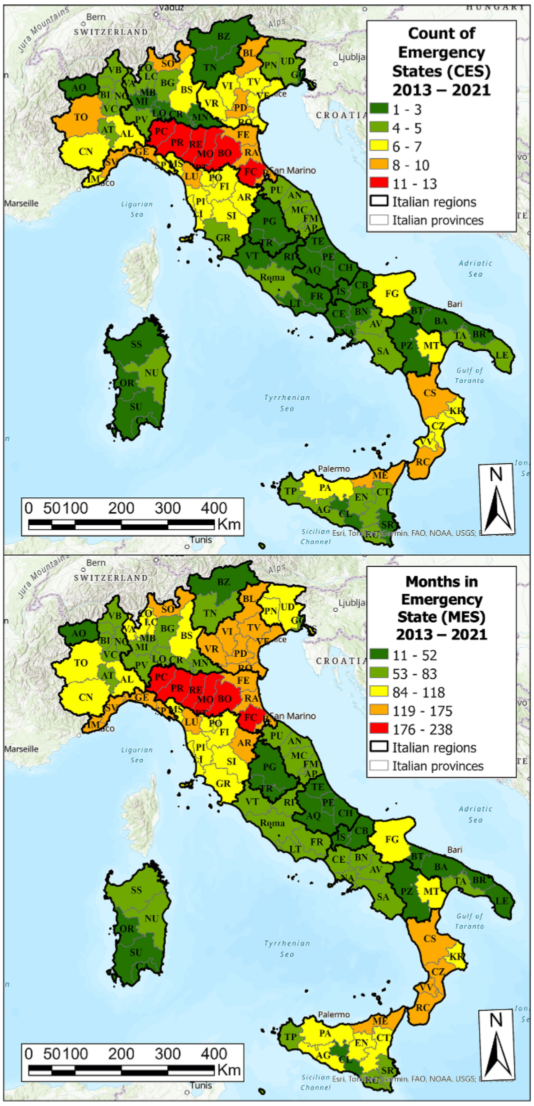

Figure 1. (a) Count of emergency states (CES), (b) months in emergency state (MES) in the Italian provinces.

all district-level maps into a comprehensive, nationwide, hazard and risk map.

Moreover, ISPRA overlaid this spatial information with a dataset constantly updated by ISTAT and containing social and demographic data, providing aggregated indicators at all administrative levels (region, province, municipality), thus creating a wide range of indicators to account for hydrogeological hazard (quantification of hazardous areas of different levels in each administrative unit) and risk (quantification of exposed elements in the hazardous areas).

These open-access data were provided through IdroGEO [41], a governmental WebGIS platform sharing information about population, buildings, local business units and cultural assets at risk from landslides and floods [43]. The raw dataset was downloaded with province-level aggregation to obtain the same spatial detail as IVs. These indicators, updated until 2021 at the time of elaborations, include 124 different variables, which were filtered to 33 by selecting all those linked to HGDs, such as the surface extent of hazardous areas or the number of different types of buildings exposed at each risk level (annex 1 contains a complete list).

2.2.2. Soil sealing-related variables

A second group of indicators was used to account for land consumption processes leading to soil sealing, defined as '*the permanent covering of an area of land and its soil by impermeable artificial material (e.g. asphalt and concrete)*' [44] involving a change from a non-artificial landcover to an artificial land cover of the ground [42, 45, 46].

Soil sealing data for Italy are provided by ISPRA: an open dataset is available, with 123 indicators aggregated at the municipality, province, regional and national levels [47]. This high number of indicators accounts for many aspects related to soil sealing (including e.g. ecological variables); the number of indicators used in this work was limited to 19, including only those related to hydrogeological features, such as soil sealing at different levels and types of risk areas (annex 1 contains a complete list). At the time of the elaborations, data were available until 2021.

2.2.3. Compound indicators

CES and MES mostly refer to complex and widespread events, where an extreme rainstorm hits a wide territory flooding several locations and contemporarily triggering hundreds of landslides. However, all the above mentioned environmental variables refer either to landslides or to floods. To better reflect the combined effect of both processes, two additional indicators were created by combining four core environmental indicators:

-Severe-Risk Indicator (SRI) is the total area of sealed soil mapped in the highest risk class for floods (high risk) and landslides (very high risk), according to the official maps provided by ISPRA (ha);

-Mild-Risk Indicator (MRI) is the same as above, but considering the second-highest classes (medium flood risk and high landslide risk) (ha).

2.3. Statistical analyses

The 57 environmental indicators listed in annex 1 were combined with the two impact variables (CES and MES), obtaining 114 pairs of variables. Each pair underwent the following statistical analyses.

The coefficient of determination R^2 was used as a preliminary estimate of the degree of correlation between the environmental parameters and the persistence and frequency of hydrogeological disasters, observing the distribution of the pairs of values for each province in EV-IV diagrams.

The χ^2 test was used to understand if the spatial patterns of EV-IV pairs match each other or if their values are randomly spatially distributed. Italian provinces were sorted into quartiles according to observed IV and EV values, and contingency tables were populated with the observed and the theoretically expected distribution of samples in each combination of quartiles. The discrepancy between observed and expected values was assessed and compared with the theoretical χ^2 value (16.919 in our case), allowing to consider two variables correlated when their χ^2 is higher than 16.919 (more details on the procedure in annex 2).

Finally, we adopted the Poisson model as the main estimation approach. The Poisson generalized linear model (GLM) is a statistical model used to analyze count data, representing the number of times an event occurs. It assumes that the count data follow a Poisson distribution, which is appropriate for data where the counts are non-negative and discrete. For each EV-IV pair, the model was used to estimate the *p*-value, a coefficient indicating the strength and direction of EV's effect on the dependent variable (in our case CES or MES) (further details in annex 1).

2.4. Dynamic analysis

Once the aforementioned tests identified the existence of significant correlations between pairs of IVs and EVs, the dynamic trend of the latter was analyzed to evaluate if it change after critical hydro-geological events. The analysis consisted of selecting a reference year at a time and, for each province hit during that year, calculating EVs variation in a ±3 years time window as follows:

$$\left(\frac{\mathrm{EV}_{\mathrm{StartingYear}}+x-\ \mathrm{EV}_{\mathrm{StartingYear}}}{\mathrm{EV}_{\mathrm{StartingYear}}}\right)/100 \qquad (1)$$

where $x = 1, 2, 3, -1, -2,$ and -3 years (±3 years time window).

3. Results

3.1. Statistical correlations

The R^2 values calculated for each of the 57 IV-EV pairs are reported in annex 1 and range from 0.00 to 0.47. In general, each EV shows a similar R^2 with respect to the two IVs: the correlation with MES is usually higher than with CES. The highest R^2 values are obtained between MES and MRI (0.47) and the other highest observed values suggest that this relationship is driven more by floods than by landslides: soil sealing in medium hydraulic-risk areas has $R^2 = 0.42$ and the variables 'business units'/'buildings in medium hydraulic risk areas' have both $R^2 = 0.42$.

Figure 2 shows that the MRI-MES and MRI-CES distribution is characterized by a group of provinces with extreme values for both variables. This association of extreme values of both inspected variables is the main responsible for the high R^2 scores: indeed, by removing the 4 and 10 top provinces from the analysis, the correlation coefficient drops to 0.43 and 0.15, respectively. This outcome demonstrates that

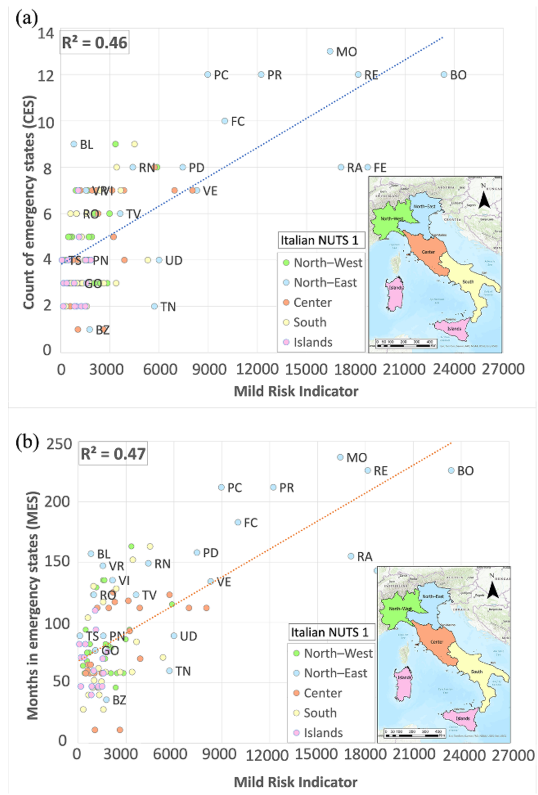

Figure 2. MRI versus CES with Italian NUTS 1 (a) and MES (b).

the selected variables alone do not explain the spatial distribution of HGDs across Italy, and suggests that where impacts are more recurrent and persistent, extreme building activity is observed in medium-risk areas.

The χ^2 test was used to better investigate the correlation between EVs and IVs. As shown in Tab A1 in annex 1, the resulting χ^2 is higher than the theoretically expected one for all EVs connected with hydraulic risk, demonstrating that the distribution of the provinces in the matrix pairing these EVs and IVs is not random and shows a significant dependence between variables. The distribution of the provinces in the MRI-MES matrix is also shown in A2 and figure 3.

In the Poisson GLM analysis, smaller *p*-values indicate stronger evidence of correlation between variables. Annex 1 shows that the degree of correlation is much higher between EVs and MES than EVs and CES, with the lowest value observed with MRI. The Poisson GLM coefficients were calculated for the MRI-MES pair, showing a strong correlation: $x1$ has a low but significant estimate, tStat value is significantly higher than zero, *p*-value is extremely low (4.48×10^{-239}), with a 1.7243×10^{-06} standard error. To mitigate data dredging, Bonferroni correction was applied, reducing the risk of false positives by adjusting the significance level for multiple comparisons: the desired significance level (in this

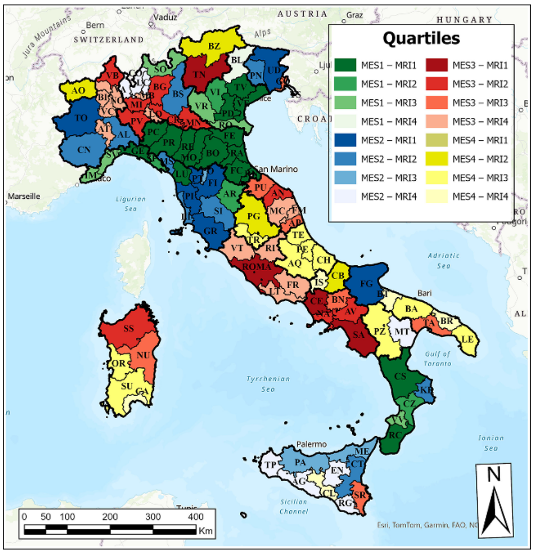

Figure 3. MES–MRI quartile distributions for Italian provinces.

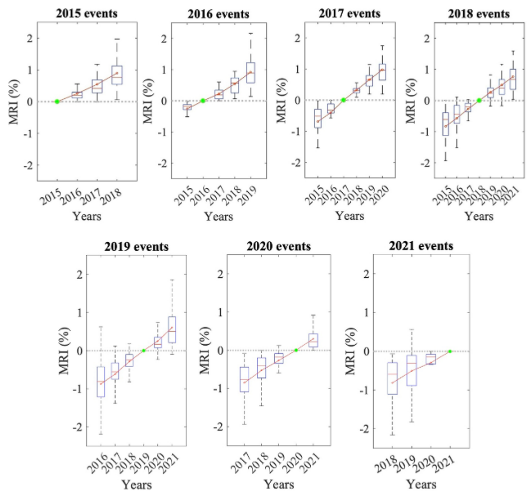

Figure 4. Yearly MRI variations in provinces affected by HGDs (±3 years, conditional on data availability).

case 0.05, standard value) was divided by the number of comparisons obtaining a post-correction value of 0.025. Since the corrected p-value is lower than the corrected significance level, the correlation can be considered robust.

3.2. Dynamic analysis of soil sealing trends

The results of this analysis were affected by some limitations of the dataset: soil sealing monitoring program began to provide homogeneous data at yearly time steps only in 2015, limiting the timeframe for which this methodology could be applied. Including previous data from other sources would have added inconsistency issues to the analyses. Consequently, only for the year 2018 a complete ±3 years time window could be observed: for the other years, the

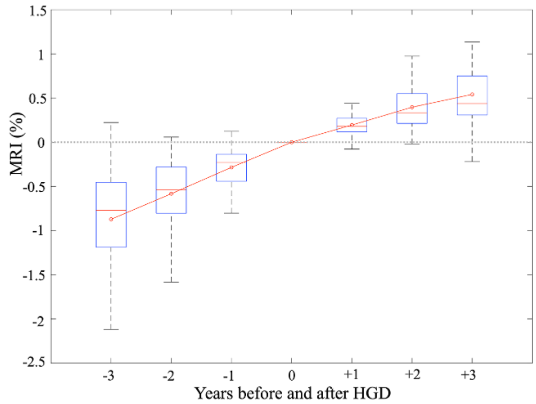

Figure 5. MRI before and after HGDs.

variation was calculated, conditional on data availability. The temporal variation of MRI in hit provinces was depicted with boxplots (figure 4), which generally show a steadily growing trend. The mean values for each year were also plotted to better highlight the increasing trend of MRI.

The results showed that despite HGDs occurring yearly, soil sealing in at-risk areas continued to increase at the same rates observed before HGDs occurred. These results were generalized to better obtain an overall picture: boxplots were generated accounting for three years before and after each province was hit by an HGD (figure 5), showing that overall soil sealing in areas at risk has always continued to increase, regardless of the impacts suffered by the urban environment.

4. Discussion

The statistical analyses revealed that MES systematically shows higher correlation values (table A1) than CES. This is an important outcome, as the number or the spatial extent of disasters is usually used in risk-related analyses: this work shows that MES conveys more comprehensive information, as it quantifies the signature of the severity of the impacts, accounting also for the persistence of long-term negative socioeconomic effects.

Concerning EVs, multifaceted relationships can be observed. The EVs related to the extent of the hazardous area, despite showing significant χ^2 values, show relatively low correlation values. The presence of relevant hazardous areas is thus a prerequisite for HGDs but, alone, is a poor proxy as the pressure exerted by population is also a fundamental factor. However, population and population density correlate very poorly with both IVs. That means that population alone cannot be considered a significant direct predisposing factor for HGDs: a closer look into the statistics of annex 1 reveals that the way the territory is used is of paramount importance.

Indeed, EVs related to (generically) buildings or (specifically) business units located in flood-prone areas show stronger correlations. However, the strongest correlation (R^2 and p-values, confirmed by significant χ^2) is observed between MRI and MES.

This outcome is consistent with empirical evidence. In hazardous areas, extreme hydrogeological processes are expected with a relevant probability; they become risky areas only when anthropogenic elements are built there, as the interaction between natural processes and the urban environment determines destructive impacts [19]. This is well consolidated in scientific disciplines related to disaster management and natural processes; nevertheless, this work could provide relevant help to policymakers, as it provides nationwide evidence and further insights on where and how the land is urbanized.

Indeed, annex 1 shows that soil sealing in general is not necessarily strongly correlated with HGDs: total soil sealing and soil sealing outside hazardous areas correlate poorly with HGDs. One of the most unexpected and significant results is that soil sealing in high-risk areas (SRI) does not correlate well with HGDs, while the strongest correlations are found with urbanization in medium-risk areas (MRI). This outcome has two explanations. First, according to European directives, national and regional regulations impose heavy restrictions on maximum-risk areas. There, building activity is forbidden, and new infrastructures are allowed only for exceptional reasons; thus, only buildings built before the most recent regulations are present. In medium-risk areas, restrictions are milder, allowing derogations or simply allowing new buildings provided remedial works are implemented. Second, due to climate change, extreme events have become more frequent and their spatial patterns are changing [48–51]. Consequently, even areas once mapped as exposed to medium-level hazards are experiencing a growing number of unexpected extreme events.

The implications in terms of policies are relevant, and the results of our analysis suggest that the importance of intermediate risk levels is underestimated: soil sealing trends in medium-risk areas are not significantly affected by the occurrence of HGDs, remaining almost unchanged before and after relevant disasters. Taking 2018 as a reference year (the only one that allows a complete ±3 years window), figure 6 shows that MRI trends are almost identical for hit and non-hit provinces. The relationship between soil sealing and HGDs is clearly inadequately addressed by decision-makers, fostering a downward spiral in which land use and territorial planning contribute to accelerating the frequency of HGDs and the persistence of their impacts. To invert this spiral, we suggest revising land planning policies: either restrictions are increased in medium-risk areas, or national mapping is updated, according to site-specific studies, extending high-risk areas.

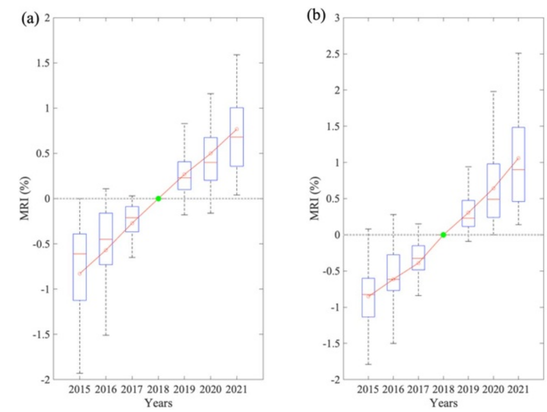

Figure 6. Comparison between MRI variations before and after 2018 in provinces that were (a) and were not (b) hit by HDGs during that year.

We remark however that MRI alone cannot be considered a reliable regressor for MES or CES: this study highlights a correspondence between Italian provinces with highest hydrogeological impacts and provinces with the highest MRI, but a more multifaceted combination of interplaying hydrogeological, social and economical factors should be considered to obtain a predictive model to accurately assess the susceptibility of all provinces to HGDs. Moreover, further analyses should be performed before generalizing the findings of this research beyond Italy. e.g. considering the political and scientific debate about a new soil deal in Europe, this research highlights the need to investigate spatial relationships among sealed surfaces and high/medium hydrogeological risk areas also outside Italy.

5. Conclusion

This work explored the correlation between two variables describing the impacts of hydrogeological disasters (HGDs) and many environmental variables (EVs) in Italian provinces. The cumulative duration of the national-level emergencies that were issued to restore the normal condition of life (MES) showed stronger statistical correlations than the count of disasters affecting each province (CES). This is the first study in which MES was introduced and tested in a nationwide assessment. MES accounts for both the frequency of HGDs and the persistence of their negative effects, thus being a meaningful indicator for future research on natural hazards.

Statistical analyses revealed a complex interrelationship between the considered variables, showing a multifaceted situation where natural and anthropic factors come into play. The EV most correlated with HGDs was the amount of soil sealing in medium-level risk areas, while soil sealing in high-risk areas and in safe areas exhibited weaker and very weaker (respectively) correlations with HGDs.

A dynamic analysis showed that soil sealing trends in hazardous and non-hazardous areas remain equal before and after disasters.

Thus, present policies foster a downward spiral as the urban expansion model actually maximizes the impacts of HGDs, which in turn do not trigger relevant policy changes. This 'business as usual' approach is not sustainable, and more careful considerations are required by policymakers, especially in the provinces already exposed to relevant impacts. However, this study suggests that a generalized stop in soil sealing is not necessary, as further urbanization may be viable, if the location of the next expansions is more carefully evaluated.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.mdpi.com/article/10.3390/data8100151/s1.

Conflict of interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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