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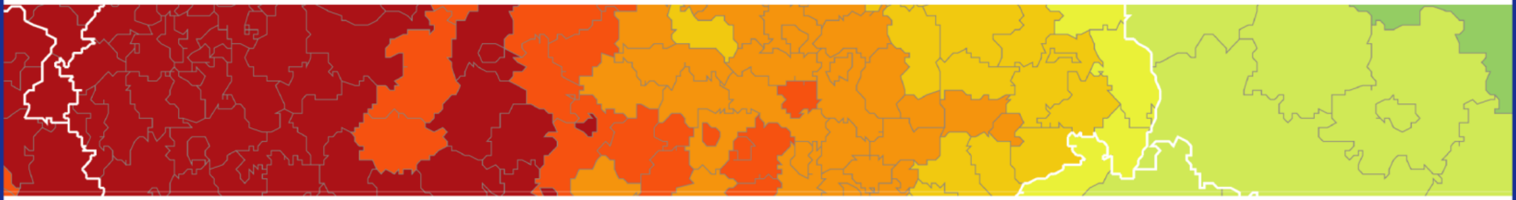

ESPON-TITAN
Territorial Impacts
of Natural Disasters

Applied Research

Final Report – Annex 1
Hazard Analysis

June 2021

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ESPON-TITAN
Territorial Impacts of Natural Disasters

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Abbreviations

CPI	Consumer Price Index
CRED	Centre for Research on the Epidemiology of Disasters
EAA	European Economic Area
EC	European Commission
ECB	European Central Bank
ECU	European Currency Unit
EDO	European Drought Observatory (JRC)
EFAS	European Flood Awareness System
ELSUS	European Landslide Susceptibility
ESDAC	European Soil Data Centre
ESPON	European Territorial Observatory Network
ESPON EGTC	ESPON European Grouping of Territorial Cooperation
EU	European Union
GCM	Gloal Climate Model
GDO	Global Drought Observatory
GloFAS	Global Flood Awareness System
HANZE	Historical Analysis of Natural Hazards in Europe
HICP	Harmonized Index of Consumer Prices
JRC	Joint Research Center
NATECHS	Natural-technical hazards
NUTS	Nomenclature of Territorial Units for Statistics
PGA	Peak ground acceleration
RCM	Regional Climate Model
SHARE	Seismic Hazard Harmonization in Europe project
SPI	Standardized Precipitation Index
WISC	Windstorm Information Service
WMS	Web Map Service

1 Introduction

In this Annex, we present the methodologies for hazard maps for floods, droughts, windstorms, earthquakes, and landslides. We also show two additional hazard maps for droughts and windstorms for the period 1995 to 2017 comparable to the time period of the economic impact assessment in ESPON-TITAN.

The flood hazard is represented by river floods; the drought indicator represents best meteorological droughts; storms are represented by winter storms (extra-tropical storms); earthqakes are represented by the seismic hazard they cause; the landslide indicator refers to landslide susceptibility, which can indicate also suceptiblity to other types of mass movements.

Table 1.1 lists the geographical coverage of each hazard map. The data have a good coverage of Europe, but no data has been available for the overseas departments of France, Madeira and the Acores (Portugal). For the Canarias (Spain) only the drought hazard was mapped.

Table 1.1.Geographical coverage of the mapped natural hazards. (x) indicates that the data does not cover the entire country

Countries	River floods	Droughts	Storms	Earthquakes	Landslides
Austria	x	x	x	x	x
Belgium	x	x	x	x	x
Bulgaria	x	x	x	x	x
Croatia	x	x	x	x	x
Cyprus		x	x	x	x
Czech Republic	x	x	x	x	x
Denmark	x	x	x	x	x
Estonia	x	x	x	x	x
Finland	x	x	x	(x)	x
France	x	x	x	x	x
France (Guadeloupe)					
France (Guyane)					
France (Martinique)					
France (Mayotte)					
France (Reunion)					
Germany	x	x	x	x	x
Greece	x	x	x	x	x
Hungary	x	x	x	x	x
Ireland	x	x	x	(x)	x
Italy	x	x	x	x	x
Latvia	x	x	x	x	x
Lithuania	x	x	x	x	x
Luxembourg	x	x	x	x	x
Malta			x	x	(x)
Netherlands	x	x	x	x	x
Poland	x	x	x	x	x
Portugal	x	x	x	x	x
Portugal (Acores)					
Portugal (Madeira)					
Romania	x	x	x	x	x
Slovakia	x	x	x	x	x
Slovenia	x	x	x	x	x
Spain	x	x	x	x	x
Spain (Canarias)		x			
Sweden	x	x	x	x	x
Iceland		x	x	x	x
Liechtenstein	x		x	x	x
Norway	x	x	x	x	x
Switzerland	x	x	x	x	x
Albania	x	x	x	x	x
Bosnia and Herzegovina	x	x	x	x	x
Kosovo under UN Security Council Resolution 1244/1999	x	x	x	x	x
Montenegro	x	x	x	x	x
The former Yugoslav Republic of Macedonia	x	x	x	x	x
Turkey	(x)	x	(x)	x	
Serbia	x	x	x	x	x
United Kingdom of Great Britain and Northern Ireland	x	x	x	x	x

In the subsections below, we describe for each individual map, the data sources, the reliability and limitations of the data, as well as the mapping methodology. In Aggregated hazards 3, we present an updated methodology for the mapping of aggregated hazards and in Section 4, a map that shows the co-occurrence of seismic hazard and landslides. In addition, an overview of reviewed data sources is available in Section 5.

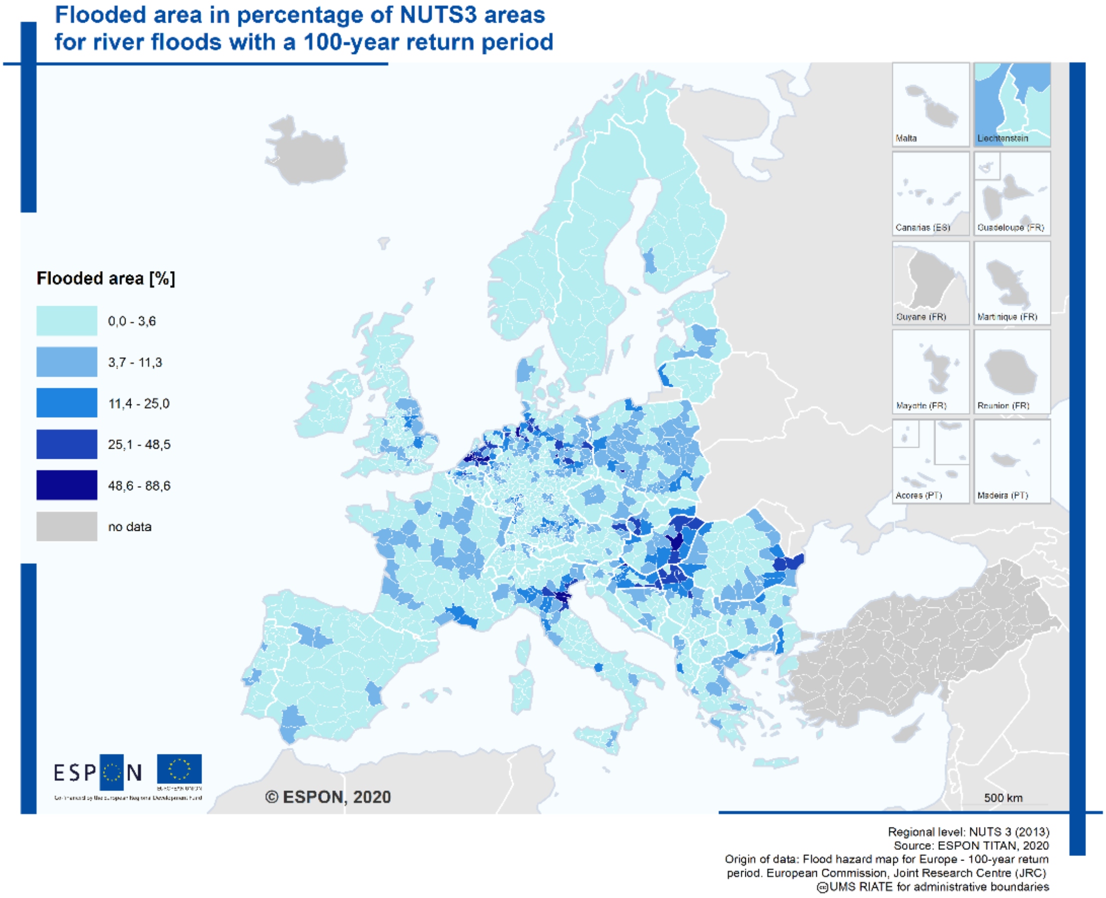
The data of all maps were grouped into five classes. The limits of the five classes are given in the original physical units describing each hazard. Only the map for landslide susceptibility is based on a descriptive scale with five classes ranging from 1 (very low) to 5 (very high). Because the different physical units of the individual hazard indicators are not directly comparable, the aggregation or combination of several hazards requires a normalization of the data into a scale from 0 to 1 (0 corresponding to the smallest indicator value on the map and 1, to the highest).

2 Distribution and analysis of floods, droughts, storms, eartquakes and landslides

2.1 River floods

The flood hazard map (Map 2.1) shows the percentage of flooded land area per NUTS3 for riverine floods. The map is based on the Joint Research Center (JRC) flood hazard map for Europe – 100-year return period. The JRC flood hazard maps are based on the Lisflood hydrological model (Van Der Knijff et al., 2010).

Map 2.1. Flood hazard map (flooded area in percentage of NUTS3 areas for river floods with a 100-year return period)



Regional level: NUTS 3 (2013)
Source: ESPON TITAN, 2020
Origin of data: Flood hazard map for Europe - 100-year return period. European Commission, Joint Research Centre (JRC)
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Even though the JRC flood hazard maps reproduce the flooded areas fairly well compared to national and regional reference flood hazard maps, there are some limitations that have to be understood (Alfieri et al. 2014):

- The maps do not include flood defence measures. This means, the maps overestimate the flooded area in countries and regions with extensive flood protection measures.
- Small catchment areas are not well represented. First, the model is based on upstream areas with a minimum extent of 500km^2. Second, the data input to the model does not work well for small river basins.
- The flood depth tends to be overestimated for areas with pronounced topography.

- The flood depth (and extent) tends to be underestimated for river deltas, because the model does not consider the impact of sea tide and storm surges.
- The calibration of the model is based on discharge measurements of minimum 6 years between 1995 and 2010. For 37% of the covered area there were no discharge data available. This contributes to the uncertainty of the results.
- The calculation of the 100-year flood is based on an only 21-year discharge time series. Considering that climatic data are usually calculated on a 30-year basis, this is a rather short time span.

The ESPON-TITAN flood map displays the affected NUTS3 areas of floods in major catchment areas with a reocurrence of 100-years. Indeed, only very few NUTS3 areas are not connected to larger catchments areas that experience at least some floods. Since minor river basins are not represented well in this map, it is very probable that also those NUTS3 areas that appear non-affected might count with riverine flooding. A further observation derived from this map is that several highly industrialized areas count with a high percentage of flooded area, so that special attention should be placed on this hazard to avoid risk chains, such as interruptions in the production and trade (flooded or destroyed transport routes), as well as Natural-technical hazards (NATECHS), i.e. flood events leading to environmental impacts (flood waters washing out contaminants of industrial areas and brownfields). Such NATECHS might have impacts on groundwater qualities as well as water bodies downstream, including riverine and maritime coastal areas.

Other types of floods, e.g., flash floods, are often very local events and could possibly affect all NUTS3 areas. As most climate change models conclude that heavy rain events will increase (Collins et al. 2019), this means that flood management should in fact play a role in landuse planning and regional development of all NUTS3 areas of the ESPON space.

2.2 Droughts

The drought hazard map (Map 2.2) shows the number of droughts and the number of months under drought conditions for each country (NUTS0). The map is based on information retrieved from the European Drought Observatory (EDO) of JRC. The hazard assessment utilizes the Standardized Precipitation Index for three-month periods (SPI3), which is based on observed precipitation values (Spinoni et al., 2019). The SPI3 indicator shows deviations from the average three-monthly cumulative precipitation. The indicator has proven to detect actual drought events fairly reliable (Spinoni et al., 2019). According to the fact sheet provided by EDO[1], SPI3 is a suitable indicator for short-term impacts such as reduced soil moisture or reduced flow in small creeks. However, actual drought impacts depend strongly on other factors such as air temperature, soil type, land use, or irrigation systems.

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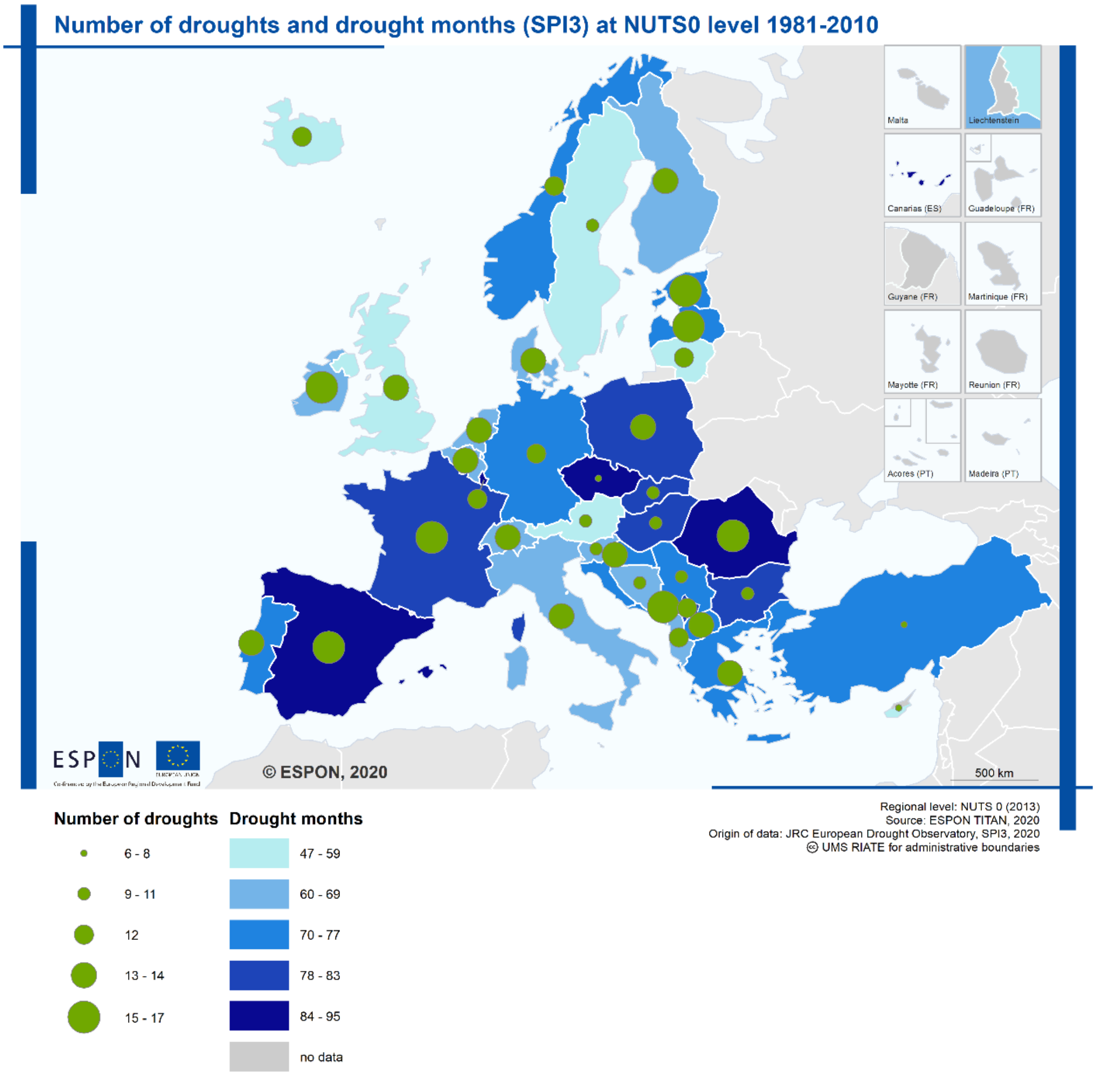
[1] https://edo.jrc.ec.europa.eu/documents/factsheets/factsheet_spi.pdf

Map 2.2. Drought hazard map (number of droughts and drought months at NUTS0 for the period 1981-2010)



Regional level: NUTS 0 (2013)
Source: ESPON TITAN, 2020
Origin of data: JRC European Drought Observatory, SPI3, 2020
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For the drought hazard map, we calculated monthly SPI3 values at country level for the period 1981-2010. In line with Spinoni et al. (2019), we calculated the start of the drought period as the first of two consecutive months with a SPI3 index smaller than one standard deviation (SPI3 < -σ). The end of a drought period was calculated as the SP3 index rising above zero (SPI3 > 0).

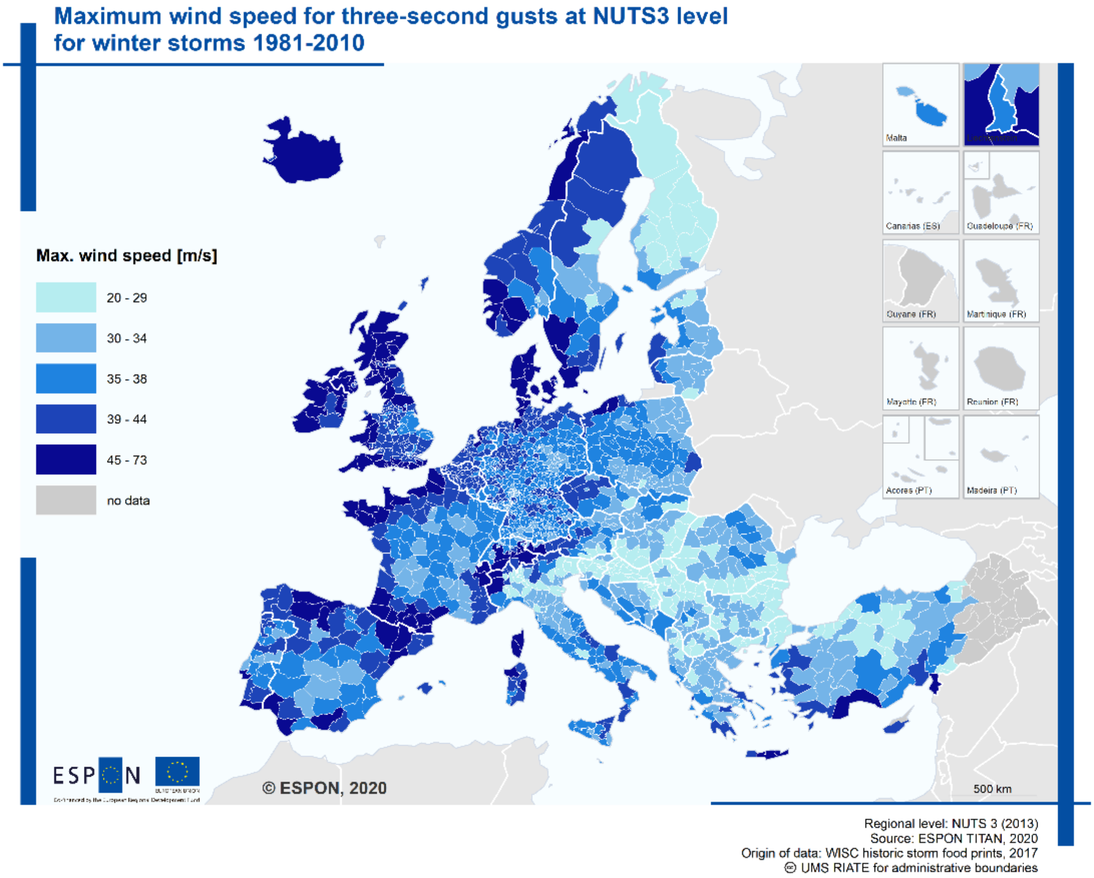
The display of the drought hazard is extremely complicated for the entire ESPON space, as Europe covers a multitude of climate zones. Further, many countries in Europe cover two and more climate zones. Besides, it must be taken into account that the effect of droughts also largely depends on local geology (e.g., groundwater aquifer structures), topography (e.g., plains, mountains), landcover (e.g., vegetation, built-up areas) and landuse (e.g., forest, agriculture, industrial). In other words, the effects of droughts vary both among and within the countries of the ESPON space. A further challenge is the data resolution, i.e. the drought hazard is displayed in relation to the average precipitation of the respective country. This means that a direct comparison of the drought hazards between countries is challenging. It must further be taken into account that the number of droughts is in fact a variation of the precipitation within a certain time period. In other words, a variation of the precipitation must not necessarily lead to negative impacts, e.g., it might be that an observed drier-than-usual time period is surrounded by relatively wetter periods. The data used for this map would not allow such interpretations. What can be derived from this map is an overview on the ESPON territory that droughts occur in several countries that might usually be seen as rather rainy. And it may be observed that drought hazard affects a large number of countries, but to varying effects. Some countries have both, a large number of drought events that also last long, meanwhile others have a large number of drought events that do not last too long. The interpretation of this map is therefore that each country must derivate own measures to mitigate the effects of droughts, but cross border initiatives cannot be concluded with the used datasets. For that, data based on catchment areas would be better suited.

2.3 Storms

The storm hazard map (Map 2.3) shows maximum 3-second gust speeds (m/s) over a 72-hour time period for winter storms in the years 1981-2010 at NUTS3. The maximum 3-second gust is retrieved for each NUTS3 area from 46 storms that were considered “insurance relevant” (WISC, 2020). This maximum can be interpreted as wind speed with a pseudo-30-years return period (WISC, 2020).

The data was retrieved from a set of historical storm footprints for the years 1940 to 2016 produced by the UK Met Office as part of the Windstorm Information Service (WISC) project (Davies et al. 2005; Maisey et al. 2017). The historic storm footprints were created with the UK Met Office Unified Model and reanalysis data from ERA-Interim and ERA5.

Map 2.3. Storm hazard map (maximum wind speed for three-second gust at NUTS3, 1981-2010)



Regional level: NUTS 3 (2013)
Source: ESPON TITAN, 2020
Origin of data: WISC historic storm food prints, 2017
© UMS RIATE for administrative boundaries

The storm hazard map clearly shows that the areas most affected by windstorms are coastal regions of the North Sea and exposed coastal areas of the Baltic Sea. Further affected are some specific coastal areas of the Mediterranean region by local windstorm patterns, as well the mountain regions of the Pyrenees and the Alps. As a general observation, this implies that particularly coastal areas must take this hazard into account in planning systems, and along with rising sea levels caused by climate change even more so. Windstorm events have impacts on local coastal erosion patterns, which is also affected by rising sea levels. In addition, temporarily risen sea levels due to windstorm events can block rivers from discharging into the sea and affect riverine flood patterns in the hinterlands. Combined river and storm surge analysis are thus highly recommended for coastal areas in the ESPON space.

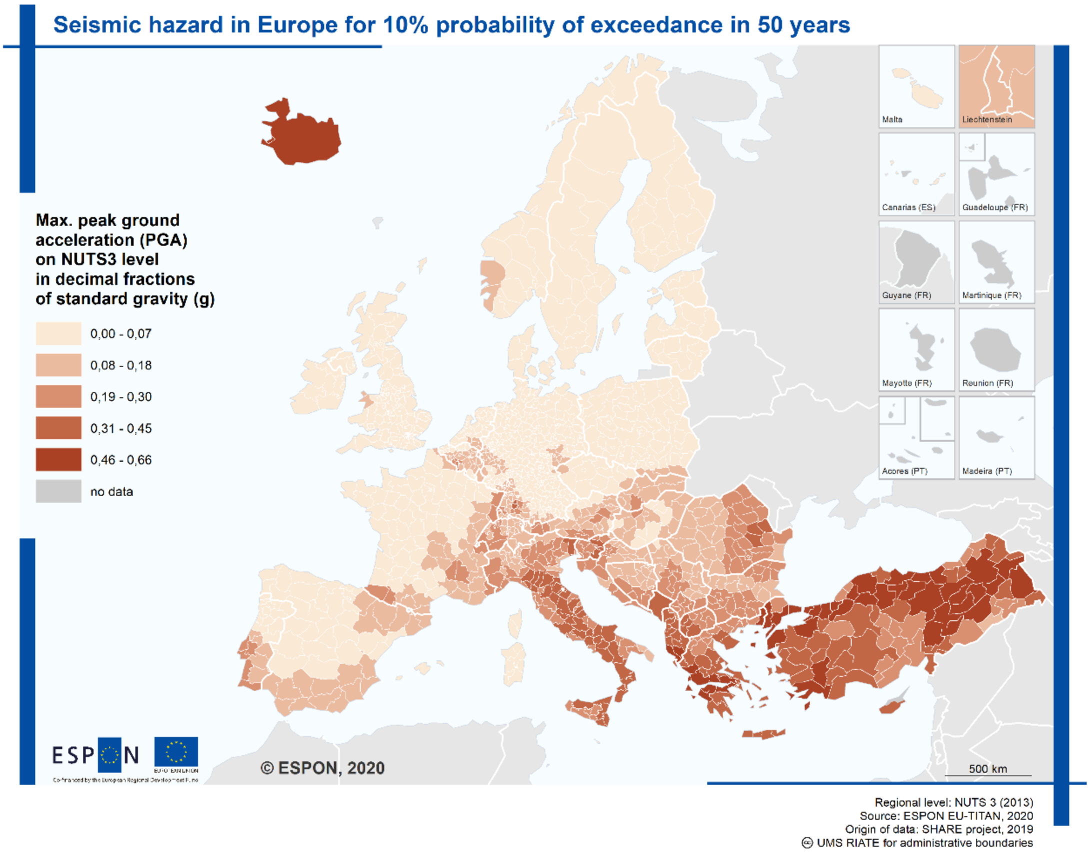
2.4 Earthquakes

The seismic hazard is mapped based on the information provided by the Seismic Hazard Harmonization in Europe project (SHARE) (Gardini et al., 2013, 2014). Rather than the occurrence of earthquakes at specific locations, the seismic hazard map displays the territorially distributed intensity of ground-shaking with a certain probability of exceedance. The calculation of the seismic hazard includes in addition to records of earthquake events, e.g., fault structures, the strain of the Earth's crust, and other factors affecting ground motion (Gardini et al. 2014). The data are available via the European Facilities for Earthquake Hazard and Risk webpage.

SHARE provides a European dataset of peak ground acceleration (PGA) in proportion to acceleration of gravity (m/s^2) with a 10% chance of exceedance in 50 years. Earthquake engineers are using these values to calculate the seismic risk and the earthquake loading for buildings in each hazard zone following existing building codes especially for key buildings such as hospitals, dams, nuclear power stations and other buildings (Smith, 2004; EFEHR, 2017).

Map 2.4 shows the maximum PGA value in each NUTS3 region based on the SHARE dataset. These values for the NUTS3 regions FI1D1 and IE013 are based on the average max. PGA of the adjacent NUTS3 regions, because the original SHARE dataset does not cover these regions.

Map 2.4. Earthquake hazard map (maximal peak ground acceleration in decimal fractions of standard gravity at NUTS3)



Regional level: NUTS 3 (2013)
Source: ESPON EU-TITAN, 2020
Origin of data: SHARE project, 2019
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The earth's crust is in continuous movement. There is no region in Europe with no ground motion. This is of particular interest, and well-respected in standardised guidelines, e.g., for nuclear power plants. The seismic hazard map virtually divides Europe into four major regions. The most strongly affected is Northern and Central Turkey, the Eastern Mediterranean and the Black Sea coasts, and the Balkan, followed by a lesser hazard degree in the Western Mediterranean region, the Alps and the Carpathian mountain ranges. The next zone covers areas along other partly active fraction zones in the Rhine valley, the Pyrenees, the Massive Central and the Ore mountains. The fourth region is the one covering large areas with only little ground motion. In addition, Iceland has high seismic activity being placed on the Mid-Atlantic

Ridge. The seismic hazard (Peak ground acceleration-PGA) must be analysed locally, and ideally the location of active faults are respected in local land use plans and building codes. Earthquake-proof construction is possible, if all regulations, codes and standards are followed closely. It must be further taken into account that seismic events can cause tsunamis, and therefore information and education in this hazard potential should be offered in potentially affected areas.

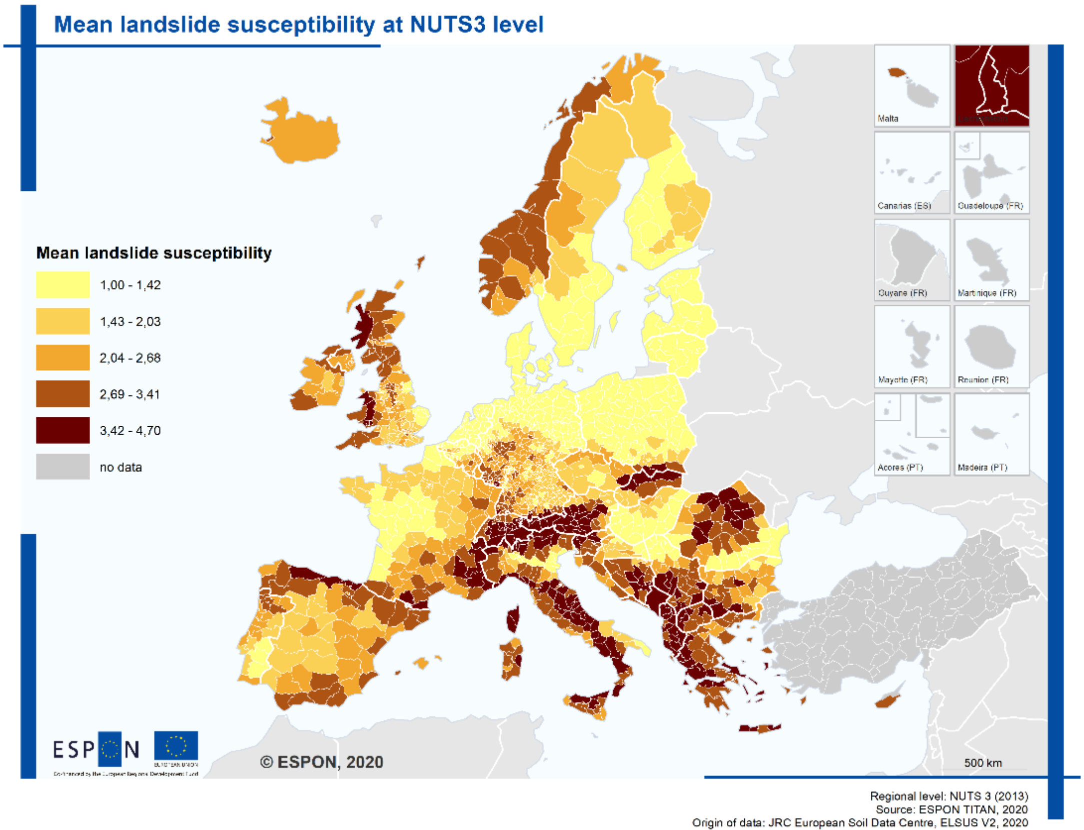
2.5 Landslides

Additionally to the previous four hazards presented, committed by ESPON-TITAN at the Inception Report, landslides are also presented at EU scale. Landslides are included because it is a very widespread natural hazard in Europe, even though they affect very localised areas. Landslides are also important for the combined analysis of hazards, since they can be triggered by floods and earthquakes. The inclusion of this hazard to the report was possible due to the improved data situation, after the publication of the new JRC European Landslide Susceptibility Map in 2018.

The landslide hazard map (Map 2.5) shows the mean landslide susceptibility at NUTS3. The map is based on the data of the JRC European Landslide Susceptibility Map, version 2 (ELSUS v2) (Wilde et al. 2018; Günther et al. 2014). The data are provided by JRC European Soil Data Centre (ESDAC). The ELSUS v2 map includes topographic information (elevation, slope angle), shallow sub-surface lithology, landcover, and more than 149.000 landslide events. The data provides no information on the actual frequency, timing or magnitude of landslide events (Wlide et al. 2018). In addition, the reliability of the ELSUS v2 map could evaluated against actual landslide events for only 65% of the mapped area. Especially in relatively flat areas (e.g., Northern part of Germany, Netherlands, Denmark, Belgium, Poland, the Baltic countries, and Finland) and some other areas (Iceland, parts of the Balkan area) had no information about landslide events (Wilde et al. 2018; Günther et al. 2014).

ELSUS v2 classifies landslide susceptibility in five classes (1= very low; 2= low; 3= moderate; 4= high; 5= very high) at a resolution of 200m x 200m. To present landslide susceptibility at NUTS3 average for each NUTS3 area was calculated. As a consequence, the five classes of Map 2.5 do not coincide with the classes of ELSUS v2.

Map 2.5. Landslide hazard map (mean landslide susceptibility at NUTS3)



Regional level: NUTS 3 (2013)
Source: ESPON TITAN, 2020
Origin of data: JRC European Soil Data Centre, ELSUS V2, 2020
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In fact, landslide is only one form of mass movements, but since term landslide is the most commonly understood, it is used here to represent all forms of mass movements exemplarily. The landslide hazard is mostly present in European mountain areas, which is quite obvious, as gravity plays a major role in mass movements. As a rule of thumb, the steeper a slope is, the higher is the mass movement potential. For certain, local geological features strongly affect the landslide potential, as well as climate and vegetation. The human factor also plays a very important role, as land-use can severely affect the landslide potential. Landslide potential should thus play a vital role in land-use planning and building codes of mountainous areas.

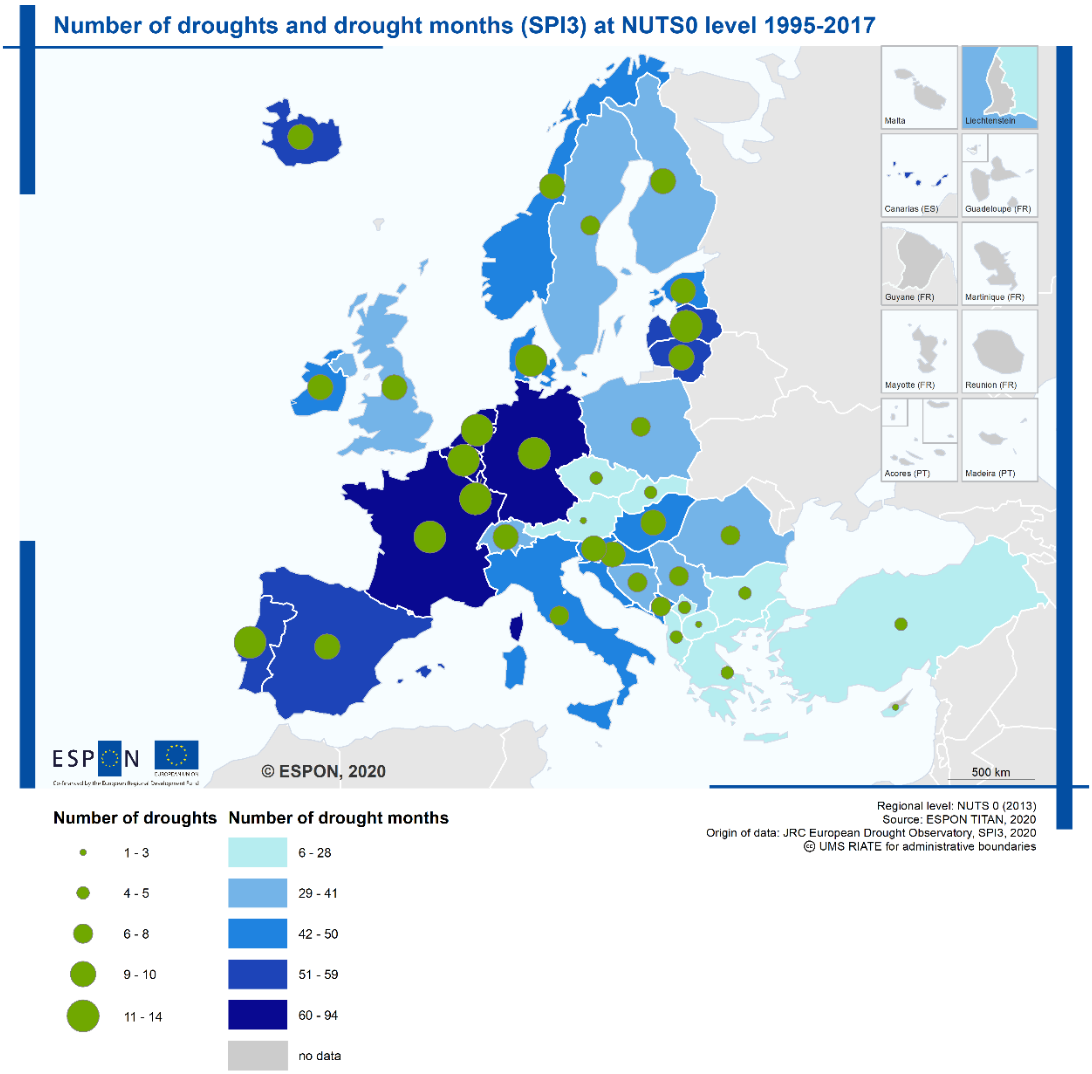
2.6 Drought and winter storm maps for the period 1995 to 2017

In addition to the single hazard maps in the interim report and presented above, we produced hazard maps for droughts and winter storms for the period 1995 to 2017. On these maps we present these hazards for a time period comparable to the time period of the economic impact assessment.

The drought map (Map 2.6) for the years 1995-2017 was produced with the same methodology as the drought map 1981-2010 (Map 2.2).This means, Map 2.6 shows the number of droughts (as circles of different sizes) and number of months under drought conditions at country level (as the colour of the NUTS0 areas) based on the Standardized Precipitation Index for three-month periods (SPI3). Although the two time periods have an overlap of 16 years the resulting drought patterns look different. There is a clear decrease in drought months in Eastern Europe (in absolute and relative terms), but an increase in Germany the Benelux countries and the Baltic states.

For any further analysis it must be kept in mind that the period 1995 to 2017 is too short to be representative for climatic conditions (these should be covered by at least 30 years).

Map 2.6. Number of droughts and drought months (SPI3) for the period 1995 to 2017



Regional level: NUTS 0 (2013)
Source: ESPON TITAN, 2020
Origin of data: JRC European Drought Observatory, SPI3, 2020
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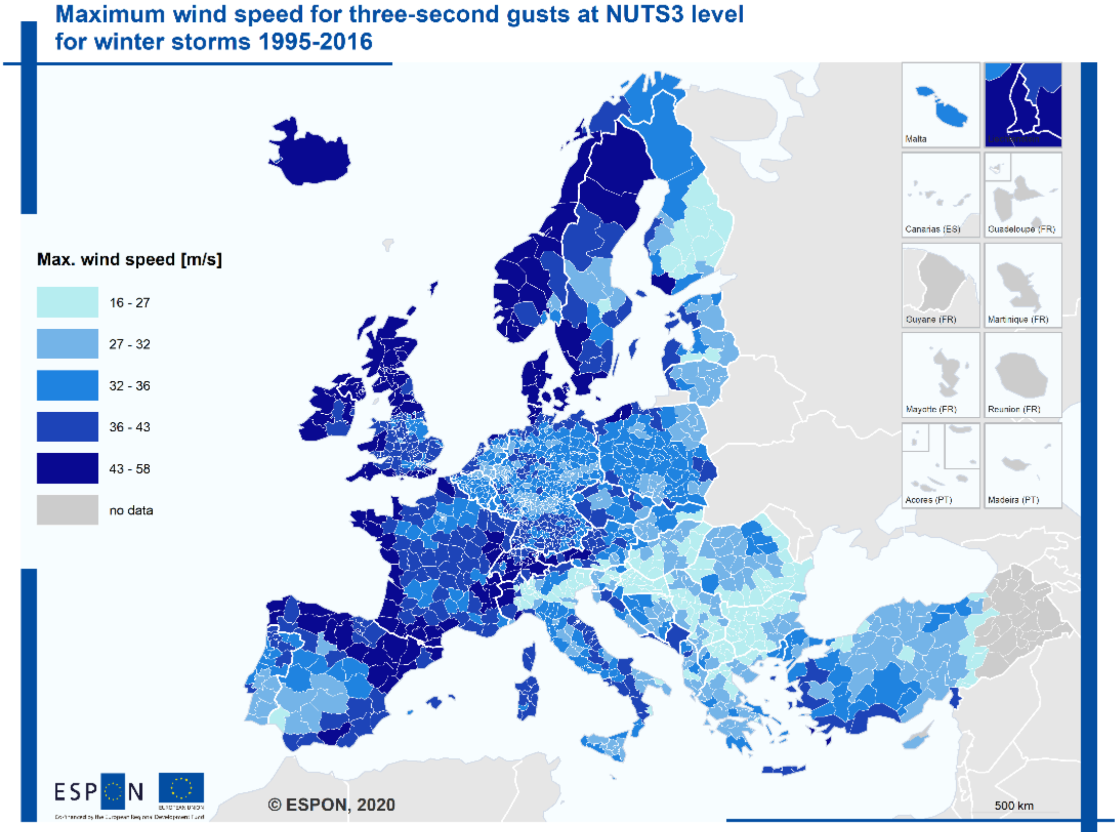
The winter storm map (Map 2.7) for the years 1995 to 2016 was produced with the same methodology as the winter storm map for the period 1981 to 2010 (Map 2.3) and includes 31 individual storm footprints. Map 2.7 shows the maximum windspeed for three-second wind gusts at NUTS3 level. This winter storm map does not cover the full period of the economic impact assessment for winter storms, because the WISC database on historic storm footprints extents only to 2016, whereas WISC provides Tier 3 indicators for economic damages up to 2017 (WISC webpage, 2020). Whereas maximum windspeeds for individual NUTS3 regions differ between the two mapped periods, the general patterns of the most affected areas do not change considerably.

For any further analysis it must be kept in mind that the period 1995 to 2016 is too short to be representative for climatic conditions (these should be covered by at least 30 years).

Map 2.7. Storm hazard map for the period 1995 to 2016 (maximum wind speed for three-second gusts at NUTS3)



Regional level: NUTS 3 (2013)
Source: ESPON TITAN, 2020
Origin of data: WISC historic storm food prints, 2017
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The hazard maps for river floods, seismic hazards, and landslides have not been calculated for the period 1995 to 2017. The river flood hazard map is based on the JRC flood hazard map for floods with 100-year return period. The underlying Lisflood model has been calibrated with discharge measurements between 1995 and 2010 (Alfieri et al. 2014). Seismic hazard is virtually independent of climatic conditions therefore the hazard map is equally valid for periods 1981 to 2010 and 1995 to 2017. Landslide susceptibility is only partially dependent on climatic conditions. The JRC European Landslide Susceptibility Map version 2 (ELSUS v2) does not consider climatic conditions (Wilde et al. 2018; Günther et al. 2014). The landslide susceptibility assessment of ELSUS v2 includes 149,117 generic landslide locations, but these data are not related to a specific time period.

3 Aggregated hazards

The source of data used to weight the individual hazards for the aggregated hazard map was EM-DAT database (EM-DAT 2020). The database contains essential core data compiled from various sources on the occurrence and effects of disasters in the world from 1900 to the present day. EM-DAT data gives the estimated damage costs of natural hazards in US dollars in the value of the year of occurrence. Since the ESPON-TITAN hazards are related to European area, the total damage costs were decided to be presented in Euros instead of US dollars as was previously done in the ESPON-TITAN Interim report. To convert the values from US dollars, the exchange rates from US dollars to ECU (European Currency Unit, used as a monetary unit from 13.3.1979 to 31.12.1998) and from US dollars to EUR (Euro, used from 1.1.1999) were used. A consistent set of exchange rates from 1971 to 2019 is provided by Eurostat (Eurostat 2019). Converting the total damage costs from US dollars to Euros were done by multiplying each hazard's total damage cost in US dollars with the EUR/ECU exchange rate of the year of the event.

After converting the values from US dollars to Euros, all the EM-DAT price estimates of the total damages were brought to one reference year for summing the economic losses from different years. In the Interim report the calculations were done by using the Consumer Price Index (CPI). When using Euros, the consumer price inflation can be measured by the Harmonized Index of Consumer Prices (HICP), provided by the European Central Bank (ECB). ECB provides a consistent HICP dataset for the Euro area from 1961 to present (European Central Bank 2020). The data in this dataset are based on the Eurostat HICP from 1996 onwards (Eurostat 2020). Data prior to 1996 are backdated based on non-harmonised national consumer price indices. The reference year chosen for the calculation was 2015. The changes in prices were calculated for each individual natural hazard from years 1981-2010 by using the formula below:

$$Value\ in\ 2015\ euros = Value\ in\ X\ euros \times (\frac{100}{HICP_X}), where{:}\ X\ is\ a\ specific\ year.$$

After the total damage cost data was brought to the same reference year, the relative weight of each individual natural hazard was calculated by using the cumulative damage costs from EM-DAT for the period 1981-2010 for the ESPON space (EU member states, Iceland, Liechtenstein, Norway, Switzerland, United Kingdom of Great Britain and Northern Ireland). Relative weight means a percentage between 0% and 100% that is assigned to determine the relative weight of total damage costs for each ESPON-TITAN hazard

Table 3.1).

Table 3.1.Sums of total damages (1981-2010) and relative weights of the five ESPON-TITAN hazards

Hazard	**Cumulative total damage costs 1981-2010 (in 2015 thousand of Euro values)**	**Relative weight**
Winter storm/ Extra-tropical storm	73 010 360	38,8 %
River flood	69 855 236	37,1 %
Drought	23 928 282	12,7 %
Earthquake	21 154 277	11,2 %
Landslide	262 597	0,1 %
Grand total	188 210 752	100 %

Source: ESPON-TITAN (2020)

In the EM-DAT database many of the floods and storms are not further specified, i.e. there is no information available about the type of flood or storm. These hazard data were automatically categorized as “Other natural hazards”, which could have distorted the results when comparing the relative weights of ESPON-TITAN hazards and other natural hazards. All unspecified floods were taken off from the calculations if there was no specified triggering origin mentioned for the disaster in the EM-DAT database. Each individual unspecified storm that had an event name in the EM-DAT database was studied using storm databases (e.g. Extreme Wind Storms Catalogue) to find out if they were winter storms or other storms. From that base, the named storms were specified as either ESPON-TITAN hazards (winter storms and extra-tropical storms) or other natural hazards. Unnamed storms excluded from the calculation. In EM-DAT, the total damage costs for wind storms include storm damages and damages caused by associated storm surges as (personal communication with EM-DAT 8/12/2020, personal communication with Munich RE 29/12/2020).

Table 3.2 shows the total damages and relative weights of all EM-DAT natural hazards. The five selected hazards are separated from the others to express the aggregated hazard map’s coverage of the total cumulative damage costs.

Table 3.2. Sums of total damages (1981-2010) and relative weights of all EM-DAT natural hazards

Natural hazards	**Total damages (in 2015 thousand of Euro values)**	**Relative weight**
ESPON-TITAN hazards	188 210 752	75,3 %
Other natural hazards	61 818 729	24,7 %
Total	250 029 481	100 %

Source: ESPON-TITAN (2020)

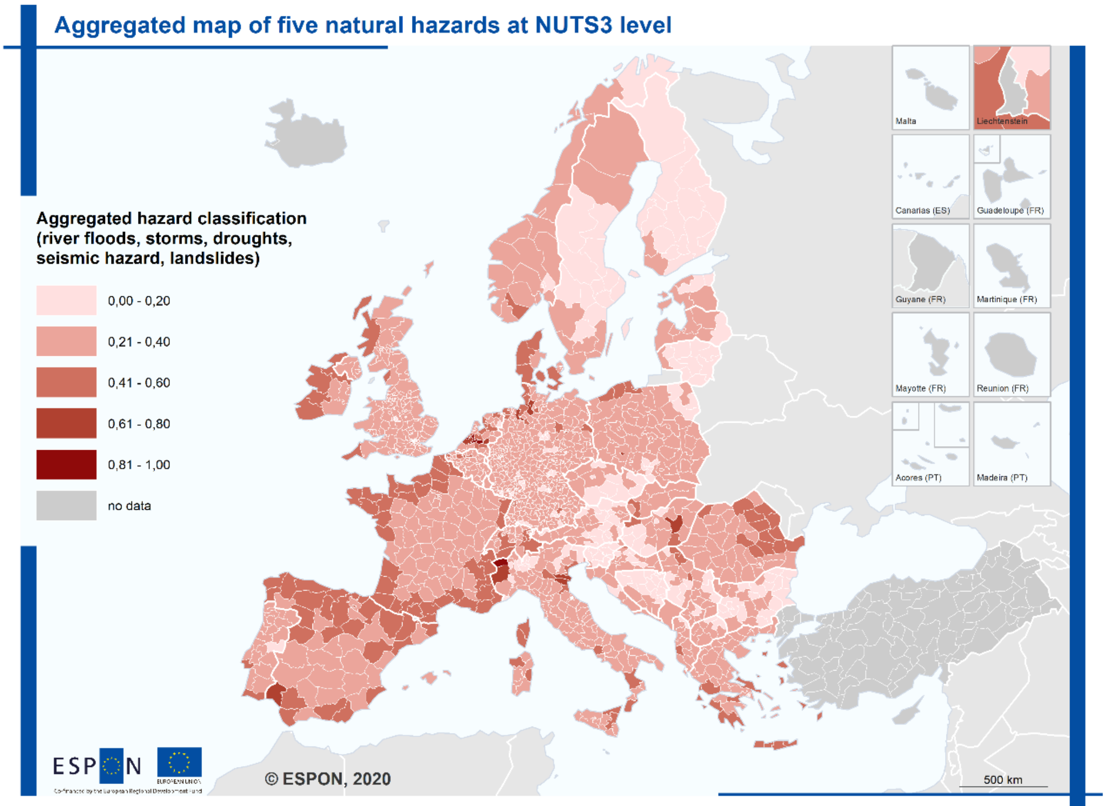
The normalized hazard indicator values (0-1) were multiplied with the calculated relative weight for each hazard of the chosen five ESPON-TITAN hazards:

$$\begin{aligned} &Aggregated\ hazard \\ &\qquad = 0{,}388 \times storm_{norm} + 0{,}371 \times flood_{norm} + 0{,}127 \times drought_{norm} \\ &\qquad + 0{,}112 \times earthquake_{norm} + 0{,}001 \times landslide_{norm} \end{aligned}$$

The summed and normalized resulting values are shown at NUTS3 on an aggregated hazard map (Map 3.1). Those areas that have an incomplete data coverage for all five hazards area shown as “no data”.

The indicators for riverine floods, storms, earthquakes, and landslides, could be directly normalized, because the respective hazard maps are at NUTS3 and show only one indicator. The two indicators for droughts were transferred from NUTS0 (national level) to NUTS3, normalized and summed with equal weights for number of droughts and number of drought months. The resulting merged indicator was normalized as input for the aggregated hazard map (drought$_{norm}$ in equation the equation above).

Map 3.1. Aggregated hazard map



The normalized indicators for river floods, storms, droughts, seismic hazards, and landslides are weighted with the factors retrieved from their cumulative total damage costs in the period 1981 to 2010 in all EU member states, Iceland, Liechtenstein, Norway, and Switzerland (based on EMDAT data).
The resulting indicator is normalized.

Regional level: NUTS 3 (2013)
Source: ESPON TITAN, 2020
Origin of data: JRC Flood hazard map for Europe - 100-year return period, 2016; WISC historic storm food prints, 2017; JRC European Drought Observatory, 2019; SHARE project 2019; JRC European Soil Data Centre, ELSUS v2, 2018; EMDAT, 2020
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The interpretation of this map must consider that the weighting of the aggregated hazards is based on the economic damage caused during the period 1981-2010. In this period, floods and storms have contributed to nearly 76% of all damages, followed by droughts and earthquakes, responsible only for almost 24% of the damages. According to EM-DATA data, economic damages caused by landslides are next to neglectable, from European perspective. The high intensity of the windstorm hazard – combined with high weight of windstorms when compared to other hazards – is represented in the higher hazard classes, mostly on areas closer to exposed coasts. Many of these coastal zones, partly low-lying areas, also experience river floods. Other areas with higher aggregated hazard values are based on the combination of other important hazards, such as floods and droughts (e.g. Eastern Romania). It must be taken into account that the aggregated hazard map does not respect any flood protection measures, therefore some areas have a high aggregated hazard potential, meanwhile the effective risk is neglected. Also, the drought potential is displayed on NUTS0, which partially leads to strong contrasts at national borders. It must be further considered that the weighting of the aggregation is based only on economic damages, and not human fatalities or damages to historic buildings. The map will certainly be very different if fatalities would be used for the weighting instead of economic damages.

3.1 Cumulative total damage costs versus Delphi method as weighting methods

Other than suggested in the inception report of ESPON-TITAN we decided to replace Delphi as weighting method after careful consideration. The Delphi method is a forecasting process framework based on the results of multiple rounds of questionnaires sent to a panel of experts, by a weighting method that is based on cumulative damages caused by multiple hazards.

The application of the Delphi method in ESPON Hazards and ESPON Climate projects had some limitations (Greiving 2006; Greiving et al. 2011). First, it is difficult to find a suitable set of experts with sufficiently broad experience to cover all hazards equally well. And the experts' judgement can be biased by individual areas of expertise or recent events that affect the weight estimates for certain hazards (Greiving et al. 2006 refer to the tsunami in 2004 as an example). Second, most people will refer to their own environment and experiences in their weighting. The experts scrutinize the impacts of a hazard in their country more closely than in locations far away. This is unproblematic in local and regional case studies, but critical in a European assessment. The result is rather the accumulation of placed-based judgements than a truly European perspective. Finally, hazards are experienced by the actual events and the caused damage (damage costs, fatalities, etc.). This means, it is almost impossible to exclusively judge hazards without considering the vulnerability and weaknesses of the system at stake. The weights suggested by experts always include assumptions about the potential damages and risks posed by the hazards. As Olfert et al. (2006, p. 130) point out when asking for the weighting of hazards, "the question is asked on the borderline between hazard and risk".

There are several benefits in using the method that is based on cumulative damages caused by multiple hazards for the weighting of the five hazards covered by ESPON-TITAN. The cumulative damage costs provide a real picture of the relative importance at European level instead of national or local level. The data provided cover the five ESPON-TITAN hazards but also other main natural hazards. Therefore, it is possible to estimate the importance of the five hazards compared to a fairly comprehensive range of other natural hazards.

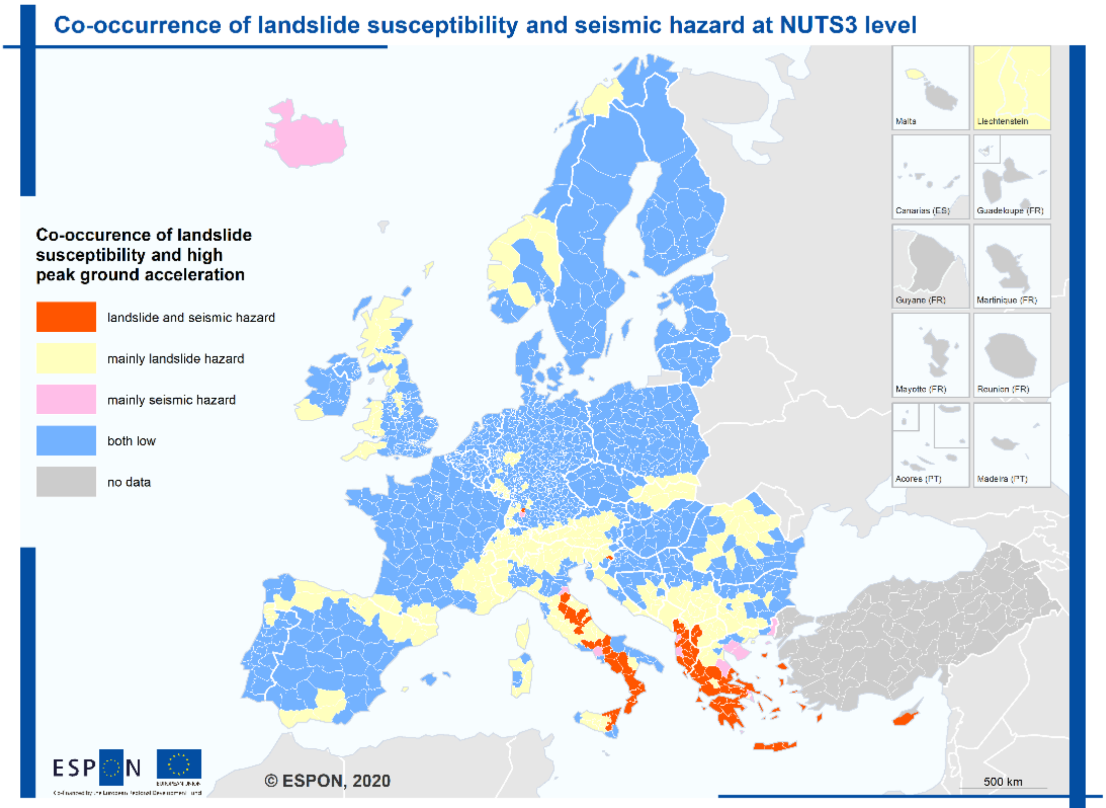
4 Combined hazards

It is well understood that natural hazards can interact, overlay or trigger further hazards. For example: floods or earthquakes can trigger landslides; coastal storms are related to storm surges; storm surges can block rivers from discharging into the sea and cause hinterland floods, droughts can increase the probability of forest and wildfires (Collins et al. 2019; Tarvainen et al. 2006). Based on the five natural hazards presented in this report, the co-occurrence of river floods and landslides, and earthquake hazard and landslides are analysed.

With the given indicators (flooded area and landslide susceptibility) and the spatial representation at NUTS3, we could not detect any meaningful pattern for the co-occurrence of river floods and landslides. This is due to the used hazard indicators and not an evidence of the unrelatedness of river floods and landslides. Whereas landslide susceptibility depends strongly on the slope steepness (Section 2.5), large flooded areas appear typically in flat areas.

Based on the PGA values of Map 2.4 and the landslide susceptibility of Map 2.5 there are patterns of co-occurrence of seismic hazard and landslide susceptibility. In Map 4.1, areas are considered prone to a hazard, if the normalized indicator rise above 0,5 (landslide susceptibility and peak ground acceleration). A co-occurrence of both hazards is assumed if the values for normalized landslide susceptibility and normalized peak ground acceleration are greater than 0,5.

Map 4.1. Co-occurrence of landslide susceptibility and seismic hazard



Regional level: NUTS 3 (2013)
Source: ESPON TITAN, 2020
Origin of data: JRC European Soil Data Centre, ELSUS v2, 2018;
SHARE project, 2019
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Especially in Italy and Greece many areas are prone to both hazards. Whereas most areas in Europe are not exposed to either of the hazards, there are some exceptions near the Rhine valey and at the eastern fringe of the Alps.

5 Overview and evaluation of data and data sources for the ESPON-TITAN hazard maps

Data sources for five natural hazards (earthquakes, storms, floods, droughts, and landslides) were identified and evaluated, and literature which is using or has producing the data sources studied. If data was not freely available or the access to it was restricted, contact persons hosting the data sources have been contacted to clarify the terms and conditions to use the data.

In the following an overview of different data sources for each hazards is given. The data sources used for the ESPON-TITAN natural hazards maps are listed fist. Alternative data sources follow.

5.1 Earthquakes

Data source: **SHARE Project.**
Name of indicator/variable: **Harmonized Seismic Hazard Model (Giardini et al. 2013).**
Resolution: Raster data (size 0.0666 degrees).
Time period: 1000-2007.
Unit: Pga (peak ground acceleration in proportion to acceleration of gravity (m/s^2) with a 10% change of exceedance in 50 years).
Geographical coverage, limitations: Europe with Turkey.
Data format: .shp and others.
URL: http://www.share-eu.org/
Status: available.

Alternative *Data source*: **Global Seismic Hazard Assessment Program (GSHAP).**
Name of indicator/variable: **Homogenous seismic hazard map for horizontal peak ground acceleration (pga) that is representative for stiff site conditions (Grünthal et al., 1999).**
Resolution: Raster data (size 0.0833 degrees).
Time period: -
Unit: Pga (peak ground acceleration in proportion to acceleration of gravity (m/s^2) with a 10% change of exceedance in 50 years).
Geographical coverage, limitations: global.
Data format: GRID
URL: http://static.seismo.ethz.ch/gshap/global/caution.html
Status: available.

5.2 Storms

Data source:**WISC Project.**
Name of indicator/variable: **maximum 3-second gust speeds over a 72-hour period for significant winter storms between 1940 and 2014 (Maisey et al. 2017).**
Resolution: 4 x 4 km.
Time period: 1950-2016.
Unit: m/s.
Geographic coverage, limitations: ESPON space, Balkan area, Turkey. Does not include oversea areas, Acores, Madeira, Canarias.
Data format: tiff and netcdf.
URL: https://wisc.climate.copernicus.eu/wisc/#/help/products#footprint_download
Status: available, requires registration.

*Alternative Data source 1***: EEA wind storms data.**
Name of indicator/variable: **Projected changes in extreme wind speed (98th percentile of daily maximum wind speed) based on GCM and RCM ensemble (Donat et al. , 2011a; 2011b).**
Resolution: 25 x 25 km.
Time period: up to 2100.
Unit: m/s.
Geographical coverage, limitations: Data show projections based on climate models (GCMs and RCM).
Data format: to be clarified after request of data.
URL: https://www.eea.europa.eu/data-and-maps/indicators/storms-2/assessment
Status: needs to be requested official from EEA.

Alternative Data source 2: **NatCat Service, Munich Re.**
Name of indicator/variable: **Approximate probability of having winter storms and for tropical storms probable maximum intensity.**
Resolution: NUTS3.
Time period: 100 years.
Unit: SS: Saffir-Simpson hurricane scale with an exceedance probability of 10% in 10 years (equivalent to a "return period" of 100 years).
Geographical coverage, limitations: global, the affected areas in the reports or on NUTS 3 to NUTS 2 level.
Data format: .pdf (as reports), no spatial data available.
URL: https://www.munichre.com/en/reinsurance/business/nonlife/natcatservice/index.html
Status: only overview reports can be created, no spatial data can be accessed, no free access to spatial data.

Alternative Data source 3: **HANZE database of historical damaging floods in Europe, 1870-2016.**
Name of indicator/variable: **Coastal flood events. The dataset is a compilation of past damaging floods in Europe, which contains information on dates, locations and losses for 1564 events (1870–2016). The database includes three flood types: river floods, flash floods, coastal floods (Paprotny et al., 2018).**
Resolution: NUTS3.
Time period: 1870-2016.
Unit: Area flooded, Flood losses, number of flood events.
Geographical coverage, limitations: Lack of information.
Data format: Excel.
URL: https://data.4tu.nl/repository/uuid:5b75be6a-4dd4-472e-9424-f7ac4f7367f6
Status: available.

Alternative Data source 4: **ESPON Project 1.3.1 data.**
Name of indicator: **hazards class.**
*Resolution***:** NUTS3
Time period: 100 years.
Unit: hazard classes 1-5 according to ESPON 1.3.1 methodology.
Geographical coverage, limitations: old ESPON space (2003).
Data format: Excel.
URL: not applicable.
Status: available.

5.3 Floods

Data source: **Joint Research Centre: Flood Hazard Maps at European and Global Scale.**
Name of indicator/variable: **Map Data is based on streamflow data from European and Global Flood Awareness System (EFAS and GloFAS) and computed using two-dimensional hydrodynamic models (Alfieri et al. 2014, Dottori et al. 2016).**
Time period: 21-year continuous discharge time series between 1990 and 2010.
Unit: Water depth (m).
Resolution: - 100 x 100 m.
Geographical coverage, limitations: Uncertainty in the estimation of input data, limited data accessibility at trans-national level. Does not include Turkey and Iceland. Guyana, Martinique, Guadeloupe, and La Réunion are not covered.
Data format: Geotiff image.
URL: https://data.jrc.ec.europa.eu/collection/floods
Status: available.

Alternative Data source 1: **HANZE database of historical damaging floods in Europe, 1870-2016.**
Name of indicator/variable: **The dataset is a compilation of past damaging floods in Europe, which contains information on dates, locations and losses for 1564 events (1870–2016). (Paprotny et al., 2018).**
Resolution: NUTS3.
Time period: 1870-2016.
Unit: Area flooded, Flood losses.
Geographical coverage, limitations: Lack of information.
Data format: Excel.
URL: https://data.4tu.nl/repository/uuid:5b75be6a-4dd4-472e-9424-f7ac4f7367f6
Status: available.

Alternative *Data source* 2: **Pan-European data sets of river flood probability of occurrence under present and future climate (Paprotny et al., 2017).**
Name of indicator/variable: **River floods occurring in Europe under present and future climate. Includes gridded (GeoTIFF) datasets of river flood extents (in two variants, with or without flood protection) and water depths.**
Time period: -.
Unit: water depth.
Geographical coverage, limitations: Predictions.
Data format: GeoTIFF.
URL: https://data.4tu.nl/repository/uuid:968098ce-afe1-4b21-a509-dedaf9bf4bd5
Status: available.

Alternative Data source 3: **Global Active Archive of Large Flood Events.**
Name of indicator/variable: **River floods occurring in Europe. Includes gridded (GeoTIFF) datasets of river flood extents and water depths. (Kundzewicz et al., 2013).**
Time period: 1985 – present.
Unit: eg. Country, other country, dead, displaced, main cause, severity.
Resolution: -
Geographical coverage, limitations: Uncertainty if the input data.
Data format: Excel, GIS Files.
URL: https://www.dartmouth.edu/~floods/Archives/
Status: available.

Additional Data:

- **MunichRe**: Flood losses report: https://natcatservice.munichre.com/
- **Copernicus emergency management**: Rapid mapping. https://emergency.copernicus.eu/mapping/#zoom=2&lat=27.06375&lon=37.2948&layers=0BT00
- **EFAS, European flood awareness system**: Historical simulations of river discharge and precipitation. https://www.efas.eu/data-download

- **The EU Floods Directive**. https://ec.europa.eu/environment/water/flood_risk/links.htm "Directive 2007/60/EC on the assessment and management of flood risks entered into force on 26 November 2007. This Directive now requires Member States to assess if all water courses and coast lines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk. With this Directive also reinforces the rights of the public to access this information and to have a say in the planning process."

  Limitations: The flood hazard data and information is not presented consistently between countries. Data would have to be collected from each national source individually and compiled into one consistant database.

5.4 Droughts

Data source: **European Drought Observatory (EDO).**
Name of indicator/variable: **Standardized Precipitation index (SPI).**
Resolution: Raster Data (0.25 degree) or point data.
Time period: 1981-2019.
Unit: Range from -2 (dryer than baseline) to +2 (wetter than baseline); available for 1-month, 3-, 6-, 9-, 12-, 24-, 48-month periods.
Geographical coverage, limitations: EU-28 plus 4 associated countries, as well as The former Yugoslav Republic of Macedonia, Turkey, Montenegro, Serbia, Albania, Bosnia and Herzegovina, Kosovo under UN Security Council Resolution 1244/1999.
Guyana, Martinique, Guadeloupe, and La Réunion are not covered.
Data format: WMS (Web Map Service), geotiff on request.
URL: https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1111
Status: EDO provided data in geotiff format.

Alternative Data source 1: **ESPON 2013 data base**
Name of indicator/variable: **Drought frequency (based on Standardized Precipitation evapotranspiration index SPEI) (ESPON 2013 Programme, 2013; Vicente-Serrano et al., 2010).**
Resolution: NUTS3.
Time period: 1991-2010 or 1951-2010 (unclear information; 1951-2010 could be the period for the baseline).
Unit: Very low (drought frequency: <12.1 %); Low (drought frequency: 12.1 -14.0 %); Moderate (drought frequency: 14.1-16.0 %); High (drought frequency: 16.1-18.0 %); Very high (>18.1%).
Geographical coverage, limitations: EU-27 plus 4 associated countries.
The former Yugoslav Republic of Macedonia, Turkey, Montenegro, Serbia, Albania, Bosnia and Herzegovina, Kosovo under UN Security Council Resolution 1244/1999, Guyana, Martinique, Guadeloupe, and La Réunion are not covered.
Data format: Excel.
URL: https://apps.espon.eu/db2/
Status: available, but unclear how the SPEI indicator was translated into drought frequency on NUTS3 level.

Alternative *Data source* 2: **Global Drought Observatory (GDO).**
Name of indicator/variable: **Drought events (Spinoni et al., 2019).**
Resolution: country or macro region.
Time period: 1951-2016.
Unit: Score from 0 to 25 (based on a large number of indicators): 0-7 moderate drought event; 8-11 severe drought event; 12-25 exceptional drought event.
Geographical coverage, limitations: global, but with limited resolution (only country level).
Data format: currently only WMS (Web Map Service).
URL: https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2020
Status: currently only available via WMS. Contact to EDO/GDO representatives is existing.

5.5 Landslides

Data source: **JRC European Soil Data Centre (ESDAC).**
Name of indicator/variable: **JRC European Landslide Susceptibility Map version 2 (ELSUS v2).**
Resolution: 200 x 200 m.
Time period: -.
Unit: Landslide susceptibility (0=no data; 1=very low; 2=low; 3=moderate; 4=high; 5=very high).
Geographical coverage, limitations: All European Union member states except Malta, in addition to Albania, Andorra, Bosnia and Herzegovina, Croatia, FYR Macedonia, Iceland, Kosovo, Liechtenstein, Montenegro, Norway, San Marino, Serbia, and Switzerland.
Data format: geotiff.
URL: https://esdac.jrc.ec.europa.eu/content/european-landslide-susceptibility-map-elsus-v2
Status: requested and received

6 Conclusions

The mapping of the hazards benefited from the improved data availability compared to earlier ESPON projects (Greiving et al. 2011, ESPON 2013 Programme, 2013). All of the individual hazard maps could rely on single data sources, which greatly improved the consistency compared to previous maps compiled from different data sources. In most cases, the geographical coverage included the EU Member States, Liechtenstein, Norway, Switzerland, Iceland and United Kingdom of Great Britain and Northern Ireland, as well as the Balkan area and Turkey. However, some of the islands (Acores, Madeira) are not covered and there is a notorious lack of data for the French oversea areas.

In addition to the lacks in geographical coverage, there are further limitations. As far as possible, the data for climatic hazards refer to the reference period 1981-2010. This was possible for storms and drought, but the data for river flooding are based on shorter time series within the reference period. Landslides and seismic hazard are presented without a reference period, but these hazards are also less dependent or independent of climatic factors. In addition, we prepared maps for storms and droughts for the period 1995-2017 in line with the economic impact assessment in ESPON-TITAN.

All hazard indicators are based on empirical climatic data and/or observed hazard events, but they also include the modelling and reanalysis of data.

The assessment of cascading effects and interrelations between different types of natural hazards based on single indicators has proven to be challenging. A proper assessment would require to disentangle the indicators and to look at the root causes of the hazards (e.g., heavy precipitation for floods and landslides).

The selected hazards provide a good coverage of relevant hazards at European scale. Riverine floods, winterstorms, droughts, and earthquakes account for 75,14% of the cumulative total damage costs in Europe. Landslides add 0,14 percent points. Other natural hazard not covered by ESPON-TITAN (e.g., different types of floods, avalanches, heat waves or wild fires) caused 24,72% of the cumulative total damage costs.

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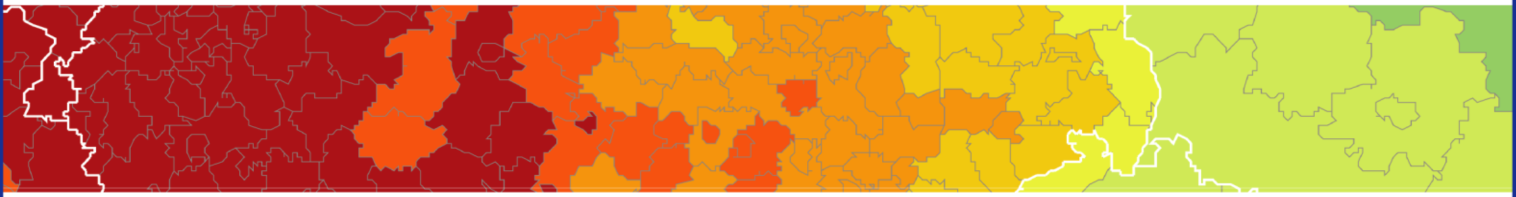

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