Supplement of Nat. Hazards Earth Syst. Sci., 24, 3703–3721, 2024
https://doi.org/10.5194/nhess-24-3703-2024-supplement

Natural Hazards and Earth System Sciences
Open Access

Supplement of

The effect of wildfires on flood risk: a multi-hazard flood risk approach for the Ebro River basin, Spain

Samuel Jonson Sutanto et al.

Correspondence to: Samuel Jonson Sutanto (samuel.sutanto@wur.nl)

Supplementary Data

Data sources and details are provided in Table S1 and Table S2. Table S1 provides data sources and information about the indicators for the baseline scenario with indicators that change in the future written in bold. Table S2 provides information about the indicators' sources and assumptions for the future scenarios.

Table S1. Data sources and specification for the indicators for the baseline period. Cells in bold are assumed to change for the future scenarios

Indicator	Data type and year	Data details	Data source
Hazard Component			
1. **Runoff coefficient**	**Runoff:** NetCDF-4 (1971-2000) **Rainfall:** NetCDF-4 (1971-2000)	**Runoff:** Mean runoff 30 year average – 5km x 5km - VIC-WUR - RCA4 (SMHI, Sweden) - HadGEM2-ES (UK Met Office, UK) – Version r1i1p1 **Rainfall:** Mean rainfall 30 year average – 0.11 degrees - VIC-WUR - RCA4 (SMHI, Sweden) - HadGEM2-ES (UK Met Office, UK) – Version r1i1p1	**Runoff:** https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-hydrology-variables-derived-projections?tab=form **Rainfall:** https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-hydrology-meteorology-derived-projections?tab=form
2. **Burnt Area**	Esri Shapefile (2012-2020)	Burnt areas from wildfires with size and time of occurrence. Selection for Spain and for years 2012 until 2020	https://effis.jrc.ec.europa.eu/applications/data-and-services
Exposure Component			
1. **Population density**	GeoTIFF Raster (2020)	Population density in approximately 1km x 1km Version 4.11	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals-rev11/data-download
2. **GDP in millions**	Excel-file (2019)	GDP in millions per region in the Ebro River basin (See 'EbroGDPTotal' Excel-file)	https://datosmacro.expansion.com/pib/espana-comunidades-autonomas?anio=2019
3. Distance from highways	Esri Shapefile from Living Atlas (2022)	Polylines of roads of Spain	https://www.arcgis.com/home/item.html?id=ff34eeee825c4b76a32bfb0cb6a15b41
4. Distance from river	Geopackage with Shapefiles (2019)	Polylines of river network of the Ebro	https://land.copernicus.eu/imagery-in-

		River basin	situ/eu-hydro/eu-hydro-river-network-database?tab=download
Vulnerability Component			
1. Elevation	GeoTIFF Raster (2019)	25m x 25m DEM Version 1.1. – E30N10 & E30N20	https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1
2. Slope	GeoTIFF Raster (2019)	25m x 25m DEM Version 1.1. – E30N10 & E30N20	https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1
3. **Land use/land cover**	GeoTIFF Raster (2015)	1km x 1km Global 7 land types map	https://zenodo.org/record/4584775#.ZBL14nbMK3D
4. Soil texture	GeoTIFF Raster (2021)	250m x 250m Version 0.2 Adapted USDA classification soil texture classes at 10cm soil depth	https://www.openlandmap.org/#/?base=Stamen%20(OpenStreetMap)&center=42.3218,-2.4616&zoom=7.075025308026625&opacity=40&layer=sol_texture.class_usda.tt_m&depth=10
5. Saturated hydraulic conductivity	GeoTIFF Raster (2017)	1km x 1km Saturated hydraulic conductivity at 15cm soil depth (KS-sl3.tif)	https://esdac.jrc.ec.europa.eu/content/3d-soil-hydraulic-database-europe-1-km-and-250-m-resolution#tabs-0-description=0
6. GDP per capita	Excel-file (2019)	Household income, measured in GDP per capita per region in the Ebro River Basin ('EbroGDPperCapita' Excel-file)	https://datosmacro.expansion.com/pib/espana-comunidades-autonomas?anio=2019
7. Distance from fire station points	Major fire stations locations (2023) in Excel file	Geographic coordinates from Google Maps for 25 major fire stations (See 'a02EbroMajorStationPoints' Excel-file)	https://www.google.com/maps/

Table S2. Data sources and specification for the indicators for the future SSP-RCP scenarios

Indicator	Data type and year	Data details	Data source
Hazard Component			
Runoff coefficient	**Runoff:** NetCDF-4 for RCP2.6 & RCP8.5 (2050, 2100) **Rainfall:** NetCDF-4 for RCP2.6 & RCP8.5 (2050, 2100)	**Runoff:** Mean runoff 30 year average 2041-2070, 2071-2100 – 5km x 5km - VIC-WUR - RCA4 (SMHI, Sweden) - HadGEM2-ES (UK Met Office, UK) – Version r1i1p1 **Rainfall:** Mean rainfall 30 year average 2041-2070, 207-2100 – 0.11 degrees - VIC-WUR - RCA4 (SMHI, Sweden) - HadGEM2-ES (UK Met Office, UK) – Version r1i1p1	**Runoff:** https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-hydrology-variables-derived-projections?tab=form **Rainfall:** https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-hydrology-meteorology-derived-projections?tab=form
FWI	NetCDF-4 for RCP2.6 & RCP8.5 (2050, 2100)	Seasonal FWI (June, July, August & September) for 2050 and 2100 – multi-model mean case - v2.0	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-tourism-fire-danger-indicators?tab=form
Exposure Component			
Population density	GeoTIFF Raster SSP1-RCP2.6 & SSP5-RCP8.5 (2050, 2100) & Excel file	Population density in approximately 1km x 1km Version 4.11 adapted to future assumptions **Future assumptions:** OECD country Population variable from IIASA SSP Public database Version 2.0 (See 'EbroPopulationDensityFuture' for more details	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-adjusted-to-2015-unwpp-country-totals-rev11/data-download **Assumptions for future growth:** https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=40
GDP in millions	Excel-file (2019) + Excel-file for SSP1-RCP2.6 & SSP5-RCP8.5 (2050, 2100)	GDP in millions per region in the Ebro River basin adapted to future assumptions **Future assumptions:** OECD country GDP|PPP variable from IIASA SSP Public database Version 2.0 (See 'EbroGDPTotalFuture' for more details	https://datosmacro.expansion.com/pib/espana-comunidades-autonomas?anio=2019 **Assumptions for future growth:** https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=40
Vulnerability Component			

Land use/land cover	GeoTIFF Raster for SSP1-RCP2.6 & SSP5-RCP8.5 (2050, 2100)	1km x 1km Global 7 land types map for the future	https://zenodo.org/record/4584775#.ZCGFUnZBy3D
Distance from fire station points	Major fire stations locations SSP1 & SSP5 (2050, 2100)	Geographic coordinates from Google Maps in Excel file adapted to future assumptions **Future assumptions:** Based on article from Ebi (2014). SSP1: 2050 :+8 stations 2100: +2 stations SSP5: 2050: +3 stations 2100: +4 stations (See 'EbroMajorFireStations(scenario,year)' for more details)	https://www.google.com/maps/ **Assumptions for future growth:** https://doi.org/10.3390/ijerph110100030

Supplementary Method

Analytical Hierarchy Process

After the indicators have been reclassified according to the risk classes (Section 2.4.2-2.4.4), the weights for each indicators need to be defined based on the importance of indicators on floods. Expert interviews in the field of natural disasters were held to give their judgements on the importance of different indicators contributing to flood risk and explain their choices. All experts have a background in wildfire risk, flood risk or in multi-risk in terms of natural hazards. A template in the form of an Excel-file from Goepel (2013) is used to execute the AHP. According to Roy et al. (2021) the AHP can be structured into 4 main steps:

1. Filling in the pairwise comparison matrix for both indicators as well as components
2. Normalization of the weights
3. Calculating the Consistency Index (CI) to check whether answers of experts are consistent
4. Calculate the Consistency Ratio (CR) by checking the CI with the Random Index (RI)

Step 1

During the interviews, the experts are asked to pairwise compare the indicators and components in the form of a matrix, as shown in Equation S1 and rank them on a scale of 1-9 in which a score of 1 means that the indicators/components are equally important and 9 that one has extreme importance over the other. The reciprocal values are taken for the inverse comparison. This scoring is based on the Saaty (1988) scale, as presented in Table S3.

Table S3. Scale of importance for pairwise comparisons (Saaty, 1988)

Value	Scale of importance
1	Two indicators/components have equal importance to each other
3	Moderate importance of one indicator/component over the other
5	Strong importance of one indicator/component over the other
7	Very strong importance of one indicator/component over the other
9	Extreme importance of one indicator/component over the other
2, 4, 6, 8	Intermediate values between adjacent value
Reciprocals (1/2, 1/3, ... 1/9)	The inverse comparison between the concerning indicators/components

In total there are four matrices the experts need to fill in: one for the hazard indicators, one for the exposure indicators, one for the vulnerability indicators, and one for the components itself. The pairwise comparison matrix A for an N x N matrix is shown in Equation S1 and is adapted from Roy et al. (2021) and Gupta and Dixit (2022). The criterion for A is that $A = aij$ in which a is the indicator or component in the ith row and in the jth column.

$$A = \begin{pmatrix} 1 & a12 & \dots & a1j \\ a21 & 1 & \dots & a2j \\ \dots & \dots & \dots & \dots \\ ai1 & a23 & \dots & aij \end{pmatrix} \qquad S1)$$

A is the pairwise comparison matrix receiving the Saaty's values for indicators in each component (Hazard, Exposure, Vulnerability, or Components itself) and where aij is the indicator or component value in the ith row and compared to indicator or component in the the jth column.

Step 2

When the experts have given their judgements, the scores have to be aggregated, averaged, and normalized by using the weighted geometric mean, which are adapted from Goepel (2018) and Roy et al. (2021). Since there are multiple experts, the normalized weights need to be aggregated and averaged to get the final weights given by the experts (Xij) as shown in Equation S2.

$$X_{ij} = e^{\frac{\sum_{k=1}^{N} w_{(k)} ln_{aij(k)}}{\sum_{k=1}^{N} w_{(k)}}} \qquad S2)$$

Where X is the final weights based on the consolidation of weights from all experts for the indicators or components in the ith row and the jth column, w is the weight given by each expert (k), a is value of the indicator or component for the expert k in the ith row and the jth column and N is the number of indicators or components.

Step 3

In order to calculate the Consistency Index, the principal eigenvalue needs to be generated (λmax, Eq. S3), which are the maximum priorities, or the summed normalized weights for each row divided by the number of indicators or components, which is adapted from Aydin and Birincioğlu (2022). Once the principal eigenvalue is calculated, the CI (Eq. S4) can be calculated according to Roy et al. (2021).

$$\lambda \max = \frac{1}{n} \sum_{i=1}^{n} \frac{Nw_{(i)}}{w_{(i)}} \qquad S3)$$

$$CI = \frac{\lambda max - n}{n-1} \qquad S4)$$

where λmax is the principal eigenvalue, Nw the normalized weight for the indicator or component in the ith row, w the weight for the indicator or component in the ith row, n is the number of indicators or components, CI is the consistency index.

Step 4

To make sure the experts' judgements are consistent and to correct for biases of the experts, a consistency check is necessary. To check consistency, a comparison between CI and RI has to be performed, which then generates CR ($CR=CI/RI$). The RI gives different values depending on the number of criteria that is selected for the indicators or component (Kazakis et al., 2015). The *RI* values presented in Table S4 are: 0 due to 2 parameters present in the Flood Hazard Index (FHI), 0.58 due to 3 components present in the flood risk equation, 0.9 due to 4 parameters present in the Flood Exposure Index (FEI), and 1.32 due to 7 parameters present in the Flood Vulnerability Index (FVI). The *CR* should be lower than 0.10 to be able to make sure the respondents weighting is consistent and validated (Roy et al., 2021).

Table S4. Random Index (RI) table to calculate the CR for the number of criteria (adapted from Saaty, 1988). Bold numbers are the RI values for different components and flood indices.

Number of criteria	1	2	3	4	5	6	7	8	9
RI value	0	**0 FHI**	**0.58 C**	**0.90 FEI**	1.12	1.24	**1.32 FVI**	1.41	1.45

Supplementary Figures

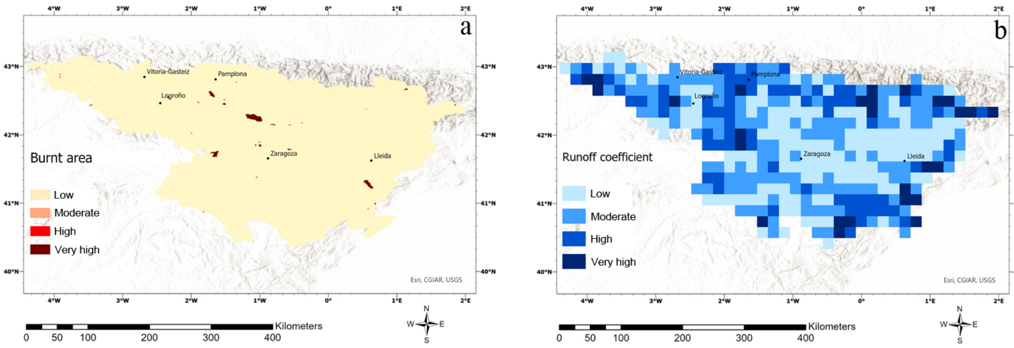

Figure S1. Spatial distribution of the classification for the hazard indicators for the baseline scenario with a) the burnt area and b) the runoff coefficient.

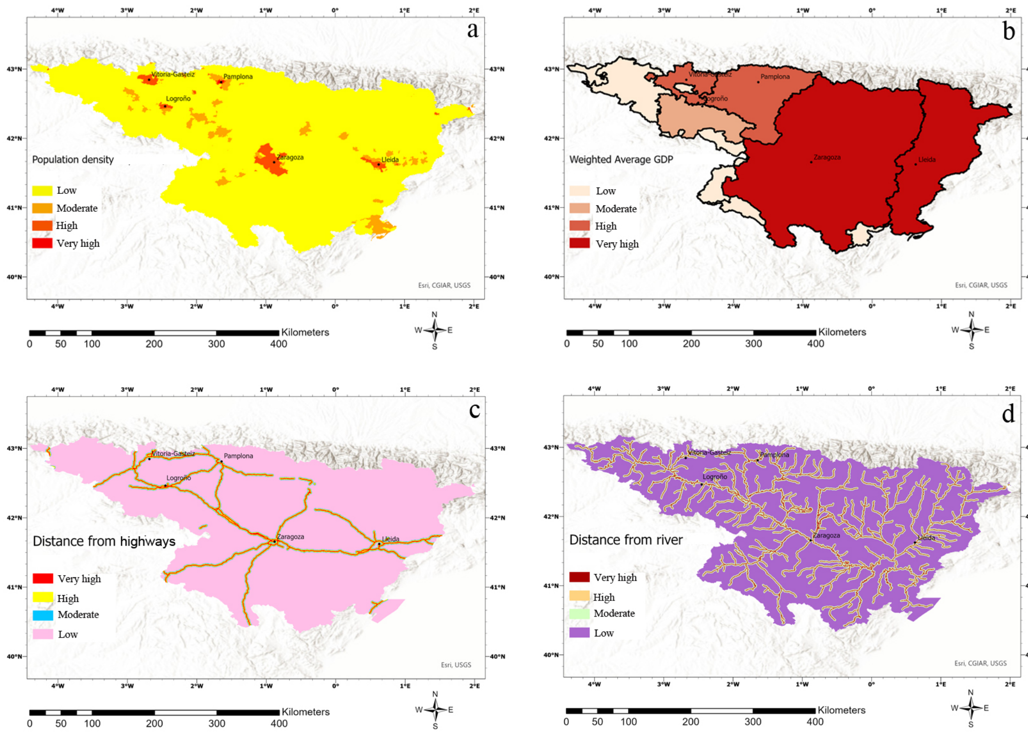

Figure S2. Spatial distribution of the classification for the exposure indicators for the baseline scenario with a) the population density, b) the total weighted average GDP, c) the distance from highways, and d) the distance from river.

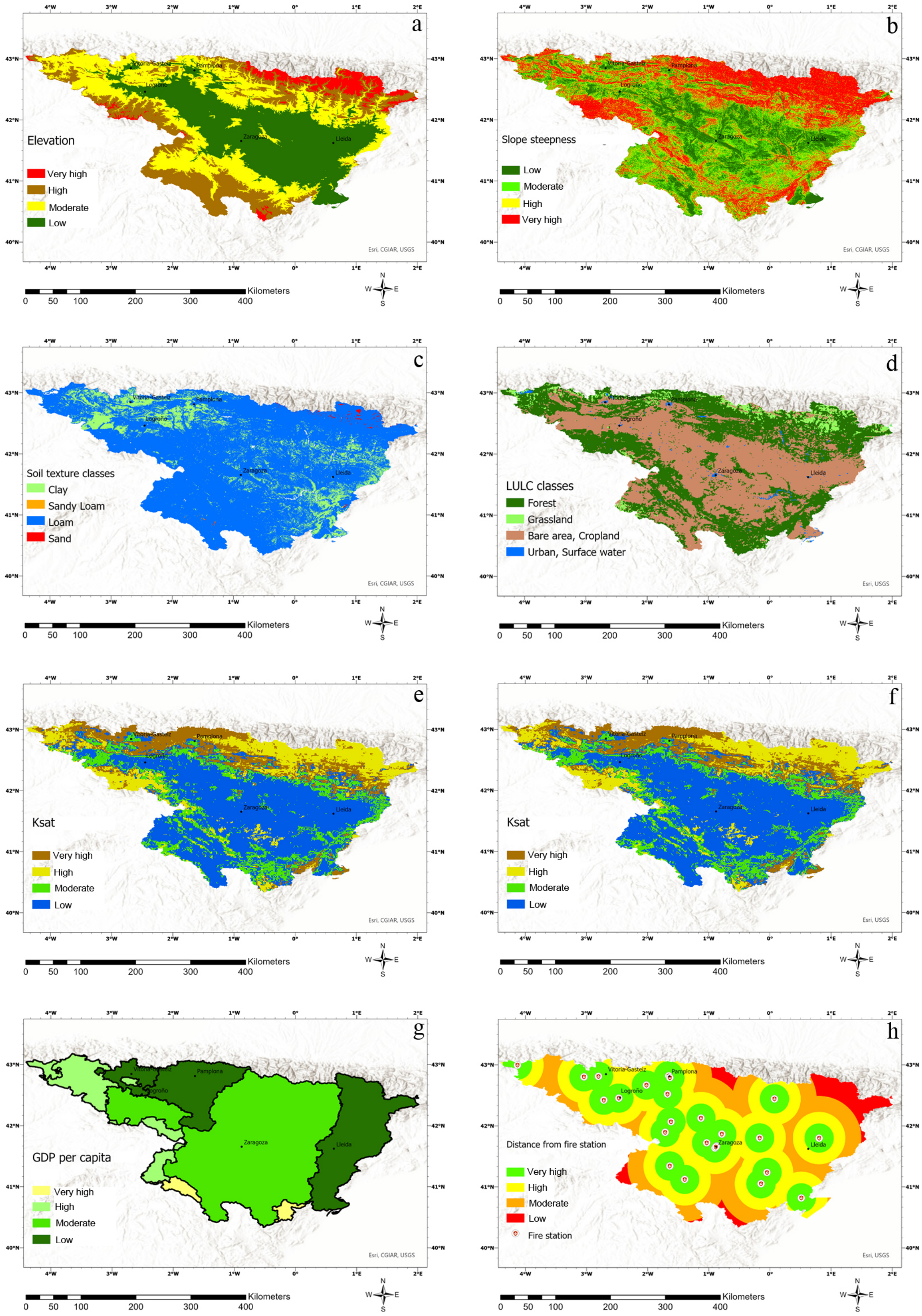

Figure S3. Spatial distribution of the classification for the vulnerability indicators for the baseline scenario with a) the elevation, b) the slope steepness, c) the soil texture, d) the land cover/land use, e) the saturated hydraulic conductivity with wildfire effects, f) the saturated hydraulic conductivity without wildfire effects, g) the GDP per capita, and h) the distance from fire stations.

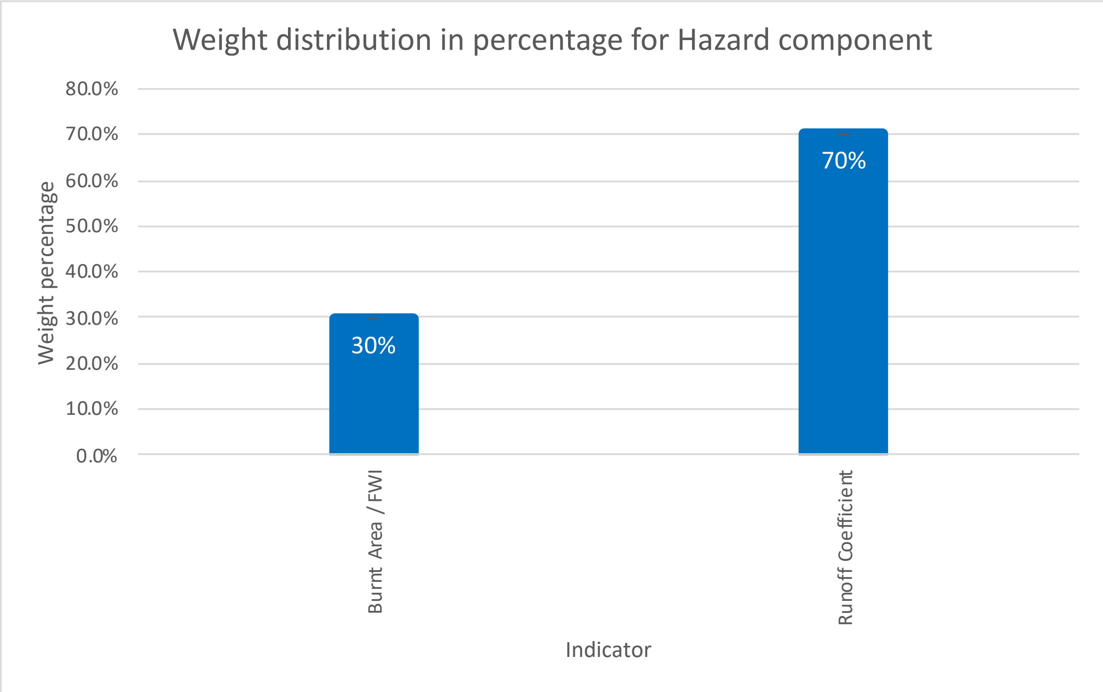

Figure S4. The weight percentage of hazard prioritization based on the experts' perception.

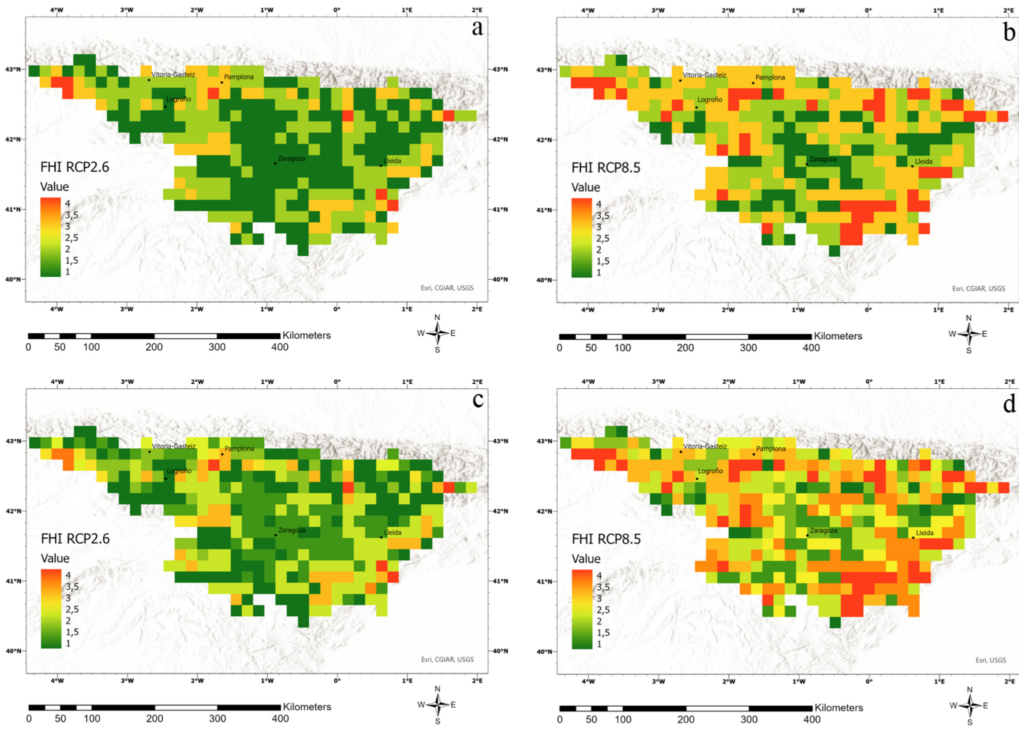

Figure S5. Spatial distribution of the FHI without wildfire effects for a) SSP1-2.6 year 2100 and b) for SSP5-8.5 year 2100, and with wildfire effects for c) SSP1-2.6 year 2100 and d) SSP5-8.5 year 2100.

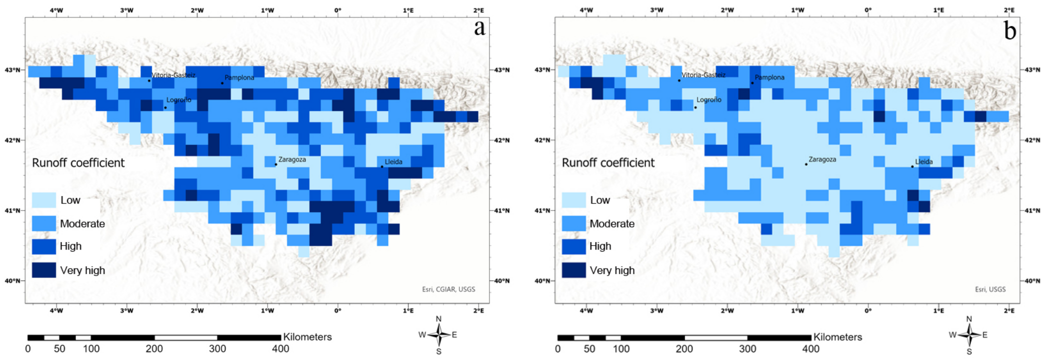

Figure S6. Spatial distribution of the runoff coefficient classification for a) SSP1-2.6 year 2100 and b) for SSP5-8.5 year 2100.

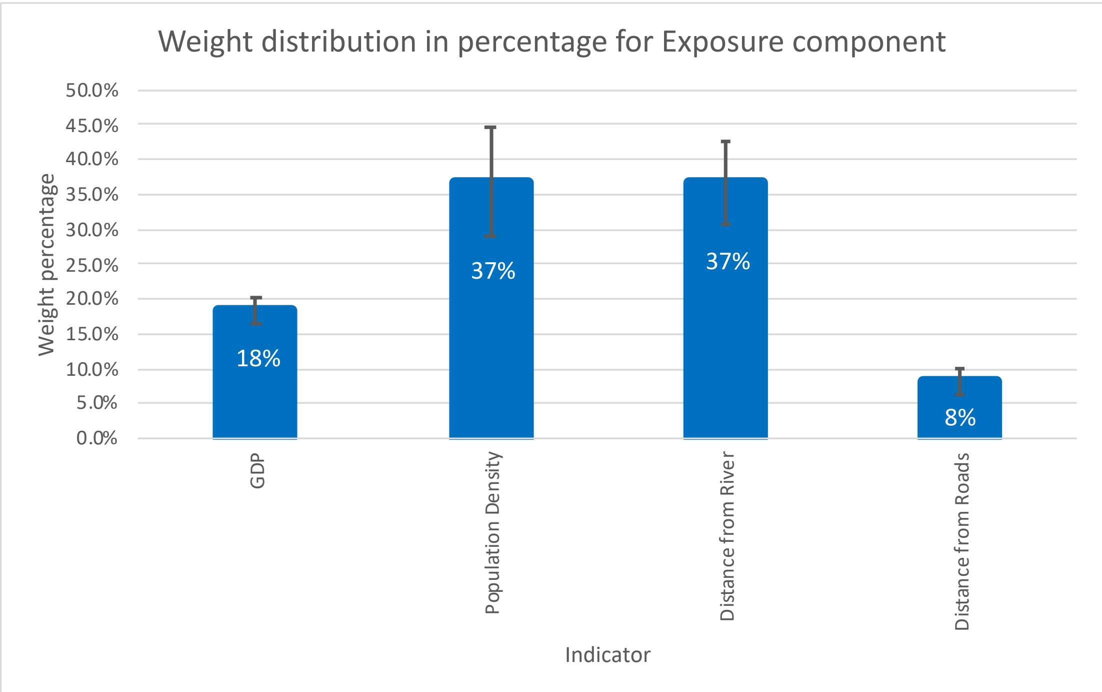

Figure S7. The weight percentage of exposure prioritization based on the experts' perception. The error bar indicates the standard deviation of each indicator based on the experts' opinions.

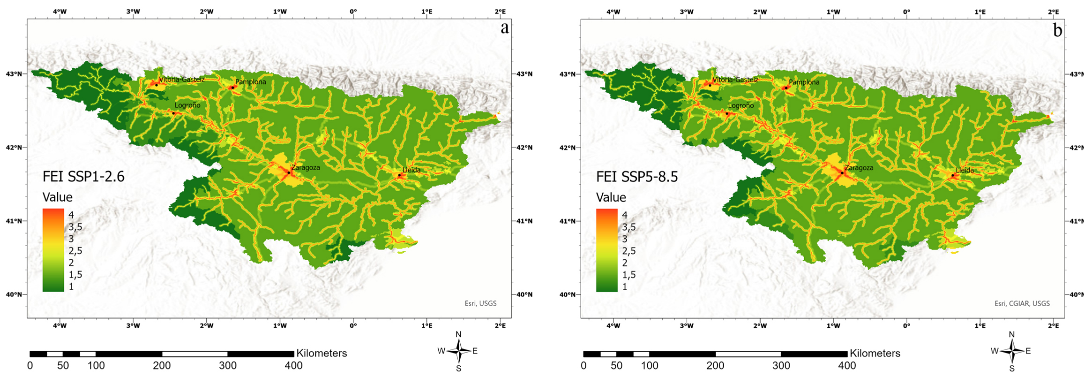

Figure S8. Spatial distribution of the FEI for year 2100 based on a) SSP1-2.6 and b) SSP5-8.5.

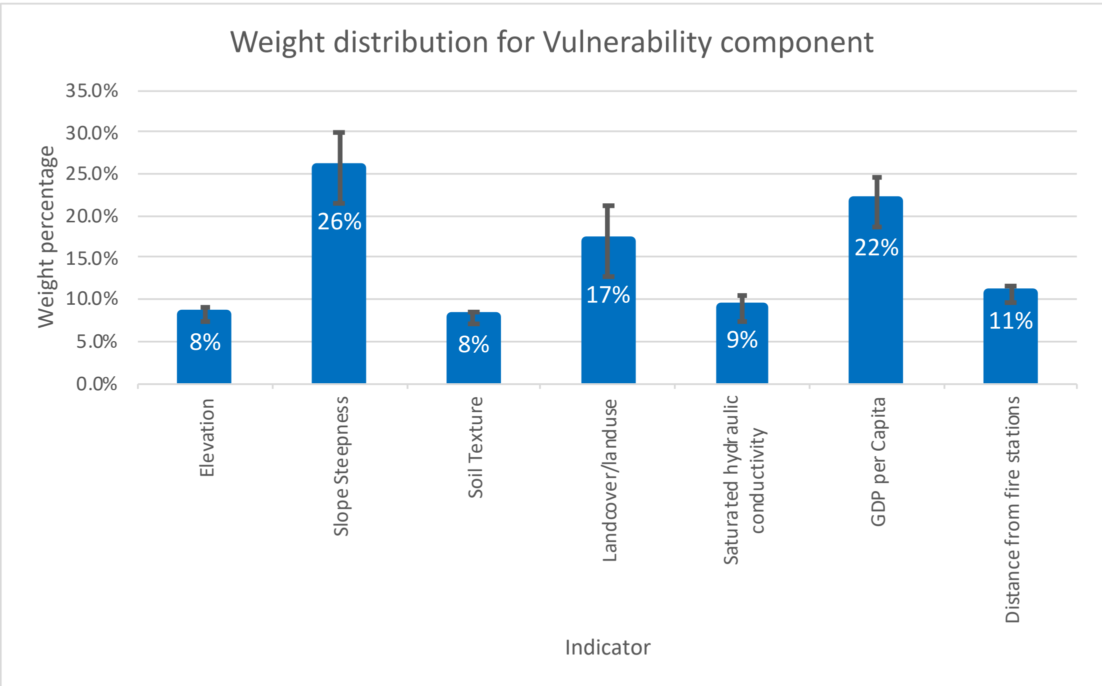

Figure S9. The weight percentage of vulnerability prioritization based on the experts' perception. The error bar indicates the standard deviation of each indicator based on the experts' opinions.

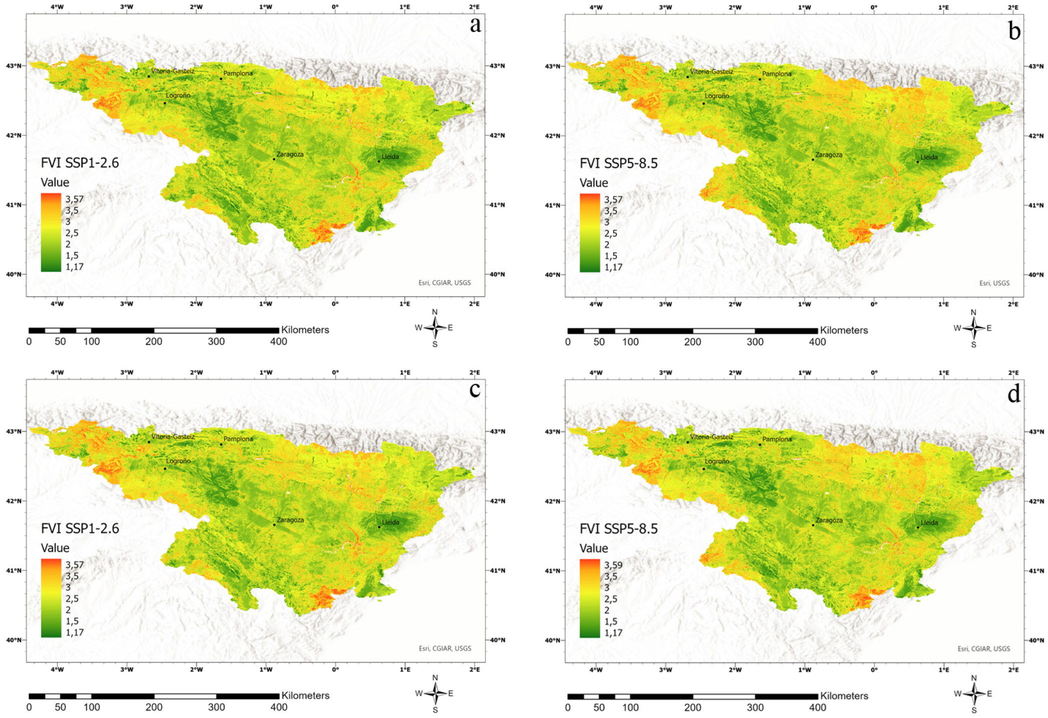

Figure S10. Spatial distribution of the FVI without wildfire effects for a) SSP1-2.6 year 2100 and b) for SSP5-8.5 year 2100, and with wildfire effects for c) SSP1-2.6 year 2100 and d) SSP5-8.5 year 2100.

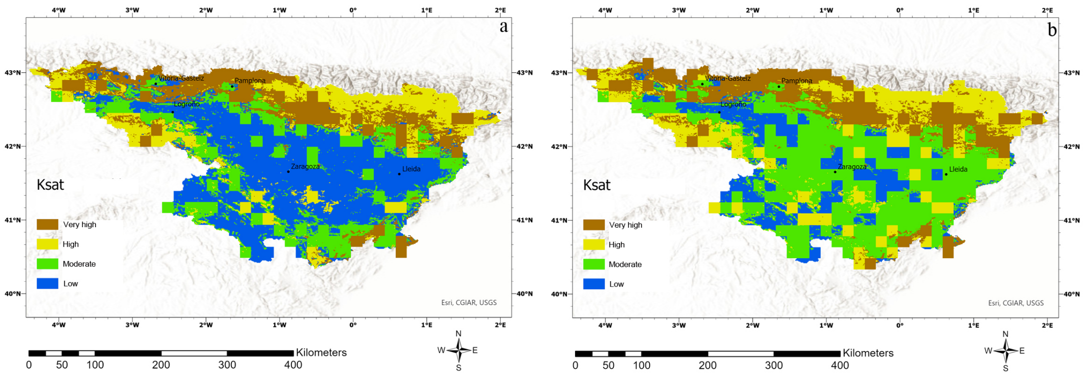

Figure S11. Spatial distribution of saturated hydraulic conductivity with wildfire effects for a) SSP1-2.6 year 2100 and b) for SSP5-8.5 year 2100.

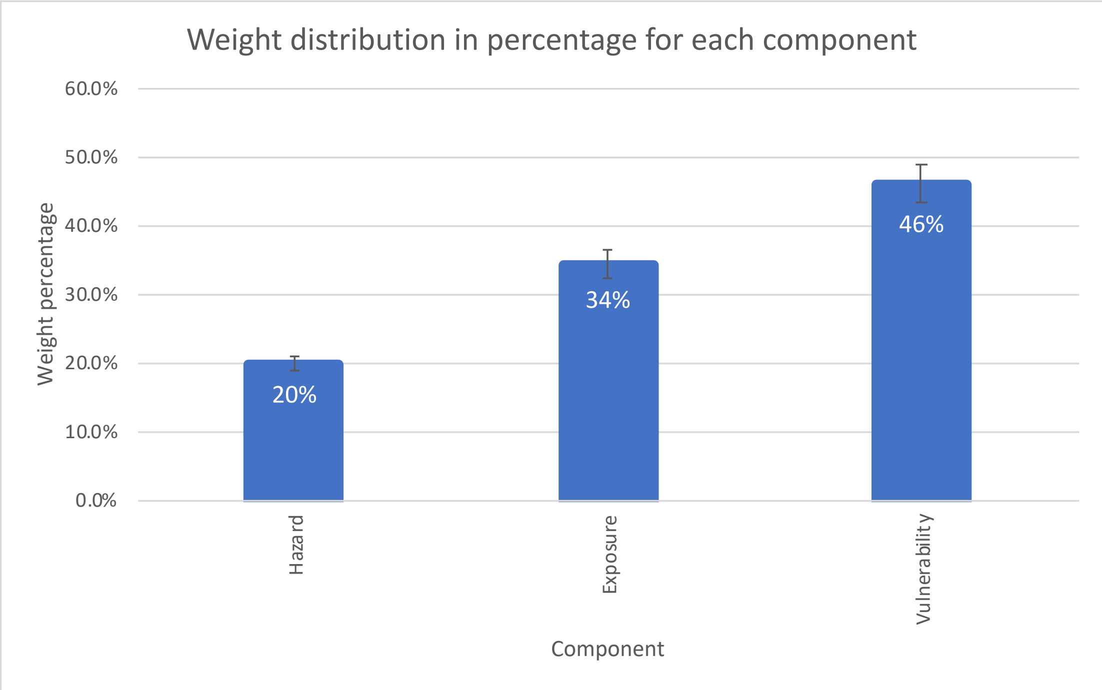

Figure S12. The weight percentage of risk components prioritization based on the experts' perception. The error bar indicates the standard deviation of each indicator based on the experts' opinions.

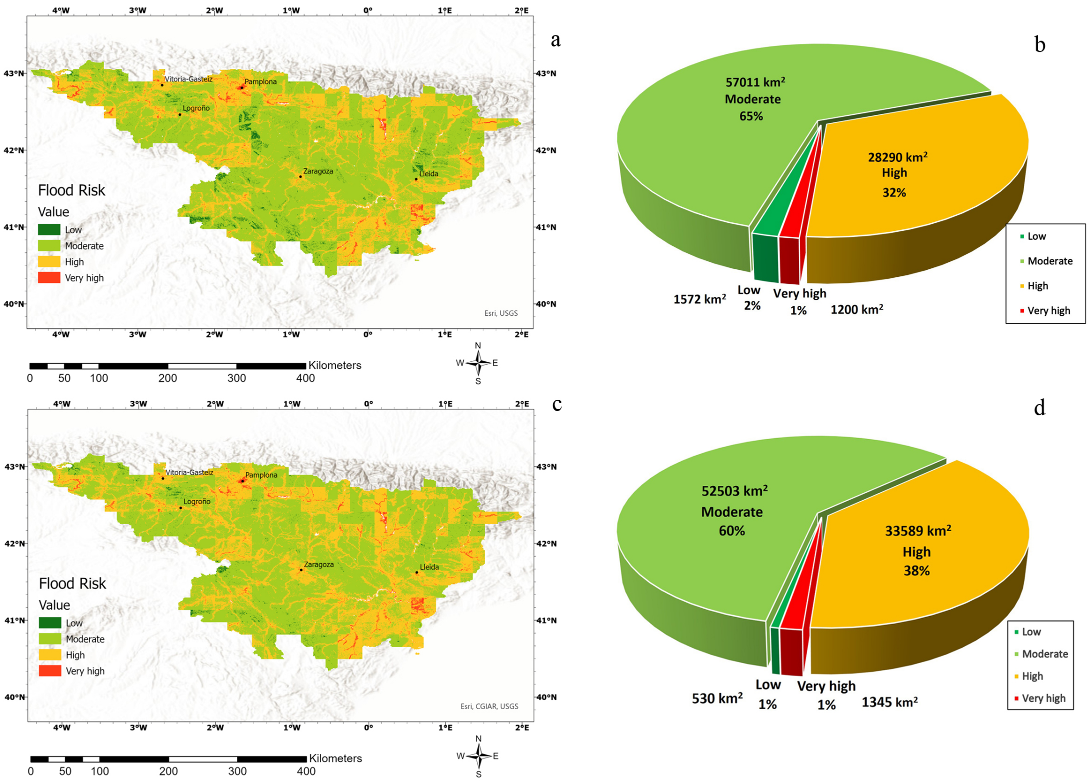

Figure S13. a) Flood risk map without wildfire effects in the Ebro River basin for SSP1-2.6 year 2100, b) distribution of flood risk classes without wildfire effect for SSP1-2.6 year 2100 corresponding to surface area in km², c) same as a but with wildfire effect, and d) same as b but with wildfire effect.

Supplementary Table

A summary of experts' statement obtained from the interview is presented in Table S5. Expert number 4 and 5 did not give their statements regarding their scoring for exposure and vulnerability.

Table S5. A summary of statements made by the experts during the AHP interview

Expert	Hazard	Exposure	Vulnerability	Risk component
1	Equally important because wildfires have a big effect on runoff and vice versa	GDP and population are equally important and correlated. Area with higher GDP usually has higher population and vice versa. Exposure is less when distance from river and road is far away. Distance from river is more important than distance from highway.	Slope steepness leads to more runoff and wildfire will spread quicker. Low elevation has higher vulnerability due to accumulation of water. GDP is also strongly important compared to elevation because more resources will be available to move out and recover. Distance from fire station is also important. Land cover is more important than soil texture due to fire fuel.	Hazard has strong and moderate importance compared to exposure and vulnerability, respectively. If there is no hazard, it does not matter if there is exposure or vulnerability. Vulnerability is less dependent on hazard and more socio economic conditions. You cannot manage hazard but you can manage exposure and vulnerability. Exposure and vulnerability are equally important
2	Burnt area can be a small part of the catchment and runoff is more important in the whole catchment	Population is more important because live is more important. GDP is moderate importance compared to distance from river and highway because GDP creates economic exposure	Higher runoff is generated by steep slope. Elevation is slightly more important than soil texture because flood tends to occur in low land. Landcover also influences the runoff. Saturated hydraulic is more important than elevation because it influences infiltration. High GDP makes high adaptation capacity. Distance from fire station is not important because fire does not always happen.	Exposure and vulnerability are more important than hazard because there is no risk if there is no exposure. Exposure related to people and economic is more important than vulnerability.

3	Burnt area is affected the catchment and increases runoff	Population is more important than GDP. Exposure from river is also important because it has higher risk if population lives close to river.	Slope stepness is highly important for flood and generates fast and higher runoff. Soil texture, landuse, and hydraulic conductivity are related and strongly important. GDP or income makes society more vulnerable or not. Fire station cannot do everything to avoid flood.	Human component is very important and therefore hazard is less important. Consequences are really important especially the degree of exposure to flooding.
4	Burned area is also related to a higher runoff coefficient. Hence, I put runoff as having a higher importance. Burned areas on the other hand increase erosion and can increase the sediment load during flash floods	-	The most important indicator is slope stepness and GDP. Vulnerability is driven by runoff coefficient (slope) and how vulnerable in term GDP the region is.	Vulnerability is the most important component than hazard and exposure. Exposure is more important than hazard.
5	Runoff is more important	People are more important than assets. Distance from river is important in term of exposure	-	Vulnerability has very strong importance and exposure has moderate importance than hazard. Exposure and vulnerability define how a system is impacted. Vulnerability says much more about the effects of the hazard.
6	Even we do not have fires, we can still have high runoff. Indeed, burnt area affects runoff coefficient	In Catalonia, economy has more impact compared to people. People know when the flood occurs. Population is more important than distance from river and highway. Distance from river is more important than distance from highway.	Elevation and slope are equally important. It depends on where the location is, such as delta or mountain. Elevation is more important than soil texture, landcover, hydraulic conductivity, and distance from fire station. Higher GDP will make the area able to protect themselves. Fire station has less influence for flooding.	All components are equally important.

7	Burnt area impact on flood risk depends on the intensity. How long will it take to recover is very important. Runoff on the burnt area is very important	Population has strong importance than GDP. The rule is people first and then infrastructure and nature. Distance from river has strong importance than distance from highway.	Elevation is more important than soil texture, landuse, hydraulic conductivity, GDP, and distance from fires, except for slope, which is equaly important. Elevation is important because many people live in flat area.	We cannot influence the hazard but we can modifiy exposure although most people are living in the flood prone areas. Vulnerability is more important than exposure and hazard.