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Social flood risk in Austria: assessing flood risk using detailed projections of socio-economic vulnerability

Max Tesselaar[1], Timothy Tiggeloven[1], Wouter J.W. Botzen[1]

[1] Institute for Environmental Studies, Vrije Universiteit Amsterdam

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M. Tesselaar[1], T. Tiggeloven[1], and W. J. W. Botzen[1]

[1]Institute for Environmental Studies, Vrije Universiteit Amsterdam

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1 Introduction

Established methods to estimate flood risk combine three aspects; flood hazard; exposure; and vulnerability. Flood hazard comprises the extent of inundation caused by river discharge that occurs with a certain probability, exposure encompasses the built environment that is inundated by such an event, and vulnerability captures the extent to which exposed assets are damaged by inundation. Flood risk assessments often focus on the biophysical processes that cause flooding, while applying generic assumptions regarding the exposure and vulnerability components (Jurgilevich et al., 2017). However, research shows that socioeconomic change (Winsemius et al., 2016), and local differences in and changing flood vulnerability (Pörtner, 2022) have a substantial impact on flood risk projections.

Vulnerability in flood risk assessments is most commonly applied in the form of depth-damage curves, which express a (usually non-linear) relationship between the inundation depth and the damage that it causes. Although such depth-damage curves are often verified based on empirical evidence, generalizations across spatial scales and building types limits their application from capturing local characteristics (Jongman et al., 2012a). For example, depth-damage functions presented in Moel et al., 2016 are applied in several high-impact flood risk studies (Ward et al., 2017; Winsemius et al., 2016), but establish a single flood depth-damage relationship for residential buildings per European country. This simplification is useful for large-scale flood risk assessments, but may fail to capture local differences in flood vulnerabilities. Firstly, in terms of physical damage, building materials and structure types impact vulnerability (Englhardt et al., 2019), which means there are spatial differences in physical flood vulnerability. Secondly, direct physical damages are only one aspect of flood impacts, which encompasses further direct and indirect effects, including the disruption or loss of livelihoods, (mental) health impacts, and economic effects (Jongman et al., 2012a). A more comprehensive approach to flood risk modeling, which includes a more comprehensive definition of vulnerability, requires an assessment of flood hazard with socioeconomic vulnerability indicators.

The danger of modeling flood risk using simplified damage functions is that it may advise inefficient and unjust adaptation investments. Resulting flood risk maps may instruct flood risk management to prioritize adaptation in areas where exposed assets are highest, which may not necessarily be areas where impacts, using the broader definition, are highest. Therefore, an alternative approach to conventional depth-damage curves may be required to supplement policymakers with information to make just flood risk management decisions, including where to prioritize flood protection investments, but also where and for which population groups soft measures, such as enhancing insurance coverage, stimulating risk-reduction measures, and increasing knowledge on disaster response, should be considered.

The need for more sophisticated flood vulnerability assessments has culminated into the idea of a social vulnerability index (Yoon, 2012). Such indexes identify variables that signify flood vulnerability, which can then be applied to observed population or neighborhood characteristics to estimate flood vulnerability. Considered variables often include socio-economic characteristics, such as income, education, age, and ethnicity (Cutter et al., 2003; Yoon, 2012), but may also consider neighborhood characteristics, such as the amount of parks in the area, or the distance to the nearest hospital (Leis & Kienberger, 2020). There are several studies that apply vulnerability indexes in spatial flood risk assessments (Forrest et al., 2020; Koks et al., 2015; Leis & Kienberger, 2020).

This study adds to existing literature on social vulnerability to flooding by developing a social vulnerability index and applying this with a detailed (1x1km) socioeconomic dataset for Austria to identify where the most flood vulnerable populations are located. The resulting vulnerability map is overlain with flood hazard maps of the same spatial scale to construct a "social flood risk" heatmap and identify "hotspots", which are defined as areas where the combined hazard, exposure, and social vulnerability is most acute. The most important scientific innovation of this method is the integration of climate change simulations to project future flood hazard conditions. Although Leis and Kienberger, 2020 also include climate change scenarios to project vulnerability hotspots, they apply extreme rainfall projections as a proxy for fluvial flood hazard. However, local precipitation and fluvial discharge are different geophysical processes, leading to different hazard conditions. Since there are several large river systems flowing through Austria, and there are dense population and industrial areas bordering their embankments, it is important to consider how future extreme river discharge may impact society, and in particular considering how certain populations may be more vulnerable to these floods than others.

2 Constructing the social flood risk indicator

The aim of task 3.1 is to identify flood vulnerability “hotspots”, which are areas where flood hazard and high vulnerability due to socio-economic constraints coincide, i.e. where suffering may be highest. This is in contrast to standard flood risk simulations which provide insight into the overall physical (monetary) damage. This requires an overlay of riverine flood risk/hazard maps with spatially detailed socio-economic data that reflects to a degree the level of vulnerability to flooding. This section will first describe the flood risk modeling procedure, followed by the socio-economic data and how it is used to construct the social vulnerability indicator, and ends with describing the spatial overlaying procedure.

2.1 The flood risk simulation

For the simulation of flood risk, the GLOFRIS cascade framework is used (Ward et al., 2017; Winsemius et al., 2016). This model combines flood hazard, exposure, and vulnerability to assess flood damages on a 30' x 30' (arcseconds) scale (approximately 1x1km). Since the novelty of this study is assessing social vulnerability to floods, the flood exposure maps and vulnerability estimation used in GLOFRIS are replaced by detailed socio-economic statistics for Austria and vulnerability indicators based on this data. However, to determine the extent to which our approach to estimate social vulnerability to floods differs from the established approach to estimate flood risk, we also compare the results from this study with the flood impact estimates from GLOFRIS. Therefore, this section also briefly describes how exposure and vulnerability are used in GLOFRIS.

Riverine flood hazard in this study equals the probability and extent of inundation, caused by river discharge exceeding flood protection standards. To assess flood hazard, GLOFRIS applies the hydrological model PCR-GLOBWB (Van Beek & Bierkens, 2008), which estimates river discharge based on several meteorological fields (including precipitation, temperature, and evaporation), using 40-year time-series. Based on this, GLOFRIS is able to estimate annual extreme values of water depths and inundations, which are associated with certain probabilities of occurrence. In this study, we compare inundation levels associated with several probabilities, which are, expressed as return-periods, inundations that occur once every 50, 100, and 250 years. These flood probabilities provide insight into a useful range of flood intensities, and are roughly similar to the range used by the Austrian flood authority to create flood risk management policy (30, 100, 300 year return-periods).

Importantly, GLOFRIS assesses flood risk for river systems with a Strahler stream order of 6 and larger. This means that smaller stream systems, for example that flow through the Tyrolean valleys, are excluded from the hydrological simulation and, therefore, also from our study. Streams below the Strahler order of 6 are, of course, also prone to flooding, but these floods are considered more ”flashy” or pluvial in nature (Winsemius et al., 2013). Flood simulations of such stream-systems require a different approach than the one used in this study.

Figure 1 shows the extent of flood inundation in meters associated with a 50-, a 100-, and a 250-year return period, from top to bottom panel respectively. It can be seen that areas around the Danube are most severely impacted by such floods, which is due to the large catchment size of this river. Although the Danube has a high runoff capacity, extreme events (such as peak water-levels that only occur once every 50-, 100-, or 250 years) can be more disastrous in such large river systems. The most severe flooding under both scenarios occurs around Linz, particularly where the river Traun enters the Danube, as well as west of Vienna, before the Danube enters the city. Besides the water-level caused by peak-discharge, also the terrain surrounding the main river-channel determines the extent of inundation. The potentially inundated areas are particularly large in certain areas bordering the Danube because much of this land is not much higher than the river itself. That is, the inclination of the embankment is much lower than in more mountainous regions. Besides the Danube and several of it's tributaries, some parts of the Drau-basin, in Karinthia, are also severely inundated by these two flood events.

Comparing the three flood scenarios, it can be seen that the 250-year flood shows more severe inundation. Although the area of inundation is not considerably different from the 50-, and 100-year flood scenarios, the areas that are expected to be inundated will be so more severely. For Austria overall, the 50-year flood will cause 4020 cells (km2) to be flooded, with a mean level of 0.76 meters. For the 100- and 250-year floods the flooded surface is respectively 4380 and 4650 square kilometers, and the average inundation depth is 0.9 and 1.1 meters. To limit the amount of information within the main text of this report, we will focus on the 250-year flood in the figures that follow.

The hydrological model PCR-GLOBWB is also used to simulate future flooding conditions, considering meteorological changes as a result of global warming. For this, the meteorological fields, used to establish the extent and probability of extreme river discharge, are projected for future scenarios. Whereas data used to estimate baseline (2010) flooding conditions are time-series ranging from 1960-1999, future flood hazard simulations are run using meteorological forecasts from Global Circulation Models (GCMs), which use Representative Concentration Pathways (RCPs) as input. Future flood hazard projections are based on 40-year long climatological runs to obtain an extreme value probability distributions around the years 2030, 2050, and 2080. This study applies the GCM HadGEM2-ES (Martin et al., 2011), which is applied in the IPCC's fifth assessment report (AR5) (Emori et al., 2016). To assess the sensitivity of results in this study to climate change impacts, we compare a "mild" climate change scenario (RCP4.5), representing a future where the 2°C limit set by the Paris Climate Agreement is met (Riahi et al., 2017; Tribett et al., 2017), with a more extreme scenario of greenhouse gas accumulation (RCP8.5).

Figure 2 shows the 250-year flood hazard projections for 2080 under RCP4.5 and RCP8.5. Overall, the amount of flooded spatial cells increases from 4650 in 2010 to 4950 under RCP4.5 and

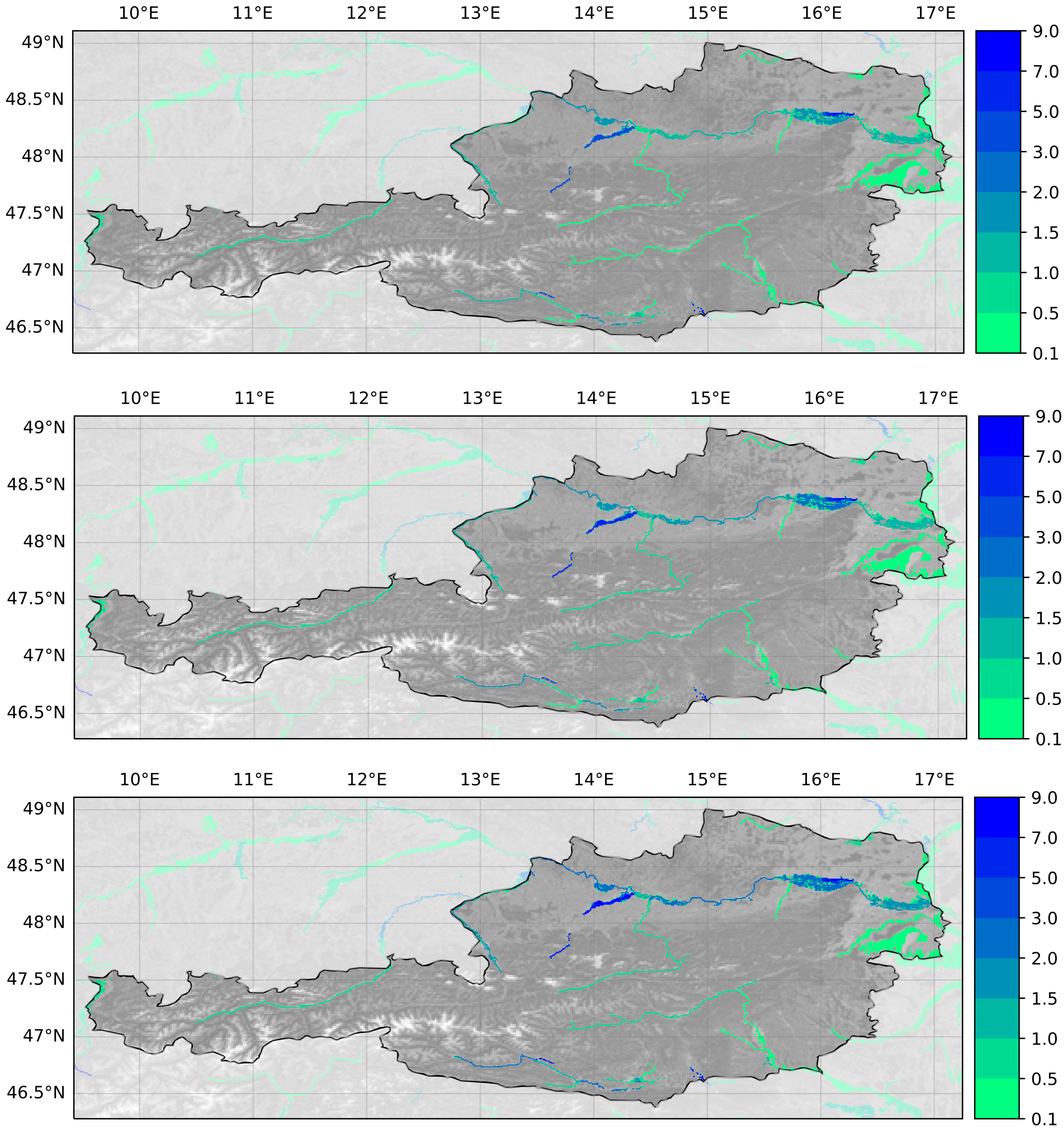


Figure 1: Inundation in meters for the baseline year (2010), for a flood with a 50-year return period (top), a 100-year return period (middle) and a 250-year return period (bottom).

to 5170 under RCP8.5. Although the flooded area increases for future projections, the severity of inundation decreases on average from 1.1 meters in 2010 to 0.88 meters under RCP4.5 and 0.91 meters under RCP8.5. One of the most striking differences between the 2010 and 2080 projections can be seen where the river Traun enters the Danube. Whereas this area showed some of the most severe inundation in the 2010 projections, flood hazard decreases considerably in this area due to climate change. The reason for this is that the discharge of the Traun river system is to a large degree water that originates from relatively low-lying glaciers in the eastern alps. By 2080, these glaciers are projected to be largely molten, causing the base-flow of the Traun river to be considerably lower. This finding was confirmed to be consistent amongst the remaining four GCMs in the CMIP5-project.

Flood inundation projections are overlain with exposure data to determine how much built environment is potentially damaged by a flood. In GLOFRIS exposure is assessed by estimating the share of each spatial cell that is built up. This assessment applies land use data from the HYDE database (Klein Goldewijk et al., 2011). The flood exposure is given an economic value by assigning a monetary estimate per square kilometer, which is based on Jongman et al., 2012b.

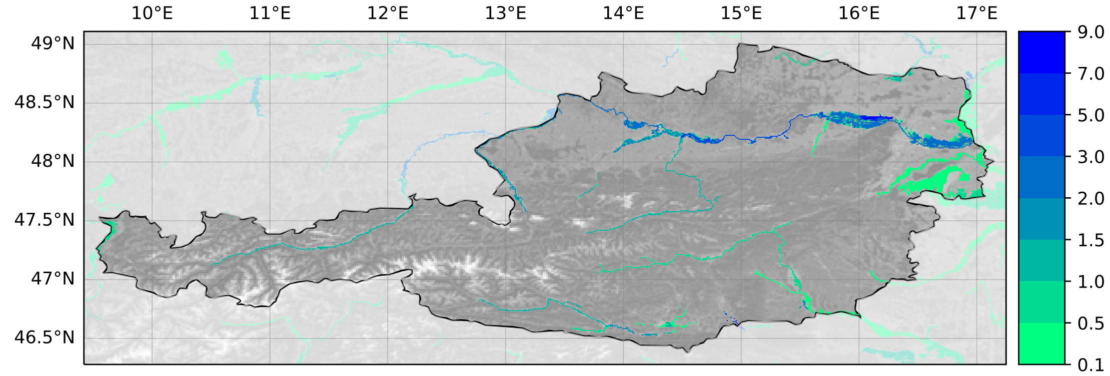
Flood damages are assessed in GLOFRIS using stage-damage curves, which are depth-damage functions that represent the relationship between inundation depth and exposed buildings. The depth-damage function is taken from Moel et al., 2016, and is applied for the whole of Austria.

The resulting damages, associated with a 250-year flood, can be seen in Figure 3. Unsurprisingly, major inundation in the Traun basin causes substantial damage of up to €100 million per square kilometer. An interesting observation is that Vienna, although not facing high levels of inundation, does face high damages with a flood of this magnitude. This is because of the high density and value of exposed assets in the Austrian capital. Another noteworthy observation is that the floodplain West of Vienna, while showing some of the most severe levels of inundation, does not show equally severe damages. This is because the density and value of exposure in this area is relatively low.

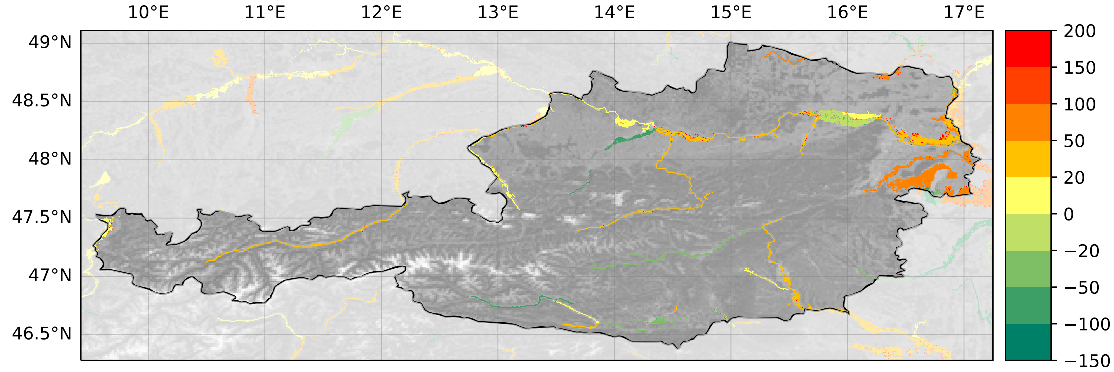
2.2 The social vulnerability indicator

This study aims to replace the established stage-damage functions that express flood vulnerability in GLOFRIS, with a novel social vulnerability index for Austria. Whereas common flood risk assessments focus predominantly on physical damages to the built environment, this study applies the concept of flood vulnerability in a broader sense, by considering indicators that reveal differences in the capacity of households to cope with and adapt to flooding.

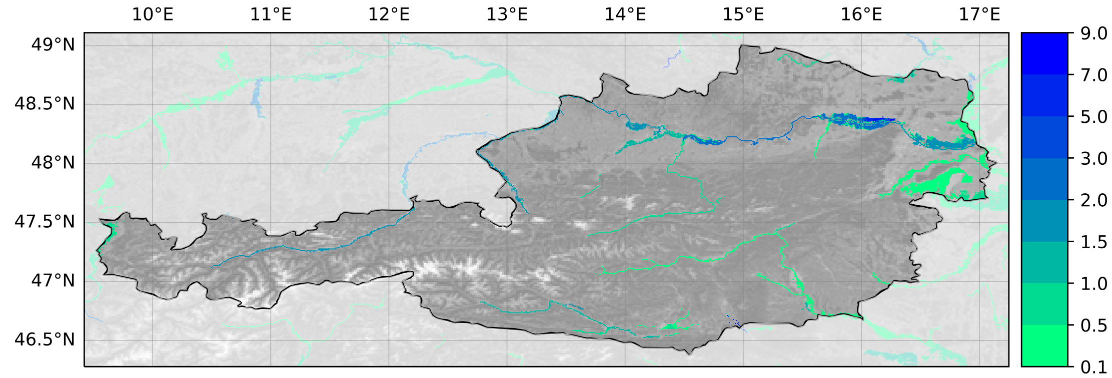
The developed flood vulnerability index applies spatially detailed statistics on household income, and slightly coarser data on household composition. The income data, made available by StatisticsAustria, is on 1x1km-scale for most of Austria, and includes several categories of income sources, the amount of individuals of retirement age (+65), and a quartile range of income.



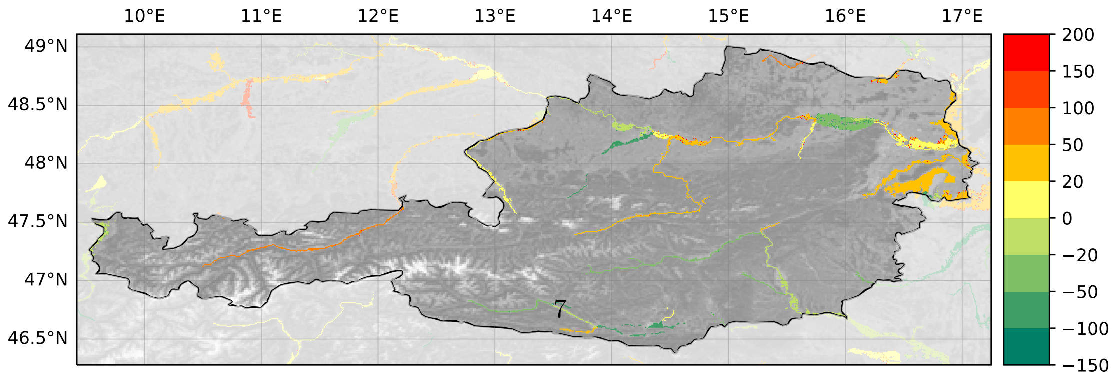
(a) 250-year flood inundation in meters, in 2080, under RCP4.5



(b) Percentage difference between Figure 2a and the bottom panel of Figure 1



(c) 250-year flood inundation in meters, in 2080, under RCP8.5



(d) Percentage difference between Figure 2c and the bottom panel of Figure 1

Figure 2: Flood inundation in meters in 2080 and projected difference between 2010 and 2080

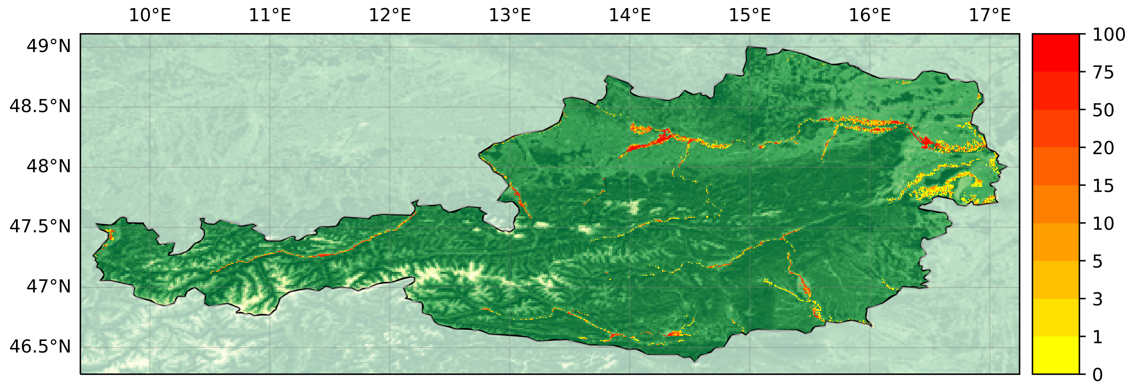


Figure 3: Physical flood damages (in $100 million) associated with a 250-year flood in 2010.

The flood vulnerability literature widely recognizes elderly to be substantially more vulnerable to floods (Cutter et al., 2003; Koks et al., 2015; Sayers et al., 2018), most importantly due to their lower capacity to evacuate (Phraknoi et al., 2023). Therefore, a higher amount of elderly individuals in an area suggests a higher social flood vulnerability in this area.

Household income is found to be a strong indicator of socio-economic status, which impacts social vulnerability to floods in multiple ways (Rufat et al., 2015). Households of lower socioeconomic status are often less educated, which generally leads to a lower perception of flood risk and lower capacity to process information in the case of an emergency (Deria et al., 2020; Lechowska, 2018). Besides this, low income directly constrains the coping capacity of households, which may be due to lower insurance coverage and less robust social safety nets (Cutter et al., 2003). Moreover, although higher income households often live in more expensive dwellings, meaning the impact they face in terms of economic losses is potentially greater, the relative impact of a destroyed property on their overall wealth is more severe for low-income households (Deria et al., 2020). Moreover, affordable housing, inhabited by low-income households, may be less robust to withstand a flood, increasing the extent to which a flood causes damage to the property (Deria et al., 2020).

To assess income vulnerability in this study, we consider the lowest income quartile per square kilometer, and the amount of individuals within that income category. Areas where the lowest income quartile is considerably low and where there are many households in this earnings category will be regarded as highly vulnerable in terms of income. Figure 9 presents the lowest quartile of the income distribution per spatial cell in Euros. It can be seen that around the urban areas of Vienna and Linz, the lowest quartile of the income distribution is relatively high. On the other hand, the lowest earners per grid cell are considerably less well-off in more rural areas. To determine vulnerability due to low income, we account for the amount of individuals associated with the lowest income quartile per grid cell.

Household composition is an important characteristic to consider. Particularly single parent households are found to be vulnerable to flood emergencies (Cutter et al., 2003). Single-parent families may be less mobile, particularly when children are young. Also, the higher effort that is required of single parents to raise children reduces the feeling of worry about natural disasters, which causes single parents to be less prepared for such events. This statistic is also obtained from StatisticsAustria, but at a coarser administrative scale (Bezirke).

To establish the social vulnerability index per grid cell, firstly the spatial cells that are not flooded are excluded from the socio-economic dataset, since these cells are irrelevant for the analysis. In order to combine the different vulnerability indicators into a single index, each of the individual indicators are standardized using a max-min rescaling procedure, as described in Yoon, 2012. Equation 1 shows how a specific vulnerability indicator x in cell i is standardized using this approach, resulting in an indicator v_i that expresses it's vulnerability in that specific area relative to the rest of Austria.

$$v_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{1}$$

The individual vulnerability indicators per spatial cell are summed up to create a composite vulnerability index. This approach is favored over a more complex method of assigning weights to differentiate the importance of certain indicators in the overall vulnerability index. This is because the social vulnerability literature does not find straightforward results regarding the relative importance of individual indicators (sources). Besides equal weights (Cutter et al., 2003; Koks et al., 2015), there are various approached to determine and apply weights, including expert judgement (Leis & Kienberger, 2020), pareto ranking (Rygel et al., 2006), regression analysis (Heß, 2017), and explained variance weighted sum (Cox et al., 2006; Schmidtlein et al., 2008). Since results vary widely based on the method used, we decided to apply the least complex weighting scheme, which is equal weights.

Figure 4 presents the composite vulnerability index, which is the aggregate of vulnerability indicators described above. It can be seen that major urban centers, including Vienna, Linz, Graz, and Innsbrück, show higher vulnerability values compared to more remote regions. This is a sensible finding considering that a larger population generally means there are more elderly individuals and single-parent households (see Appendix). Concerning low income, although average income is higher in cities than in the countryside (see Appendix), the number of individuals with low income may be higher in certain urban areas.

2.3 Social flood risk

The final step in constructing the flood vulnerability hotspot is overlaying the composite vulnerability index with the inundation associated with a certain flood return period. This overlaying

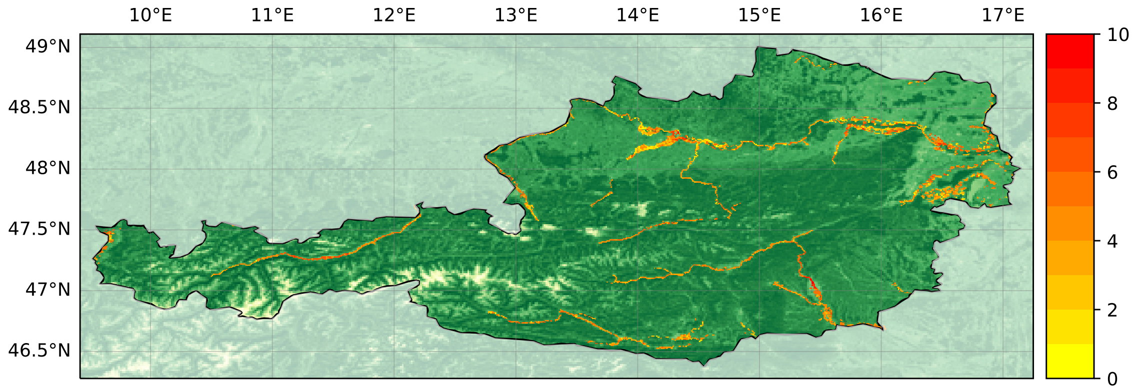


Figure 4: The composite vulnerability index for Austrian floodplains, ranging from 0 (least vulnerable) to 10 (most vulnerable to flooding). This vulnerability index is an aggregate of multiple vulnerability indicators, which are: low income, old age, and single parents.

procedure is done by multiplying the composite vulnerability index with flood inundation in meters. Before this procedure, inundation data is rescaled so that the minimum value is 1. The result of the multiplication of social vulnerability and hazard data is normalized using a square root transformation. This is done to reduce the weight of relative outliers that result from the multiplication, but does not affect the findings of this analysis.

The result of this overlaying procedure is a map projecting social flood risk. Figure 5 presents this map, using baseline inundation associated with a 250-year flood. It can be seen that certain areas where social vulnerability is relatively high in Figure 4, the relative social flood risk is not particularly severe (e.g., areas around Graz and Innsbrück). This is because lower levels of flood inundation are less damaging, even for socially vulnerable populations. On the other hand, some regions that are less socially vulnerable to floods show relatively high levels of social flood risk when combined with flood inundation. Even less vulnerable societal groups are highly impacted by severe inundation. This is most notably the case in the Traun floodplain, but also in the large floodplain West of Vienna, and in several places in Karinthia.

3 Results and discussion

The objective of this study is to develop a novel framework that captures a a broader aspect of flood vulnerability than the concept applied in most flood risk assessments. By focusing only on vulnerability of buildings, and often applying single vulnerability indicators for large geographical areas, such assessments fail to account for differences in vulnerability, either because of age, income, or household composition. As a result, flood risk management may prioritize to protect areas where economic values are greatest, rather than areas where the most vulnerable populations reside, who are the least able to cope with damages caused by floods. Considering

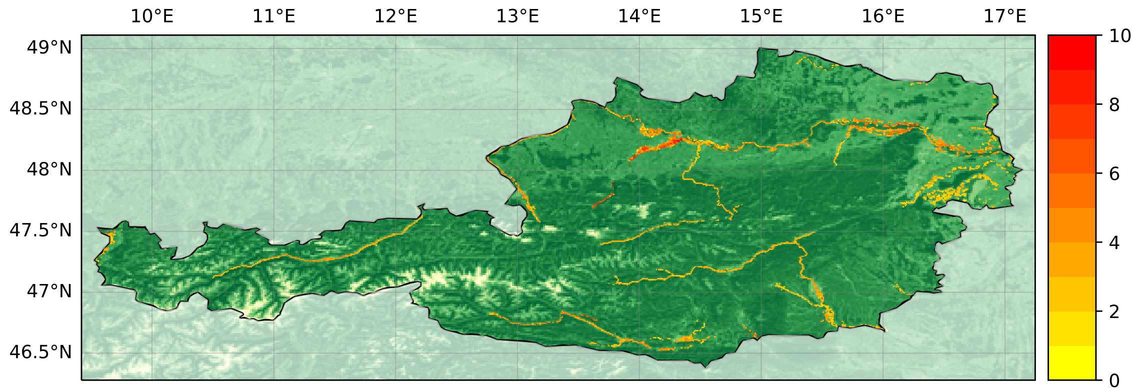


Figure 5: Social flood risk hotspot as a product of the composite vulnerability index and inundation associated with a 250-year flood.

this objective, an important analysis of this study is to compare the result of the social flood risk developed in this study with the flood risk projection using the established stage-damage curves to represent flood vulnerability. For this purpose, we can compare Figure 5 with Figure 3, which was presented earlier. It can be seen that the major social flood risk hotspot at the Traun-Danube connection is also one of the most impacted regions considering physical damages. An interesting difference when comparing the two figures is that Vienna shows relatively less social flood risk, whereas the physical damages there are amongst the most severe in Austria. High flood damages there are a result of the density and value of buildings that are impacted by a flood. On the other hand, more wealthy households in this area has a positive influence on how the population may cope with and prepare for floods, which means the social vulnerability is relatively less severe compared to, for example, the Danube basin West of Vienna. Although there are some cells in this area where physical damages are determined to be costly in Figure 3, it can overall be seen that social flood risk is more prominent in this area. Therefore, the clear difference in some areas between flood impacts when expressed in physical damages and social risk highlights the importance of considering different flood vulnerability indicators. Should physical damages, in terms of economic values, be prioritized when making flood risk management decisions? Or should socially vulnerable populations to floods be prioritized?

So far, we have presented and analyzed results based on historical flood inundation data. However, meteorological changes due to global warming may cause different future flood conditions. Since flood risk management decisions, particularly investments in flood protection, are often made with the idea that these will enhance safety for a long period of time, it is important to take changing flood conditions into account. Moreover, since flood risk, both in terms of physical damages and social flood risk, will likely change due to socio-economic development, we need to take changes in exposure into account.

As was shown in Figure 2, flood inundation in 2080 is expected to slightly increase on average for Austria. However, for some specific regions a decline in inundation depth is projected under both climate change scenarios, largely due to the declining influence of glaciers in the discharge of these river systems. Differences in how climate change impacts inundation depth between river systems means that a tailored approach to flood risk management is needed. For example, although inundation and flood risk is currently high along the Traun-Danube intersection, this is expected to decrease due to climate change. Investing in strengthening long-term flood defenses in this area may not be as beneficial compared to regions where flood risk remains high, or increases, in the future.

Future inundation is overlain with the social flood vulnerability indicator to determine the future intensity of social flood risk in Austrian floodplains. To account for socio-economic changes over this time, the individual social vulnerability indicators are adjusted based on the growth in exposure of the particular vulnerable groups. The growth in exposure is accounted for by rescaling the amount of individuals in each social group (lowest income quartile, retirement age, single parent households) with the expected population growth factor associated with the socio-economic scenario (SSP). Before this procedure, the SSP population growth projections are downscaled to the same 1x1km spatial cells used in this study, data for which is obtained from Marbler, 2024. Figure 6 presents the social flood vulnerability heatmap for 2080 under SSP5. Comparing this projection to Figure 4, the most notable observation is the concentration of social flood vulnerability in Vienna, and considerably lower relative social vulnerability particularly in more rural areas. The explanation for this development is that this socio-economic scenario projects a strong concentration of population growth in cities. Vienna, being Austria's largest city, has the strongest pull-factor for population settlement in this assessment. A note on this projection is that, whereas we assume that population growth causes social vulnerability to increase proportionally, future developments in terms of income inequality and age distributions may turn out differently. However, such projections are highly complex and uncertain, and exceed the scope of this study.

The composite social flood vulnerability indicator for 2080, considering SSP5, and the inundation associated with a 250-year flood in 2080, under RCP8.5, produce the social flood risk heatmap presented in Figure 7. As expected, less inundation in this future scenario around the river Traun causes social flood risk to substantially decline there through 2080. For similar reasons, relative social flood risk declines around the river Drau in Karinthia, except for several square kilometers just before the river enters Slovenia. The most prominent area in terms of social flood risk in 2080 is along the Danube basin, and particularly in the area West of Vienna.

The results presented in this study have several implications for Austrian flood risk management. Firstly, the clear social flood risk hotspots visible in Figures 5 and 7 call for measures to adequately protect these areas. Traditional "hard" flood protection measures, including dikes and levees, may be constructed to protect against these flood events. Currently, many of the

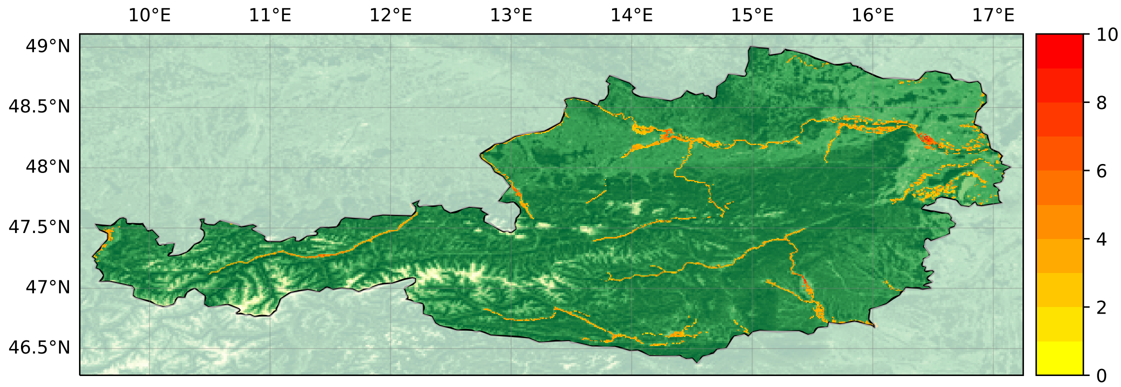


Figure 6: The composite flood vulnerability indicator in 2080, considering socio-economic growth under SSP5.

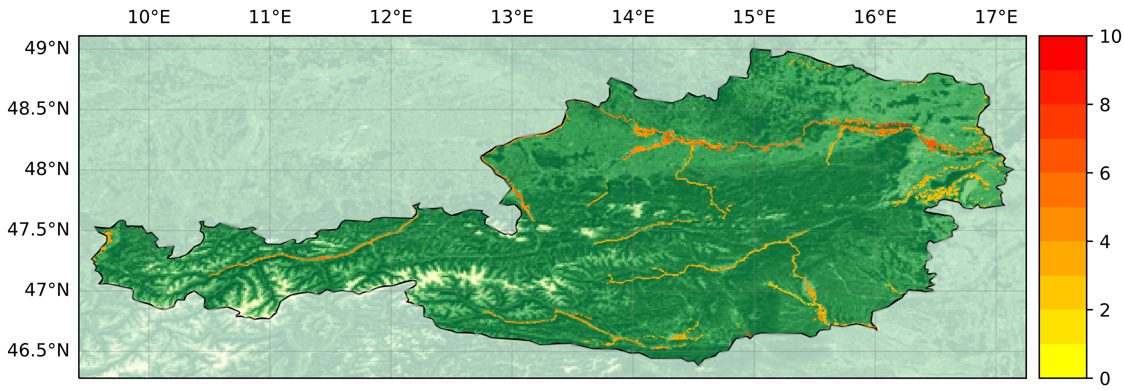


Figure 7: Social flood risk in 2080 for a 250-year flood, considering RCP8.5-SSP5.

areas that were found to be particularly at risk of flooding have protective measures that prevent water-levels with return-periods between 30- and 100-years from causing floods (LRT, 2021). This means that, from the scenarios assessed in this study, 50- or 100-year floods may be mitigated in some areas, but 250-year floods will likely not be.

A notable downside of raising large-scale flood protection infrastructure, besides high investment and maintenance costs, is that it creates a feeling of safety in the protected area, which often stimulates economic development in these areas (Haer et al., 2020). This "safe-development paradox" may ultimately render the protection investment useless, as the increased exposure counteracts the reduced flood probability. Instead, or complementarily, flood risk managers may apply "soft" measures, which are often designed to stimulate risk-conscious decision-making by households. To reduce flood risk, households may apply risk-reduction measures, including dry- or wet-flood-proofing (Aerts, 2018), avoid settling in floodplains, or ultimately move out of harm's way. Measures to encourage such risk-adaptation may include flood risk awareness campaigns, or increasing the financial attractiveness of such decisions, such as through subsidies or loans (Kousky, 2019), or through insurance incentives (Tesselaar et al., 2023).

Investment decisions in both "hard" and "soft" measures to reduce flood risk should considerably weigh the social flood risk, particularly when choices have to be made about which areas to prioritize. This study shows that only considering the monetary value of physical damages for such choices may lead to sub optimal societal outcomes. Areas where physical flood damages are high may not be areas where the impacts on livelihoods are most severe. Moreover, investment decisions should take future flood hazard and exposure into account when deciding where to invest. Current flood risk hotspots that call for measures may become less urgent in the future. For this reason it may not pay off to invest in expensive and long-term protection measures, since benefits (mitigated flood risk) may decline in the future. Instead, alternative risk reduction measures may be considered, which effectively reduce current (social) flood risk, while being less costly. For example, local governments may improve early warning systems that inform residents of impending flood risk, and give them advise on short-term measures to limit the impact a flood may have (Kreibich et al., 2016). Local governments may also prepare evacuation manuals, which should include a detailed account of where less mobile households are located.

Besides improving emergency response, policymakers may pursue strategies that improve the flood risk coping capacity of socially vulnerable households, such as targeted flood awareness campaigns in areas where social flood risk is particularly high. Increased flood risk awareness may lead households in these areas to apply measures to reduce the vulnerability of themselves and their homes. For example, households may pay more attention to weather and river conditions, and be more prepared to evacuate when a flood is imminent. Part of this preparation may include moving expensive belongings and appliances to higher levels of the house, which are relatively simple measures to reduce flood impacts. Reducing vulnerability further may include structural adaptation measures, such as flood barriers, or flood-proof floors and basements.

Since the installation of these measures are more expensive, low-income households may require financial assistance for their application. Targeted subsidies or low-interest loans for vulnerable populations may, therefore, be effective to reduce social flood risk.

Finally, insurance is an important mechanism for vulnerable households to cope with flood damages. Without flood insurance coverage, flood damage may only partially be compensated by the government (through the Katastrophenfonds), which means that part of the reconstruction needs to be paid from savings. Lacking insurance coverage is, therefore, likely to slow down recovery amongst the socially vulnerable populations impacted by a flood, since these have less means at their disposal to finance this. In Austria, the Katastrophenfonds typically covers between 20-50% of residential flood damages (Hanger et al., 2018). Concerning the remaining 80-50% of flood risk, only 5% of Austrian households have insurance coverage for this (Europe, n.d.). Reducing the flood insurance protection gap should, therefore, be a priority for Austrian flood risk management. For households of lower socioeconomic status, this may be achieved by raising flood risk awareness in areas of high social flood risk, or through various forms of nudges (Robinson et al., 2021). Policymakers may also instate flood insurance uptake requirements, as is done in the US and several European countries (OECD, 2016). Particularly for low-income households, flood insurance premiums may be a large financial burden, and may even be unaffordable (Tesselaar et al., 2020). This issue is particularly severe when premiums are risk-based, meaning it is to a considerable extent reflecting the risk of the structure and local flood hazard conditions. Developments in projecting flood risk are enabling insurers to increasingly apply such procedures to set premiums (Hanger et al., 2018). To reduce the burden that flood insurance premiums pose for low-income households, and make insuring against flood risk more attractive, governments may subsidize coverage for these households. However, as this policy may trigger moral hazard, where insurance coverage reduces the incentive for households to mitigate or adapt to flood risk, a more effective approach may be to subsidize or provide low-interest loans for installing risk-reduction measures. This policy is particularly effective when the reduced flood risk after applying these measures results in an insurance premium-discount. In the described insurance system, insurance becomes more affordable for low-income households, while simultaneously their vulnerability decreases.

4 Conclusion

Flood risk models are an important tool to support flood risk management decisions. Many flood risk models, however, focus on the total economic value of damage caused by floods, and fail to account for differences regarding the vulnerability of populations exposed to floods. The danger of considering only economic damages in flood risk management is that policy to reduce flood impacts may prioritize more wealthy societal groups, which is not necessarily the population group whose livelihoods are most severely impacted by a flood disaster. Literature finds several socio-demographic indicators for flood vulnerability, of which low income, old age, and single parent household are prominent. This study modifies the established flood risk analysis, by combining spatial riverine flood hazard data with detailed maps on socio-demographic indicators of flood vulnerability for Austria. The result is a map indicating the degree of "social flood risk", which is a spatial heatmap of where high flood risk and areas densely populated by vulnerable groups coincide.

Comparing our map of social flood risk with a flood risk map based on exposed economic value we find some similarities, but, importantly, also some differences. Whereas economic flood risk is pressing in the center of Vienna, social flood risk is a quite minor issue there. Instead, several areas, where economic flood risk is low, show to face considerable social flood risk. Based on this finding, policymakers may make more informed decisions regarding where to prioritize flood protection or other forms of flood risk management.

Another finding of this study is the importance of considering future flood risk developments under climate change. Our assessment shows that some areas which face substantial social flood risk now, may face much less pressing issues in the future due to lower flood hazard. On the other hand, in some areas, particularly in major urban areas, social flood risk increases due to growing populations there. Particularly concerning expensive and long-term flood protection infrastructure, our study finds it is important to consider such future projections.

Appendix

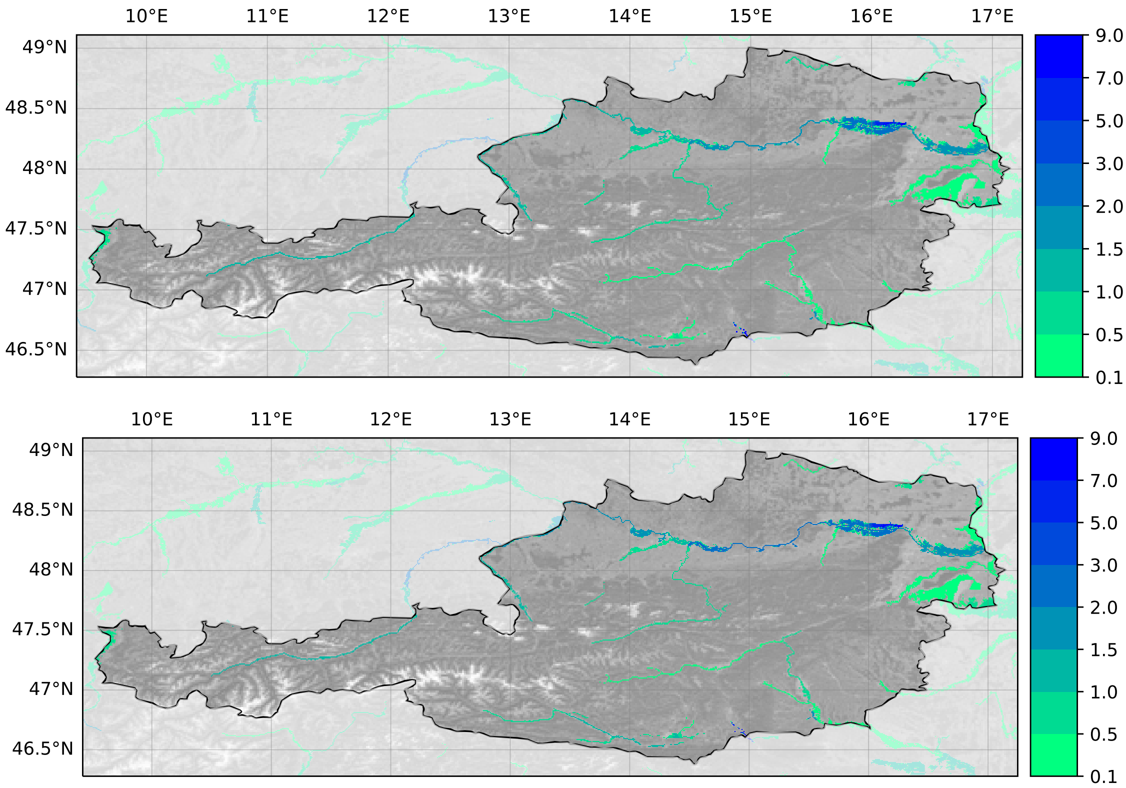


Figure 8: Inundation in meters for a 250-year flood in 2050 under RCP4.5 (top), and RCP8.5 (bottom).

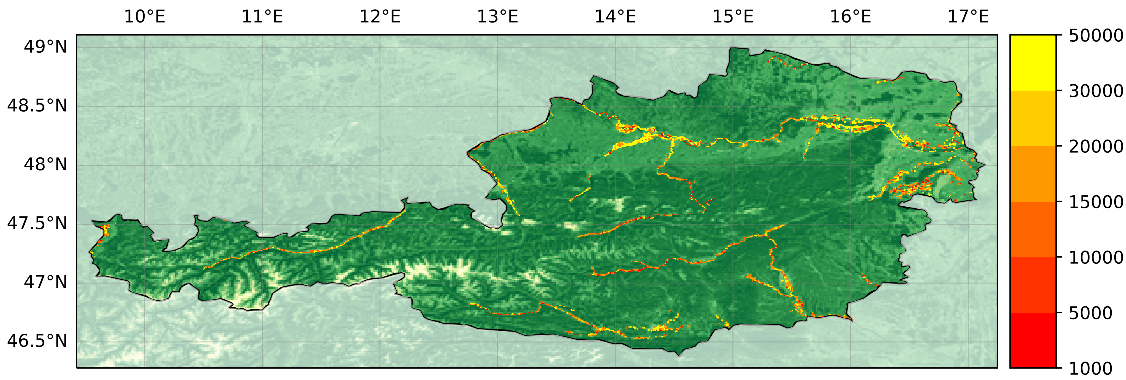


Figure 9: The first quartile of yearly household income in Euros.

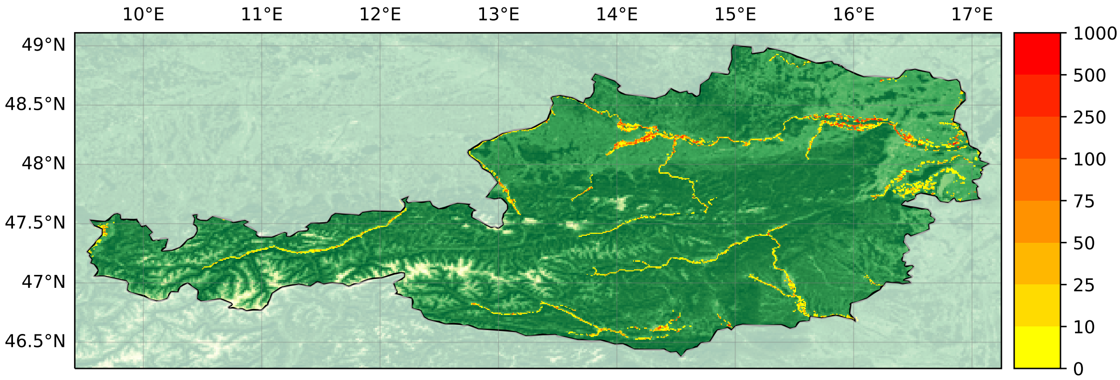


Figure 10: The total amount of elderly individuals per 1x1km-cell

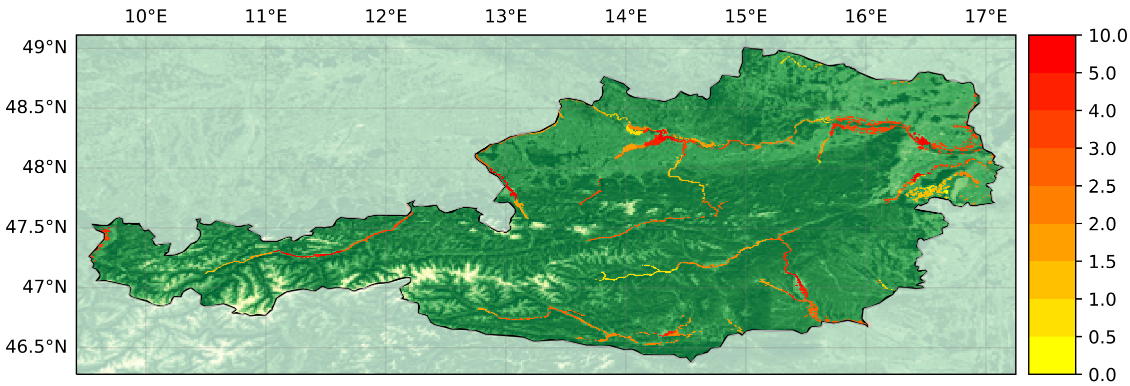


Figure 11: A standardized vulnerability indicator of the amount of single parent households. A standardized score is necessary because this data is only available on a larger spatial scale (bezirke), which means we cannot exactly determine the amount of single parent households on a 1x1km-scale.

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