Sheltering 10 billion people in a warming and resource-scarce world: challenges and opportunities

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Chapter 5: Embodied emissions from building materials at risk of climate-driven flooding hazards in Europe

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Abstract

Climate and land-use changes have driven an increasing risk of extreme flooding events to life and infrastructure. These events may drive large material losses and associated embodied emissions. Here we map building materials at risk of flooding hazards and material-related greenhouse gas (GHG) emissions across 49 European countries under current and future climate-change and land-subsidence. We show that currently 11.7 Gt of building materials, or 11.6% of those in-use, are at risk of a 1-in-100-year flooding event. Expected annual damage (EAD) to building materials, in the absence of flood protections, reaches 329 Mt per year, equivalent to ~109 MtCO_2eq per year of embodied GHG emissions. With assumed current flood protection standards fully in place, the current emissions from EAD are reduced by nearly 92% (~100 MtCO_2eq, nearly 20% of the current annual building material related emissions in Europe). Emissions see an increase of 71% to 180 MtCO_2eq per year in 2080 under a high-emission climate scenario (RCP 8.5). Climate mitigation from RCP 8.5 to RCP 4.5 reduces these embodied emissions by 25 MtCO_2eq (14%) to 147 MtCO_2eq per year. Overall, we show that climate mitigation and flood protection are crucial in reducing material losses and embodied emissions.

5.1 Introduction

Buildings provide basic needs for shelter, survival, and well-being[1-3]. Adequate housing for all is an essential Sustainable Development Goal (Goal 11) of the United Nations[4]. The development of new buildings uses about half of the world's mineral materials (nearly 20 Gt)[5-7] and sees investment of 6 trillion USD (7% of GDP)[8,9] annually. Material extractions and financial investments are expected to only increase in meeting the demands of growing consumption and populations[7,10,11]. However, material extraction and production at such scales have contributed to major climate and ecological impacts and present a significant challenge to multiple national and international targets[12-18].

Natural hazards present major risks to numerous established buildings and proposed new infrastructure globally. For instance, the 2022 deadly flooding in Pakistan destroyed more than 1.2 million houses and thousands of kilometers of road and hundreds of bridges[19]. The devastating 2021 European floods damaged tens of thousands of homes across Germany, Belgium, and the Netherlands. Over half of US building stock is estimated to be at risk of potentially catastrophic natural disasters (i.e., earthquakes, floods, hurricanes, tornados, and wildfires) and 1.5 million buildings are located in hotspots of two or more disasters[20].

Floods represent the most prevalent and costly natural hazards globally[21], accounting for nearly half of total disaster events reported over the past two decades[22] and over 70% of modelled hazard-related damages to transport infrastructures (among earthquakes, cyclones, and floods)[23]. Global flooding is expected to intensify with climatic changes and land-use change (e.g., vegetation clearing and subsidence)[24-26], posing an increasing threat to buildings. Flood impacts on buildings and materials are also especially severe in lower-income regions where buildings are less developed, have lower protection[27,28], and which face disproportionate increases in flooding risk[24,29].

These combined trends may cause substantial material losses to floods, a need for repairing and rebuilding, and additional material-related environmental impacts such as GHG emissions, further threatening local and global climate targets. Previous studies have explored flood risks on population[21,25-29] and the economy[25,29-35]. However, none have evaluated flooding impacts on actual materials and embodied emissions due to a lack of high-resolution geospatial information on how in-use building stocks and major types of materials consisting them are distributed on large scales from continental to global[36,37]. Recent advances in computational, digital and earth observation technologies (e.g., satellite-derived night-time lights) have given rise to new possibilities for such assessments[38,39].

Here we make the first step by estimating the European building materials at risk of flooding hazards and GHG emissions related to this loss under climate, land-use and flood protection scenarios. We use two types of high-resolution maps: 1) night-time lights-based building material stocks (including 6 material types for residential and non-residential buildings)[38] and 2) inundation maps of riverine and coastal floods across different return periods for the baseline (reference year 2010) and future climatic and land-use conditions - under moderate (RCP 4.5) and high (RCP 8.5) emission scenarios by 2080. We analyse the exposure of building materials to riverine and coastal flooding events, i.e., materials located in areas where inundation depth is over 0. We then estimate the expected annual damage (EAD) of building materials by further considering the full range of 9 return periods (1-in-2, -5, -10, -25, -50, -100, -250, and -1000 years) and damage probabilities given by a depth–damage function. We calculate the embodied GHG emissions of building materials for repairing and rebuilding using a life cycle assessment (LCA) approach.

A known limitation of flood risk analysis is limited information on flood protection measures especially on large scales. Existing research either do not consider any protection[27,40] or consider only roughly estimated protection standards based on proxies such as income levels[23,41]. In this study, we calculate current EAD and embodied emissions in two scenarios: in the absence of flood protection and the implementation of estimated subnational flood protection standards[41]. This allows for an estimate of the benefits of envisaged protection measures or, in other words, the cost of protection failures (please see Methods for further details on methods and data).

5.2 Results

We find that currently ~11.7 Gt of building materials (11.6% of the total building material stock) may be exposed to 1-in-100-year riverine (11.4 Gt) or coastal (1.2 Gt) flooding events in 45 out of 49 investigated European regions (the remaining are small regions not on major rivers such as the Faroe Islands, Gibraltar, Monaco, and Vatican City) (Figure 5.1). Italy, France, and the Netherlands see significant exposure (each representing over 10% of the European total), followed by Germany, Spain, and the UK. These nations have accumulated a large quantity of building stocks in coastal, large river basins or lowland areas. By mass, the main material type exposed to 1-in-100-year floods is concrete, accounting for ~80% of the total, followed by wood and steel, each responsible for nearly 8%.

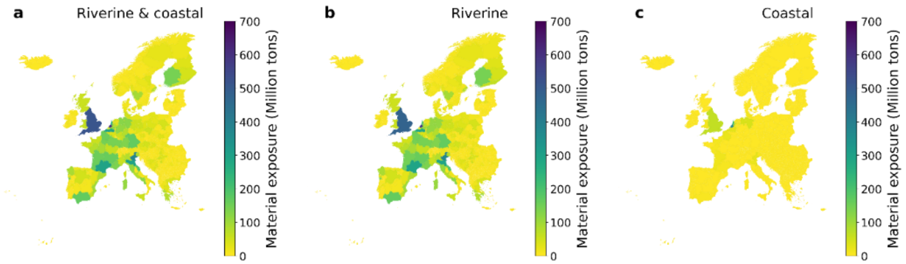

Figure 5.1 Building materials at risk of 1-in-100-year riverine and coastal flooding events under the baseline climatic conditions (reference year 2010).

In the absence of flood protection, the current EAD to building materials from riverine and coastal floods is ~329 Mt, very unevenly distributed among 41 out of 49 countries (again, regions having material exposure and no EAD are small states including Aland, Andorra, Malta, and San Marino). The highest EAD is seen in the Netherlands (185 Mt), where land is generally lower and flood depth can be much higher than other nations seeing similarly high material exposure values. This is why the Netherlands is developing some of the best flood protection systems in the world that have largely reduced the risks[42]. Germany (23 Mt), France (20), Italy (18), and Spain (17) all have EADs of over 10 Mt.

Climatic and land use changes (such as subsidence) are likely to significantly impact the EAD of materials in coming decades. Not considering flood protections, the overall EAD is likely to increase by 46% under moderate emissions (RCP 4.5, including land subsidence), reaching 482 Mt of material in 2080 (material stocks modelled at the current level, see Methods) (Figure 5. 2). High emissions (RCP 8.5) will further increase the EAD to 557 Mt in 2080. Regional EAD trends vary widely, with 22 regions increasing (in absolute terms led by the Netherlands, Italy, and Germany) and 19 regions decreasing (in absolute terms led by Spain, Greece, and the Czechia) under RCP 4.5. Particularly pronounced increases are seen in Jersey, Cyprus, Belgium, Ireland, Denmark, and Lithuania, which may more than double their EADs.

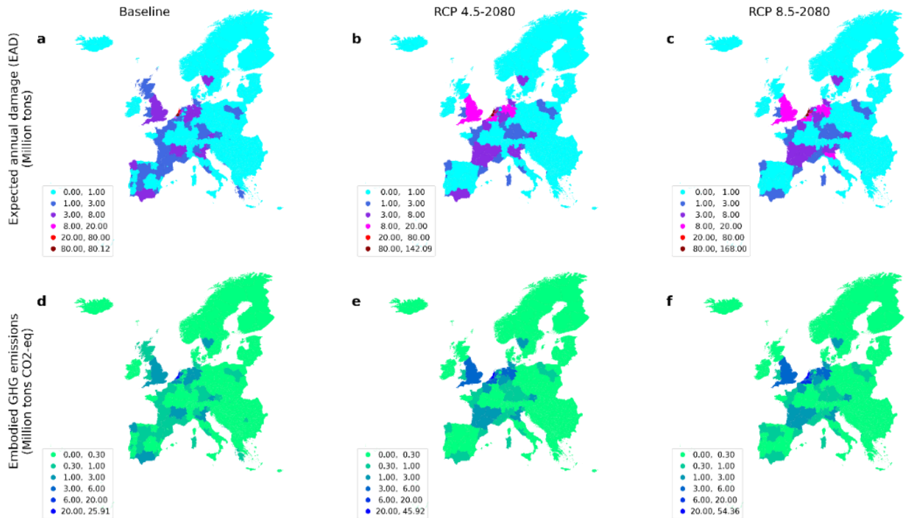

Figure 5.2 Expected annual damage (EAD) of building materials from riverine and coastal flooding hazards in the absence of flood protection (in Mt) and embodied greenhouse gas (GHG) emissions (in Mt CO_2eq). **a-c**, EAD under the baseline (reference year 2010) and future climatic and land use conditions. **d-f,** GHG emissions from the production of materials equivalent to the EAD across scenarios.

The current EAD of building materials without considering flood protection, if remanufactured in the same quantity and type to repair and reconstruct, is associated with ~106 Mt CO_2eq of GHG emissions (Figure 5.2d), with steel (58%), concrete (33%), and wood (6%) being the main emitters. These emissions see an increase by 47% and 71% to 156 and 180 Mt CO_2eq, respectively, under moderate (RCP 4.5) and high (RCP 8.5) emission scenarios by 2080. This demonstrates the scale of embodied GHG emissions that can be avoided through ultimate protections.

In general, there is a lack of accurate fine-scale datasets of flood protection measures due to limited information on existing protection and the fact that flood protection implementation is by nature a highly dynamic process. However there is an evolving global database[41] available with sub-national protection standard estimates (based on literature or income levels). Assuming these potential flood protection standards across Europe, results in embodied GHG emissions are almost 92% lower when compared to no flood protection (Figure 5.3). The reduced emissions, ~100 Mt CO_2eq per year, are almost 20% of the building material related emissions in Europe in 2020 (assuming that building materials were responsible for 11% - the share of global building materials in global total GHG emissions[11] - of total GHG emissions in Europe). This highlights the vital role of flood protection measures in mitigating material losses and regional emission pressures in addition to the widely recognised / verified benefits of livelihood and economic savings[29,35,43].

Regional reductions vary significantly. With estimated flood protection standards implemented, we find > 95% EAD reductions in the Netherlands, Denmark, Iceland, Belgium, and the UK, whereas over half of the EAD remains in 14 regions such as Bosnia and Herzegovina, Albania, Bulgaria, Montenegro. In general, lower-income regions have significantly less developed flood protection systems[27,41] as designing and maintaining long-term adaptation strategies can be complex and costly[44,45].

International cooperation in technology and investment are thus important to address flooding risks in lower-income regions. An example of such development is the “loss and damage” funding developed at the 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27), which may help address flooding risks and losses in lower-income nations suffering severe climate impacts. In addition, local geographic and socio-economic conditions need to be considered to select resource-and cost-effective flood protection measures[44]. Overall, against future climate and land use changes, flood protection standards need to be upgraded in many regions especially in those having low-level protections (mainly in poorer regions) and those that may have higher protection standards but see intensified flooding hazards (such as the Netherlands)[46].

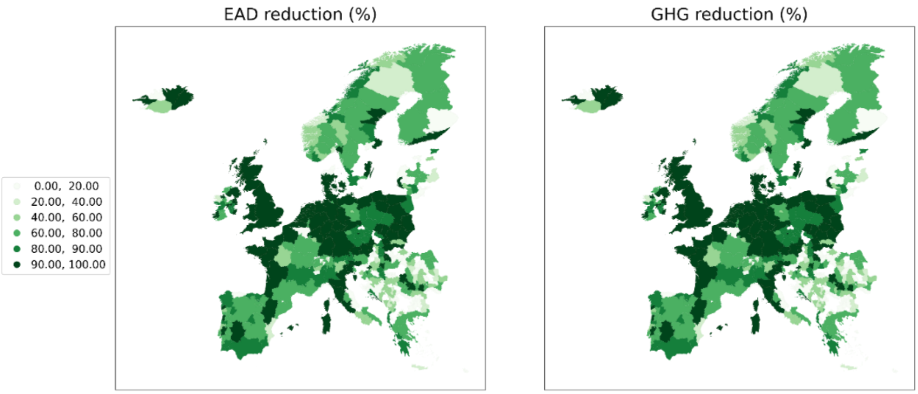

Figure 5.3 Percentage reduction in current expected annual damage (EAD) of building materials and embodied greenhouse gas (GHG) emissions for simulations run with assumed current flood protection standards compared to no flood protection.

In addition to strengthening flood protection measures, increasing flood hazards call for a systematic transformation in the built environment. First, future urban planning and real estate investment decisions should consider hazard hotspots and climate outcomes, avoiding urban planning failures such as accumulating cities and homes in flood-prone areas as seen around the world in the past decades[20,21,47,48]. Further, the next generation of engineers will need to build resilience into buildings during construction[49]. For example, structures designed to allow water entry and exit[50], foundations with higher depth and corrosion resistance[51], waterproof materials[52] may significantly help buildings survive flooding. Finally, flood-prone regions should develop waste management protocols to properly and efficiently inventory and dispose of construction materials post-disaster[53,54]. Dedicated efforts are needed to reduce harm and pollution, accelerate reconstruction and rehabilitation, and make sure the right type of impacted materials can be sorted and recovered[54,55].

Overall, the framework presented in this work may be used to map flooding impacts on building material stocks and embodied emissions on multiple scales. Our ongoing efforts are dedicated to conduct a high-resolution global analysis. A future improvement is to consider the trend of building material stocks over time, driven by socioeconomic changes, which is especially important for rapidly developing countries where the majority of homes in 2080 are to be built. Another improvement is to estimate the net emission savings from flood protection measures. To this end, embodied emissions of flooding protection infrastructure such as dikes are to be assessed. Finally, we propose that future cost-benefit analysis of flood protections need to also incorporate avoided GHG emissions given a rapidly shrinking emission budget.

5.3 Method

Flood under scenarios

We used global riverine and coastal flood maps from the Aqueduct Floods Hazard dataset (updated October 20, 2020)[56,57]. The dataset provides information on the extent and depth of riverine and coastal floods, gridded to 30 arc seconds (roughly 1 km at the equator). It provides simulated flood events for current (2010) and future projected climate conditions in 2030, 2050, and 2080 at several return periods (2, 5, 10, 25, 50, 100, 250, and 1000 years). Future climate conditions are projected based on RCP 4.5 and RCP 8.5. Future riverine flood hazards are distinguished by five global climate models (GCM): HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M. Future coastal flood hazards are distinguished by whether future land subsidence is considered. The dataset represents the best open-source information of the impact of future climate changes on riverine and coastal flood hazards on a global level[35,58].

Building material stocks

Material stocks of buildings used in this study are derived from ref[38]. The material dataset provides the volume of six types of building materials (concrete, steel, aluminium, copper, glass, wood; distinguished by residential and non-residential uses) located in each Nighttime Light Cell (NLC) across Europe. NLCs are distinctly shaped cells of variable sizes with the smallest composed of a single pixel of 0.1 km (i.e., isolated patches of light, surrounded by areas with no nighttime lights).

Calculation of material exposure

Materials exposure in this study define the volume of materials impacted by floods, that is materials located in a flooding area where inundation depth value exceeds 0 m. It is computed by intersecting the gridded inundated areas with building material stocks. For pixels where riverine and coastal floods overlap, we retain the higher inundation depth values of the two datasets, following the approach used elsewhere in the literature[27].

Calculation of maximum potential material damages

A fraction of materials exposed to flood hazards may be damaged. Maximum potential material damages in floods can be evaluated by combining impacted material volumes and inundation depth values that are further translated into a damage percentage via the flood depth-damage functions. The flood depth-damage functions in this analysis are derived from ref[59], a globally consistent database depicting fractional damage function of water depth across continents and building classes (residential, commercial, and industrial buildings). A further disaggregation between the material stock data (residential and non-residential) and the depth-damage function classes (residential, commercial, and industrial) is necessary. Following the literature[56], we assume that non-residential building material stocks consist of 60% commercial, and 40% industrial building materials.

Calculation of expected annual material damages

Different return periods (2, 5, 10, 25, 50, 100, 250, and 1000 years) of flood hazards represent different annual average exceedance probabilities (i.e., 1/return periods). Each impact indicator (e.g., material exposure, maximum potential material damage) is calculated per return period (probability). By considering the material damage of flooding over the full range of probabilities, flood risk can be further measured as the expected average annual damage (EAD) of building materials from flood hazards[60]. EAD is calculated using the damage-probability curve, where the flood probabilities (i.e., 1/return periods) are plotted on the x-axis and the maximum material damages on the y-axis. The area or the integral under the curve is the EAD (before incorporating flood protections; see the following paragraph). Future EADs are calculated for each of the five GCMs and the reported values in this study are the average.

Material damage from flood hazards can be reduced with infrastructure such as dikes. We account for flood protection standards by adding a vertical flood protection line[56] to the damage-probability curve, which truncates the overall area under the curve into two areas showing the protected/avoided (i.e., the area to the left of the flood protection line) and the unprotected/expected (i.e., the area to the right of the flood protection line) damages. That is, the represented damage to the right of the flood protection line is assumed as avoided (and set to zero). Current flood protection standards are derived from the FLOPROS[41], a database providing state-level flood protection estimates across the globe.

Calculation of material-related emissions

Material-related GHG emissions are equal to material production volumes required to reconstruct or repair buildings multiplied by the GHG emission factors (i.e., emissions per kg of materials production). To estimate material volumes, we assume a one-to-one replacement ratio between the new materials needed and the old materials damaged. That is, the same magnitudes and categories of building materials will be reproduced after the flood hazards to revive the impacted building stocks. The GHG emission factor for each type of materials are derived from the Ecoinvent 3.6 database[61], employing the global warming potential (with a 100-year time horizon) approach, and the 'cradle-to-gate' material production system boundary (referring to only the production of materials, from raw material extraction to the manufacturing of finished products).

5.4 Data availability

This research relies entirely on publicly available data as referenced.

5.5 Code availability

Python and R code used for the modelling is available from the authors upon request.

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