Increased human and economic losses from river flooding with
anthropogenic warming

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Abstract

River floods are among some of the costliest natural disasters [1], but their socioeconomic impacts under contrasting warming levels remain little explored [2]. Here, using a multi-model framework, we estimate human losses, direct economic damage, and subsequent indirect impacts (welfare losses) under a range of temperature (1.5°C, 2°C, and 3°C [3]) and socioeconomic scenarios, assuming current vulnerability levels and in absence of future adaptation. At 1.5°C, depending on the socioeconomic scenario, it is found that human losses from flooding could rise by 70 to 83%, direct flood damage by 160 to 240%, with a relative welfare reduction between 0.23 to 0.29%. In a 2°C world, by contrast, the death toll is 50% higher, direct economic damage doubles, and welfare losses grow to 0.4%. Impacts are notably higher under 3°C warming, but at the same time, variability between ensemble members also increases, leading to greater uncertainty regarding flood impacts at higher warming levels.

Flood impacts are further shown to have uneven regional distribution, with greatest losses observed over the Asian continent at all specific warming levels. It is clear that increased adaptation and mitigation efforts – perhaps through infrastructural investment [4] – is needed to offset increasing river flood risk in the future.
River floods result in severe direct damages and fatalities, yet also have considerably wider and longer-term adverse economic consequences [5]. Even though the observed increase in flood impacts can be largely attributed to population and economic growth in flood prone areas [6,7], the expected intensification of floods due to climate change effects [8] may pose a further threat to future generations. Understanding global flood risk for Specific Warming Levels (SWLs) is imperative to evaluate the feasibility and support the implementation of the stringent mitigation and adaptation targets stipulated in the Paris Agreement [3], as well as the Sendai Framework for Disaster Risk Reduction and Sustainable Development Goals [9].

A number of global flood risk assessments have been presented in literature that map population [10,11], GDP [12,13,14] and economic losses [13,14] exposed to river floods at distinct points in time under various scenarios of climate change and socio-economic projections. Few studies have focused on direct flood losses and population exposed at global scale for different levels of warming [2]. Moreover, floods also give rise to indirect economic losses [15]. A lower output of the economy in the aftermath of the event may reduce the available resources for investment in subsequent years, resulting in longer-term economic impacts on economic production and households’ welfare for the region [16]. Even though systemic effects can be substantial for large-scale events, as exemplified by Hurricane Katrina for which indirect losses constituted 40% of the total impacts [17], assessments of the indirect effects of river floods at continental scale are rare [18] and do not exist at global scale. Also, in spite of more than 200,000 fatalities worldwide since 1980 [19], few studies have presented projections of loss of life from flooding under global warming [7,12], and projections at country scale are not available.

We present a global dynamic assessment of human and economic river flood losses for the mitigation targets set out in the Paris Agreement to keep global warming “well below 2°C” compared to pre-industrial temperatures and pursue a tougher target of 1.5°C [3]. We also take into consideration 3°C warming that is closer to what could be expected by the end of the 21st century if adequate mitigation strategies are not taken [20]. Our approach integrates a detailed modelling framework to simulate river flow and flooding processes with a growth model of the
world economy and the most recent global datasets of exposure, flood protection and flood-loss relations (See Methods). We account for climate and hydrological uncertainty by using the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) ensemble of river flow projections [21] that comprises ten hydrological models and five driving climate runs. This allows for providing more robust estimates compared to previous global river flood risk studies that did not consider hydrological model uncertainty [2,10,11,12,13,14].

Four kinds of impacts are quantified: population exposed, number of fatalities, direct damages and welfare changes, thus offering the most complete picture of the consequences of floods on society to the best of our knowledge. Population exposed and direct damages are computed as in [2], while loss of life estimates are based on current mortality rates calculated as in [7,12]. Indirect dynamic economic effects are simulated with the Macro-econometric of the Global Economy (MaGE) model [22]. Total resulting economic effects are expressed as changes in welfare corresponding to the consumption that is foregone due to flooding. Flood impact models are known to be characterized by significant uncertainty pertaining to the components and datasets representing hazard, exposure, and vulnerability [2,4]. Therefore, we evaluated the skill of all the modelling components based on both literature review and new analyses. These include, for the first time in a global-scale study, the validation of estimates of direct damages and population exposed against reported data from two global disaster datasets (see SI). To further increase the robustness of the analysis, we focus on trends and relative changes rather than absolute impacts.

We present river flood impacts under different levels of warming and socio-economic scenarios, as socio-economic changes are likely to continue to be a key driver of future flood risk [12,13]. We combine climate projections based on RCP8.5 with the Shared Socio-economic Pathway data on population, GDP and urbanization corresponding to SSP3 and SSP5 [23]. In all the analyses we assume present-day flood protection and vulnerability conditions in order to avoid hypotheses on the evolution therein up to the end of the century. As such, calculated impacts represent a reference scenario (no future adaptation) for policy makers and stakeholders. We present undiscounted impacts, as time discounting remains a key and controversial issue in evaluating the impacts of climate change [24,25]. In the following, results refer to the ensemble mean if not specified differently.
At present, each year about 58 million people are exposed to river flooding globally, more than half of them located in Asia. Limitations in observed global flood loss datasets restrict the quantification of the accuracy of these modelled estimates (see SI), yet this number is similar (<10% difference) to results reported by previous global studies [15]. At 3°C warming, this amount could range between 90 (113) and 186 (241) million people for SSP5 (SSP3), with an average increase of more than 120% (188%) (Figures 1b - S3b) compared to present. In the case of limiting warming to 2°C, an increase of 76% (102%) in the ensemble mean is expected, while 50% (60%) more people than now would be exposed if the ambitious mitigation target of 1.5°C is reached. The higher numbers of people exposed to flooding under SSP3 relate to the stronger population growth projected in South-Asia, Southeast Asia, Sub-Saharan Africa and South-America under this scenario. Comparison with a climate-only scenario based on static population (Figure S2) shows that climate change dominates the dynamics in future population exposed to flooding. The strongest rise in population exposed is projected in Asia and parts of Africa, South-America and Western Europe (Figures 1a, S3a). In a 3°C warmer climate, people exposed to river floods could more than triple in India, Bangladesh, Niger, Egypt, Ireland, the UK and Ecuador under both SSPs. Contrary to the global trend, population exposed to floods is projected to decrease with warming in a number of countries located in the Middle East, Eastern Europe and North Africa, due to the projected decrease in precipitation [21].

Global flood mortality shows a more pronounced rise with warming, from an average of nearly 5,700 fatalities per year in the reference climate to 9,700 (+70%), 11,500 (+103%), and 15,900 (+180%) for 1.5, 2 and 3°C global warming, respectively, under SSP5 (Figure 1c). Under SPP3, fatalities are projected to be higher and amount to 10,400 (+83%), 13,300 (+134%) and 20,800 (+265%) for the SWLs (Figure S3c). Under both scenarios of socio-economic development the range of ensemble results widens with the level of warming, suggesting a larger uncertainty in climate change and impacts with higher levels of global warming.
**Figure 1. Impacts on population under the SSP5 scenario.** Spatial distribution of the relative increase in the number of people exposed to floods under 3°C global warming with respect to the reference period (1a). Darker blue indicates higher relative increase. Hatching indicates that the confidence level of the average change is less than 90%. Number of people exposed (1b) and killed (1c) aggregated at macro-region scale (Figure S1) in the reference period (dashed grey) and under different levels of warming (1.5°C in grey, 2°C in blue, 3°C in red). Filled bars reflect the ensemble-average, with the error bars indicating the ensemble min and max. Histograms within the shaded background refer to left x-axis scale.

The more rapid rise of fatalities compared to people exposed at global scale implies a strong increase in exposure to flooding in countries with high human vulnerability, as exemplified by India (included in South Asia in Figures 1c and S3c), which combines high exposure, low flood protection and high mortality rates. At present it accounts for 18% (7%) of global mortality (people exposed) and these shares are projected to gradually climb with warming to reach 35% (16%) at 3°C warming for both SSP scenarios. Countries with higher income levels, for example China, show lower human vulnerability [7] and the high number of people exposed translates into lower mortality compared to South Asia (China represents ~18% of global people currently exposed while accounting for ~12% of global mortality).

At present, global direct river flood damages are estimated to be 110 billion €/year on average. The estimate is comparable (~10% to 90% higher) with previous global studies [2,4]. The difference (more than a factor two) between simulated and observed losses are within the accuracy currently attainable by impact models, given the inherent limitations of global models and the large uncertainty in global loss datasets (see SI for more details).

For the SSP5 socio-economic scenario global direct flood damages are projected to gradually rise to 375 (+240%), 687 (+520%), and nearly 1,250 (+1000%) billion €/year under the three considered levels of warming, respectively (Figure 2). For SSP3, the rise in absolute direct damages is considerably smaller (+160%, +320 and +620, respectively; Figure S4), reflecting the slower economic growth projected under this scenario. More than half (56%) of present global direct losses occur in Asia, predominantly in China (42%), followed by Europe (22%), the Americas (9%), Oceania (7%) and Africa (6%). The share in global absolute damages for
Asia is projected to grow steadily to 76% for SSP5 and 78% for SSP3 under 3°C warming, with similar shares consistently projected by all ensemble members.

In several regions of the world, direct damages as share of GDP decreases with warming. This is especially true for fast growing economies where the rise in direct damages is outpaced by the strong projected rise in GDP, which follows from the power law relation between construction costs and GDP used to adjust the damage relations (see Methods). The share of direct damage in GDP is therefore also lower under SSP5 compared to SSP3, even though the reverse is true if damages are expressed in absolute terms (Figures 2 and S4). The global ratio is mainly determined by the shares and sizes (weights) of the regional economies, with large weight coming from Western Europe, North America, Japan and Korea.

At global scale, the largest part of direct losses relates to damage to capital (commercial, industrial and infrastructure) and residential buildings, with a minor contribution of agricultural production losses (Figures 2 – S4). In low-income regions with a higher share of agriculture in GDP [26], like South and Southeast Asia, agricultural damages are more pronounced.

Figure 2. Direct flood damages for the baseline period and future warming levels under the SSP5 scenario. Damages are expressed in billion€ (upper graphs) and as a share of GDP (lower graphs), aggregated at macro-region scale (see Figure S1). Filled bars reflect the ensemble-average, with the spread indicated by the ensemble min and max. Colours indicate the share of
each damaged sector (green for agriculture, yellow for capital and blue for residential).

Histograms within the shaded background refer to left x-axis scale.

The increase in direct flood damages leads to welfare losses for all regions at all warming levels. The global welfare reduction with respect to a scenario without climate change is projected to reach 0.27%, 0.40% and 0.53% at 1.5, 2 and 3°C warming, respectively, for SSP5 (Figure 3, upper graphs). Under the SSP3 scenario, which implies slower development and lower absolute welfare levels, direct damages become more relevant with the increase of warming levels and produce higher relative welfare losses compared to SSP5 (Figure S5, upper graphs).

The global figures on welfare loss mask significant inequalities across regions. Some advanced economies like Japan & Korea and North America are barely affected. However, at 3°C warming, largely populated developing regions, such as China and South Asia (which includes India) would undergo welfare losses much higher than the global average. Welfare losses close to the global average are projected for Southeast Asia, Oceania, Russia, Sub-Saharan Africa and the Rest of Former Soviet Union (FSU) region, while the remaining regions would face lower welfare losses. Higher warming implies not only greater mean welfare reductions but also higher uncertainty in potential impacts. For example, in the worst-case scenario China has a welfare reduction of 3% at 3°C warming.

The lower graphs of Figure 3 show that the ratio of welfare loss to direct damage increases with warming (time) because of the persistence of the damages in the economy. As a result, welfare losses can be close to twice the direct damage under 3°C warming and SSP5 in some regions. The ratios of welfare losses to direct damages are smaller for the SSP3 case, because direct damages grow slower with time (see the discussion in SI).

Another relevant aspect of the economic analysis concerns the redistribution of the economic impacts due to international trade [27], which is not captured by MaGE. Damages in one region could affect its trading partners, aggravating or alleviating their economic losses (see discussion in Section S3).
Figure 3: Welfare losses for future warming levels under the SSP5 scenario. Top: regional distributions of welfare change from river floods at the three warming levels considered under the SSP5 scenario (with a table reporting mean values for each WL). Welfare changes are expressed as % change compared to a reference MaGE model run that considers only socio-economic projections without warming-induced changes in direct flood damage. Bottom: ratio of welfare losses to direct damage (both in absolute terms). In all graphs and tables, data for the 1.5°C WL are indicated in black, 2°C in blue and 3°C in red.

Besides the climatic and hydrological uncertainty represented by the ensemble spread through our analyses, it is important to bear in mind that flood impact estimates are affected by additional uncertainties, the magnitude of which could not be completely defined despite the validation analyses performed (see discussion in SI). Also, our framework does not include coastal, pluvial and flash flooding processes. Notwithstanding these limitations, results do show consistent trends in risk projections under different levels of warming. The combined analysis of potential future impacts and current trends in flood risk may provide indications about the progress towards the objective of substantially reducing global disaster impacts by 2030, set by the Sendai Framework [9]. Even in the case that global warming levels are successfully
maintained below 1.5°C, if current protection and vulnerability levels are not improved a large number of countries will face severe increases in flood impacts on population and economy.

Most of the additional burden will affect low- and middle-income countries, which will need to find effective adaptation strategies to successfully manage increased flood risk.

The declining trends in social and economic flood vulnerability observed for most of world regions and income levels [7,12] suggest that ongoing efforts at global scale could partially offset the effects of climate and socio-economic changes on flood hazard and exposure. For instance, China carried out large infrastructural investments over the last 20 years to increase flood protection levels. However, vulnerability levels have been found to vary significantly across regions, income levels and period considered, and are highly dependent on models and datasets used [7]. Even if it is almost certain that adaptation to floods will continue, it is unclear where, how and how much adaptation will take place, as future adaptation trends cannot be easily inferred from past trends. In regions with low flood protection levels and valuable assets at risk (e.g. urban areas) there is room for reducing hazard through structural measures that have been widely implemented in high-income countries (e.g., dykes, retention systems) [4].

However, these measures require considerable economic investments that might not be available for lower income countries, aside the maladaptive nature of large flood protection infrastructures [28]). Alternatively, a wide range of non-structural and accommodation measures may be considered [29], such as loss sharing mechanisms [30], flood monitoring and forecasting [31], strategic relocation of structures and people [32]. To progress further, we believe that more research efforts should aim at developing plausible adaptation scenarios to flood risk based on cost-benefit analyses of potential measures in different geographical and socio-economic contexts, observed changes in vulnerability and future socio-economic development, including the interplay between society and disasters [33]. Similarly to the widely used SSPs socio-economic projections, such scenarios would complement ongoing efforts in improving global flood risk modelling and help provide a more complete picture of future flood risk.
Main Text references


3) UNFCC. Adoption of the Paris Agreement. FCCC/CP/2015/L.9 (2015).


**Methods**

**Scenarios**

We present changes in average annual human and welfare losses between the reference period (1976-2005) and 30 year time windows centred on the year that global average temperature is 1.5, 2 and 3°C above preindustrial temperature (Table S1). Note that, while the pre-industrial period is not explicitly defined in the Paris Agreement, the IPCC 5th Assessment Report used the 1850-1900 period as a proxy [34]. Considering this period as reference, the 1976-2005 baseline is on average 0.7°C warmer. The year of passing these Specific Warming Levels (SWLs) is defined as the first time that the 30 year running mean of the projected global averaged annual mean temperature surpasses the SWL.

Climate projections are based on RCP 8.5 only as they typically exceed 3°C warming by the end of the current century, hence all three considered SWLs could be analysed in the same set of simulations [35]. This assumes that flood hazard and impact levels at SWLs are independent of the timing of the warming and of the pathway of greenhouse gas concentrations [36]. We assess flood impacts for the SWLs for socio-economic conditions under the two Shared Socio-economic Pathways (SSP3 and SSP5) that are consistent with RCP8.5 [23]. We used spatially distributed datasets of population from [37], while we applied country scale projections of GDP per capita [36] and regional scale projections of urban and cropland changes [38].
River flood database

We constructed a river flood database employing the ISIMIP fast track multi-model hydrological ensemble [21]. The ensemble comprises daily runoff simulations of 50 combinations of 10 global hydrological models (GHMs) and bias-corrected forcing from 5 global climate models (GCMs), all of them included also in the fifth phase of the Climate Model Intercomparison Project (CMIP5) [39], under a Representative Concentration Pathway (RCP) 8.5 scenario.

The ISIMIP ensemble is designed to represent the variety of state-of-the-art models in their respective field. Tables S1 and S2 provide a list of the global circulation models (GCMs, Table S2) and global hydrological models (GHMs, Table S3) applied for the study. Additional details can be found in the corresponding references and in Warszawski et al [40]. The ISIMIP model ensemble represents a collection of many well-established models from different modelling centres worldwide.

The model climate forcing, including all the variables used to drive the hydrological models, were bias corrected with the statistical trend-preserving method documented in Hempel et al. [41]. The method is based on transfer functions generated to map the distribution of the simulated historical data to that of the observations. Those transfer functions are subsequently applied to correct the future projections. Key features of this method include preserving the absolute changes in monthly temperature and relative changes in monthly precipitation, and correcting the daily variability around the monthly mean. Note that the baseline period 1976-2005 is based on model simulations and not on observed climatology. The skill of GCMs in simulating extreme precipitation is evaluated in SI and summarized in section “Analysis and evaluation of results”.

Bias corrected climate forcing was used as input for the ten hydrological models to produce global 0.5° gridded daily runoff simulations for the total simulation period (1976-2100). Runoff simulations were then used to produce river discharges downscaled to 0.25° resolution with the CaMa-Flood model [42]. The downscaling of runoff forcing is performed by the mass-conservative routing scheme in CaMa-Flood, therefore the downscaled daily river flow is
simply obtained as output from the model. The skill of GHMs in simulating extreme river flows is evaluated in SI and summarized in section “Analysis and evaluation of results”.

For each of the 50 ensemble members, in each 0.25° pixel a Generalised Extreme Value (GEV) distribution was fitted through the annual maximum discharges of the downscaled daily river flow data for the baseline period. Simulated annual river discharges for each time window were then translated into recurrence frequencies from this distribution to understand to what baseline recurrence frequency future maxima correspond. If the thus obtained recurrence frequency of the annual maximum discharges exceed the local flood protection level \([43]\), CaMa-Flood was used to obtain the corresponding inundation area at 0.5 min resolution (approximately 5 km at equator), which is the resolution used to calculate flood impacts. More in detail, inundation depths computed at 0.25° from annual maximum discharges were first downscaled onto a 18 arc-second (approximately 500 m at the equator) high-resolution DEM by determining whether the elevation of the DEM pixels was lower than the modelled water level. This method is similar to Winsemius et al. \([44]\). Because CaMa-Flood incorporates the same high-resolution sub-grid topography, the water volume before and after downscaling is consistent. The 18 arc-second inundation map was then upscaled to a 2.5-arc minute horizontal resolution to overlay population data in the same horizontal resolution. In addition, the information on inundated area fraction calculated at 18 arc-second resolution for each cell is preserved and used to adjust the impact calculation. In SI we perform a detailed validation of the inundation maps used in the present work, with the main outcomes summarized in section “Analysis and evaluation of Results”.

Note that in order to avoid bias in the 10 hydrological models we did not calculate inundation areas directly from discharge values. Instead, we followed the approach by Hirabayashi et al. \([10]\) and we linked recurrence frequency to water depth according to depth - frequency relationships based on a retrospective MATSIRO simulation forced by observation-based climate data with the CaMa-Flood river routing (the retrospective simulation was the same as in \([10]\)).

In the analysis we used present-day flood protection levels obtained from FLOPROS \([44]\) to calculate present and future flood risk, thus assuming no further investments to upgrade flood
protection. For instance, a flood protection standard set to protect against events with 100 year
return period (RP) under baseline climate will in the future protect against events with the same
intensity. However, events with such intensity may become more (or less) frequent, meaning
that the protection standard expressed in future return frequency will in fact be lower (higher).

Flood risk calculation: direct socio-economic impacts
In our modelling framework, direct socio-economic impacts are evaluated considering all flood
events occurred in the given reference period (e.g. the baseline period or future warming
scenarios) and then calculating the annual average value. Note that a flood event is defined as
any discharge event with an estimated return period above the design level of local flood
defences.
Population exposed by each simulated flood event for the baseline was obtained by overlaying
flood inundation maps with the global population distribution from the Global Human
at 250 m spatial resolution were aggregated to match the resolution of the flood maps. An
evaluation of the methodology to calculate population exposed is presented in the SI. For the
SSP3 and SSP5 socio-economic scenarios future population distribution was obtained from [37]
available at 1/8 resolution and re-gridded to the resolution of the flood maps. For the
computation of mortality rates we followed the approach proposed by [7] and [12]. Fatalities
from river flooding per country were collected for the period 2006-2015 from EM-DAT [46]
(http://www.emdat.be/) and NatCatSERVICE of Munich RE [19]
(http://www.munichre.com/natcatservice). Mortality rates were then defined as the ratio of the
annual average fatalities recorded in EM-DAT and NatCatSERVICE to the modelled annual
average exposed population over this period. Mortality rates were calculated over sets of
countries grouped by region and income level as defined by the World Bank. Note that we used
constant present-day mortality rates to calculate future projections, in order to avoid hypotheses
on future adaptation.

Direct damages were calculated by combining the simulated inundation extent and depth for
each flood event with country specific stage-damage functions [47] for five sectors (i.e.,
residential, commercial, industrial, infrastructures and agriculture) and maps of percent land use
pertaining to each sector derived from the GlobCover
(http://due.esrin.esa.int/page_globcover.php) at 10 second (~300 m) resolution [48]. The extent
of urban land use was estimated assuming percentages of occupation for each sector in cells
belonging to urban areas. We used uniform percentages at global scale based the results of a set
of studies carried out in cities in different continents, who reported similar average percentages
of occupation of different sectors in cities across the globe (see references in [47] for more
details). The calculation of direct flood damages under SSP scenarios was performed by scaling
values and extent of exposed assets according to GDP and land use projections. To scale
exposure values we used a set of power law functions elaborated by Huizinga et al. [47] that
relate GDP per capita and construction costs (as a proxy of damages) at global scale for the
considered economic sectors. Note that this approach implies that damages are not proportional
to GDP per capita. Rather the power law functions show exponents smaller than one, indicating
the construction costs and direct damages grow slower than GDP per capita. The same approach
has also been used in the validation of the simulated direct damages against reported damages
from the global loss datasets (see Supplementary Information). To calculate the future spatial
exposure of assets, present-day land use maps were scaled using macro-regional projections of
urban and cropland changes [38].

Flood risk calculation: welfare impacts

Welfare impacts (measured as changes in consumption) have been calculated with MaGE, a
global econometric growth model [22]. The model is based on a large database of economic
variables at country level, mainly coming from international organisation such as the World
Bank, International Monetary Fund and United Nations [20]. In the model, the growth of an
economy depends on investments, which are used to replace a capital stock that depreciates at a
constant rate. The investment results from savings in the economy which, in turn, depends on
the age structure of the population and on its income. MaGE is a dynamic recursive model,
which means that an impact on the GDP or on the capital stock occurring in one year has
persistent effects on the economic performance in subsequent periods. In particular, the growth
model captures the persistence of impacts via the capital accumulation process (SI Section S4).
The reduction in output (due to agriculture damages and a lower capital stock) affects
production and consumption levels of the following years, even in the absence of additional
flood damages in those years. The three categories of direct flood damage are interpreted
differently: agriculture damage dampens production, damage to infrastructures reduces the
capital stock of the economy and the damage to residential buildings reduces household
consumption. More in detail, the destruction of the capital input, i.e. infrastructures, buildings or
machineries, and the loss of agricultural production lowers the available national income in the
year of the disaster, which in turn affects negatively the level of domestic investments,
calculated as a function of income. This initial decrease is aggravated because, in order to repair
the damage, the government or the firms must disinvest from other productive activities,
inducing a generalized reduction of the total capital stock of the economy. A similar effect
operates in the case of the destruction of residential buildings; to repair their houses, households
must reduce consumption in other goods, which induces a generalised decrease of their overall
welfare. In addition, a lower national income causes also the domestic savings to fall due to the
causal relationship between income level and saving rate. Because domestic investments are
financed partly by domestic savings, the level of investments of the economy falls further and
reduces the capital stock. Finally, the recursive nature of capital stock accumulation, investment
and saving decision processes make these initial effects persistent in the economy.
The narratives of the SSPs regarding technological and institutional development are translated
into the MaGE model parameters according to \[49\]. The underlying assumptions regarding total
population, population age structure and the education level are based on the IIASA projections
for SSP3 and SSP5 \[50\]. We report changes in welfare compared to a reference model run in
which MaGE is forced with the socio-economic projections without additional shocks from
changes in direct flood damage due to climate change.

**Analysis and evaluation of results**

Ensemble-average (over the 50 runs) human and welfare loss estimates were aggregated at
country, macro-region (Figure S1) and global scale to analyse results and trends.
The agreement of country aggregated impact estimates among the ensemble of 50 combinations
of climate and hydrological models was assessed with the Student’s t-test on the projected
changes in impact between the baseline and period centred on each SWL (see Figure 1 for the
results regarding affected population). Note however that in larger countries (e.g. Russia) flood
impacts may differ within country sub-regions, due to different trends in precipitation and river streamflow [21].

All impact estimates are expressed in €2010 values. The welfare impacts are additional effects due to changes in flood hazard impacting on society under the specific warming levels as the baseline flood damages are implicitly assumed in the base year of the economic model.

In order to evaluate the overall reliability of the modelling framework, in SI we investigated the possible sources of uncertainties of each hazard, exposure, and vulnerability component. Here, we summarize the main outcomes of the analysis regarding the skill of the modelling components. Most of the models and datasets have been validated to some extent against observed or higher resolution data in past research works. Kharin et al. [51] found that global circulation models included in the CMIP5 database can reproduce precipitation extremes in terms of 20-year return values, with discrepancies in the 20% range, when compared with observational data sets. Uncertainties are larger in the tropics and can locally exceed 50%, though observational uncertainty is also significant for extreme [52]. Zhao et al. [53] compared with monthly and daily discharge observations the peak discharge simulated by nine GHMs (including some models used in the present study) coupled with CaMa-Flood routing. For the single models, land area-based bias on annual discharge maxima were between 41% and 52%, comparable with other global-scale models. Hirabayashi et al [10] evaluated discharges simulated by the CaMa-Flood model coupled with MATSIRO hydrological models at 32 selected river basins worldwide, and found that the overall bias across all basins, for multi-model means of annual average, annual maximum, and 100-year discharges were < 22%, < 38% and < 43%, respectively.

For the inundation mapping component, we performed a dedicated validation exercise with official hazard maps because no sufficient literature was found. We found that, depending on map resolution and study area, simulated flood maps have an accuracy similar to other global scale models, ranging between 0.62 and 0.17 (i.e. only 62% - 17% of the flooded and not flooded areas are correctly identified by the model). When used to calculated impacts, the simulated flood maps could identify exposed population with ~50% overestimation in respect to estimates based on official flood maps. More details are included in section S6 of the Supplement.
Finally, the overall reliability of the modelling framework was tested by performing a detailed quantitative evaluation of the modelled direct impacts against historical loss estimates derived from global disaster databases and recent global flood risk assessments. The main outcomes are summarized in the main text while the detailed analysis is reported in the SI.

**Data availability**

The global annual maps of impacts (e.g. direct economic damage and affected population) and tabular data at country level (e.g. people affected and mortality rates, welfare impacts) produced by the model ensemble are freely accessible at the ISIMIP portal (https://www.isimip.org/outputdata/).

**Methods references**


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**Author Contributions**

L.F. and J.C.C. designed the flood risk modelling framework; F.D and L.A. computed direct socio-economic impacts; I.M., W.S. and J.C.C. calculated economic impacts on welfare; F.Z. and K.F. performed flood simulations and produced inundation maps; Y.H. contributed to the calculation of mortality; A.B. elaborated exposure maps and figures; R.A.B. developed the SWL approach; F.D. performed validation exercises; all authors contributed to the writing of the paper.