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River Flood Risk

Scientific justification of the information produced for the chapter 'Flooding' of 'The Geography of Future Water Challenges' (2018), The Hague: PBL Netherlands Environmental Assessment Agency .

pbl.nl/future-water-challenges

Main messages

- Without any further adaptation, the number of people around the world affected by river flooding may rise (under the most extreme scenario) from currently 39 million people per year on average to 134 million people per year, by 2050. About two thirds of this growth will be due to increases in the severity and frequency of flooding as a result of climate change, and one third due to population growth in flood-prone areas.
- The largest numbers of people affected by river flooding relative to the total population are to be found in countries within Southeast Asia and Equatorial Africa.
- Many of the countries in our top 20 are also politically unstable or conflict-prone areas.
- From the top 20 most affected countries (applying the worst-case scenario), the largest increases in the number of people affected by river flooding are projected for Pakistan, Nepal, Myanmar, Sudan and Bangladesh, if no further measures are taken. Increases of 100% or more can be expected. Most of these increases are due to climate change, although non-balanced growth in population in flood-prone regions represents a strong second driver.
- The top 3 countries with the most urban damage annually, both in present-day conditions and in 2050 projections, are the United States, China and India. It is important to note that these countries, given their strong capital position, can cope much more easily with the impact of flooding than poorer countries (see e.g. Winsemius et al., 2015).
- In terms of urban damage relative to a country's GDP, many countries in Africa and a number of countries in South America and Southeast Asia (Vietnam, Cambodia) are in the top 20 most vulnerable countries. This means that river flooding hits these countries much harder than countries with more capital that suffer more damage in absolute terms (in US dollars (USD)).
- Socio-economic growth results in very large increases in the value of assets and number of people exposed to flooding. This is exemplified by the fact that, even if flood protection were to be improved between 2010 and 2050 to keep pace with climate change (with the level of flood protection thus effectively remaining the same), total global annual urban damage would increase

from USD 78 billion in 2010 to USD 395 billion by 2050. These numbers are based on the assumption that building standards and flood zoning practices stay the same between 2010 and 2050.

- Flood protection does help: present-day flood protection reduces the number of people affected annually on a global scale from about 2% to about 0.5% of the world's population.
- West Africa's agricultural production, in particular, is frequently affected by flooding. For example, the annual maize yield that is potentially affected, on average, is 13% (970t; standard deviation 4.5%) in the impacted areas. The region is strongly reliant upon its own food production, and should therefore be considered a hotspot.

1.1.1 Introduction

Globally, flood risks (river, coastal and pluvial) account for about one third of all losses due to natural hazards, and, over the last 30 years, economic losses have exceeded USD 1 trillion (2013 values) according to the NatCatSERVICE database of Munich Re (Munich Re, 2013). Not only does flooding entail a large cost for society, it is also highly disruptive and has a potentially significant impact on poorer people, aggravating the differences between rich and poor (Hallegatte et al., 2016). In this background document, we extended global assessments of river flood risks, to include the impact on people, the economy, and more specifically on agricultural yield (which has an indirect impact on people).

River flood risk has a **direct** impact on a number of Sustainable Development Goals:

- SDG 1. End poverty in all its forms everywhere: poor countries lack sufficient financial resources to adequately protect themselves against flooding. As a result, they are hit more often by flooding, leading to damage on a regular basis which in turn restricts economic growth.
- SDG 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture: floods destroy crops and lead to loss of yield. This can affect food availability particularly in regions that cannot afford to import food on a large scale.
- SDG 3. Ensure healthy lives and promote well-being for all at all ages: floods cause casualties and spread diseases and pollutants. In addition, repeated flooding causes stress among the local population.
- SDG 6. Ensure availability and sustainable management of water and sanitation for all: floods spread diseases and pollutants, and can pollute drinking water.
- SDG 13. Take urgent action to combat climate change and its impacts: climate change is likely to increase flood risks unless adequate adaptation strategies are implemented.

These impacts will be even worse in the case of coastal flooding: salt water pollutes freshwater reserves (even groundwater) for a long period of time, affecting the availability of freshwater resources and restricting land use for food production.

River flood risk also has an **indirect** impact on a number of Sustainable Development Goals:

- SDG 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all: repeated flooding affects the resilience of flood-prone regions. Businesses, for instances, avoid these areas. Thus, flood-prone regions can find themselves caught in a poverty trap that, in turn, leads to insufficient means to improve flood protection.
- SDG 9. Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation: similar to SDG 8. Industry and infrastructure in flood-prone regions suffer more from repeated flood damage than regions with good flood protection. As a result, investments in such areas are kept at a lower level.
- SDG 10. Reduce inequality within and among countries: the more flood-prone a region is, the more difficult it will be to make cities and communities there sustainable.
- SDG 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels: repeated flooding could lead to conflict as a result of its impact on poverty, hunger and migration. In

addition, the regions that are most flood-prone generally correspond to regions where governance is weak.

Global trends in flood risk so far: more exposure, more vulnerability, more disasters

Disaster risk is considered to be a combination of three components: *hazard* (the potentially dangerous naturally occurring event, such as a storm, heat wave or flood, its severity and frequency), *exposure* (of the population and economic assets located in hazard-prone areas), and *vulnerability* (the susceptibility of the exposed elements to damage from the hazard) (IPCC 2012). Hazard, exposure, and vulnerability are not static; they change over the course of time. Exposure, for instance, increases as the population grows in hazardous areas, and as improved socio-economic conditions raise the value of assets (Global Facility for Disaster Reduction and Recovery 2016).

The IPCC concludes with confidence that the increasing exposure of people and economic assets has been *the* major cause of long-term increases in economic losses from weather- and climate-related disasters (IPCC 2012). River flooding, in particular, occurs on a regular basis and causes ever more damage and affects a great number of people (IPCC 2014; Visser et al. 2014). The need to adapt is especially acute in developing countries in Asia, given that 14 of the top 20 urban agglomerations projected to have the greatest exposure to flooding in 2070 are in developing countries in this region (IPCC 2012).

Increasing exposure to flooding has been the main cause of the steeply rising trend in global river flood losses over the past decades. However, various analyses of historical loss databases have not yet been able to derive a clear link between climate change and these increasing losses (Visser et al., 2014). This trend will continue to rise: between 2010 and 2050, the estimated population that is likely to be exposed to river and coastal flooding worldwide is expected to increase from 992 million to 1.3 billion (Jongman et al., 2012 in: Global Facility for Disaster Reduction and Recovery 2016).

1.1.2 Objective

The objective of this document is to provide estimates on global scale river flood risk for 2010 (the current situation) and 2050, and thereby show those areas that are particularly vulnerable to river flooding: the regions of the world where the relatively poor are hit disproportionately badly—the hotspots. In contrast to previous works, we focus here on the impact on people, expressed in terms of the average number of people affected in a given area as well as the percentage of affected people within that area. By affected people we mean people who are directly impacted by floodwater, i.e. not only those who become injured or die, but also even those who only have to deal with wet feet. In addition, we will also present estimates of annual average economic damage in 2010 and (projections for) 2050.

Our work is based upon earlier work using the GLOFRIS global flood risk model (Ward et al. 2013; Winsemius et al. 2013, 2015). We show how flood risk, expressed in terms of the number of people affected per year, could change due to the combination of climate and socio-economic changes. We also show the relative contribution of climate change and the increase (or decrease) in population in flood-prone areas to the number of people affected. We show how much flood protection measures have reduced flood risks. Our analyses are, for now, limited to river flood risks.

Finally, we provide the first ever assessment of the impact of river flooding on global food production. We did this because food production is essential to the well-being of people, particularly in areas where people have to rely on local food production. Hence, affected food production can act as an indicator of an indirect impact on people and the economy. We decided to do this by assessing the affected potential yield of four major crops. However, our analysis is currently limited to past impacts for the period from 1960 to 1999. For different regions around the world, we show whether flooding is likely to occur during the growing season and then assess the potential impact on food production.

1.1.3 Methods and Analysis

Number of affected people and economic damage

Our calculations are based on the GLOFRIS modelling framework, which estimates global large-scale river flood risk (not pluvial or flash flooding), and which comprises a hydrological flood model PCRGLOB-WB (Van Beek et al. 2011) and an impact model forced by time series of current and future climate and socio-economic projections (Ward et al., 2013; Winsemius et al., 2013). We used GLOFRIS to estimate the number of people affected by flooding and the resultant urban damage, with multiple return periods (2, 5, 10, 25, 50, 100, 250, 500, and 1000 years). These were subsequently integrated to derive the annual expected number of people affected and the annual expected damage. We then estimated the number of affected people, relative to the total population, in spatial units (water provinces and countries) (Figure 1). The same was done for damage, but then relative to the unit's GDP. To quantify present-day risk conditions, we forced GLOFRIS using meteorological reanalysis data (Weedon et al., 2011) to provide hazard maps for several return periods, and using current gridded population (Bright et al., 2010) to represent the current potentially exposed population. For the future projections, we used bias-corrected meteorological data from an ensemble of 5 Global Climate Models (GCMs) taken from CMIP5 (Taylor et al. 2012) as provided by the ISI-MIP project (Hempel et al., 2013). We used SSP socio-economic projections (O'Neill et al., 2012) downscaled from national to grid-cell level using a set of algorithms (van Vuuren et al., 2007), updated to also take account of differences between rural and urban growth rates in the future projections. We used the chosen scenario combinations to assess future changes in affected population for each possible return period.

This document only shows the results for the SSP2 and RCP6.0 scenario combination, although results are quite robust across all scenarios. The data for all scenarios is provided as excel files and the results for the other scenario combinations can therefore be easily reproduced.

Effect of adaptation

To date, river flood risk estimates have been done without considering flood protection measures. We, however, used the first ever global database of protection standards, FLOPROS (Scussolini et al. 2016), to assess the effect of flood protection on flood risk globally. We assessed present-day flood risks, both with and without taking existing flood protection into consideration, and show to what extent flood protection has contributed to a reduction in the number of affected people. Furthermore, for future conditions, we demonstrate three different adaptation storylines:

- No adaptation: i.e. we assume that in the future the level of dykes and other protection measures will remain the same. In this case, when flooding events become more (or less) frequent and more (or less) severe, the protection standard will become lower (or higher);
- Full adaptation: i.e. we assume that the world will adapt its dykes and other measures so that the protection standard remains the same, so that, with increasing frequency or severity of flooding events, dykes will be raised to ensure the level of flood protection remains the same. In the same way, dykes will be lowered (!) if climate change would result in less extreme flooding;
- Double protection: we assume that countries will double their level of protection, compared to the current level. For instance, a country that has 5-year flood protection at present would be assigned a 10-year flood protection standard.

These three adaptation storylines can be used to gain an insight into how adaptation can lower flood risk.

Impact of flooding on agricultural yield

Finally, we assessed the potentially affected agricultural yield (Figure 1). We focussed on the four key global crops maize, rice, soybeans and temperate cereals, and distinguished between rain-fed and irrigated agriculture. Maize, rice, soy and wheat are the four crops that make up a major part of the scientific literature on climate impacts on crops. These crops collectively account for approximately 20% of the value of global agricultural production, 65% of the harvested crop area, and just under 50% of calories directly consumed (FAO, 2016 in: Moore et al., 2017).

For agriculture the loss potential is a question of seasonality as opposed to other damage categories, for example flood damage to buildings. We identified present-day agricultural impact hotspots by analysing the period from 1960 to 1999 by month. Forcing GLOFRIS with EU-WATCH data (Weedon et al. 2011), we derived monthly hazard maps for this period. The agricultural input to GLOFRIS consisted of several components. Agricultural production was estimated using the coupled hydrology and dynamic vegetation model LPJmL (Sitch et al., 2003, Bondeau et al., 2007) which has been widely applied to study the effects of climate change on water availability and requirements for food production on a global scale (Gerten et al., 2011, Falkenmark et al., 2009). Following the approach of Biemans et al. (2016), and calibrated for the period 1990 to 2000, we simulated yearly potential production. As the impact of flooding on agriculture is highly dependent upon when that flooding occurs (Brémond et al., 2013), the spatially different growing seasons also needed to be considered. MIRCA2000 (Portmann, 2011) is a global spatially explicit monthly dataset on irrigated and rain-fed crop areas. We used this dataset to establish which areas might be inundated during the growing season of each crop, for both irrigated and rain-fed production. We calculated the potentially affected agricultural yield by converting the potential production to crop yield per Water Province, for which we applied the cropland fractions from LPJmL.

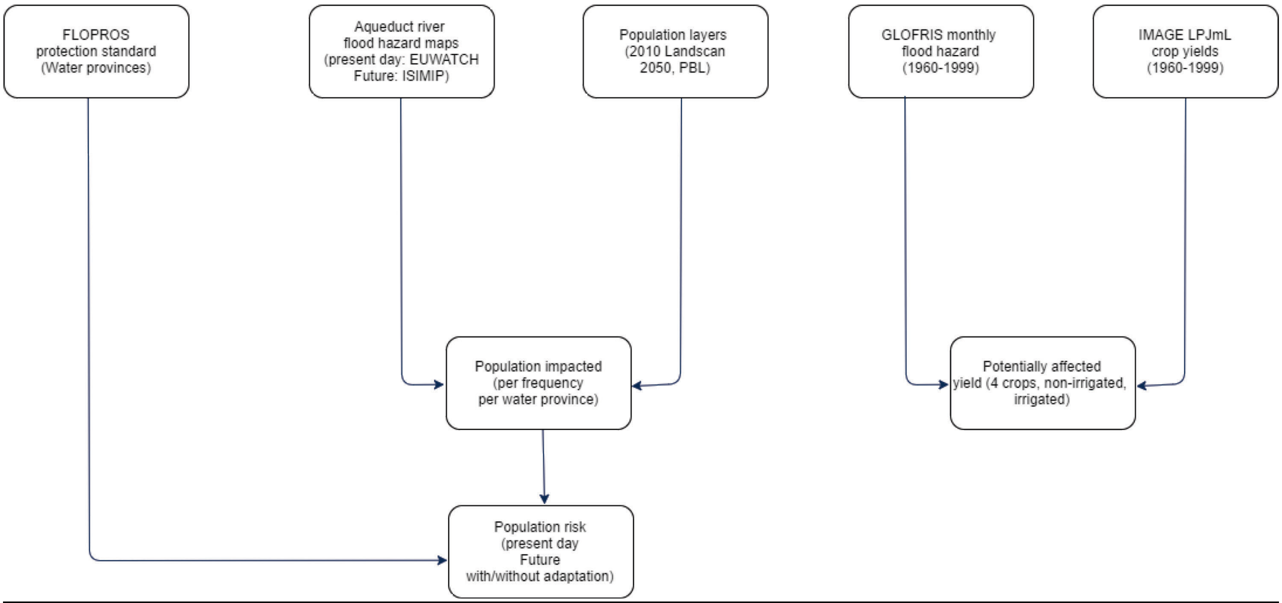

Figure 1. Model set-up to estimate the impact of flooding and to show annually expected number of affected people, annually expected damage, and potentially affected crop yield for both the present-day and the future (2050).

1.1.4 Results

Present-day affected population

Assuming the estimated flood protection standards in FLOPROS, the absolute majority of affected people can be found in Southeast Asia (Figure 2). Population density in Southeast Asia is among the greatest of all the distinguished regions in the world. This region also has a particularly low protection standard against flooding. In relative terms, however, the highest risks are found for countries around the equator in Africa (Figure 3). NB: we only looked at flooding from large rivers with large catchment areas (> ~5,000–10,000 km^2); countries that only have small river catchments were not, therefore, included in our calculations. A typical example of this is Indonesia, which has river catchments that are relatively small even though the country does experience significant flooding. Europe and the United States exhibit very low numbers of annually affected people, relative to their total populations, and this is mainly due to the high protection standards in these countries (see Figure 4). However, even if we were to assume that there is no protection at all globally, we would still see southern African countries as the major risk-prone areas. A no protection scenario is delivered as part of this project, but is not displayed here.

The effect of flood protection on reducing the number of people affected by flooding annually is presented in Figure 5. In the absence of flood protection, an average of 151 million people (2% of the world's population) would be at risk of flooding annually. Present-day protection has reduced this number to 39 million people annually (0.56% of the world's population). The latter figure corresponds to data in the global database EM-DAT[1] which shows that 69 million people per year are affected by flooding and is thus in the same order of magnitude. The difference between 39 and 69 million people could be due to differences in the definition of affected people (and thus who are included in the count as affected), uncertainties in our models and in the estimates of the level of flood protection, or the fact that EM-DAT also includes people affected by smaller scale events such as flash flooding.

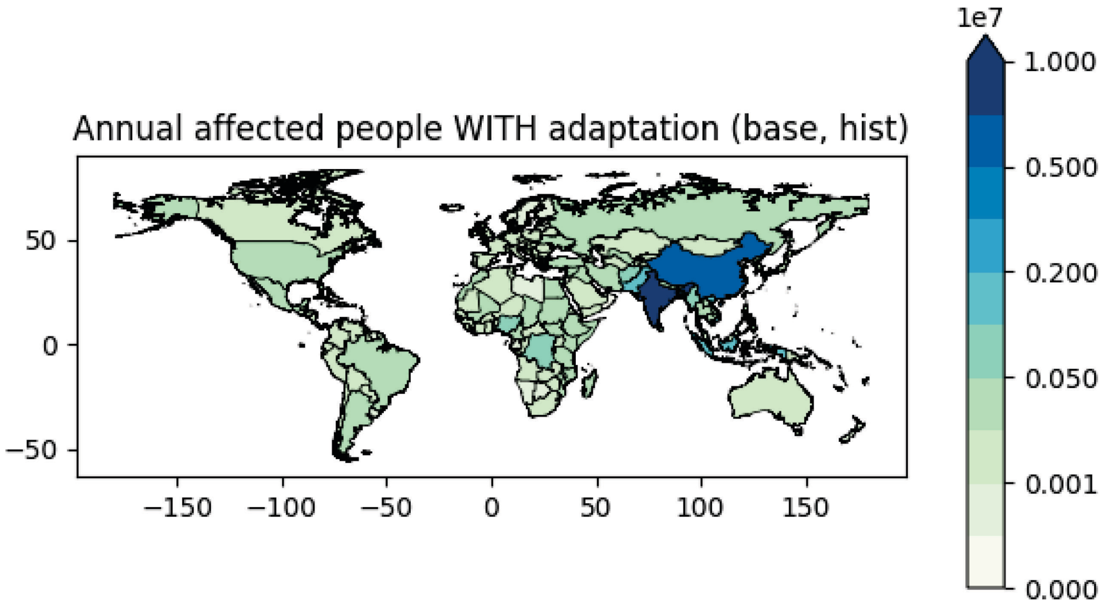

Figure 2. Absolute annual average number of people affected in present-day climatic and socio-economic conditions, assuming the estimated flood protection standards in FLOPROS.

[1] http://www.em-dat/net

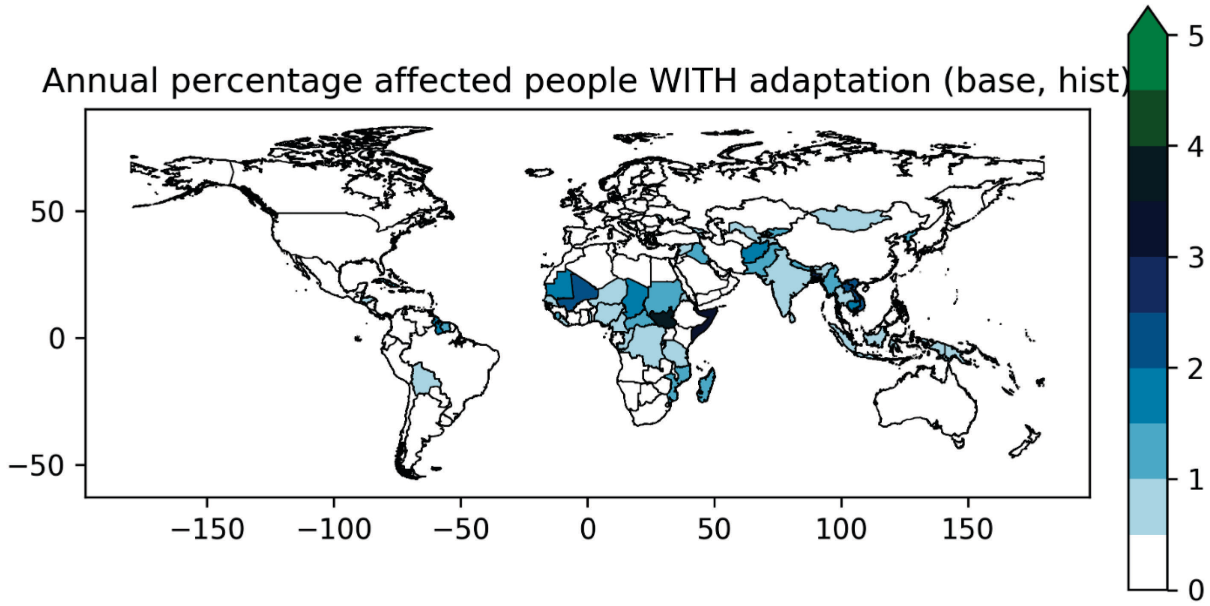

Figure 3. The percentage of the population affected by flooding annually, in the present-day, assuming the estimated flood protection standards in FLOPROS.

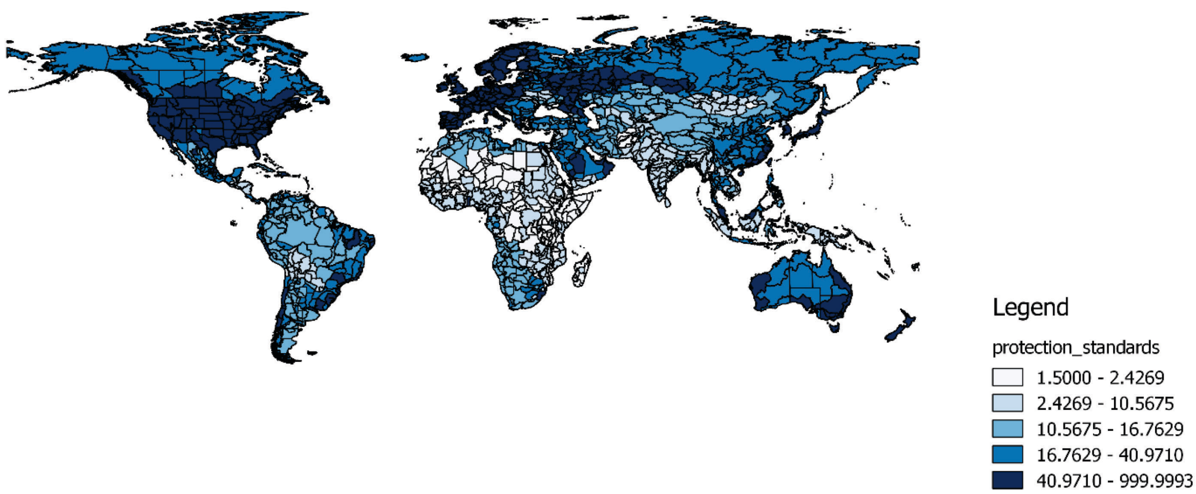

Figure 4. FLOPROS protection standards, subdivided over water provinces. Unit is return period in years.

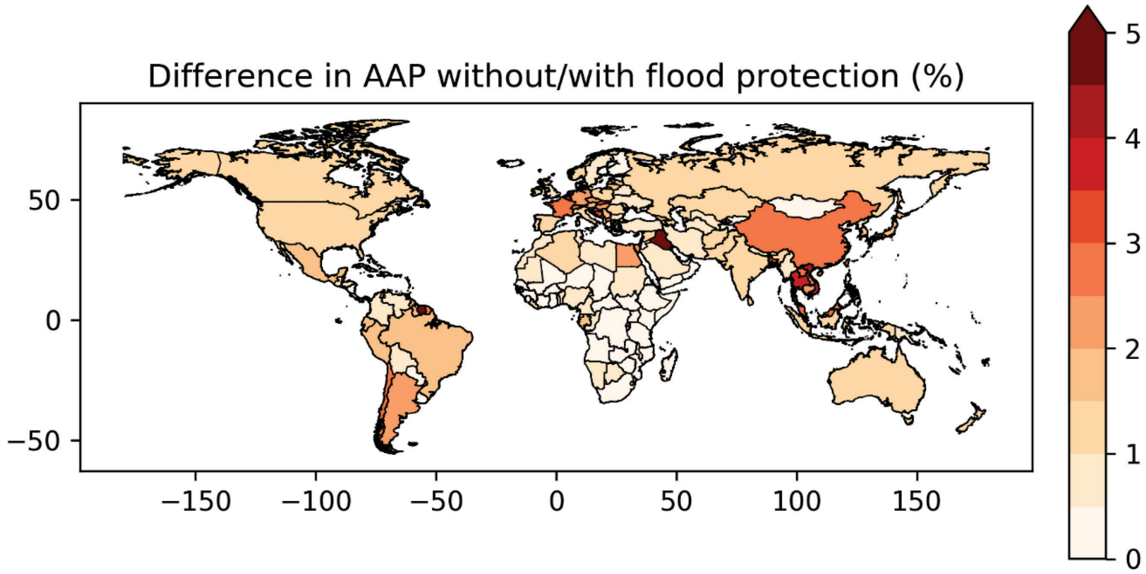

Figure 5. Added value of flood protection in preventing people from being affected, in the present-day. The figure shows the difference between the percentage of people affected per year with and without flood protection.

Changes in risk and hotspots

Without any further adaptation, the number of people around the world who are affected by river flooding may grow (in the most extreme scenario) from currently 39 million people per year (on average) to 134 million people per year by 2050 (SSP2 RCP6.0 scenario). About two thirds of this is due to increases in the severity and frequency of flooding as a result of climate change; one third is due to population growth, particularly in flood-prone areas. Figure 6 shows the top 20 countries with the largest numbers of people affected, annually. The colours of the circular plots show to what extent the changes in flood risk, from now to 2050, result from socio-economic growth or climate change. The plots in this graph are biased towards very large countries or countries with a large population. The graph thus obscures areas where the number of people affected is large compared to the total population.

This is why we then turned to look at risk in terms of relative numbers. Figure 7 presents the top 20 countries in terms of the average number of people affected by river flooding annually, but now as a percentage of the total population of the country, in present-day conditions and for 2050 (with no further investment in flood protection between 2010 and 2050). We have only showed countries where the absolute number of people affected annually is at least 50,000. This is one example for SSP2/RCP6.0 and we used the average of the 5 GCM model runs used to represent changes due to climate change (NB: results of individual GCM runs are available as a deliverable of this project).

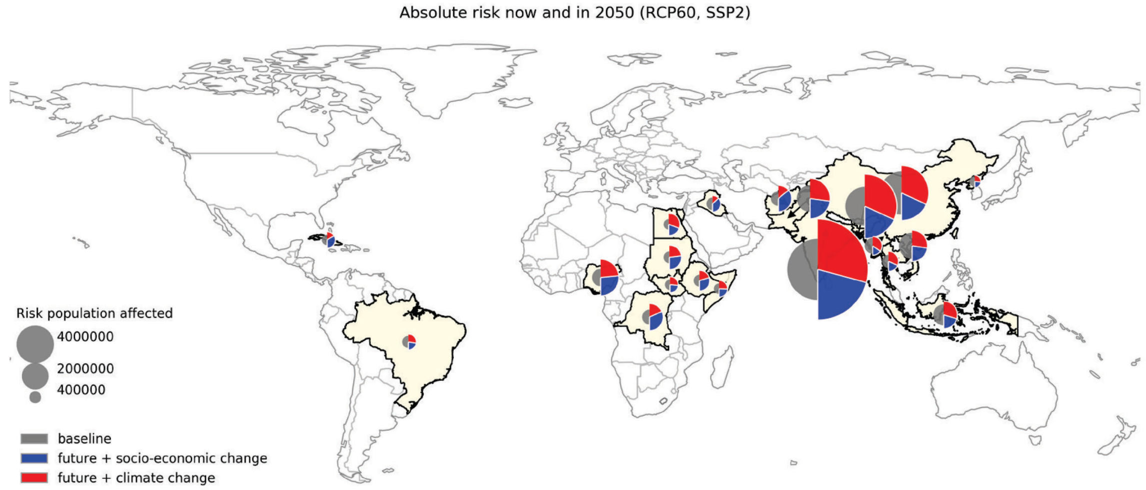

Figure 6. Average number of people affected annually by river flooding now and in 2050. The top 20 countries with the largest numbers of people affected annually are coloured yellow and outlined in black. The left half of each circular plot shows present-day risk and the right half shows the situation for 2050. The colours red and blue represent the contributions of the drivers *climate change* (red) and *socio-economic change* (blue) to future river flood risk. The level of flood protection in 2010 was taken from FLOPROS (see Figure 4) and we assumed no further investment in flood protection between 2010 and 2050.

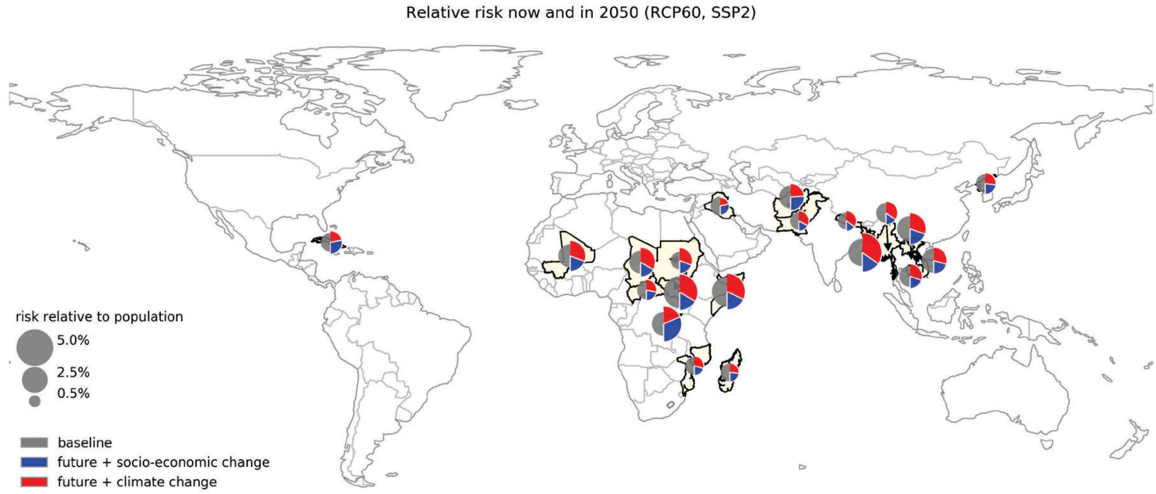

Figure 7. Average number of people affected annually by river flooding divided by the country's total population, now and in 2050. The top 20 countries with the largest numbers of people affected annually are coloured yellow and outlined in black. The left half of each circular plot shows present-day risk and the right half shows the situation for 2050. The colours red and blue represent the contributions of the drivers *climate change* (red) and *socio-economic change* (blue) to future river flood risk. The level of flood protection in 2010 was taken from FLOPROS (see Figure 4) and we assumed no further investment in flood protection between 2010 and 2050.

Interestingly, India and China are not among the top 20 in terms of present-day risk when considering the relative numbers. This does not mean that risk is not high; it just means that those countries are so large that many unaffected regions compensate for those regions within the country that are strongly affected.

Important conflict regions or regions with political unrest, such as Sudan, South Sudan, Rwanda, Mali, Chad, Ethiopia, North Korea, Afghanistan and Pakistan, are in the top 20. Some of these countries are in fact also drought-prone, as can be seen from the accompanying results of the hydrological drought analysis. Sudan, Pakistan, Bangladesh and Rwanda, in particular, have a strong overlap in risk levels for both flooding and drought.

The top 5 are Pakistan, Nepal, Myanmar, Sudan and Bangladesh. Increases of 100% or more in the average number of people affected per year are expected. Most of these increases are due to climate change, although non-balanced growth in population in flood-prone regions represents a strong second driver.

Besides population growth, strong economic growth is also expected; GDP per capita will probably increase. Consequently, population growth will itself result in socio-economic change having a greater impact on flood risk expressed in economic terms. We therefore also calculated estimates of "urban damage"[2] globally, and this reveals a worldwide increase in annual average urban damage from about USD 78 billion per year in 2010 to about USD 560 billion per year in 2050. These numbers would be USD 45 billion (2010) and USD 423 billion (2050) (average of 5 GCM runs), if present-day flood protection standards were twice as high and would be kept at this level in 2050. If dykes were to be raised between 2010 and 2050 to keep pace with climate change, with the level of flood protection therefore effectively remaining the same, annual average urban damage in 2050 would be USD 395 billion. These results show that even significantly improved flood protection (either by a factor of 2 compared to the present, or an increase along with climate change) cannot prevent a strong increase in flood damage. This is due to socio-economic growth (and population growth). There is, therefore, much to gain from 'flood-proof building', as well as proper flood zoning if we want to adapt to climate change. The issue of increasing exposure to natural hazards is also highlighted in GFDRR (2016).[3] In this case, the greater contribution to total urban damage comes from socio-economic growth (57%) whilst climate change makes a smaller contribution (43%).

[2] Urban damage is defined as any non-agricultural damage.

[3] NB: data and figures for other scenario combinations are also available. These have not been presented here, but are delivered as part of this project in the form of Excel sheets, JSON tables and GeoJSON GIS files.

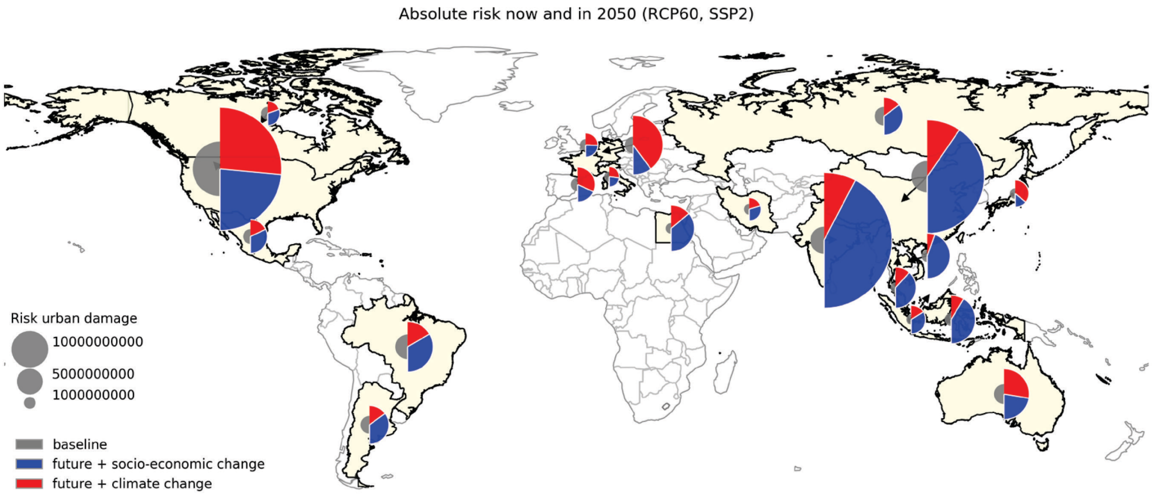

Figure 8. Changes in average, absolute damage per year (in USD) due to climate change and socio-economic change between 2010 and 2050. The left half of each circular plot shows present-day damage and the right half shows damage in 2050. The different colours represent the contributions of the drivers *climate change* (red) and *socio-economic change* (blue). The level of flood protection in 2010 was taken from FLOPROS (see Figure 4) and we assumed no further investment in flood protection between 2010 and 2050.

Figure 8 shows the absolute amount of expected average damage per year in the top 20 most impacted countries today, with today's flood protection. This top 20 looks very different to the top 20 for affected people, because the potential economic impact of flooding is much higher in richer countries. The top 3 consists of the United States, China and India. It is important to note that these countries, given their stronger capital position, can cope much more easily with the impact of flooding (see e.g. Winsemius et al. 2015). We therefore also display the numbers relative to the country's GDP (see Figure 9), and we can reveal that again, just as for the affected population, many countries in Africa are heavily affected. A number of countries in South America and Southeast Asia (Vietnam, Cambodia) are also in the top 20. Looking at these relative numbers, we can reveal that (in contrast to the most affected countries in terms of the absolute numbers in Figure 8) climate change plays the most important role here. This can be explained by the fact that, as the economy increases, urban damage also increases. Hence, relative damage only goes up when either the hazard increases due to climate change, or when socio-economic growth is disproportionally high in flood-prone areas (versus the case where socio-economic growth is the same everywhere).

Finally, we can demonstrate our first-cut analysis of affected yields. From our computations, we calculated the 40-year average potential yield loss for 4 different crops in both irrigated and rain-fed agricultural areas. This potential yield loss covers the period from 1960 to 1999. Maize, in particular, is a sensitive crop and potential yield losses seem to occur in West Africa in particular (see Figure 10., the data and figures for all the other crops are delivered as part of this project as well). In the impacted areas in West Africa where maize is currently grown, the potential yield loss due to flooding on an annual basis over this study period is, on average, 13% (standard deviation: 4.5%) of the total potential yield without flooding. In absolute terms, this is about 970t. As this region is strongly reliant upon its own food production, this potential yield loss should be further considered. From a flooding and agricultural perspective, West Africa should be considered a hotspot. The amounts should, however, be compared to yield losses due to drought to find out whether this number is significant, and information on crop vulnerability should also be included to assess actual yield loss estimates (see also section 1.1.7).

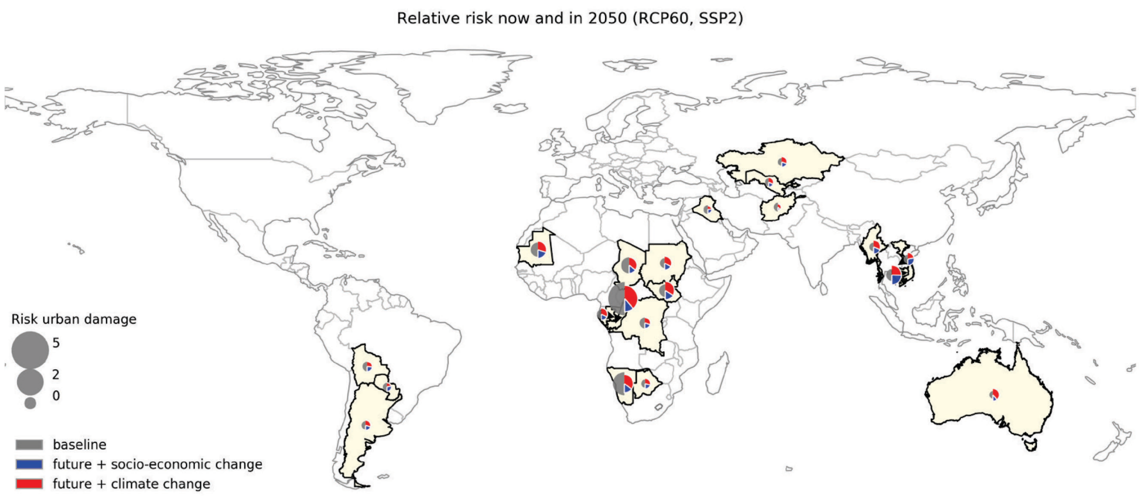

Figure 9. Changes in the average relative amount of damage per year (in USD) due to climate change and socio-economic change between 2010 and 2050. The left half of each circular plot shows present-day damage and the right half shows damage in 2050. The different colours represent the contributions of the drivers *climate change* (red) and *socio-economic change* (blue). The level of flood protection in 2010 was taken from FLOPROS (see Figure 4) and we assumed no further investment in flood protection between 2010 and 2050.

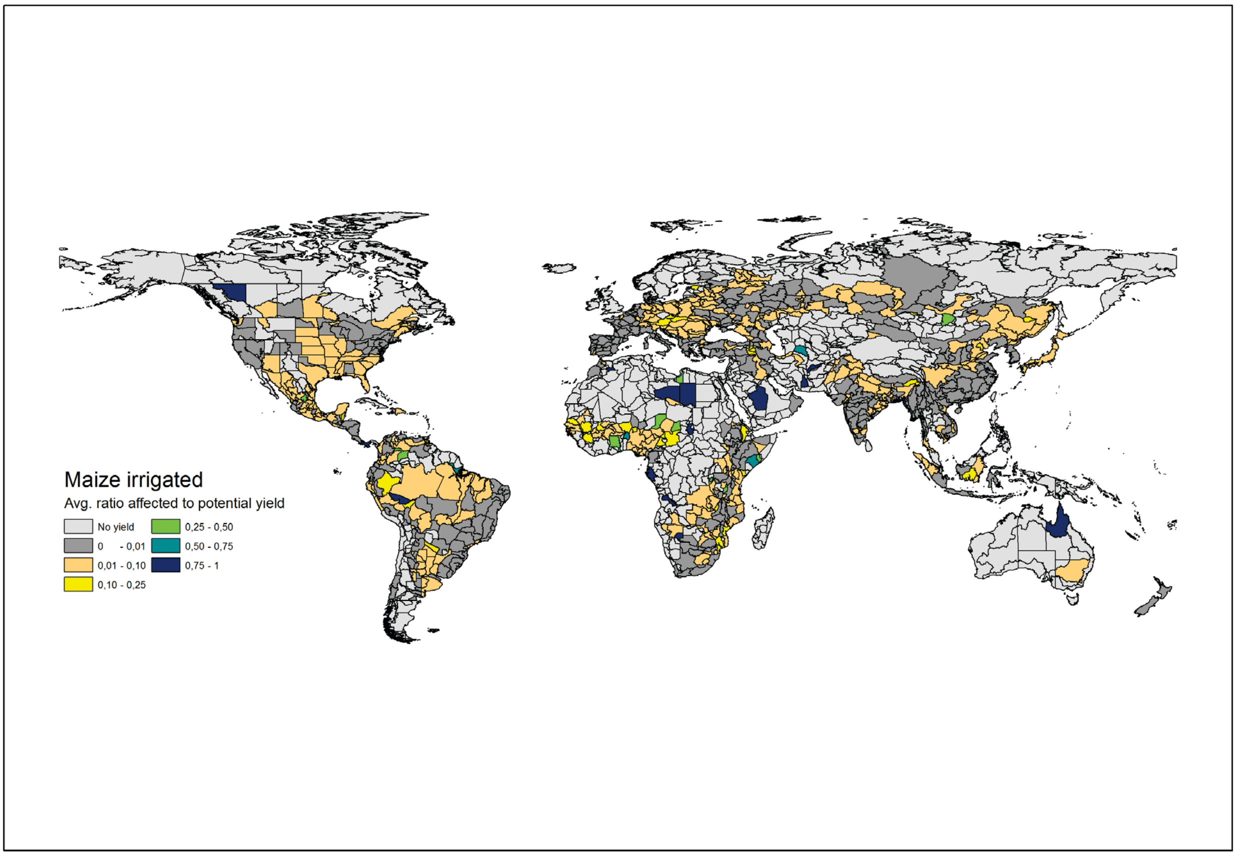

Figure 10. Annual average potential yield loss due to flooding in the period from 1960 to 1999, in areas where irrigated Maize is currently grown.

1.1.5 Discussion

Uncertainties and Limitations

The present-day and future risk estimates presented contain several uncertainties, which may have an impact on the estimated risk or change in risk. In this study, the propagation of random errors due to uncertainties in the extreme value distribution, as well as uncertainties in future projections, were included to ensure that our conclusions on the future change in flood risk were as robust as possible. However, a large number of uncertainties still remain. In this section, we will briefly discuss the most important uncertainties and reflect how these could impact the scenario results in terms of absolute risk, as well as the relative change in risk.

Limitations in flood process representation: our model framework has, to date, only been set up to specifically simulate large-scale river flooding, which is one of the most damaging processes in terms of monetary value. Coastal flooding also causes a lot of damage, but requires a very different type of model, driven by other meteorological variables, as well as tide and/or wave simulations. We are currently working on such simulations and, in a further phase of this work, we may consider adding coastal flooding as an additional flood mechanism and compute the impact accordingly. Smaller scale pluvial and flash floods are not represented in the model cascade either. Our model cascade maps flooding in river catchments larger than ~5,000–10,000 km^2. With a typical forcing grid size (precipitation, temperature) available globally from reanalysis and GCMs of approximately 0.5 x 0.5 degrees (2,500 km^2), such a river would receive its forcing from about only 2 to 4 grid cells. Given this limitation in forcing data, we are not suggesting that we can make statements about changes in river flood risk in smaller rivers at this time.

Since we used the same process representation for present-day and future risk, our estimates of changes in risk are not biased as a result of this limitation.

Hydrology and meteorological forcing: the chosen hydrological and hydraulic model, as well as the forcing data applied, will introduce a significant amount of uncertainty (Haddeland et al., 2011) given the known limitations in quality, parameterisation and the uncertainties in schematisation. Like Hirabayashi et al. (2013), we assumed that the changes in frequency of extreme events, and therefore the change in risk, are still robust enough to support our conclusions. It is likely that the choice of models that translate the forcing into hazard maps, and consequently into risk estimates, will affect the absolute estimates of risk much more than the relative change in risk. To further investigate how uncertain the absolute risk estimates are, as a result of uncertainties in forcing and models, a multi-model and multi-forcing experiment would be required like the one performed for water scarcity in the ISI-MIP project (Schewe et al. 2014). Incidentally, even multi-model and multi-forcing experiments will not fully resolve uncertainties in the models and forcing used, as global models are known to produce similar errors in specific areas. For instance, global hydrological models typically overestimate flow, and consequently flooding, in semi-arid regions where there is strong atmospheric feedback from seasonally inundated floodplains (e.g. in the Niger basin, Liersch et al. 2013) which is not accounted for in the processes of hydrological models.

Uncertainties as to flood protection standards: in a recently submitted paper (under review in Nature Climate Change), we addressed the sensitivity of risk estimates to the accuracy of the estimated flood protection standard. We showed in this that a factor two increase or decrease in flood protection standards leads to about a 50% decrease or increase in risk estimates.

Urban growth assumptions: we estimated urban growth assuming that urban areas would not extend spatially. This means that the only possible growth would be through the densification of assets within already existing urban cells. This limitation works in two ways. Firstly, if cities expand towards flood-prone regions, this would mean a relatively larger part of the urban area will be exposed, whereas if cities grow into areas that are not susceptible to flooding, the relative exposure would reduce. Secondly, if part of the urban growth is indeed due to a further densification of existing urban areas, this growth would probably only be due to an increase in building height, which would mean that an increase in exposure would have no effect as the additional growth would effectively be out of harm’s way, and would therefore mean a relative reduction in vulnerability. Future research should focus on the further development of spatial expansion scenarios and look at how the vulnerability of assets in urban areas may change as a consequence of vertical growth.

Agriculture: in the current set-up of the study, our analysis assumes that if there is an inundation during the growing season, the cell’s entire crop yield for that calendar year will be affected. The scope of this first global scale agricultural impact analysis therefore focused on “affected crop yield” rather than loss of yield. Loss of yield would require, for example, more information on the degree of inundation tolerance of the different crops. Next to seasonality, our current analysis also assumes that if there would be an inundation during the growing season, the cell’s maximum yield at the time of the inundation would be affected. Along with seasonality, Brémond et al. (2013) found that for the studies on smaller scale agricultural flooding they reviewed, water depth was the most commonly applied flood parameter. We consciously refrained from implementing a vulnerability curve for agriculture and concentrated on identifying impact hotspots, as vulnerability to varying water depths is highly crop-specific, and an in-depth literature review to upscale this methodology to the global scale would be necessary. Taking into consideration the advances in crop production and agricultural productivity due to, for example, the use of fertilisers, pesticides, and advancing technology during the second half of the 20th century (Ray et al. 2012, Ruttan 2002, Tilman et al. 2002), the modelled values for crop production and the cropland fraction in our time series prior to 1990 may have overestimated the actual harvests, because the calculations inherently assumed that the more advanced technology was also in place between 1960 and 1990. Furthermore, the spatial resolution of the LPJmL output is 0.5 x 0.5 degrees. In order to match the higher resolution of the hazard map we used in GLOFRIS, we resampled the data using the nearest neighbour method. This rather simple method could be improved, for example by taking into account a high-resolution digital elevation model and an allocation of crops based on relative elevation to water bodies, in order to refine the interpolation.

How do the results relate to other relevant studies?

Our results show that Africa and Southeast Asia are likely to see a dramatic increase in the number of people affected by river flooding, due to both climate change and socio-economic change. Southeast Asia, in particular, which is already strongly represented in the list of regions with the largest number of people affected by river flooding, will see the largest increase in the number of affected people. These results reflect similarities with the studies by Winsemius et al. (2015) and Hirabayashi et al. (2013), and they show that population growth in flood-prone areas results in a strong increase in the number of affected people. In Africa, particularly, affected people are, for the most part, likely to be from relatively poor households, as shown by Hallegatte et al. (2016).

These hotspots are also identified by Alfieri et al. (2017), but their study only looks at the effects of climate change. Their study includes regions representing 73% of the world's population and 79% of global GDP and takes the impact over the 1976–2005 baseline period, as a reference. Central estimates of global flood risk in this baseline period total 54 million people affected and EUR 58 billion (USD 75 billion) of damage per year. The findings of this study indicate that, when compared to 1976–2005, the expected damage and population affected by river flooding are likely to increase by 120% and 100%, respectively, in the study area, if global warming increases by 1.5 °C compared to pre-industrial levels. At 2 °C global warming, the estimated increase in expected damage and population affected by river flooding is 170%. At 4 °C global warming, the numbers are astonishingly higher, with a 500% increase in damage and a 580% increase in population affected (Alfieri et al., 2017). According to their study, current river flood risk is relatively high in Asia and Africa, which together account for 95% of the people affected and 73% of the economic damage, for the 1976–2005 baseline period. The largest future increases in flood risk were found for the United States, Asia, and Europe. The largest absolute impacts were found for China, where current estimates of 9 million people affected and EUR 25 billion damage per year are projected to rise through global warming, reaching 40 million people and EUR 110 billion per year, at 4 °C warming. A strong (more than 20-fold) increase in the flood risk was also found for India and Bangladesh at 4 °C warming, which puts them at the top of the countries with largest affected population. Remarkably, the projected increase in flood risk is relatively high for the European Union as a whole, as well, in spite of the relatively high standards of flood protection in the EU countries (Alfieri et al. 2017).

With respect to high-frequency flood zones, and including exposure to both coastal and river flooding, in 2000, about 30% of all urban land worldwide was located in such zones; by 2030, this will reach 40%. A broad shift is projected in urban exposure, from the developed world to the developing world, between 2000 and 2030. The emerging coastal metropolitan regions in Africa and Asia will be larger than those in developed countries and will thus have larger areas exposed to flooding. By 2030, India, South Asia, and Southeast Asia are expected to have almost three quarters of the urban land at risk of high-frequency flooding (Güneralp et al. 2015).

Globally, urban land exposed to both flooding and droughts is expected to increase by over 250%. In 2000, particularly South Asia, India, and South America had the most urban land in areas exposed to both frequent flooding and recurring droughts. Mid-latitudinal Africa is expected to join these three regions, by

2030. The largest increase in the amount of urban land exposed to both flooding and droughts is expected to be in South Asia (Güneralp et al., 2015).

The results in this document stress the importance of socio-economic change compared to climate change with respect to economic damage caused by flooding. This corresponds to the results of Hallegatte et al. (2013). They quantified present and future flood losses in the 136 largest coastal cities. In that study, average global flood losses in 2005 were estimated to be approximately USD 6 billion per year, increasing to USD 52 billion by 2050, as a result of the projected socio-economic changes alone. Even if adaptation investments help to maintain a constant probability of flooding, subsidence and sea level rises will still lead to an increase in global flood losses to USD 60–63 billion per year, in 2050. To maintain present-day flood risk levels, adaptation will need to reduce the probability of flooding to below current values. An increase in the magnitude of losses when flooding does occur in the future makes it critical to prepare for larger disasters than we are currently experiencing. The cities that were identified to be most vulnerable to these trends are situated all over the world, with a concentration in the Mediterranean Basin, the Gulf of Mexico and east Asia. There are no European cities in the top 20 cities ranked by risk in 2005 (expressed in terms of the largest average annual economic losses). Furthermore, there are no European cities in the top 20 cities with the largest average annual economic losses in 2050 either, assuming an optimistic sea level rise of 20 cm between 2005 and 2050 and a policy where the current probability of flooding is maintained. Even if adaptation investments maintain a constant probability of flooding, subsidence and sea level rises will nevertheless lead to an increase in flood losses.

The results in this document show that, in absolute terms, the potential economic impact of river flooding is highest in rich countries. The top 3 comprises the United States, China and India. This corresponds to the results of Jongman et al. (2012). In their simulations, they found that the largest absolute changes in terms of exposure of urban assets, between 1970 and 2050, were in North America and Asia. In relative terms, the largest increases were projected for northern Africa and Sub-Saharan Africa (Jongman et al., 2012). The results are based on a large number of assumptions, however, and should only be interpreted as a first estimate of indicative values.

Adaptation strategies

Our results show that additional flood protection could help to reduce the impact of flooding in the future. It is important for there to be a careful assessment of the different measures and options that are available to this end. These can generally be split up into measures that reduce different elements of the contributory risk factors. We describe and reflect on these below.

- Hazard reduction measures: measures that can reduce the flood itself and thereby its impact, by reducing the probability or severity of flooding. Dykes, emergency retention areas, and flood control reservoirs are typical examples. Recently, a global scale study was carried out to investigate the costs and benefits of dykes all over the world (Ward et al. 2017). This study revealed that in many regions of the world, including high-income countries and countries that are currently undergoing significant economic growth and/or are expected to do so in the near future, the benefit-cost ratio is more than one; this essentially means that the benefits of building dykes are greater than the investment and maintenance costs. For large parts of North America, Australia, northern Europe, and East Asia, these optimal standards could reduce future absolute Expected Annual Damage (EAD) (in 2080) to below current values. However, for most of the world, dyke building would still lead to overall increases in absolute EAD, as a result of great economic growth. The effect of the flood protection scenarios, as presented in this document, could therefore pay off but not necessarily everywhere, or at least not when expressed in absolute economic terms (other things to investigate would be the impact on the loss of life or on poverty, but these impacts are beyond the scope of this work). It should be noted that this study only investigated the economic viability of dykes. There may be many other considerations that are not accounted for here but which are mentioned in the discussion section of Ward et al. (2017). These include the presence of humans and livelihood activities, soil subsidence, or reduced sediment accretion; or non-economic factors relating to structural defences, such as the loss of existing amenities, tourism, ecosystems, and fisheries. In addition, the construction of structural flood protection measures can lead to lock-in and the so-called levee effect (Di Baldassarre et al. 2013). Another important consideration is the pace at which dykes can be constructed, given the availability of capital and manpower. Our own country serves as a good example here. The Netherlands has a long history of establishing flood protection through the construction and maintenance of dykes, which is no small undertaking. The Dutch flood protection programme (Hoogwater Beschermingsprogramma, HWBP) comprises a total of 3,500 km of dykes. These dykes are now being improved to be ready for climate change, but at a slow pace of only 25 km dyke per year. In other words, even the Netherlands, a country with a rich history of dyke protection, has difficulties keeping up with the pace of climate change and general maintenance. In much larger delta systems with longer rivers and coastal waters to protect against, dykes alone are therefore unlikely to be feasible. They could be combined with the potential of other, nature-based measures in these areas. Nature-Based Flood Defences (NBFD) can reduce flood hazards whilst at the same time maintaining the ecosystem's dynamics and preventing the loss of natural sediment accretion and subsidence. The potential of NBFD have not yet been investigated globally, but Deltares is currently working on investigating their contribution to flood management.

- Vulnerability reduction measures: measures to prevent the impacts of floods can also be to make society less susceptible to flooding or make flooding easier to cope with. Typical examples of direct vulnerability reduction measures include building codes which would make buildings, and/or their interiors less vulnerable to flooding. Another clear example is an early warning system, which is particularly useful for ensuring that fewer fatalities occur and that livestock and goods that can easily be moved to higher ground are not killed or damaged. More indirect methods, that relate more to a society's coping mechanism, include financial schemes such as emergency funds or insurance. Jongman et al. (2015) combine physical global flood modelling, using the same model setup as presented here, with empirical evidence. They showed that humans have apparently been able to reduce their susceptibility to flooding and that this is a function of rising income; that fatalities and losses as a share of the exposed population and GDP are declining; and that, as income in low-income countries have increased over the last 3 decades, their vulnerability to flooding has started to converge with that of high-income countries. The study could not reveal what the mechanisms behind this decline are, but they could definitely include vulnerability reduction measures. Early warning systems, in particular, have the capacity of significantly reducing the number of casualties caused by flooding, even though the total number of people affected stays the same. A good example is Bangladesh, which saw a significant drop in the number of casualties due to flooding, following the implementation of an early warning system.

- Exposure reduction measures: these include, in particular, flood zoning i.e. ensuring that there is no new expansion of inhabited areas into flood-prone areas and if such an area is already inhabited start a managed retreat i.e. move away from the area that is flood-prone. Sea level rises, which result in a permanent increase in flood hazard, is already causing societies to divert to this latter option. Low-lying Small Island Development States (SIDS) are particularly affected by sea level rises because they are unable to move to higher ground. Societies on these islands tend to leave even before the threat of flooding reaches an unacceptable stage, mainly because of the fact that their drinking water resources are usually also severely affected (Weiss 2015). With respect to the measures for reducing the impact of river flooding and in many cases also coastal flooding, removing assets from an already built-up area is difficult and has been deemed infeasible (Aerts and Wouter Botzen, 2011). More likely options, therefore, include retrofitting assets so they will be more flood-proof.

1.1.6 Conclusions

Our results show that absolute numbers alone can easily obscure the real hotspots of vulnerability to river flooding. Relative numbers, such as the amount of damage per capita, are better indicators. For instance, African countries hardly show up at all on our plots when shown in absolute numbers, as they are relatively scarcely populated compared to India and China, for example; but they do show up in the relative numbers (both for affected population and urban damage) indicating that they are heavily represented in the high-risk countries. Equatorial African countries, in particular, have a similar level of risk to some of the Southeast Asian countries where this pertains to the numbers of people affected. Flood protection (or the lack of it) plays an important role in these risk levels.

One important conclusion is that the risk of flooding and hydrological drought is high in a number of key countries that are known to have unstable political climates or that are conflict-prone. These countries should be monitored to see whether any relationships between political unrest, conflict and migration could be found. This applies particularly to Sudan, Pakistan, Bangladesh and Rwanda.

The main driver of the increase in risk between 2010 and 2050, in essence, depends on which scenario or which indicator is chosen. In general, climate change is the most important driver of the increase in the number of people affected by flooding. Except for urban damage (i.e. damage to built-up assets), socio-economic change is the dominant driver; growth in both population and GDP per capita have a significant effect and lead to increased risk.

Due to the limited space available in this document, it does not show the estimates of top 20 countries with high river flood risk under the various SSP–RCP scenario combinations other than the combination of SSP2 and RCP6.0 presented here. Our calculations, however, show that our top 20 is very robust when set against the other combinations. This all suggests that it would be important to see whether these countries also demonstrate high risks in other areas such as water scarcity, food security and geopolitical conditions, which could then culminate in hotspots that require further attention.

1.1.7 Gaps and recommendations for future research

Agricultural impact of flooding

Our analysis provides the first overview of the main affected areas and indicates the degree to which flooding affects agricultural production. The approach used for the agricultural impact simulation could be advanced in several respects.

The main restriction in the current method is the assumption that the entire yield of a cell is affected if flooding occurs, but no actual loss is computed. This approach could be advanced by incorporating a differentiation of growing periods including, for instance, growing seasons that extend over the next year, or the consideration of multiple harvests within a year. Furthermore, a crop’s vulnerability at different growth stages could also be taken into account. This can be implemented by applying damage coefficients to the season of the year, in monthly or crop-specific growth stage steps, as has been applied on (generally) smaller scale studies (e.g. Citeau 2003; Förster et al. 2008; Neubert & Thiel; 2004).

In addition, a stage-damage function could be incorporated to establish agricultural flood damage as a function of water depth (e.g. Dutta et al. 2003; Jonkman et al. 2008). Brémond et al. (2013) found that water depth is, generally, the only flood parameter in the studies they reviewed that strongly relates to damage to farm buildings and contents, and damage to crops. When planted cropland is flooded, damage is usually inevitable to some extent. Since the spatial scale of those studies was mainly sub-national, and vulnerability to varying stages of water depths can be assumed highly crop-specific, an in-depth literature review to upscale this methodology to the global scale would be essential before implementing such curves.

As an extension to this, the potential to take flood duration into account in a large-scale study should also be explored. As demonstrated by the Pakistan flood in 2010, for example, there are wider, cumulative impacts on the agricultural sector as a result of flooding. In Pakistan, about 70% of farmers lost more than half of their expected income, 4.5 million workers from both in and outside the agricultural sector were affected, and growth in the agriculture sector dropped from 3.5% in 2009 to 0.2% in 2010 following the flood (this was back up to 1.9% by 2011). Clearly, there were cascading impacts in this country where agriculture represents a quarter of its GDP (FAO 2015).

In addition to the estimates of agricultural flood impact and risk described here, the challenge for future research would be to broaden the perspective to include the potential consequences for macroeconomic effects in affected countries and the impact on livelihoods and food security, for example.

This document looks at yield loss as a result of flooding. Zampieri et al. (2017) stress that estimates of yield loss due to 'too much' water as a result of climate change impacts should not be restricted to flooding, but should also focus on water excess in a more general sense. Even without flooding, too much water can affect agricultural yield. Looking at wheat yield, they stated that extreme amounts of precipitation and water excess in the soil can also be responsible for loss of wheat yields due to the proliferation of pests and diseases, leakage of nutrients, inhibition of oxygen uptake by the roots, and interference with agronomical practices (e.g. water logging during harvest). In a wider sense, they stressed the importance of heat waves, droughts and water excess. According to their global assessment, heat stress remains, globally, the most important factor for determining wheat yield anomalies, whereas water excess explains the yield anomalies of important wheat producers such as China and India.

Coastal flooding

So far, coastal flooding has not been assessed, in a similar manner. Research is currently underway to prepare global data sets on coastal flooding and flood impacts, using the Aqueduct Global Flood Analyzer. These estimates include the impacts of sea level rises, soil subsidence (with a first-ever global scale subsidence model) and socio-economic changes. This work could be advanced to establish a hotspot analysis of coastal flood risks as well, expressed in terms of various socio-economic indicators. One big difference between this research with these new data layers and earlier research into global coastal flood risk, is that our research uses physically based models to assess coastal surge levels (Muis et al. 2016), which have proven to be much more accurate than estimates used so far from, for example, the DIVA model (Muis et al. 2017). Furthermore, inundation routines use a much more accurate representation of elevation with respect to mean sea level. This study was presented during the European Geosciences Union 2017 (see http://meetingorganizer.copernicus.org/EGU2017/EGU2017-5487.pdf) and lead to a lot of attention from the press. As a final point, we are the first research group to bring soil subsidence into the equation.

The results of our work should be analysed further to demonstrate how impacts result in risk, given today's protection standards, and where the risk hotspots in terms of coastal risk are or where they can be expected in the future as a consequence of sea level rises, soil subsidence (highly relevant in specific areas) and demographic changes.

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