LETTERS
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Increasing stress on disaster-risk finance due to large floods

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Recent major flood disasters have shown that single extreme events can affect multiple countries simultaneously[1–3], which puts high pressure on trans-national risk reduction and risk transfer mechanisms[4–6]. So far, little is known about such flood hazard interdependencies across regions[7,8] and the corresponding joint risks at regional to continental scales[1,9]. Reliable information on correlated loss probabilities is crucial for developing robust insurance schemes[5] and public adaptation funds[10], and for enhancing our understanding of climate change impacts[9,11,12]. Here we show that extreme discharges are strongly correlated across European river basins. We present probabilistic trends in continental flood risk, and demonstrate that observed extreme flood losses could more than double in frequency by 2050 under future climate change and socio-economic development. We suggest that risk management for these increasing losses is largely feasible, and we demonstrate that risk can be shared by expanding risk transfer financing, reduced by investing in flood protection, or absorbed by enhanced solidarity between countries. We conclude that these measures have vastly different efficiency, equity and acceptability implications, which need to be taken into account in broader consultation, for which our analysis provides a basis.

Major river floods are typically driven by large-scale atmospheric circulations[8,13,14]. As a result, single flood episodes can affect vast areas in a short period of time, irrespective of economic and political boundaries[1,3]. This was demonstrated in June 2013 by the blocking of the planetary waves of the atmospheric flow regime in the Northern Hemisphere[2], which led to extensive flooding and €12 billion losses[15] in nine different countries across central and eastern Europe. Understanding the risk posed by large-scale floods is of growing importance, as their impacts are rising owing to socioeconomic development[6,16], and their frequency and intensity may increase under a changing climate[1,9,12,17].

Well-devised risk management of climate-related extremes, including floods, is therefore considered to be an important pillar of climate adaptation[18]. Rising flood losses already force insurance companies to increase their capital base and may lead to more years of below-zero profitability[5]. Uninsured risks are a growing concern, as a lack of financial means for relief, recovery and reconstruction negatively affects the wellbeing of people, the economy and a country's budget[6,19]. Accurate information on the joint probability of flood losses that takes into account spatial correlations between river basins across different countries is essential for developing insurance mechanisms[5] and public compensation schemes[10] robust to present and future extreme losses. This information is especially required and informative in the European Union (EU), where international disaster financing is increasingly connected through insurance regulations[21], climate change adaptation strategies[20], and a joint compensation mechanism between member states[10].

So far, methods for producing large-scale flood risk estimates have either been based on specific hazard event scenarios, or are upscaled from lower to higher spatial levels by summation of basin-level risk[16,22–24]. In both cases, natural correlation between events is neglected (that is, full spatial independence across river basins is assumed) and reliable estimates of extreme losses cannot be made. Hence, flood risk projections available to the disaster risk reduction community do not accurately represent geographical risk patterns and are not probabilistic in nature. We demonstrate here that natural dependencies among risks in different regions can be accounted for (Methods), and we present probabilistic projections of flood risk in the EU.

We find monthly peak river discharges in the 1,007 sub-basins to be a good proxy for the occurrence of reported damaging flood events[17] on a European scale, as shown in Supplementary Fig. 1. The results show high positive cross-correlations in observed peak discharges between the river sub-basins in Europe, indicating a large degree of spatial interdependence in extreme river flows. Spearman's correlations are significant ($\alpha = 0.05$) in 63% of all sub-basins, and in 98% of the sub-basins showing strong correlations (that is, $r > 0.7$; Supplementary Table 1).

Strong positive cross-correlations in peak discharge occur between basins in central and eastern Europe, following the patterns exhibited during the 2002 and 2013 floods across multiple countries in this region (Fig. 1a). Peak discharges in this area are often linked to the atmospheric circulation pattern Vb, or Genoa Low; that is, a low-pressure system travelling from the Atlantic southeast across the Mediterranean towards central Europe[1]. High-to-strong cross-correlations amongst southern European basins (Fig. 1b) are known to be caused by the occurrence of regular Mediterranean depressions[25], whereas regional negative cross-correlations are also observed under the influence of Atlantic depressions[26]. We also find high-to-strong correlations in peak discharges amongst basins in western European countries, which have been linked to the occurrence of atmospheric rivers and extra-tropical cyclones[13] (Fig. 1c). On the basis of the peak discharge correlations, we assigned countries to 5 main regions, which are used for computing country-specific losses and the required compensation payments

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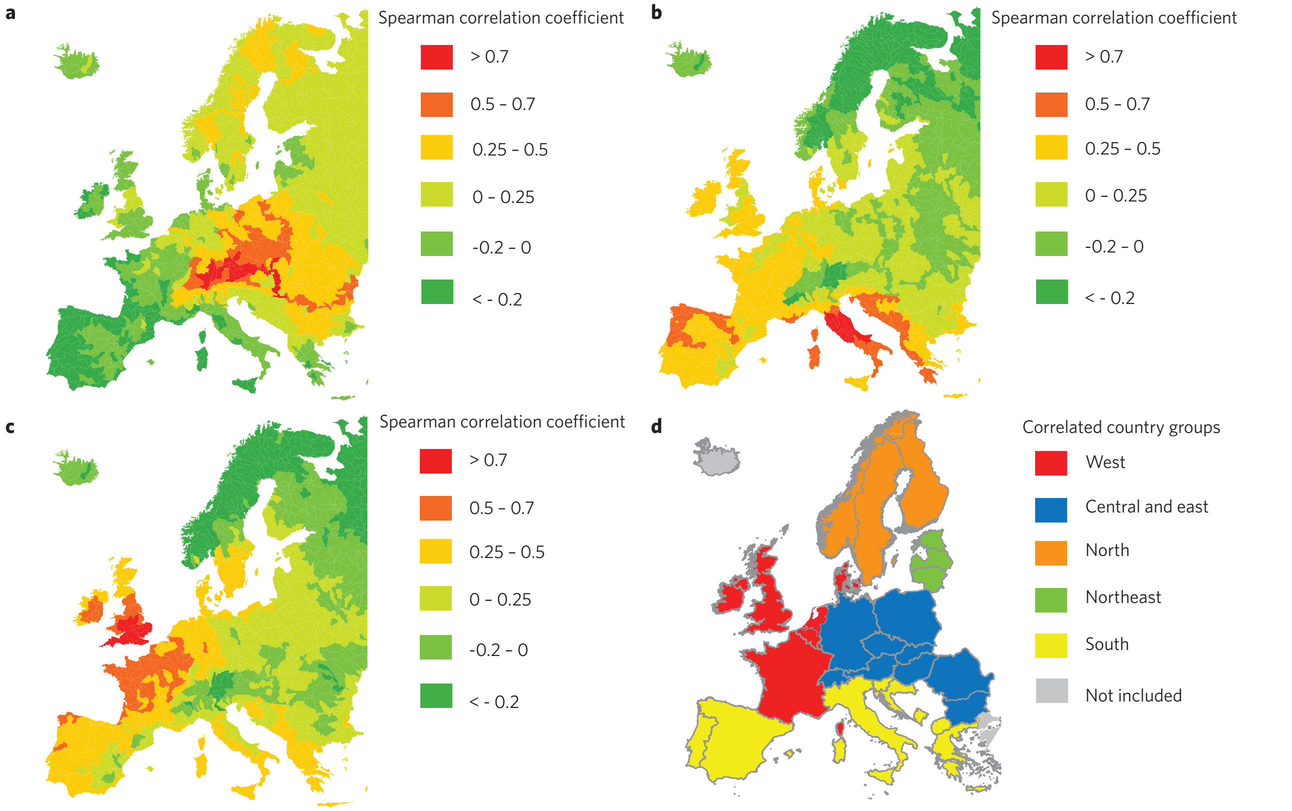

Figure 1 | Correlations of monthly peak discharges between basins in Europe. Spearman's rank correlation coefficient of extreme monthly discharges among European river sub-basins, calculated on the basis of LISFLOOD[30] simulations forced by observed daily climate data for the period 1990–2011 (Supplementary Fig. 1; Supplementary Table 2). **a**–**c**, The correlations of all river basins with the basin containing the cities of Vienna, Austria (**a**); Rome, Italy (**b**); London, United Kingdom (**c**). **d**, We derived best estimates of aggregated natural discharge correlations between countries and identified 5 main regions of correlated extreme discharges. These regions are used to convolute probability distributions on an EU level and calculate country losses (Methods).

(Fig. 1d; Methods). In this study, the correlations were computed over the entire time series for which discharge data were available (1990–2011; Methods). The results may vary depending on the selected time periods, because some of the atmospheric circulation patterns and resulting peak discharges show seasonal variation (Supplementary Fig. 2); and the circulation patterns, and hence rainfall distributions and intensities, may be influenced by climate change[1,9,13,17]. Uncertainty in these changes, however, remains high[12].

Estimates of present and future potential flood damage (that is, damage that is expected if a flood event would occur) were computed using an ensemble of high-resolution climate simulations and projected gross domestic product (GDP) under the SRES A1B scenario (Methods), and thus include both climate change and socioeconomic development components. One of the main obstacles in estimating flood risk from potential damage on a continental scale has been the lack of aggregated information on flood protection standards maintained along rivers in different countries[16,22,24,27]. Existing studies assume either no protection[16,23], a uniform protection level for all countries under analysis[24], or GDP per capita as a proxy for the level of protection[27]. One previous study used differentiated flood protection levels based on literature and expert judgement, but only for a selection of coastal cities and limited empirical information[28]. For our analyses, we carried out and validated the first continent-wide estimates of flood protection standards for all 1,007 EU sub-basins, using a combination of literature study and modelling (Methods and Supplementary Fig. 3 and Table 2).

We used the potential damage estimates, protection standards and peak discharge relationships to develop a joint probability distribution of flood losses in the EU (Methods and Supplementary Methods). We estimate expected average annual flood losses in the EU at €4.9 billion per year for the period 2000–2012, corresponding to reported average annual losses of €4.2 billion in the same period[15], and show that these losses may increase to €23.5 billion by 2050 (Fig. 2a). Annual losses of the magnitude of the 2013 European floods (∼€12 billion, or 0.1% of EU GDP; ref. 15) have a simulated expected occurrence probability of once in 16 years at present, and once in 10 years by 2050. Losses of this magnitude are projected to be below average modelled losses per year from 2030 onwards, mainly owing to rising losses from low-probability events. Under the SRES A1B scenario and the ensemble of climate change models we applied here (Supplementary Methods), about two-thirds of the modelled risk increase by 2050 is due to economic growth, and one-third due to climate change. The exact effect of climate change on rainfall patterns and the corresponding flood risk is still surrounded by significant regional uncertainties[12]. Although we addressed these uncertainties to some extent by using an ensemble of climate models, the risk projections should be continuously updated as our understanding of climate change impacts on river discharges advances.

Empirical insurance penetration rates are used to estimate insured losses as a percentage of total losses across the EU (Methods). Assuming the present estimated insurance coverage (Supplementary Fig. 4) remains constant, average modelled insured losses per year are €1.6 billion (reported: €1.2 billion[15]) for the period 2000–2012, increasing to €4.6 billion by 2050 (Fig. 2b). Total flood insurance claims with a once in 200 year probability, which is the stress threshold used to calculate legal minimum capital

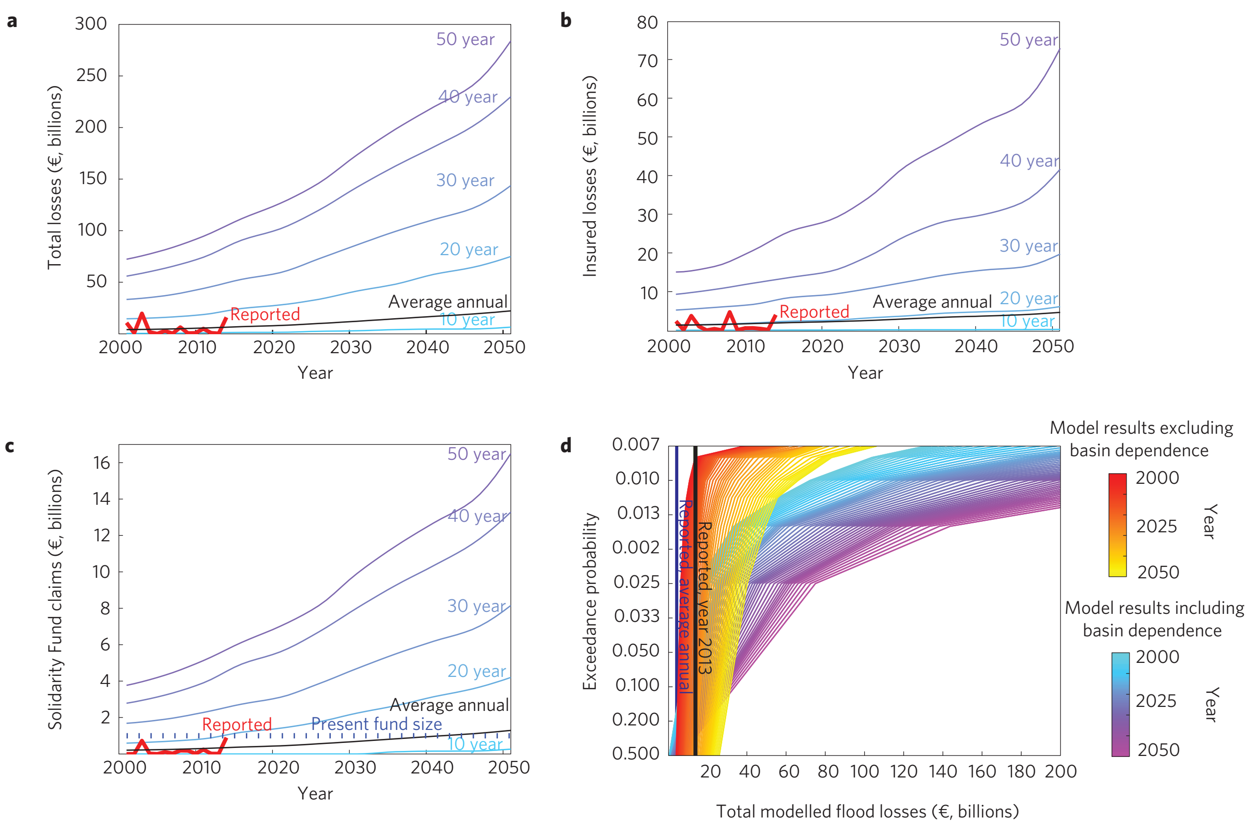

Figure 2 | Probabilistic projections of flood losses separated by financing source. Present and projected flood losses for different return periods in the European Union (EU-27) calculated using the probabilistic modelling framework (Methods). **a–c**, Total losses (**a**) are separated into: insured losses (**b**) and Solidarity Fund claims with a maximum present budget of €1 billion (dotted line; **c**). **d**, The return periods (rp) represent statistical annual probabilities, with the annual exceedance probability given by 1/rp. Reported losses are derived from the Munich Re NatCatSERVICE database and include lower-bound estimates for the 2013 European floods[15]. Incorporating the established spatial dependencies in risk assessment, as compared with assuming full independence between basins and countries, leads to higher overall loss estimates at lower probabilities (that is, it leads to a fat-tailed distribution).

requirements for insurers to avoid insolvency under the new EU-imposed Solvency II insurance regulations, are projected to increase from €116 billion in 2013 to €236 billion in 2050. In terms of uninsured risk, we estimate present annual average claims from flood risk to the EU Solidarity Fund (EUSF) at €258 million under the present guidelines (Fig. 2c). The present annual depletion risk, that is, the probability of claims exceeding the present fund size of €1 billion, is close to 5% and increases to 9% by 2050. Overall, mean uninsured losses for governments and households, after insurance and EUSF payouts under the present cover, are estimated at €3.3 billion per year in the period 2000–2012 (representing 67% of total losses; reported: €3.0 billion[15]) and are projected to increase by a factor 4 by 2050, which is significantly higher than the projected factor 2.9 growth of GDP.

Figure 2d shows that damage estimates from model runs incorporating the established basin dependencies (Methods; Supplementary Information) are higher than model results based on the traditional assumption of full spatial independence, especially for low probabilities (that is, the fat tail of the distribution). Furthermore, the graph shows that estimated probabilities of extremely low annual losses are also higher when we introduce basin correlations (that is, the likelihood of years with few disasters is higher). This result demonstrates the necessity of including correlations of peak discharges for understanding potential flood impacts at a continental scale. Changes in precipitation patterns could change the occurrence of floods[12,13] and it would be important to study effects on associated spatial correlations, as stronger correlations will result in more frequent and larger flood losses, whereas a weakening of correlations would decrease the probability of losses.

Debate is ongoing at national and EU levels on how to best manage uninsured risk, and how to allocate the respective burdens between those at risk, the insurance industry and the wider society[20]. Among others, the increasing risks can be managed by pursuing a combination of measures aimed at increased insurance penetration; improving physical flood protection standards; and expanding the budget of the EUSF. To illustrate the effect of these measures on flood risk financing, we have defined six adaptation scenarios and computed their effects on flood losses, the details of which are provided in Supplementary Fig. 7 and Table 3. Higher insurance penetration rates can, in theory, be promoted at EU level by creating favourable tax regimes for building insurers' reserves; by mandatory flood insurance coverage in high-risk areas (possibly backed-up with government finance); or by furthering the integration of the European insurance markets[21]. If an average of 50% of total losses were insured across the EU (present penetration is 30%[15]), which is approximately the case in the 1 per 100 year floodplains in the United States[5], the mean annual uninsured losses would be reduced by over €10 billion (approximately 60%) in 2050 (Fig. 3a). However, equity and insurance demand become important considerations if households are unable or unwilling to pay higher overall premiums[21], which may increase more rapidly than expected losses (Supplementary Table 3).

As an alternative to broader insurance coverage, a larger part of losses could be shared amongst EU member states by increasing the size of the EUSF (ref. 10), which is capped at present at €1

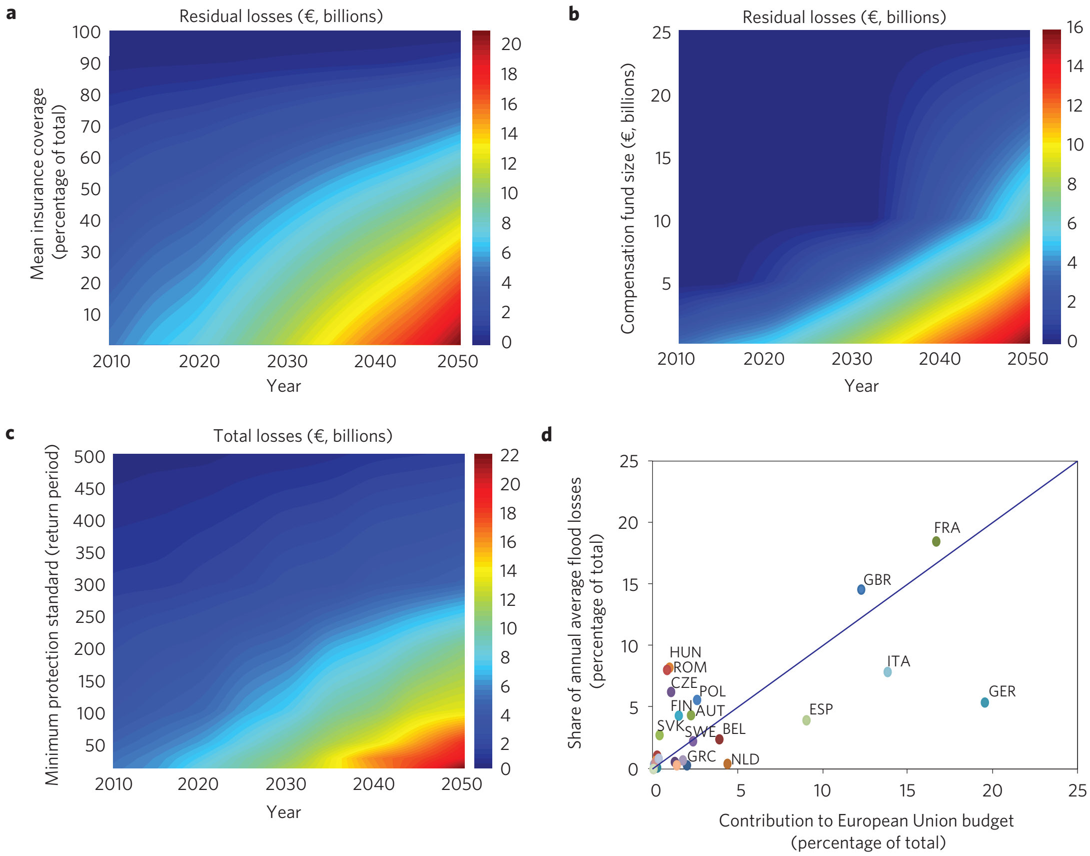

Figure 3 | Options for loss sharing and risk reduction. a,**b**, Reduction in modelled residual flood losses (that is, losses that are not insured and not covered by the EUSF) by: the implementation of a homogeneous mandatory insurance cover as a percentage of total losses (assuming the present EUSF; **a**) or launching an extended EU compensation fund (assuming present insurance coverage rates; **b**). **c**, The effect of increasing present estimated flood protection standards (Supplementary Fig. 3) to a legal minimum. **d**, Any compensation or adaptation financed from the EU budget will be subject to a distribution effect, depending on the relationship between the EU contribution and the flood risk of each country. In the long run, cross-subsidies are expected from countries with high EU contributions and low flood risk, towards countries in the opposite situation.

billion annually (Fig. 3b). As countries contribute to the fund relative to their overall contribution to the EU budget, however, cross-subsidizing will occur from countries with low flood risk relative to their contribution to countries with high flood risk (Fig. 3d)[4]. Given the fact that the EU holds solidarity among its core principles, there might be arguments for such a risk allocation, but the right balance between equity and market efficiency concerning the allocation of risk needs to be explicitly set out and negotiated. The possibilities for expanding the Solidarity Fund are mainly limited by EU budget considerations; compensating all flood losses would, at present, already consume more than 30% of the total EU budget, and would thus require an infeasible budget increase. The expansion of the EUSF is further constrained by justified concerns that the compensation mechanism might reduce national government responsibility and insurance incentives, and could thus be a disincentive (moral hazard) for risk reduction efforts[10]. We suggest it may be worth considering linking compensation by the EUSF to credible stronger efforts made by member countries to manage risk.

Although disaster financing schemes are vital for sharing the abrupt financial burden of large floods, ex-ante investments in physical flood protection are an important means of reducing the magnitude of overall flood losses[29]. Figure 3c demonstrates that increasing flood protection levels in all basins to a minimum of 1 per 100 years would decrease the total expected annual flood losses by around €7 billion (close to 30%) by 2050, and would cost an estimated €1.75 billion (Supplementary Table 3 and Fig. 7). This emphasizes that the benefits of flood prevention will increase further as losses are projected to rise under climate change and socioeconomic development. Yet, physical flood protection measures also have considerable construction and maintenance costs (Supplementary Fig. 4 and Table 3), and the security they provide may lead to increased economic development in the protected areas. Given political will, financial capacities, differential abilities to absorb risk and many uncertainties particularly relating to climate change impacts, it is generally difficult to calculate an optimal level of protection for all EU countries, and decisions on the upfront investment in flood protection could focus on offering acceptable protection levels under the present and future climate.

Methods

Potential flood losses for the period 2000–2050 for each of the 1,007 river basins were computed at a high (100 × 100 m) resolution using simulated daily discharge data, extreme value analysis, spatial inundation modelling, and an economic damage model, following the method described in earlier work[24,27]. The projections of flood hazard up to 2050 are based on LISFLOOD (ref. 30) simulations driven by an ensemble of 12 climate experiments derived from a combination of 4 general circulation models and 7 regional climate models[24] (Supplementary Methods). Both the climate change and economic development components of the flood and damage models were forced by the SRES-A1B scenario.

Flood protection standards, defined as the minimum statistical probability discharge that leads to flooding, were modelled for each basin in three steps. First, minimum and maximum flood protection standards in the EU were estimated from literature study (Supplementary Table 2) at 1 per 10 years and

1 per 500 years, respectively. A 1 per 1,000 years standard was manually assigned to The Netherlands, following the national flood defence levels in place there. Second, the EU-average flood protection was estimated by running the flood damage model with all hypothetical protection levels and analysing the intersection with reported losses[15]. A flood protection standard ranging between the minimum and maximum was assigned to each basin as a function of the average potential damage per square metre relative to the EU average. The resulting protection levels map shows a range between 1 per 10 (basin with the lowest potential damage per square metre) and 1 per 500 (basin with the highest potential damage per square metre), and a separately assigned 1 per 1,000 level in The Netherlands (Supplementary Fig. 3). Modelled protection standards are thus higher in areas where the potential damages are high, owing to a relative concentration of people and assets, than in areas where potential damages are low. This is in line with policies in major European river watersheds such as the Rhine and the Danube, where higher levels of protection are maintained in densely populated areas than in rural areas. The cubic interpolation over basins was calibrated using points of known flood protection (Supplementary Table 2). Flood protection standards were assumed constant over time for the projections presented in Fig. 2 (that is, the protection measures are assumed to be only upgraded to maintain the same failure probability under climate change, without further adaptation), and were increased to the new potential minimum standards in Fig. 3c (corresponding to the values on the y axis in this panel).

We combined the estimated potential damage with the modelled basin-level protection standards to derive probability loss curves for each year in which all modelled losses below the protection level were set to zero. We then used the peak river discharge time series to estimate natural dependencies between basins. To account for nonlinearities in the dependency structure, we use the (flipped) Clayton copula $C_\theta(u,v)$, a specific copula from the Archimedean family:

$$C_\theta(u,v) = u + v - 1 + \left[(1-u)^{-\theta} + (1-v)^{-\theta} - 1\right]^{-1/\theta}$$

The Clayton copula provided sufficient flexibility in modelling dependencies given the data at hand (Supplementary Methods, Supplementary Figs. 5 and 6). This model was used to aggregate basin loss curves to the country level in a stepwise manner using the estimated copula parameters as the ordering criteria (Supplementary Methods). In more detail, the selection of the next basin to be aggregated is based on maximizing the smallest tail dependency between the already selected basins and the potential candidates. This procedure avoids underestimation as well as overestimation of the risk. A stepwise conditional copula approach was adopted to estimate dependencies at the country level within the derived country groups (Fig. 1d): in the order of descending estimated pairwise Clayton copula parameters θ, the conditional copulas were used as stepwise extensions of the joint loss distributions. Between country groups independence was assumed. The conditional (flipped) Clayton copula with parameter θ is given by:

$$C_\theta(u|v) = 1 - \left[(1-u)^{-\theta} + (1-v)^{-\theta} - 1\right]^{-(1+\theta)/\theta} (1-v)^{-(1+\theta)}$$

Finally, we computed 1 million random samples from the multivariate flood loss model to calculate statistical loss probabilities on a country basis, for each year in the time series. Expected average losses are correspondingly defined as the mean of all samples in the year of analysis. We factored total modelled direct losses for each country by empirically estimated insurance coverage rates (Supplementary Fig. 4) to approximate expected average insurance payouts. Expected claims to the EUSF were calculated from total estimated losses following the payout regulations governing this fund, which are based on the size of the damage relative to the national GDP and an arbitrary payout threshold[10]. Finally, we computed residual losses for national public and private sectors as the total flood losses minus insurance and Solidarity Fund payouts.

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Author contributions

B.J. and P.J.W. were responsible for developing the protection standards methodology. S.H-S., G.P. and B.J. developed the probabilistic upscaling approach. B.J. and S.H-S. computed the financing distributions and adaptation scenarios. R.R. undertook the hydrological modelling and discharge correlation analysis. L.F. was primary responsible for modelling of potential damage. All authors, including J.C.J.H.A., L.M.B, R.M. and W.J.W.B., were involved in the conception and planning of the methods and analyses, and in the writing of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.J.