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FLOPROS: an evolving global database of flood protection standards

P. Scussolini[1], J. C. J. H. Aerts[1], B. Jongman[1], L. M. Bouwer[2], H. C. Winsemius[2], H. de Moel[1], and P. J. Ward[1]

[1]Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1087, 1081 HV, Amsterdam, the Netherlands
[2]Deltares, P.O. Box 177, 2600 MH, Delft, the Netherlands

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Correspondence to: P. Scussolini (paolo.scussolini@vu.nl)

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Abstract

With the projected changes in climate, population and socioeconomic activity located in flood-prone areas, the global assessment of the flood risk is essential to inform climate change policy and disaster risk management. Whilst global flood risk models exist for this purpose, the accuracy of their results is greatly limited by the lack of information on the current standard of protection to floods, with studies either neglecting this aspect or resorting to crude assumptions. Here we present a first global database of FLOod PROtection Standards, FLOPROS, which comprises information in the form of the flood return period associated with protection measures, at different spatial scales. FLOPROS comprises three layers of information, and combines them into one consistent database. The Design layer contains empirical information about the actual standard of existing protection already in place, while the Policy layer and the Model layer are proxies for such protection standards, and serve to increase the spatial coverage of the database. The Policy layer contains information on protection standards from policy regulations; and the Model layer uses a validated modeling approach to calculate protection standards. Based on this first version of FLOPROS, we suggest a number of strategies to further extend and increase the resolution of the database. Moreover, as the database is intended to be continually updated, while flood protection standards are changing with new interventions, FLOPROS requires input from the flood risk community. We therefore invite researchers and practitioners to contribute information to this evolving database by corresponding to the authors.

1 Introduction and rationale

A large portion of the world's population is exposed to flooding. Estimates of global population and assets exposed to a 1-in-100 years flood event are about 0.8 billion people and USD 50 trillion for river floods (Jongman et al., 2012; Kundzewicz et al., 2013), and 40 million people and USD 3 trillion for coastal floods (Hanson et al., 2011). River floods alone resulted in direct economic losses exceeding USD 1 trillion between 1980 and 2013, and more than 220 000 fatalities (Munich Re, 2014). Future damaging impacts of floods are projected to increase in many parts of the world, by increasing encroachment of population and economic activities on river and coastal plains resulting from socioeconomic growth, as well as by projected increases in intense precipitation due to climate change (Min et al., 2011; IPCC, 2014). Estimating the present and future risk of floods is therefore critical in the ongoing discourse on the impacts of climate change: to motivate climate change mitigation policy; to identify hotspots of risk; to plan investments in adaptation, on a range of spatial and decision-making domains, such as water management, agriculture, risk management and risk financing (Hall et al., 2012).

The last decade has seen great advances in large-scale modeling of flood hazard (Milly et al., 2002; Pappenberger et al., 2012; Rojas et al., 2012; Dankers et al., 2014), exposure (Jongman et al., 2012; Hanson et al., 2011), vulnerability (Jongman et al., 2015), risk (Nicholls, 2004; Hirabayashi et al., 2013; Winsemius et al., 2013; Rojas et al., 2013; Ward et al., 2013, 2014; Hinkel et al., 2013, 2014; Jongman et al., 2014), and other indicators of flood risk (Arnell and Gosling, 2014). In parallel, tools have been devised to make this type of knowledge accessible to a vast range of users (e.g., the Global Flood Analyzer, http://floods.wri.org). Also at the smaller scale, assessments of flood risk are becoming more sophisticated (te Linde et al., 2011; Merz et al., 2014; Miller et al., 2015; de Moel et al., 2015).

The results from the current generation of large-scale flood risk models, however, remain highly uncertain (Ward et al., 2015). Typically, these models calculate damages for floods with several return periods, and integrate these damages in their annual likelihood of occurrence to estimate the annual expected damage. Because information on flood protection standards for most places in the world is severely limited, most current assessments either assume highly simplified flood protection standards, or assume "no protection". Therefore, the integration of damages takes place along the whole spectrum of return periods, including damages of frequent (i.e., low return

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period) flood events that in reality are often prevented by existing protection. This results in a systematic overestimation of hazard, and greatly limits the accuracy of the computation of actual flood risk (e.g., IPCC, 2014; Hinkel et al., 2014). For example, Ward et al. (2013), using a global river flood risk model, found that the expected annual damage, assuming that all areas were protected against a flood with a return period of only five years, was about 40 % lower than in the absence of protection.

In this dearth of information on protection, researchers have devised solutions to circumvent the problem by assuming different standards of flood protection for different income regions across the globe (e.g. Mokrech et al., 2015; Sadoff et al., 2015; PBL, 2014). On the other hand, Jongman et al. (2014) developed estimates of flood protection covering all river basins in the European Union, using a risk-based approach (i.e., assigning higher protection values to areas of higher risk) making use of a number of available empirical data points. They then included these protection estimates in a probabilistic continental flood risk model.

While these synthetic estimations of flood protection standards indeed lead to improved results of flood damage simulations, quantifications of protection standards have not been extended beyond Europe, and the required empirical information available on protection standards is still extremely limited (e.g., Hall, 2014; de Moel et al., 2015). Some efforts, however, have been made to improve this empirical data availability. Linham et al. (2010) compiled a global list of adaptation standards for 32 coastal cities from “reports, email surveys, meetings with specialist consultancies and discussions with experts”. Later this work was implemented by Hallegatte et al. (2013), who added their expert estimates of standards of protection for an additional number of coastal cities. Information is thus limited to selected coastal cities, and the original sources are generally not available.

This paper aims at presenting the first version of an open source, dynamic, community-informed database of FLOod PROtection Standards, FLOPROS. The main motive of FLOPROS is to aid research in flood risk management and in applications such as global hydrological modeling (Bierkens, 2015), and assessments at a smaller scale. The database compiles information from different sources: specialized literature, policy documents, and modeling techniques; and aims to incorporate input from the expert community. FLOPROS covers various spatial scales, from the district to the national level. In our search we realized, as Linham et al. (2010) also did, that this information "tends to exist in unpublished reports and with experienced engineers". For this reason, we invite the community of specialists to contribute to improving the coverage, accuracy and resolution of the database. Experts, researchers and operators in specific countries and regions are encouraged to provide pieces of information to FLOPROS, which will ultimately result in a comprehensive body of information available to the flood risk assessment community. Further, because it is apparent that empirical information on protection will remain unavailable for considerable areas of the globe, we propose other ways to fill gaps in the empirical database by means of modeling and inference.

We plan to regularly update FLOPROS to incorporate the contributions of the community. This is necessary for two reasons: (1) to accommodate the flow of new information, and (2) because, by its own nature, the implementation of protection is a highly dynamic process, and likely to be accelerated under changing climatic conditions, under demographic and economic pressure, and with increased awareness of and aversion to risk. Based on the frequency and amount of new entries and updates, progressive versions of the database will be released to include the new information.

2 Methods

2.1 Aggregating multiple layers of information

FLOPROS is a database of flood protection standards, based on a wide range of sources, and on a modeling approach. The database is structured into three layers of information that are:

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(a) the *Design layer,* containing information about protection defined by engineers in the design and realisation of currently existing river and coastal flood protection infrastructure;

(b) the *Policy layer,* specifying the legislative and normative (or "required") standards of protection to river and coastal flood;

(c) the *Model layer* for river flood protection, which is based on a flood-modeling approach and on the observed relationship between per capita wealth and protection.

The general principle at the base of the composition of the FLOPROS database is the incorporation of the best information available for each location. By "best" information, we mean the most reliable (i.e., trustworthy, accurate, or closest to the hypothetical "real" protection standard), the most recent, and that with the highest resolution. To this end, a hierarchy is established between the three layers of information, on the basis of how reliable each layer is in representing the actual, existing protection (Fig. 1).

We deem the Design layer to be the most reliable to represent existing protection standards because it contains direct information concerning the standards used when designing the protection infrastructure. The two other layers, Policy and Model, contain information that is a proxy for actual protection. We consider the Policy layer to have intermediate reliability because, although it provides indication about the intended or required standard of protection, it does not indicate whether such protection is yet realized or enforced. Last, the Model layer is third in order of reliability because even though partially validated against observations (see Sect. 3.3), it involves a method to indirectly attribute protection information. The individual layers are further explained in Sects. 2.2 to 2.4.

While each of the three layers of information on protection standards can be used separately, depending on the desired scope, for large-scale applications of the database, integration of the three layers of protection standard information is desirable. We propose a method for this integration of the three layers into a Merged layer, as

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schematized in Fig. 2. In this method, for places where information is not available in the most reliable layers, information from the subsequent lower layers is employed. In practice, if information is available in the Design layer for a given sub-country unit, then this information is included in the Merged layer. If no information is contained in the Design layer, then the Policy layer information is included in the Merged layer. Finally, if information is not available even at the Policy layer, then the Model layer information is included in the Merged layer. The rationale for this structure is to enable immediate use of a database that is almost global in extent, while allowing for constant updating of the Design layer, as more empirical data on flood protection standards become available.

2.2 Design layer

For the Design layer, we compiled a list of existing measures against flooding for which a quantification of the protection standard is available in the form of the return period (years) of the flood that the measure is meant to withstand, as per the design of the measure. The sources of information were: specialists' and engineering books, peer-reviewed journal articles and scientific studies, technical reports and websites, institutional reports and documents, institutional websites, project websites, corporate websites, newspaper articles, official governmental websites, and personal communications with experts (Table 1). For each protection standard included, we assigned a score to the reliability of the source (high, medium, low). This is meant to enable the choice of a best value for locations for which more than one design standard of protection was retrieved, with a significant difference between them. The criteria for assignment of the reliability score were: (a) a qualitative estimation of the authoritativeness of the source; (b) the technical completeness of the relevant information presented; and (c) the absence of evident conflicts in the attribution of the protection standard.

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2.3 Policy layer

For the Policy layer, we gathered information on regulated standards of flood protection from policy documents and regulations, and from governmental directives (Table 2). It is often the case that laws and regulations do not correspond to factual, enforced protection, as underlined by Jonkman (2013), given that they are in the practice neglected or partially transgressed due to financial and enforcement limitations (de Moel et al., 2009). Nevertheless, this information provides at least a policy objective towards which action is oriented, thereby assigning a value that is likely more realistic than no protection (Mokrech et al., 2014).

2.4 Model layer

For the Model layer, we adjusted and extended towards the global scale the approach introduced by Jongman et al. (2014) for deriving protection standards for fluvial flooding in Europe. A modelled protection standard was calculated for administrative units at the first sub-country level (http://www.gadm.org; henceforth simply "sub-country unit"). In brief, global minimum and maximum protection standards were first assumed at 2 and 1000 years respectively. Then, as it is known that protection standards vary depending on country wealth (Feyen et al., 2012; Jongman et al., 2015), we adopted the World Bank classification of countries in four income groups, namely: high-, upper-middle-, lower-middle-, low-income (http://data.worldbank.org/about/country-and-lending-groups). Per each income group we estimated a minimum and maximum protection standard, and then performed the interpolation within each income group. Within each income group, for each sub-country unit, the potential expected annual damage (EAD) that would occur if no flood protection were in place was normalized to potential flooded area, to yield the EAD per unit of area (EAD_{area}). The sub-country units with the highest and the lowest EAD_{area} were assigned the maximum and minimum protection standard of their income group, respectively, and protection standards for the remaining sub-country units were interpolated linearly between those values.

In detail, the following steps were taken:

1. Global maximum and minimum flood protection standards were set. Here, we assumed the minimum protection standard to be "no protection". In the GLOFRIS global flood risk model (Ward et al., 2013; Winsemius et al., 2013) schematisation (Ward et al., 2013; see their step 3), no protection means a protection against flood with a return of 2 years (the natural bank-full discharge, following Dunne and Leopold, 1978), and hence this value was used. For the maximum protection standard, we assumed a return period of 1000 years as per Jongman et al. (2014).

2. Next, we estimated a maximum and minimum flood protection standard for each income group. To do this, firstly, GDP per capita (GDP_{pc}) was calculated per income group in USD 2005 at purchasing power parity. This was done using gridded maps of GDP values and of population density from the IMAGE model, the same maps used in Ward et al. (2013), developed with the method described in van Vuuren et al. (2007). Next, the maximum (minimum) protection standard for a given income group was calculated by dividing its GDP_{pc} by the GDP_{pc} of the income group with the highest (lowest) GDP_{pc}, and multiplying the obtained value by the assumed maximum (minimum) protection standard, i.e. 1000 years (2 years).

3. In the next step, the protection standard for each sub-country unit was estimated. The EAD_{area} per sub-country units was calculated using the GLOFRIS model. For each income group, the sub-country units with the highest and lowest EAD_{area} were assigned the income group-specific maximum and minimum protection standards (see step 2), respectively, and protection standards for the remaining sub-country units in the income group were linearly interpolated. GLOFRIS only simulates floods on rivers of a Strahler order 6 and higher (Winsemius et al., 2013). Hence, is was not possible to derive a modelled protection standard for

catchments with only lower Strahler order rivers, corresponding to ca. 2 % of the Earth's land surface (excluding Antarctica).

Various alternative choices for modeling protection were investigated. Before opting to use the World Bank income groups classification to perform the interpolation (step 2 and 3), we first interpolated uniformly between all sub-country regions across the globe, and also used the United Nations regions classification. Further, we performed the interpolation calculations (step 2 and 3) based on both the return period, and on the annual exceedance probability. We formulated our decision for the World Bank income groups aggregation, and for using the flood periodicity in the interpolations, on the basis of a comparison of the results with the protection standards included in the Design layer (see Sect. 3.3 and Table 5). We visualize the results of these alternative choices for the Model layer in Fig. S1 in the Supplement.

3 Results

The map in Fig. 3 visualizes the Merged layer: the aggregation of the protection standards at the scale of the sub-national unit, from the three FLOPROS layers. The underlying information, contained in the Design, Policy, Model and Merged layer can be found in the files in the Supplement: the complete lists of protection standards of the Design and Policy layers, and their references, are included in an Excel table. Furthermore, a Shapefile provides the information on the protection standards of the Model layer along with the information of the Design and Policy layers that is compatible with the sub-country unit scale of the map, and the resulting Merged layer. Information from the Design and Policy layers that is available at a scale finer than the sub-country unit is not included in the integration process, but remains available for use in its original layer. In this section, we report on the main findings for the Design, Policy and Model layers.

3.1 Design layer

Table 1 summarizes the different types of information that are gathered and organized within the Design layer. A total of 179 entries have been included in this layer. For each entry it is specified whether the measure is meant to counter riverine flood, coastal flood, or both. Empirical information on protection standards seems to be more available for river floods (122 out 160 entries). The spatial resolution is heterogeneous, ranging from city-scale (the most common with 102 out of 160 entries) to country-scale. Most of the information is gathered from institutional and technical reports.

In many occasions, information is retrieved in the form of a range of protection standard values, with a maximum and minimum value, normally to account for the spatial heterogeneity of the location, and/or for the necessarily vast uncertainties associated with the estimation of the magnitude and the probability of flood events (see also Fig. 4).

Although in many sources the type of flood defenses are not explicitly specified, it appears that measures are mostly structural, namely dikes and levees, such as the Thames Barrier for London (Risk & Policy Analysts Limited, 2006), and retention areas. "Soft" and "green" measures for flood protection (Cheong et al., 2013; Hinkel et al., 2015) tend not to have a standard of protection specified in terms of return period years, although exceptions exist, such as the flood control area realized for the town of Kruibeke, Belgium, combining flood protection with habitat creation, for which a protection standard of 350 years is specified (EU OURCOAST Project, retrieved November 2014).

3.2 Policy layer

The Policy layer is composed of 68 entries, considerably less than for the Design layer. Table 2 summarizes the characteristics of the information gathered in this layer. A list of the countries for which policy standards of flood protection have been retrieved, either at the country-, regional-, or city-scale, is provided in Table 3. In contrast with

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the Design layer, river and coastal flood protection entries are more balanced, and information is much more available at the country scale, than at the city scale. The main sources are again technical and institutional reports, followed by specialists' books.

Mostly, policy protection standards are provided in the form of coding of areas, which is assigning different standards of protection to an area based on the type of use (e.g., residential, industrial, agricultural). This is for example the case in the United Kingdom, where policy standards seem to range from 1 to 300 years, depending on the land-use (DEFRA, 1999). A recurrent form of regulating flood risk is the limitation of new developments in areas subject to flooding of a certain return period, which often depends on the urban, residential, rural or industrial use of the land.

3.3 Model layer

By default, the Model layer gives values for the majority of the sub-national units (Fig. 3). To test its validity, we compared it to the Design layer values, which are deemed closest to reality (Fig. 4). Moreover, as mentioned in Sect. 2.4, a range of options have been tested using different aggregations of sub-country units for interpolation, and different units for protection standards in the interpolations. Therefore, the comparison with the Design layer serves also as a basis for the choice of the most appropriate method for the Model layer of FLOPROS.

We use two criteria for the selection of the most appropriate solution by comparison with the Design layer: (1) the number of occurrences in which the Model layer value falls within the range of Design layer values; and (2) the average offset between the Model layer and the Design layer values.

Table 4 shows the degree of matching between the output of the selected solution for the Model layer and the Design layers, for a number of spatially-coherent comparisons (where the scale of information in the Design layer matches the resolution of the Model layer). The solution of aggregating by World Bank income groups and to use return period years for the interpolations yielded a better performance according to both criteria, with its values most of the times either falling within the range provided by the Design layer or close to the only available Design layer value (Fig. 4). We therefore considered it the one most in agreement with the Design layer and decided to adopt it for inclusion in FLOPROS. The comparison of all solutions for the Model layer to the Design layer values is found in Fig. S1.

The highest standards of protection in the Model layer are found in North America, from about 380-year return period in the west coast of the United States, to about 20 years in Mexico; in Europe, from about 250 years in regions of west Germany to about 20 years in eastern European countries, with peaks of more than 500 years in specific cities like Vienna, Paris and London; and in Russia, Australia, Saudi Arabia and Oman, with values around 50.

South America is protected with standards ranging from about 45-year return period in Uruguay and Chile, to 6 in Bolivia, Paraguay, Guyana and French Guiana. Africa presents protection ranging from 16 in northern and in southern African countries, to values of 2 in Saharan, sub-Saharan, tropical and western Africa, with peaks of about 115 in Egypt and 45 in Equatorial Guinea. Protection in Asia ranges from peaks of about 150 in Japan, to values around 2 in countries like Myanmar, Cambodia, Afghanistan or Nepal.

4 Discussion and future developments of FLOPROS

In the FLOPROS database, we have compiled information on standards of flood protection from a variety of available sources in the literature (Design and Policy layers), and with an approach based on modeling (Model layer). The collected information ranges widely in spatial scale and the reliability of the source. The differences in spatial scale pose a substantial challenge to the comparison, integration, and visual representation (Fig. 3) of the information from the three layers (see Sect. 3.3). In fact, while the Model layer is based on the sub-country units, information in the Design and Policy layers is gathered at different spatial resolutions. Therefore, while the composite, three-layer integration of the database that we propose (Sect. 2.5) is carried out at the scale of the sub-country units that are used in the Model layer, a substantial part of the Design and Policy layers information that is available at finer scales is excluded, but remains available in the respective layers. On the other hand, the observed range in the reliability of the sources implies that not all information included can be equally trusted. Although uniform reliability cannot realistically be achieved, this limitation can be addressed by the strategies that we propose in Sect. 4.1.

4.1 Type of protection

The Design and Policy layers of FLOPROS comprise at present almost exclusively information on structural measures of flood protection. These are construction works, commonly dikes, levees and reservoirs, but also less common solutions, such as river bypass channels (realized for example for the Donau in Vienna, Zurich, 2014), and are often referred to as “grey”. But examples of “soft” measures like management plans (as in the case of Copenhagen; City of Copenhagen, 2012) are included as well. Also, entries in the database commonly refer to hazard-reducing measures, i.e., measures aimed at addressing the frequency and the magnitude of flood events. In recent years flood risk reduction practices have increasingly been considered that rather than addressing flood hazard aim to reduce the exposure or the vulnerability to floods (e.g., Nicholls et al., 2008). For example, relocation of people and assets outside of floodplains of a given return period is a measure that addresses exposure; and dry-proofing (sealing off to water) residential buildings is a measure to reduce vulnerability of the assets in a flood-prone area. Further, since the introduction of the concept of Integrated Flood Risk Management, a new paradigm has taken foot, entailing hybrid and mixed approaches (e.g., Sayers et al., 2013) that combine approaches to simultaneously reduce the hazard, exposure and vulnerability elements of risk (as defined in Kron, 2005). All the above approaches and measures aim to reduce risk, and are there important for the risk calculation, that FLOPROS has the ambition to improve. We therefore suggest that future, expanded versions of the FLOPROS database should also present approaches to include exposure- and vulnerability-reducing measures.

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4.2 Comparing the FLOPROS layers

To investigate the coherence of the database in its three layers, we compared the values of protection standards included in the Design layer and in the two "proxy" layers, the Model and the Policy layers. For the sub-country units for which FLOPROS has a protection value for both the Design and the Model layers, we found highly-significant correlation between the two datasets, with both parametric and non-parametric tests (Pearson's $r = 0.76$; Spearman's $\rho = 0.70$; $p \ll 0.001$ for both correlation coefficients) (Fig. 5a). Due to the strong positive skewness of the datasets in both the Design and Model layers, data were log-transformed prior to assessing the correlation with the Pearson's r coefficient.

The correlation between the log-transformed datasets of the Design and Policy layers is also positive, but due to the low number of observations ($n = 13$) it does not reach statistical significance (Pearson's $r = 0.46$ and $p = 0.12$; Spearman's $\rho = 0.41$ and $p = 0.17$) (Fig. 5b), implying that, for the sub-country units for which both Design and Policy information was retrieved, enforced protection reflects to a some extent the policy objectives. We conclude that while both the Model and the Policy layers can be considered useful proxies for actual, enforced protection as included in our Design layer, the Model layer is a more solid proxy.

With regards to hierarchy of the three layers of information, we need to stress that the chosen order (see Sect. 2.5), with the Design layer on the top, the Policy layer underneath and the Model layer at the bottom should not be interpreted as a rigid prescription. In fact, because the Model layer approximates the Design layer values closer than the Policy layer, it could be argued that the Model layer should feature after the Design layer in the hierarchy. However, because many factors could be considered to argue for the one or the other hierarchical solution, we emphasize that layers in FLOPROS should be kept separated, and propose that users could take their own decisions regarding how to integrate them to better fit their purposes.

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Because the main motivation of FLOPROS is to provide a practical tool to support research in flood risk management, we focus on its potential applications, such as global hydrological modeling (Bierkens, 2015). The layers in the database can be utilized independently from each other, based on the scope of the investigation. The hierarchical overlaying of the three layers permits overcoming the issue of aggregation of heterogeneous information from the layers. Therefore, information can be retrieved and used both in the form of single items, represented by single entries of the database, and of aggregated information, from more entries and/or from more layers. This possibility especially reflects the necessities of large-scale assessments of flood risk (e.g., Ward et al., 2013). Further, since information of the Design and Policy layers is presented in the form of maximum and minimum values, the investigator can choose to run the modeling exercise either under the assumption of high or of low standards of protection.

A number of limitations, however, still persist; in the following we discuss them and propose directions to overcome them.

4.3 Outlook to future versions of FLOPROS

As visible in the mapped visualisation of FLOPROS (Fig. 3) on global and European scale, vast and densely-populated areas in developing regions such as Africa, South America, and the Middle-East clearly have less empirical information compared to developed countries. We advance a number of strategies aimed to extend the coverage, resolution and reliability of future versions of FLOPROS.

4.3.1 Towards an online platform for FLOPROS

The FLOPROS database could greatly benefit from the support of an online platform. This would serve two functions: (1) enabling and managing the entry of new information by experts; and (2) visualisation and download of FLOPROS by users.

Regarding point 1, experts, operators and researchers with a project portfolio in the regions of the database where data coverage is scarcer (Fig. 3) are in the position of providing local insights about protection standards, to help filling the vast gaps still present in FLOPROS.

Regarding point 2, we propose that the database should be open and freely accessible to every potential user on the internet. This will also ensure that users in less developed countries, and researchers with limited financial means will be able to use information from FLOPROS for hazard and risk assessment in their region of focus.

To allow efficient access to the database, both to the contributing community and to end-users, it is necessary to find a suitable format for its publication. In this regard, a tool should be identified that presents at least three main characteristics: (1) it should be free and open-source, and therefore readily available to any user world-wide; (2) it should provide the possibility for straightforward and structured update of information from the community, for example by including a form that can be filled in online, such as proposed in Table S2 in the Supplement for this manuscript; (3) it should permit quality-control of information by the custodians of the database; and (4) it should permit information at different spatial scales: river basin and sub-basin, administrative, and also hybrid units.

Further, another interesting potential of an online platform for FLOPROS, is the potential to enable crowd sourcing of information about actual dikes and levees, for example using volunteered geographical information (VGI) datasets (e.g. Haklay and Weber, 2008; Haklay et al., 2014). This could provide the needed parameters to convert the presence of dams and reservoirs from the GRanD database (Lehner et al., 2011) into protection standards, as described below.

4.3.2 Protection from dams and reservoirs

A database of existing dams and reservoirs with a global coverage currently exists, the GRanD database (http://www.gwsp.org/products/grand-database.html; Lehner et al., 2011). The database is nearly exhaustive and comprises 6862 dams and 6824

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associated reservoirs. We envision the following strategy to extract flood protection information from GRanD.

For each dam and reservoir in GRanD it is specified whether flood control is its main or its secondary use. A conservative estimate of the amount of flood storage, available through dam operation, can therefore be made, assuming that a portion of the flood control reservoirs is available for this purpose. Consequently, a conservative estimate of their effect on flood hazard levels, and thus the standard of flood protection they offer can be assigned to the associated river stretches and to the main cities downstream in the proximity (flood protection typically reduces further downstream of the dam, as more tributaries enter the river). Expert judgment could be employed to determine the general standards of flood protection associated with dams and reservoirs, and the extent of the protected area downstream. Or alternatively basin-specific hydrological modeling with and without consideration of this available flood storage could yield more accurate estimations of protection.

4.3.3 Using statistical correlations

While we envision that, with the community's collaboration, a better spatial coverage of the Design and Policy layers can be achieved in the future, we nevertheless expect that for many areas empirical and normative information might neither be retrieved, nor exist. A strategy to achieve global coverage and fill the persistent gaps, alternative to the approach devised for the Model layer, is to compute correlations between standards of protection in FLOPROS (using information from the Design and Policy layers), and socio-economic indices, at various scales. If a suitable multiple regression model is found, it could then be applied to infer "Index-derived" protection standards for those missing regions.

This is not a trivial exercise, and a relationship between wealth of cities and protection standards was postulated before (e.g., Nicholls et al., 2008). Linham et al. (2010) have explored the correlations between their 36 coastal cities protection dataset vs. country GDP per capita and exposed population, with poor results.

They did show that the "demand for safety" metric of the DIVA impact model could predict the protection standard within a factor of 10. Later, Feyen et al. (2012) used GDP to infer protection standards on a EU scale. Jongman et al. (2015) provided global empirical evidence on a general relationship between GDP and vulnerability, but did not relate this specifically to protection standards. An in-depth investigation some African countries, used as case studies, suggested political and economic conditions that foster action towards disaster risk management (CCAPS, 2014). Our new database enables an extensive exploration of the socio-economic determinants of flood protection (Cutter et al., 2008). Our preliminary results indicate that at country-scale significant correlations appear to exists between protection standard in the Design and Policy layers and some economic and governance indicators, such as the "Government Spending" and "Freedom from corruption" indexes (The Heritage Foundation, 2014, http://www.heritage.org/index/book/methodology, and references therein) (Fig. 6). Countries with higher public spending tend to have higher flood protection standards, as included in the country-scale entries of our Design and Policy layers.

5 Conclusions

We launch the first version of the global database of FLOod PROtection Standards, FLOPROS. The database aims to gather the most up to date, reliable, and high-resolution information available on protection standards, and to maintain a database that can be of use to research and management of flood risk, from the local to the global scale. We structured FLOPROS in multiple layers of flood protection standards: a Design layer, composed by information about standards of actual existing protection; a Policy layer, reflecting normative objectives for protection standards; and a Model layer, based on a modeling approach, which we validated against the Design layer observations. We suggest that protection standards provided in the Policy and in the Model layer are valid proxies for actual protection standards.

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We concomitantly launch a call to the expert community to contribute new and missing information to further versions of FLOPROS. We propose that the set-up of an online platform to admit and organize information in the database could facilitate this process. Further, we propose strategies that could enhance the completeness, reliability and resolution of the database.

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Table 1. Overview of the characteristics of information contained in the Design layer of the FLOPROS database (the full database is available in the Supplement).

Characteristic	Subdivision	# entries	%
Type of flood hazard	River floods	101	58
	Coastal floods	32	18
	Both	35	19
	Unspecified	8	5
Scale	City	103	58
	River stretch	37	21
	Region	22	13
	Country	14	8
Reference type	Technical report	50	28
	Institutional report/document	46	26
	Institutional website	15	9
	Personal communication	12	7
	Journal article	11	6
	Engineering book	9	5
	Specialists book	7	4
	Technical website	6	6
	Newspaper article	6	6
	Scientific study	4	2
	Project website	3	2
	Corporate website	3	2
	Wikipedia	1	1
	Not available	2	1
Reliability	High	97	55
	Medium	51	29
	Low	21	12

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Table 2. Overview of the characteristics of information contained in the Policy layer of the FLOPROS database (the full database available in the Supplement).

Characteristic	Subdivision	# entries	%
Type of flood hazard	River floods	26	38
	Coastal floods	11	16
	Both	28	41
	Unspecified	4	4
Scale	City	7	10
	River stretch	2	3
	Region	7	10
	Country	50	74
	Continent	2	3
Reference type	Technical report	22	32
	Institutional report/document	16	24
	Institutional website	5	7
	Personal communication	3	4
	Journal article	8	12
	Specialists book	6	9
	Technical website	2	3
	Scientific study	1	1
	Project website	3	4
	Not available	2	3

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Table 3. Countries for which indications of the presence of policy/legal standards of protection at national-, regional-, or city-scale were found.

Countries	National-scale	Regional-scale	City-scale
Australia			X
Belgium	X		
Canada		X	
China	X		X
Denmark	X		X
Finland	X		
Germany	X		
India	X		
Ireland	X		
Japan	X		
Netherlands	X	X	
Poland	X		
Switzerland	X		
United Kingdom	X	X	X
United States	X		X

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Table 4. Summary of the sensitivity analysis for the Model layer, and comparison to the Design layer. The criteria for the comparison are the number of occurrences in which the Model layer value falls within the range of Design layer values, and the average offset between the Model layer and the Design layer values.

Method of aggregation of sub-country units:	Calculation using:	Value falls within the Design layer range[1] (# of occurrences)	Average offset from the Design layer[2] (exceedance probability)
World Bank income groups	Return period	5 out of 8	0.053
	Exceedance probability	4 out of 8	0.059
United Nations regions	Return period	3 out of 8	0.064
	Exceedance probability	2 out of 8	0.088
No aggregation	Return period	4 out of 8	0.166
	Exceedance probability	0 out of 8	0.401

[1] For the nine comparisons for which a range of Design layer values is available (see Fig. 4).
[2] We calculate the average of the absolute value of each offset between the Model layer and the Design layer (i.e., the mean between the max and min value, if a range is available) protection standard expressed in terms of exceedance probability.

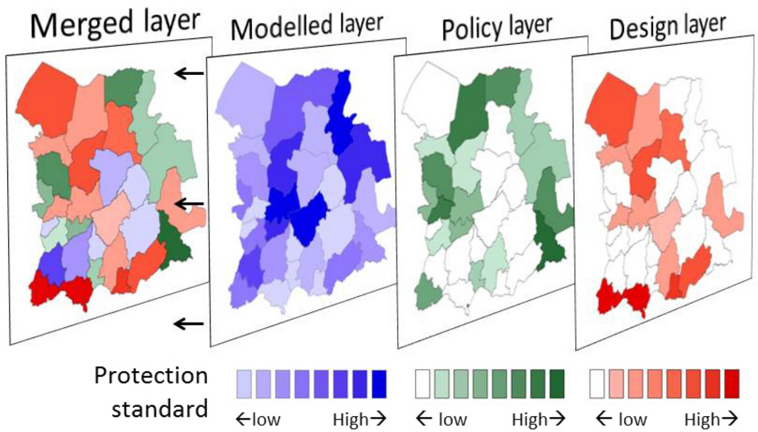

Figure 1. Hierarchical structure of information contained in the FLOPROS database. The Design layer provides information on the construction standard of existing protection measures; the Policy layer is relative to normative standards of protection; while the Model layer calculates protection using flood hazard modeling and a relationship between wealth and flood protection (see Sect. 2.4 for details). These are aggregated into the Merged layer, as explained in Sect. 2.

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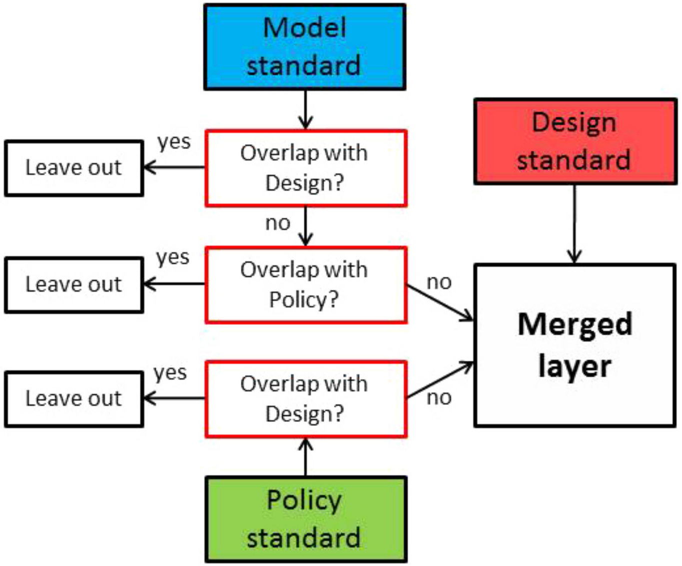

Figure 2. Procedure for the integration of protection standards information from the Design, Policy and Model layers into the Merged layer of the FLOPROS database.

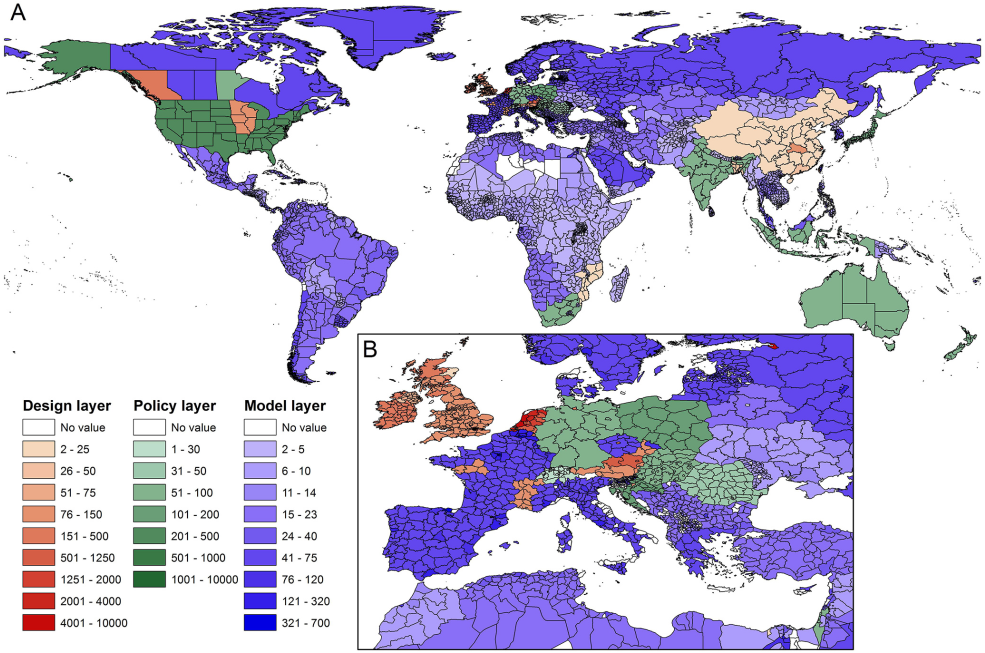

Figure 3. (a) World and **(b)** Europe maps of flood protection standards contained in the FLOPROS database, for sub-country administrative units (http://www.gadm.org) Standards of the Design, Policy and Model layers (see Sect. 2) are indicated in the red, green and blue colour-scales, respectively; these are integrated into the Merged layer, which the maps ultimately represent. White indicates no data available (see Sect. 2.4). Note that only the protection standards of the Design and Policy layers that are coherent with the scale of the sub-country units are included, and therefore part of the information of FLOPROS is not represented in the maps.

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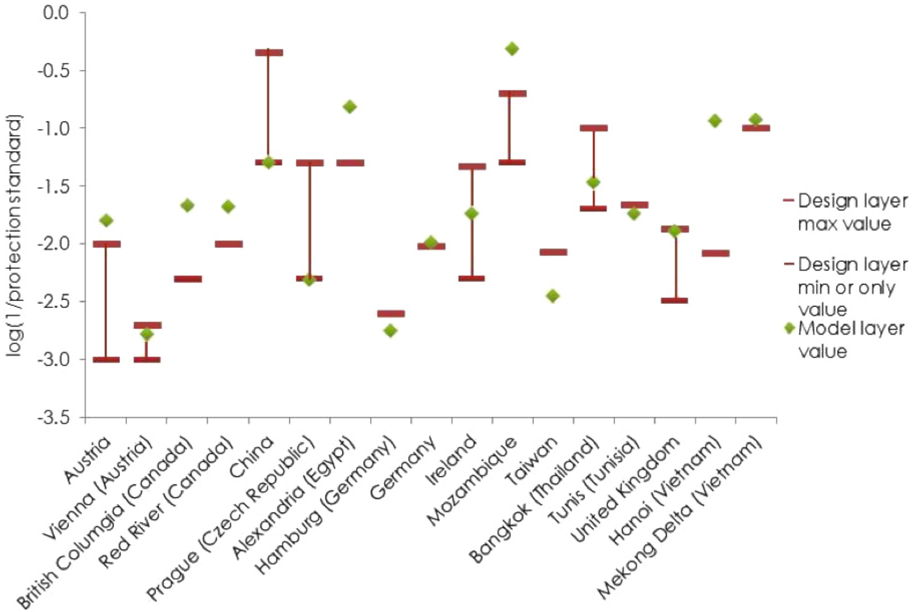

Figure 4. Comparison of the protection standards included in the Model layer (green diamonds) to those in the Design layer (red bars), for locations where the two layers can be compared on the same scale. For the Design layer, a range of values, when available, or a single value are plotted. To enhance the visualisation, values are reported as logarithm of the annual exceedance probability relative to the protection standard.

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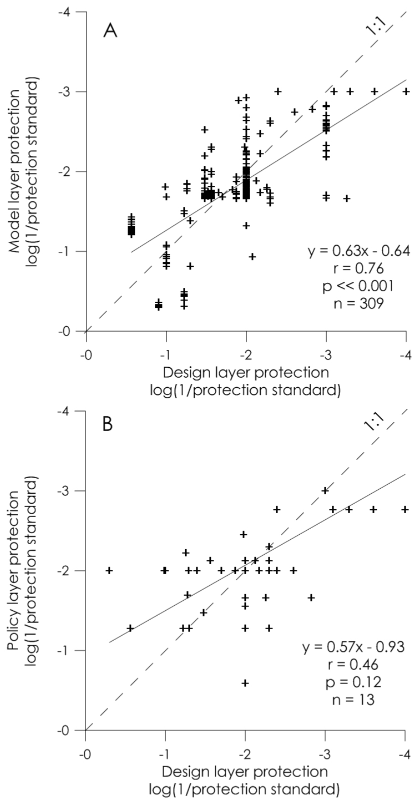

Figure 5. Correlation between datasets of **(a)** the Design and of the Model layers, and **(b)** the Design and the Policy layers. A log-transformation was applied to the values expressed as exceedance probability ($1 \times \text{return period}^{-1}$). The regression curve slope and intercept are shown, along with the r Pearson's correlation coefficient and the p value of the correlation. When a minimum and maximum protection value were present, the average of the annual exceedance probabilities (the inverse of the return period) was taken.

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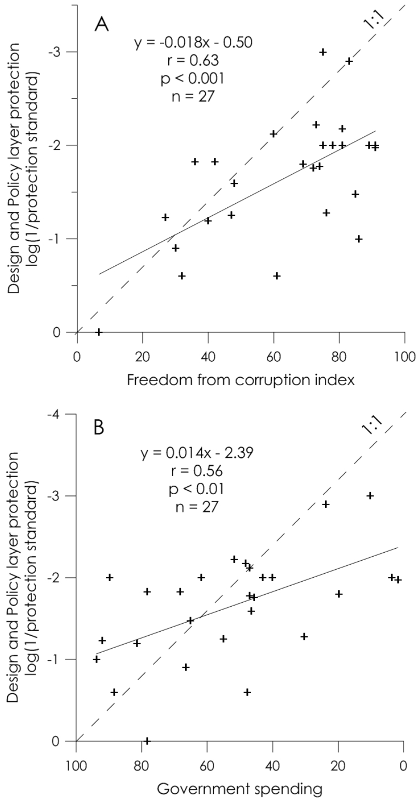

Figure 6. Examples of correlation of flood protection standards, as from our Design and Policy layer, with economic and policy indexes: **(a)** with the "Government Spending" index (note that the axis is reversed, because a 100 value of the index indicates minimum government spending, and conversely), and **(b)** with the "Freedom from corruption" index (The Heritage Foundation, 2014, http://www.heritage.org/index/book/methodology, and references therein). For clarity: to more freedom from corruption, and to more government spending correspond higher flood protection standards.

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