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The Potential for Various Riverine Flood DRR Measures at the Global Scale

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Abstract

Flooding events that occur on the Earth's rivers annually cause large amounts of monetary and human impacts. These impacts are expected to increase through the end of the 21st century for various reasons. Decision makers must take action now and implement disaster risk reduction (DRR) measures to avoid large increases to damages in the future. Several DRR measures have been posited as ways to reduce the deleterious impacts of riverine flooding. On the global scale, however, efforts to model the effects of DRR measures (beyond structural) in the future are limited. In this paper, we use a global-scale flood risk model to estimate the risk of riverine flooding, and to assess and compare the efficacy and economic performance of various DRR measures, namely dykes and levees, dry-proofing, and zoning restrictions – and evaluate them in terms of their economic performance (via benefit-cost analysis) as well as their ability to achieve a predefined risk reduction target based on current relative levels of risk, referred to here as efficacy. We show that large decreases to future expected annual damages can be obtained if certain measures are implemented throughout various sub-national regions of the world, most notably in regions with high levels of projected population growth. We see that the two aforementioned evaluation metrics, when used to select a DRR measure for implementation, result in different outcomes for three-fourths of the world's sub-national regions, most often in East Asia and the Pacific as well as South Asia. In these instances, decision makers must choose what is more important – achieving a risk reduction target, or having investments pay-off in the long run, even if it requires a large amount of up-front capital. This opens the dialogue for incorporating other non-monetary values into the decision-making process for disaster risk management, and also points to the potential of hybridising riverine DRR measures to achieve multiple risk and societal objectives at once.

Keywords

Riverine flooding; disaster risk reduction; global-scale flood risk assessment; GLOFRIS; adaptation decision making

1 Introduction

River floods are globally one of the most damaging forms of natural hazard (Guha-Sapir et al., 2015). In 2022 alone these disasters included floods in Australia (37 dead, $8.1 billion USD in damages), Pakistan (1,739 dead, $14.9 billion USD in damages), and Nigeria (612 dead, $4.2 billion USD in damages). These increasingly deadly and damaging flooding events happen for various reasons. Increased frequency and intensity of hydrologic extremes (Trenberth, 1999; Diffenbaugh et al., 2013; Yuan et al., 2015) as well as rapidly melting glacial and snow stocks in mountainous regions (Zhang et al., 2021; Milillo et al., 2019) and thawing permafrost stocks in the polar regions of the world (Demchenko et al., 2006) are resulting in larger quantities of water reaching river systems than before. Although these increases to riverine flood hazard are notable, other regional- and global-scale changes, including land subsidence (Brown and Nicholls, 2015; Syvitski et al., 2009), deforestation (Bradshaw et al., 2007; Chakravarty et al., 2012) and urbanisation (Güneralp et al., 2015; Jongman et al., 2012), are also enhancing the severity of river floods. Indeed, this trend of catastrophic and deadly flooding along rivers of all sizes is expected to continue through the 21st century due to climate change and socio-economic development (Alfieri et al., 2017; Arnell and Gosling, 2016; Hirabayshi et al., 2013; Winsemius et al., 2016; Ward et al., 2020), emphasising the global need for increased disaster risk reduction (DRR) efforts. If not met with action from decision makers at all levels, our global society will be more prone to the human and monetary impacts of river floods in the future.

While adaptive actions are needed globally, limited global-scale research exists on the effect of specific DRR measures, such as dykes, dry-proofing, and zoning, on river floods and their impacts. Willner et al. (2018) clearly state that flood protection standards around the world will have to be increased to varying degrees (e.g., doubled in the United States of America) in the future in order to reduce future flood risk to current levels, but they do not explore a specific DRR measure to do so and only focus on people affected and not monetary damages. Kinoshita et al. (2018) looked to quantify the effect of autonomous adaptation to global river flood risk but did so by changing vulnerability formulas as a proxy for adaptation and not specifically through a benefit-cost analysis for one particular DRR measure. The only studies to explicitly include future DRR measures on the global scale are Jongman et al. (2015) and Ward et al. (2017). Jongman et al. (2015) used a simple approach to project changes in future flood risk if vulnerability were reduced in all countries to the level currently found in the richest countries. Meanwhile, Ward et al. (2017) assessed the benefits and costs of dykes and levees towards the end of the 21st century but did not explore any additional DRR measures.

These global analyses often base the assessment of optimal adaptation only on benefit-cost analysis. While benefit-cost analyses are useful decision-support tools for making economically optimal decisions, they often disregard benefits and costs that are difficult to express in monetary terms, such as social welfare effects (Hwang, 2015; Kind et al., 2017) and other indirect and intangible loses experienced during inundation events (Mechler, 2016). As a result, benefit-cost analysis often favours cost-effective large-scale adaptation with dykes that mostly protect areas with high economic value and can have major impact on for instance ecosystem services. Similar risk reduction could be achieved through other strategies such as dry-proofing and zoning, which have as additional benefit that they can reduce the impacts of extreme events to some extent, albeit at higher costs. To further strengthen DRR analysis, alternative methods to cost-centric metrics should be explored (Mechler et al., 2014). As Siders & Pierce (2021) describe, much uncertainty remains in which decision-making process is actually utilised by decision makers, especially in the realm of climate change adaptation. By using other decision-making processes that are not solely based on economic performance, other values such as those described by the Sustainable Development Goals (SDGs, Hák et al., 2016) might be captured and used in making decisions regarding future climate adaptation pathways.

To fill these gaps, we evaluate several DRR measures, namely dykes and river levees, zoning restrictions, and dry-proofing, within the same flood risk assessment framework on the global scale. Zoning restrictions and dry-proofing, specifically, have not yet been assessed on the global scale for riverine flood risk. We evaluate the measures using both a traditional benefit-cost analysis as well as an efficacy metric, i.e., the ability of any given measure to achieve a preestablished risk reduction target, here set by a *relative-risk constant* objective. Our main question is how the global spread of DRR measure implementation might differ if decision makers were to use either one of these evaluation tools. To answer this question, we expand GLOFRIS, a global flood risk estimation methodology developed for riverine flooding (Ward et al., 2013) and recently modified to include various adaptation measures (Mortensen et al., 2023).

2 Methodology

The methodological components of this paper can be summarised as: risk estimation (section 2.1); simulating risk reduction (section 2.2); and measure selection (section 2.3). We apply this selection methodology by using either the benefit-cost analysis or the efficacy metric as a selection tool; we then prognosticate what the global spread of DRR measure implementation may look like in 2080 on a sub-regional level assuming one of the two aforementioned metrics are used to decide which option is best to implement. These steps are detailed in the following subsections.

2.1 Risk estimation

We extend the GLOFRIS framework to estimate future riverine flood risk. The framework was originally developed for global riverine flood risk modelling (Ward et al., 2013; Winsemius et al., 2013), and recently expanded to include additional adaptation measures beyond solely dykes and levees (Tiggeloven et al., 2022; Mortensen et al., 2023). This framework can be used to estimate either expected annual affected population (EAAP) or expected annual damages (EAD); we investigate the latter in this paper at the sub-national scale, as many policies are often implemented and monitored on this level. Sub-national scale is defined as the next administrative unit below national scale in the Global Administrative Areas Database (GADM), or GADM 01.

Current riverine flood risk levels refer to those calculated with hazard, exposure, and vulnerability data for the year 2020, while a future timestep (in the case of this manuscript, 2080) consists of the averaged conditions in the window of 20 years on either side of a given year. The risk estimation used in this paper for riverine flooding largely reflects that used by Mortensen et al., (2023) for coastal flooding, which we summarise here for completeness.

2.1.1 Risk components

This analysis uses riverine flood hazard maps generated by PCR-GLOBWB-DynRout (Van Beek et al., 2011) for the following return periods: 2, 5, 10, 25, 50, 100, 250, 500, and 1000 years. The hazard maps show the extent and depth of flooding per grid cell (30” x 30”) for each return period under current conditions (2020) and under several future conditions under five GCMs, namely GFDL-ESM2M, HadGESM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M. The resulting river flood maps are given only for with rivers of order 6 and higher, corresponding with “large rivers” (Mazur & Castner, 1990).

Exposure input includes current and future population and urban areas, current and future GDP, and maximum economic damage per grid cell (30” x 30”). For this paper, gridded data for population and urban areas and GDP are taken from the 2UP model for current and future conditions (Koomen et al., 2023; Andree & Koomen, 2017). We present our results using SSP2 (O'Neill et al., 2017), or the “Middle of the road” scenario. Maximum economic damages are estimated using the methodology of Huizinga et al. (2017), where a root function to link GDP per capita to construction costs for each country is used. To estimate future maximum damages, the current values are scaled with the GDP per capita per country from the SSP database. To calculate future risk relative to GDP, future gridded GDP values are taken from Van Huijstee et al. (2018), which uses the national GDP per capita from the SSP database as input.

While hazard and exposure inputs for our study are raster-based, vulnerability is represented here using a global database of country-specific depth–damage flood functions (Huizinga et al., 2017). These curves are used in the related analyses of Tiggeloven et al. (2020) and Mortensen et al. (2023) and are based on empirical curves that are occupancy type-specific, namely residential, commercial, and industry. The resulting damages are represented as a percentage of the maximum damage, or the total assumed economic value of the given cell. This maximum damage is reached at a water level depth of 6m.

2.1.2 Protection standards

An estimate of the current riverine flood protection standard for each sub-national region is required to calculate the current risk. We use estimates of the current protection level by applying the FLOPROS modelling approach as originally described in Scussolini et al. (2016) and most recently applied for riverine flooding by Ward et al. (2017) and Hochrainer-Stigler et al. (2021). Current levels of flood protection are retrieved from Scussolini et al., (2016). As such, each flood protection level corresponds to a certain depth of inundation. For a given scenario and protection level, and for a given grid cell, we establish the heights of the dykes as follows. First, we retrieve the discharge occurring with the return period associated with the required protection level from a Gumbel distribution of discharges, following the original method developed for GLOFRIS (Ward et al., 2013). The width and bankfull depth of the channel are taken from the hydrological model PCR-GLOBWB (part of GLOFRIS framework), using:

$$Q = hB\frac{1}{n}R^{2/3}\sqrt{i} \tag{1}$$

where Q is the discharge [$L^3\ T^{-1}$], h is the flow depth [L], B is the flow width [L], n is the Manning roughness [$T\ L^{-1/3}$], R is the hydraulic radius [L] (equal to $hB/(2h + B)$) and i is the slope of the channel [unitless]. In large rivers, flow depth is much smaller than the flow width, and R can be approximated by h, reducing equation 1 into:

$$Q = B\frac{1}{n}h^{5/3}\sqrt{i} \tag{2}$$

In our case, a part of the flow is through the main channel and part over the part of the floodplain that lies in between the dykes, both having different dimensions and roughness values. We therefore split up equation 2 into a channel part and a floodplain part as follows:

$$Q = [B_c\frac{1}{n_c}h^{5/3} + B_f\frac{1}{n_f}(h - h_{bf})^{5/3}]\sqrt{i} \tag{3}$$

where c and f are channel and floodplain respectively, and h_{bf} is the bankfull channel depth [L]. We solve this equation for h. The required height of the dyke is then $h - h_{bf}$.

We assume all regions have at least a 2-yr protection standard in 2020, with a maximum of 1000-yr protection standard in specific cases (e.g., the Netherlands and Singapore). Due to projected climate change, the protection standard of current flood protection infrastructure may decrease in the future if no improvements are made (e.g., a DRR measure that provides protection against a 100-yr event today may only protect against a 75-yr event in the future). We account for this potential degradation to protection standards in our study.

2.1.3 Risk target

To establish the future level of protection desired to be provided by DRR measures used in this paper, we establish a baseline risk reduction target against which each measure is benchmarked. While this target could be set in terms of financial or human impact using many indicators, in this analysis, the target risk reduction is set by the so-called *relative-risk constant* objective as defined by Ward et al. (2017). Specifically, as applied in Mortensen et al. (2023), we define the *relative-risk constant* target as the level of future risk in which the percentage of future EAD to future total GDP is held constant to the percentage of current EAD impacted to current total GDP. The *relative-risk constant* target is calculated for each sub-national region individually, and in this study is presented at the time-step of 2080 (the forty-year average of 2060-2099), representing conditions at the end of the 21st century.

2.2 Risk reduction

The DRR measures modelled in this analysis can be divided into three categories; measures that either reduce hazard (i.e., dykes and levees), exposure (i.e., zoning restrictions), or vulnerability (i.e., dry-proofing). For a detailed methodology of these modelled DRR measures, we refer the reader to Mortensen et al. (2023). Here we discuss basic assumptions and fundamentals of the utilised methodology.

For dykes and levees we apply the methodology by Tiggeloven et al. (2020), originally developed by Ward et al. (2017). In this study, we maintain the same physical dimensions of dykes and levees within the modelling framework as well as unit cost – namely \$7 million km m−1 (Bos, 2008). This unit cost is multiplied by a construction index multiplier to account for differences between countries (Ward et al., 2010). Operation and maintenance (O&M) costs of 1 % per year are applied, with a discount rate of 5%. Initial investments are made in 2020, with construction complete after 20 years. The flows of costs and benefits are discounted until 2100. We assume that modelled dykes do not fail for water levels below the crest level and fail completely for water levels that are higher.

Areas of potential application of dry-proofing are defined as all inundated urban cells within the 2-yr flood zone that have an inundation depth of less than 1m. In all remaining return periods, dry-proofing is assumed to be applied in inundated areas not excluded by the above delineation. We apply the costs of dry-proofing on a per area basis of buildings within urban cells. We assume costs are evenly divided over an initial period of five years, and that O&M costs are negligible. The costs are dependent on the income-level of different regions (Hudson, 2020; Aerts, 2018). Thus, we assume a cost of ~$1,300 per square meter for high and upper-middle income countries and ~$580 per square meter for lower-middle- and low-income countries (Mortensen et al., 2023).

Zoning restrictions are simulated by using the 2UP model (Koomen et al., 2023), in which expansion of new urban areas is not allowed in areas inundated by the 1000-yr return period flood in 2080. Instead, potential urban cells are reassigned to another likely location within the same country, based on simple suitability functions (Ferdinand et al., 2021). With minimal direct cost of implementation, a nominal total cost per sub-national region of $2,000,000 (for high and upper-middle income regions) or $500,000 (for lower-middle and low income regions) is applied evenly over all years of simulation (Mortensen et al., 2023; Meng, 2021; Ran & Nedovic-Budic, 2016; de Bruin et al., 2014). Altering urbanisation with zoning restrictions may produce an opportunity cost of foregone development (Kousky & Walls, 2014) and other indirect costs. For this global analysis, however, we only consider direct costs of implementation and assume any potential GDP growth still occurs in-country, only displaced away from the flood zone.

2.3 Selecting a DRR measure to implement

Making decisions in the realm of climate change adaptation remains an uncertain task. Several methods exist in determining which adaptation pathway to follow, including those which incorporate environmental and social values (Klein et al., 2015; Siders & Pierce, 2021; Bardsley, 2015). For simplicity, we begin the dialogue in this riverine flood risk analysis with two forms of DRR measure evaluation – benefit-cost ratio and target-achieving efficacy. The former focuses on the long-term economic performance of each measure, while the latter focuses on how much of a pre-defined risk target can actually be achieved by each measure.

By using these two different metrics to make a decision as to which DRR measure could be employed for a specific sub-national region, it is quite possible that two different DRR measures may be selected as the ideal candidate. The following subsections describe in detail how both metrics are calculated. We also describe how they can be used to choose a specific DRR measure for implementation and how we have applied them here in our study.

2.3.1 Benefit-cost ratio

Benefit-cost ratios (BCRs) have long been used as the sole means of determining DRR measure feasibility. Expressed by dividing the overall sum of lifetime benefits (i.e., monetary risk reductions, equation 4) by the sum of direct capital and operational costs (equation 5), a BCR is determined for each DRR measure.

$$Benefit = \sum_{t=1}^{n} \frac{B_t}{(1+r)^t} \tag{4}$$

$$Cost = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} + C_o \tag{5}$$

where t denotes time in years, n the total lifespan of the investment, r the discount rate, B_t the (linearised) benefits per year, C_t the costs per year expressed as operational and maintenance costs, and C_o the initial capital investment costs, distributed equally over the term of construction. The BCRs are calculated for 2080, meaning that we do not consider large up-front costs as a disqualifying factor in implementing a DRR measure. In our analysis we assume a BCR greater than 1 indicates that investing in a DRR measure is cost effective in the long-term. Any BCR less than 1 indicates that the investment is not cost effective over time.

The costs reported in this paper are in US$2005 at Purchasing Power Parity (PPP) and were adjusted using GDP deflators from the World Bank. Indirect benefits such as nature contributions to people (Barbier et al., 2011), are not included in this benefit-cost analysis. For this portion of the analysis, we assume in each sub-national region that the DRR measure with the highest BCR is chosen for implementation.

2.3.2 Efficacy metric

We assess the efficacy of the DRR measures by evaluating their ability to reduce risk to maintain the aforementioned *relative-risk constant* target per sub-national region. As mentioned previously, *relative-risk constant* signifies that the future proportion of EAD to GDP remains equal to the proportion of EAD to GDP in the year 2020. The difference between the two EAD/GDP ratios thus signals the risk reduction that DRR measures should achieve (equation 6).

$$EAD_{reduction\ required} = EAD_{2080} - EAD_{2020} \times \frac{GDP_{2080}}{GDP_{2020}} \tag{6}$$

In reality, a risk reduction target can be established for any number of time frames and analysed chronologically; we do not do this here, but instead set one target for the year 2080. The efficacy of the modelled DRR measures to achieve the *relative-risk constant* is expressed as the risk reduction actually achieved by the DRR measure, $EAD_{reduction\ achieved}$ (equation 7), divided by $EAD_{reduction\ required}$ (equation 8).

$$EAD_{reduction\ achieved} = EAD_{2080,without\ additional\ DRR} - EAD_{2080,with\ additional\ DRR} \tag{7}$$

$$Efficacy = \frac{EAD_{reduction\ achieved}}{EAD_{reduction\ required}} \tag{8}$$

The efficacy of each measure is calculated for each sub-national region, and the DRR measure with the highest value is chosen for implementation. The highest value for efficacy we define here is 1, meaning that all monetary risk reductions are achieved to meet the *relative-risk constant* target. In cases where more than one DRR measure achieves an efficacy of 1, we denote which measure achieves the highest efficacy.

3 Results

The results of this analysis are presented and discussed on several spatial scales, including on the global, regional (i.e., World Bank analytical regions), national, and sub-national level. We first show current and future levels of riverine flood risk (section 3.1). We then explore the expected adaptation option when selected using the BCR metric (section 3.2) and the efficacy metric (section 3.3). We also examine the differences arising from using the different metrics (section 3.4) and provide several points of discussion (section 3.5). The underlying results for future flood risk without DRR and the required risk reduction can be found in the appendix.

3.1 Current and future riverine flood risk

We project immense increases to riverine flood risk by the year 2080 (Figure 1). Assuming no action is taken to increase existing protection standards against riverine flood risk, global EAD will increase by an estimated factor of 48 from current levels. These increases are due to changes brought on by climate change as well as population growth. While under current conditions (top panel) no single sub-national region has an EAD of over $10 billion, by 2080 (bottom panel) we estimate the EAD of over 180 sub-national regions worldwide will exceed this value. Many of these regions are located in Sub-Saharan Africa and Asia.

Examining the ten countries with highest current and future levels of riverine flood risk demonstrates this increase even further (Figure 2). China is estimated to have the largest amount of EAD in 2020, at $53 billion USD, this value increases to $606 billion by 2080, an increase by a magnitude of 11. By that time, we project three countries – India, Democratic Republic of Congo, and Somalia – to have EAD values well exceeding $1 trillion USD. These patterns at the national scale are observed also at the sub-national scale, with several sub-national regions within these countries observing similar absolute and relative increases to EAD.

These estimated increases to EAD, as well as associated increases to EAAP, underscore the necessity of implementing DRR measures to reduce the risk of damages to riverine flood risk. The following two subsections examine which DRR measure would be selected per sub-national region if a decision maker were to use a BCR (determined through benefit-cost-analysis) or an efficacy metric.

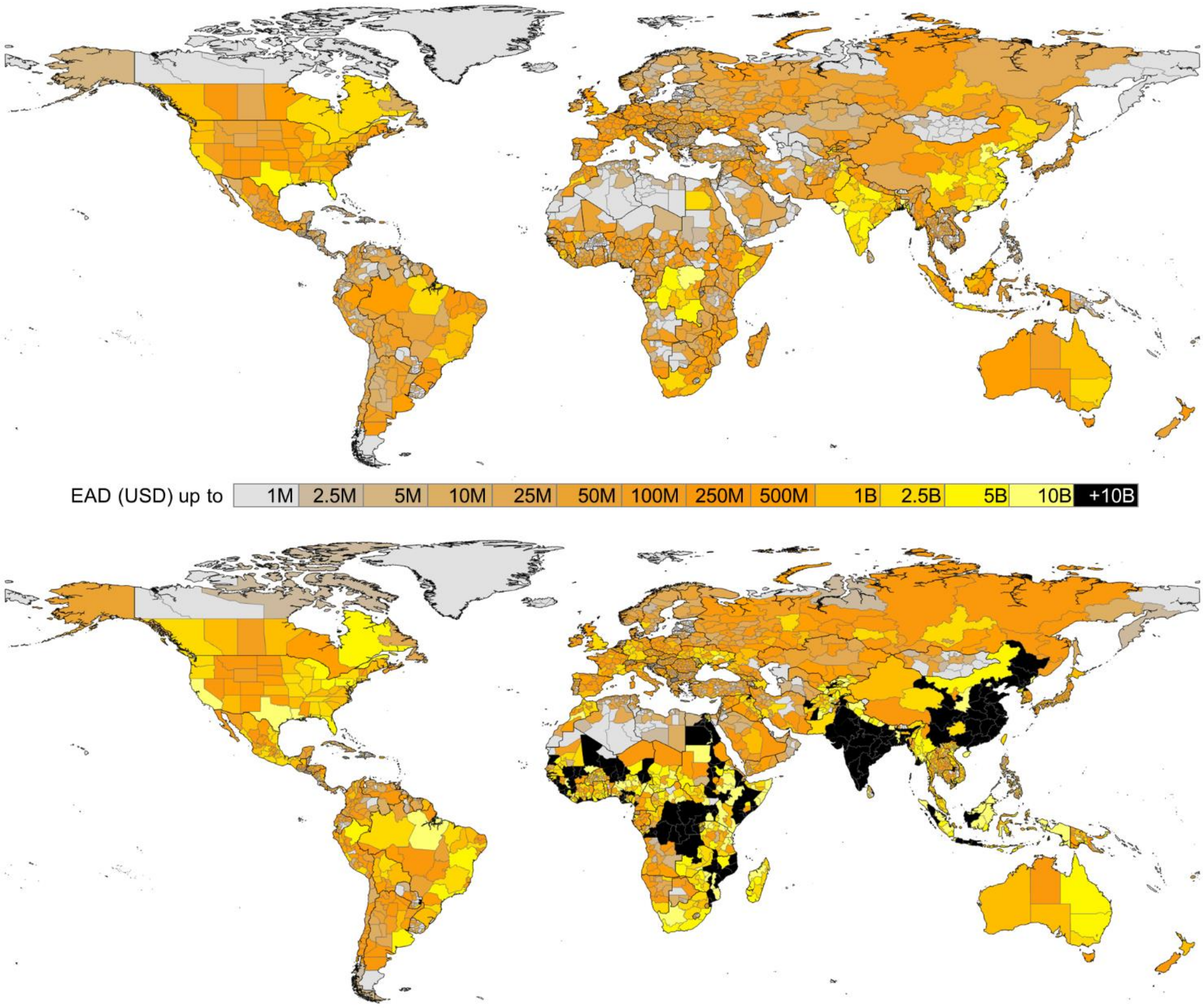

Figure 1: EAD (in US$2005) caused by riverine flooding under current (top panel) and future (bottom panel) conditions per sub-national region.

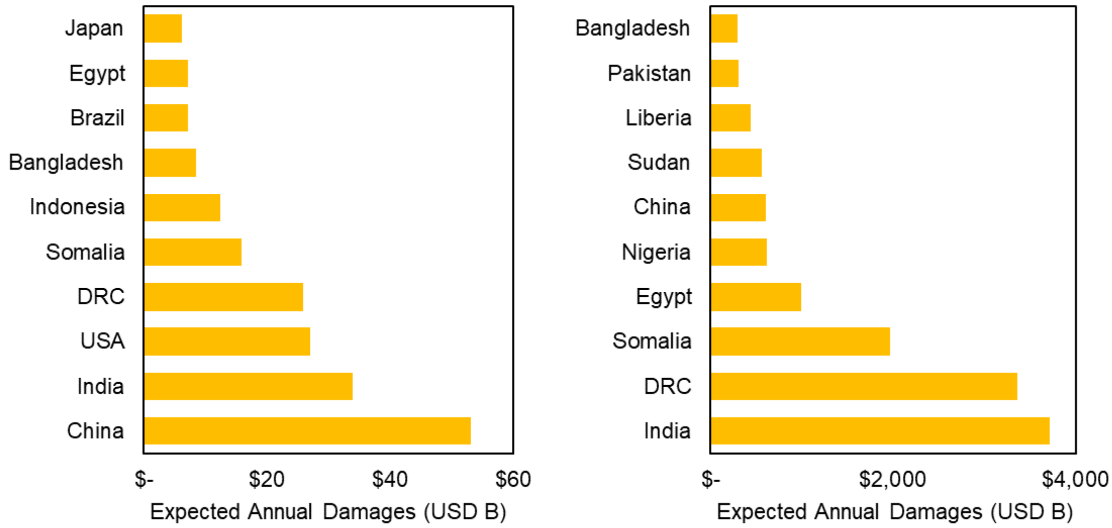

Figure 2: The ten countries with highest EAD (in US$2005) under current (left) and future (right) conditions.

3.2 Selecting DRR measures using BCR

Assuming the BCR is used to select which DRR measure is implemented in sub-national regions where an action is required, dykes and levees would be recommended for roughly 21% of sub-national regions, dry-proofing for 15%, and zoning restrictions for 64% (Figure 3).

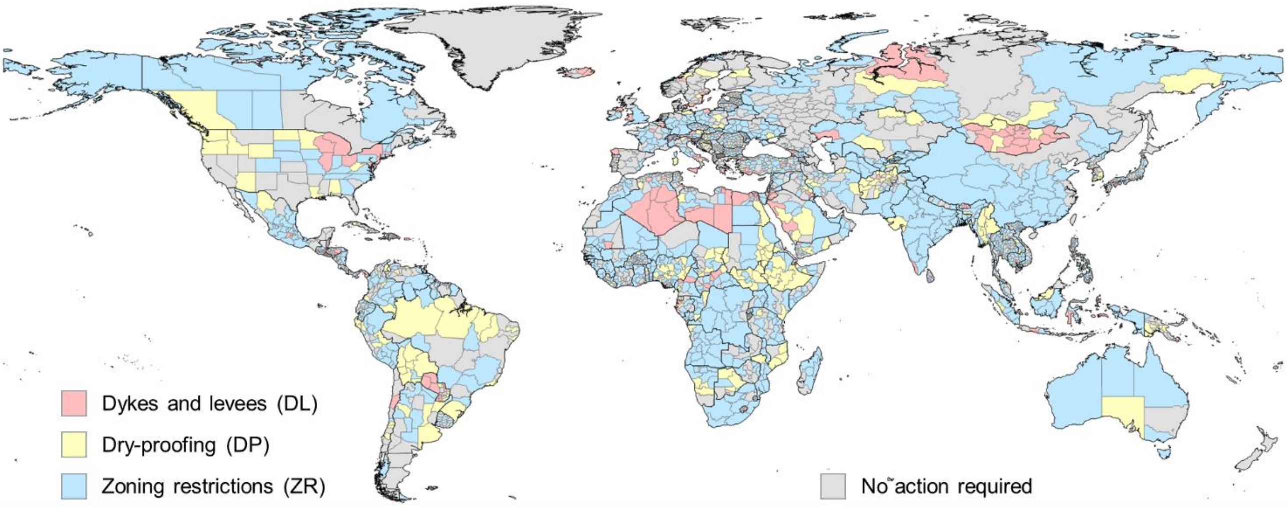

Figure 3: The resulting regional selection if BCR is used to determine which DRR measure to implement per sub-national region to reduce future riverine flood risk. Red indicates highest BCR for (and therefore hypothesised selection of) dykes and levees, yellow for dry-proofing, and blue for zoning restrictions. Light grey areas do not require additional DRR to achieve the *relative-risk constant* (i.e., the ratio of future EAD to GDP is less than the ratio of current EAD to GDP).

The globally averaged BCR of structural measures is 28.6, showing that on average building structural measures pays off in the long term. By investing in dykes and levees, $93 billion USD of damages can be avoided annually worldwide. The highest BCRs are often found in low and lower-middle income countries, for example Mauritania, Mozambique, Cambodia, Burundi, and Egypt, where only moderate dyke height increases are required to achieve *relative-risk constant* targets. In roughly 45% of sub-national regions throughout the world, though, BCRs are below 1. While many of these regions are estimated to have no existing protection standards (e.g., 90% of sub-national regions with a protection standard of 2-years are either low or lower-middle income) thus requiring substantial initial investments, two-thirds of BCRs < 1 are found in high or upper-middle income countries, where protection standards are typically higher. This means that large investments are needed throughout the world, with capital and O&M costs totalling roughly $3.7 trillion USD.

In some cases, even larger flood risk reduction benefits can be derived using dry-proofing as a DRR measure, but at a higher cost. Over $22.3 billion USD in monetary impact reductions is possible via dry-proofing; however, the estimated costs of this DRR measure, if implemented on the global scale, would reach an annualised cost of $61 million USD, or roughly one-third more the cost of dykes and levees. On the global scale, this still results in a BCR > 1; on the local scale, though, differences in BCR arise due to income level of countries as well as the amount of area required to be dry-proofed to achieve the realised risk reductions. For example, if the Netherlands were to dry-proof the equivalent of 885 km^2 of urban assets for a cost of $4.1 billion USD, only $76 million USD of benefits would be realised in EAD reduction by 2080. This may reflect the unique position that this high-income country has at the delta of a major river system. Bangladesh, also located on a major river delta, could see an investment of roughly $55.3 million USD for a resulting reduction of $6.8 billion USD to EAD in 2080.

Due to the low-cost nature of this DRR measure, the BCR of zoning restrictions is typically substantially higher than dry-proofing or dykes and levees on the global scale, as well as locally where applicable. The largest benefits in the form of monetary risk reduction, and therefore highest ratios, are found in sub-national regions that are projected to experience large amounts of urbanisation in coming decades. South Asia and sub-Saharan Africa specifically show the largest potential for benefits to be reaped from this DRR measure. Because countries like India, Bangladesh, Pakistan, Niger, and Democratic Republic of Congo all are projected to experience immense development and population growth throughout the remainder of the 21st century, several sub-national regions in these countries can have benefits ranging into the order of hundreds-of-millions of USD. The state of Bihar in eastern India, for example, could realise up to $1.5

billion USD annually in reduced EAD by restricting future developments away from floodplains. And while it is possible for any of the sub-national regions with a BCR < 1 to be scattered anywhere across the planet, many are in countries with large existing patterns of urbanisation that are not projected to experience much growth in coming decades.

3.3 Selecting DRR measures using efficacy metric

As mentioned above, a benefit-cost analysis may not be an appropriate method of selecting which DRR method is selected for implementation in various circumstances. Here we use the efficacy metric (i.e., the ability of a given DRR measure to achieve a pre-determined *relative-risk constant* reduction target) as another method to determine adaptation action. Assuming such a metric were used, the selected DRR measure per sub-national region is displayed in Figure 4.

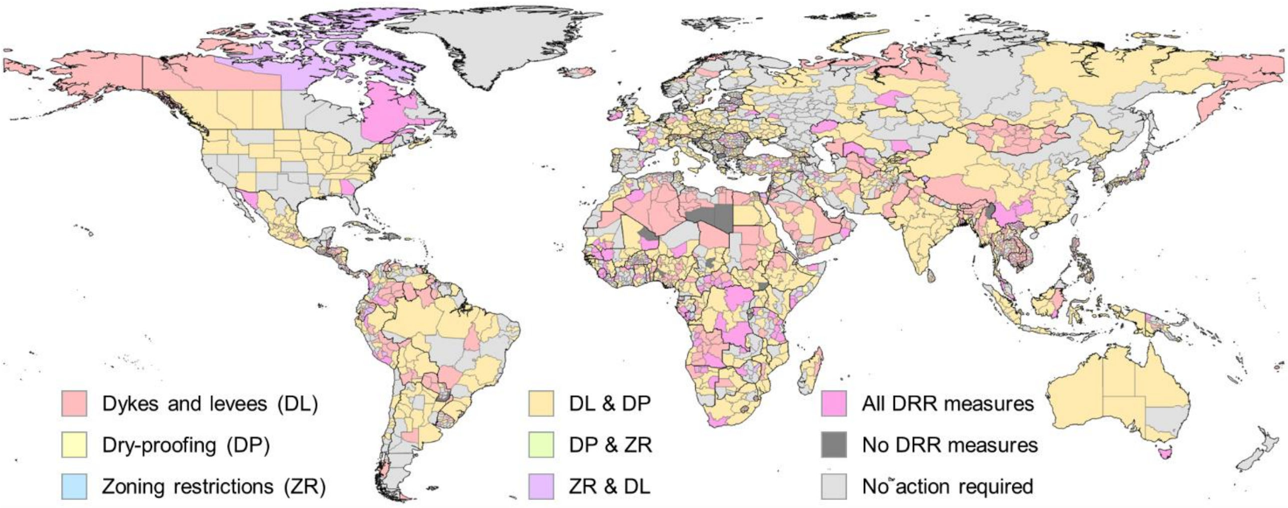

Figure 4: The resulting regional selection if an efficacy metric is used to determine which DRR measure to implement per sub-national region to reduce future riverine flood risk. Red indicates total efficacy for only dykes and levees, yellow for only dry-proofing, and blue for only zoning restrictions. Orange indicates dykes and levees and dry-proofing both achieve total efficacy, green for dry-proofing and zoning restrictions, and purple for zoning restrictions and dykes and levees. Dark grey indicates that none of the modelled options achieve total efficacy, while pink indicates all three options achieve total efficacy. Light grey areas do not require additional DRR to achieve the *relative-risk constant* (i.e., the ratio of future EAD to GDP is less than the ratio of current EAD to GDP).

The globally-averaged efficacy is 0.98 for dykes and levees. This mostly stems from the methodology; the modelled dyke and levee heightening is optimised to meet the *relative-risk constant* reduction target, which means the only time this DRR measure is not able to achieve the target in a sub-national region is when the needed increases to dyke height would exceed the level of flooding expected to occur at the 1000-yr return period. This occurs in 42 sub-national regions; these regions either have limited to no existing protection standards or already very high levels of protection. In either case, increases to dyke height are unable to mitigate low probability, high impact risk. This DRR measure is the only option in 660 sub-national regions – meaning either that this measure is the only one of the three modelled to achieve total efficacy or, if total efficacy is not realised, the measure achieves the highest efficacy.

Roughly two-thirds of sub-national regions are able to achieve their *relative-risk constant* reduction targets via dry-proofing alone. Because the deployment of this DRR measure is not optimised to the reduction target, in certain cases the amount of monetary risk reduction achieved is above the required amount of risk reduction. If a maximum efficacy of 1 is considered, though, the globally-averaged efficacy for dry-proofing is 0.71. The highest efficacy scores are typically found in sub-national regions that are highly urbanised and have existing patterns of population distribution along river systems. Dry-proofing is the outright the only option for achieving risk reduction targets in 18 sub-national regions.

Zoning restrictions have limited efficacy in terms of achieving *relative-risk constant* targets. While sizeable benefits are possible – globally almost $16 billion USD in 2080 – zoning restrictions on future development fail to address existing levels of risk, which in developed countries are already very large. The globally averaged efficacy for zoning restrictions is approximately 0.27, showing that a large portion of future risk comes from existing risk becoming larger due to increased river flood depths. Just over 240 sub-national regions can achieve their respective *relative-risk constant* reduction targets, and the majority of these areas are found in regions with large amounts of projected growth. For these sub-national regions, the pathway to risk reduction is straightforward via zoning restrictions. An additional 990 sub-national regions also achieve at least some level of risk reduction. The remaining 30% of sub-national regions see no efficacy in implementing zoning restrictions – likely because the regions that are most likely to flood now and, in the future, have already been urbanised to their fullest extent.

3.4 Outcomes of DRR measure selection and consequences

For many sub-national regions, the selected DRR measure using BCR is different from that selected by the efficacy metric (Table 1); in only roughly one-fourth of sub-national regions is the outcome of DRR measure selection the same regardless of metric used.

Table 1: The spread of DRR measure selection of the roughly 1800 sub-national regions that require action to achieve the *relative-risk constant* in 2080. The horizontal rows represent what selection is made via BCR, while the vertical columns represent what selection is made via the efficacy metric. The italicised values represent the sub-national regions where the DRR measure selected is the same regardless of method used.

Eff. BCR	Dry-proofing	Dykes and levees	Zoning restrictions
Dry-proofing	*226 (12.5%)*	43 (2.4%)	2 (0.1%)
Dykes and levees	143 (7.9%)	*232 (12.9%)*	2 (0.1%)
Zoning restrictions	754 (41.8%)	385 (21.4%)	*15 (0.8%)*

The most common flip between outcomes is witnessed from zoning restrictions chosen via the BCR metric to either dry-proofing (41.8%) or dykes and levees (21.4%) via the efficacy metric. Zoning restrictions are the most often selected via BCR, but least often selected via efficacy metric. This reflects a fundamental flaw regarding benefit-cost analysis: if only monetary considerations are included in decision making for DRR, addition value, such as reduction goals or otherwise, are not represented in actual outcomes (Mechler et al., 2016; Molinari et al., 2021). Likewise, if the efficacy metric is valued primarily, financially wasteful decisions could potentially be made in the name of achieving goals perhaps set too far away from the solution space. This points to the need to incorporate both readily quantifiable as well as intangible benefits and costs in future decision-making regarding flood DRR (Hudson & Botzen, 2019). As a visualisation of Table 1, the global distribution of discrepancies between DRR measure selected via BCR and efficacy are displayed in Figure 5.

Two major reasons for these discrepancies stem from the facts that 1) while very cost effective, zoning restrictions are unable to achieve the large-scale risk reductions needed to achieve the *relative-risk constant* reduction targets and 2) dry-proofing on a large-scale requires a large amount of upfront capital costs, meaning they are not discounted as are some of the other costs related to dykes and levees.

In a select few cases, several measures have BCRs greater than 1 and achieve total efficacy. In roughly 250 sub-national regions, though, two different DRR measures are selected via the different metrics and only perform well in one of the two metrics analysed. Regions where this is most often witnessed include South Asia as well as East Asia and the Pacific. In these instances, decision makers are stuck in a position of choosing what is more important – achieving a risk reduction target, or having investments pay-off in the long run, even if it requires a large amount of up-front capital (and explaining this to current constituents).

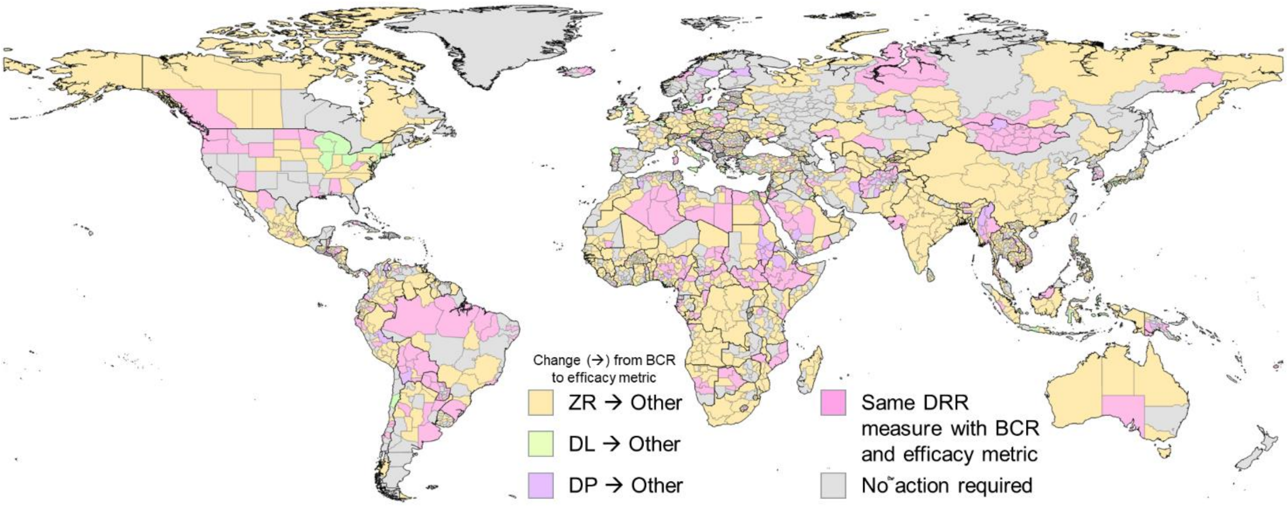

Figure 5: Global discrepancies between DRR measure selected using BCR and efficacy metric. Pink indicates that the same DRR measure is selected regardless of method (represented by the italicised values in Table 1). If a different DRR measure is selected via BCR and the efficacy metric (represented by "→" in the figure legend), one of three colours is assigned. Orange indicates that zoning restrictions are selected with BCR but not via efficacy metric. Green indicates that dykes and levees are selected with BCR but not via efficacy metric. Purple indicates that dry-proofing is selected with BCR but not via efficacy metric. Light grey areas do not require additional DRR to achieve the *relative-risk constant* (i.e., the ratio of future EAD to GDP is less than the ratio of current EAD to GDP).

3.5 Discussion

We intend our framework to be used to highlight potential savings (in the form of expected damage reductions) through strategies which increase DRR at the sub-national scale. We have determined these reductions for the entire world to facilitate a comparative analysis. Global-scale analyses such as ours are urgent (Trigg et al., 2016) and support dialogue with stakeholders, including policy and decision makers, and identify priority regions for action. This approach to DRR is essential for developing effective strategies to prevent and mitigate natural hazards faced by these individual regions and the global community (Ward et al., 2015). Through global-scale analysis, additional benefits such as gaining a comprehensive understanding of interconnected risks, addressing transboundary challenges, and promoting collaboration can be achieved.

We have developed our analysis with two decision making-metrics to demonstrate different options for future policymakers. Benefit-cost analysis, while widely used and accepted as an industry standard, often prioritises projects with narrowly-defined economic benefits, neglecting long-term resilience and social equity. Our analysis favours highly dense, urbanised areas by design, potentially leaving vulnerable communities such as those in the rural setting or lower wealth regions underserved. Effective flood adaptation requires a holistic approach that considers social, environmental, and equity factors, which benefit-cost analysis often overlooks, in additional to economic principles. It is for these reasons that we decided to include an efficacy metric that, instead of using solely monetary valuation, takes a more simplistic approach in the form of risk reduction goal achievement. This type of framing is similar to that supported by the SDGs. By focusing on another decision-making framework, such as one congruent with the SDGs, more equitable DRR could come about.

Because our goal is to determine risk reduction potentials for all sub-national regions, certain assumptions must be made for the sake of feasibility and comparison. For example, we assume that all modelled DRR measures are implemented uniformly for an entire jurisdiction. This assumption is not intended to imply that this reflects reality. On the contrary, construction standards, maintenance and operational procedures, and inspections for all DRR measures, including dykes and levees, ultimately depend on local actors and authorities. Instead of dissecting the associated uncertainty of this fact, for the sake of this analysis we hypothesise a future in which flood risk management is approached from a higher governmental level, in our case the sub-national level. From a policy perspective, this assumption of implementation relates to providing consistent and equitable protection from disasters for all communities in the future, which is related to SDGs 1, 11, and 13.

Further assumptions are made regarding the implementation of our DRR measures. For example, we assume the percentage of occupancy type per grid cell to be the same for all locations, whilst in reality it is spatially heterogeneous. We also assume building density per occupancy type. An improvement to our analysis could be made by using machine learning to improve accuracy of urban land cover and building types (Hecht et al., 2015; Huang et al., 2018). Furthermore, while we have assumed a rapid adoption of DRR measures and full effectiveness/uptake, timing, and rate of a commitment to adaptation varies per country (Haasnoot et al., 2013), which we do not consider here.

We acknowledge that the assumptions used in our global analysis do not capture a fully representative picture of what the modelled DRR measures would be, especially in terms of their effectiveness, variations around the world, and potentially dynamic nature. An avenue for future research could include developing numerous regional agent-based models based on locally surveyed information to represent these dynamics and variation. This has been conducted on larger scales, for example, by Haer et al. (2020) for Europe; however, this line of research has yet to be conducted at the global scale and therefore is difficult to incorporate into our analysis. If this information were to exist, though, a more detailed and accurate depiction of global DRR measure implementation could potentially be achieved as a result.

We do not explore the potential of DRR measure hybridisation here, as we intended our effort to be focused on the decision-making aspect of DRR rather than DRR measure optimisation. This sort of research, though, represents an interesting avenue of research and has already been conducted theoretically (Lendering et al., 2019) and on the local scale, for example in Shanghai (Du et al., 2020) and the Netherlands (Postek et al., 2019). Indeed, global-scale analysis of DRR measure hybridisation is the next frontier of natural hazard risk assessments.

4 Conclusions

In this global study, we investigate optimal selection of DRR measures through two different decision metrics. The decision of which DRR measures should be taken is dependent on which metric is used for evaluating their performance, thus we provide a first-cut estimate of what these decisions could look like on the global scale. Decisions made ultimately may reflect a combination of or alternative metrics not explored here. Moreover, the on-the-ground design of adaptation measures requires site-specific and detailed local information. By using a globally applicable model in data-scarce regions, though, we allow end-users such as UN-affiliated organisations, the World Bank, and (inter)national adaptation strategists to prioritise actions.

A BCR will provide a measurement of economically optimal DRR measures, while not necessarily looking at the ability of the DRR measures to achieve a certain risk reduction target. This is for instance the case with zoning restrictions (high BCR, but generally low efficacy). The highest BCRs for dykes and levees are found in regions where only moderate increases to relatively high protection standards are needed, whereas the highest BCRs for dry-proofing can be found in regions of highly dense urbanisation with low existing protection standards that experience only minor increases to inundation depth. Meanwhile, if an efficacy metric is used, in many cases several options may be deemed as a viable option, meaning more space for non-monetary values to be incorporated into the decision-making process. In an instance where, for example, dry-proofing, zoning restrictions, and dykes and levees are all able to achieve total efficacy, decision makers could then move towards looking at a secondary metric, such as impact on local environmental characteristics. Still, in this exercise dykes and levees as well as dry-proofing do generally achieve higher efficacy metrics than zoning restrictions. Efficacy metrics, however, can be used as a tool to shift the value placed in monetary damages and impacts towards other societal values. This result should serve as a signal to decision makers that many pathways forward in reducing risk are possible, and not solely strategies that utilise traditional, structural measures.

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Author contributions (CRediT)

EM, TT, TH, and PW expanded the existing GLOFRIS framework to include new modules that allowed for the modelling of alternative DRR measures for riverine flood risk assessment. EM conducted the main analysis, with guidance from TT in the operationality of GLOFRIS. BB, AB, and WL contributed to the development of exposure data. TH and PW assisted EM in the framing of the analysis for this written text. All authors reviewed the text and provided suggestions for revision to the final manuscript presented here.

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