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Climate change adjustments in engineering design standards: European perspective

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ABSTRACT

The European Commission Flood Risk Directive review shows that while many nations have embraced the concepts of flood risk management, there is still quite more to do in delineating risk–cost-effective measures and developing cost estimates and financing of those measures. Not mentioned are the necessary changes to existing design standards and protocols which will have to change in order to properly encompass climate change and variability, with associated uncertainties. Adjustments in engineering design standards and changes in hazards are examined, based on trend detection in observational records and projections for the future. Issues of urban and transport (motorways and railways) drainage design are also examined. Furthermore, risk reduction strategies are discussed. Finally, a way of accounting for non-stationarity in determining design precipitation and design floods is tackled. Climate change adjustments in engineering design standards, such as design precipitation and design floods, are reviewed via examples from Europe.

Key words: adaptation, climate change, climate variability, design flood, Europe

HIGHLIGHTS

- Intense precipitation and high river flows have been changing and will change, even if trend detection may not yet consistently show a ubiquitous, and statistically significant, change.
- European nations have embraced the concepts of flood risk management in line with the common Floods Directive, yet existing design standards have to change in order to properly encompass climate change and variability, with associated uncertainties.
- It is necessary to prepare for the existing climate variability, but this is not likely to be sufficient for the future. Current water management practices may be inadequate to reduce the adverse impacts of climate change.
- There is a clear gap between results of scientific studies and needs of practitioners in the domain of climate change adjustments in engineering design. Scientific results are publishable but not necessarily actionable. Both science and practice should try to improve the interface.

1. INTRODUCTION

Though deaths from flood disasters have been reduced markedly over the last century, floods continue to kill thousands of people in an average year, worldwide, and cause material losses in the order of tens of billions of US$. Therefore, risk reduction methods are of considerable practical relevance and scientific interest, virtually in all countries.

The destructive abundance of water can be caused by many different generating mechanisms, such as intense and/or long-lasting precipitation, snowmelt, rain on snow or ice, flow obstruction (e.g. by an ice jam or a

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landslide), dam failure, storm surge (coastal flooding), and inundations due to inadequate storm sewerage in urbanized areas. Recognizing that flood damages are often caused by improper floodplain management and development, White (1945) famously noted: 'Floods are acts of God – flood damages are acts of man'.

The Directive #2007/60/EC on the Assessment and Management of Flood Risks (Floods Directive, FD) of the European Union (EU) warrants a careful look (EU, 2007). This dedicated legal act was triggered by the observation of increased risk manifested in destructive floods in Europe (e.g. in 1997 and 2002). The reasons for increased risk are (i) likely increase of scale and frequency of floods in the future, as a result of climate change, increased impervious area, inappropriate river management, and construction in flood risk areas and (ii) marked increase in vulnerability due to the increasing number of people and economic assets located in flood risk zones.

The issue of floods and the impact of climate change on flood risks have not been addressed in the earlier Water Framework Directive (WFD) that had introduced the principle of cross-border coordination within river basins. The WFD set the objective of achieving good quality for all waters in the EU, but no objective was related to flood risk management that is now included in the FD. It notes that it is impossible to prevent flooding totally, but it is possible and indeed necessary to reduce and manage the negative impacts of floods on human health, the environment, cultural heritage, and economic activities.

The Directive, which entered into force on 26 November 2007, requires all (27 now, after the Brexit, without the UK) EU Member States to conduct the preliminary flood risk assessment (stage 1), to prepare maps of flood hazard and flood risk (stage 2), and – finally – to develop flood risk management plans (FRMPs; stage 3). The Directive obligated the EU Member States to meet the above three-stage objectives by the end of 2011, 2013, and 2015, respectively, and then to update them by the end of 2018, 2019, and 2021, and thereafter, every 6 years. This gives a possibility to include climate change-related adjustments corresponding to the most recent state of knowledge.

The European Commission released a report (EC, 2019) on the implementation of the WFD and FD. The first FRMPs were prepared and reported by the Member States. The report noted that:

> '*Human choices, historic but also still widespread today, have a significant effect on the occurrence and impacts from flooding and there is evidence that the number of large flood events has increased over the years. Projections are a cause for concern; under a no-adaptation scenario (i.e. assuming continuation of the current protection against river floods up to a current 100-year event), damages in the EU from the combined effect of climate and socioeconomic change are projected to rise from EUR 6.9 billion/year to EUR 20.4 billion/year by the 2020s, EUR 45.9 billion/year by the 2050s, and EUR 97.9 billion/year by the 2080s.*'

Though the EU Member States set a variety of qualitative national flood risk management objectives, and they included associated generic management measures for achieving the objectives, 'not all objectives are sufficiently elaborated to allow for implementation monitoring and not all measures are clearly linked to objectives. Taken together, these deficiencies may pose a challenge for the second cycle (2016–21), when Member States are expected to assess progress' (EC, 2019).

About half of the EU Member States made estimates of the costs of flood measures available, though, in many cases, not covering all FRMPs or measures. In other words, there is quite a bit more to do in clearly identifying the range of measures, and only 11 of 27 Member States used a cost–benefit analysis.

It is important to note that both nonstructural floodplain management measures, as well as structural ones, require a new class of analytical tools that explicitly account for the risks and uncertainties associated with climate change. In all cases, various ministries in each EU country are required to develop standards for regulating development in floodplains as well as for the design of infrastructure. It is only after such regulations and design standards are implemented that the true costs (and benefits) of the FD can be assessed accurately. The assumption of climate 'non-stationarity' in designing new infrastructure is one of the key issues that require resolution. A wide range of, as yet, unresolved analytical issues are associated with this assumption.

2. DESIGN PRECIPITATION AND DESIGN FLOOD NOTION

The assumption of stationarity, i.e. temporal invariance of the N-year annual maximum daily precipitation, R_N, or N-year river discharge, Q_N, with $1/N$ exceedance probability in any 1 year, is commonly used for designing infrastructure: storm sewers, bridges and roads, railways, culverts, as well as structural flood defenses – dikes, embankments, reservoir spillways, and relief channels. The concept of design precipitation and design flood is of crucial importance in natural hazard risk reduction, water management, and climate change adaptation. The engineering design standards (for instance R_{50} or Q_{50}, with 2% exceedance in any 1 year) serve as the basis of both designing the infrastructure and perception of tolerable risk.

However, design events for large N values, such as 500, i.e. R_{500} and Q_{500}, can be problematic even in a stationary case. Observed records extending over a hundred years in the stationary world could allow a reliable estimate of, say, a 10-year flood, Q_{10}, with 10% exceedance probability in any 1 year. However, in some cases, we may have just – say – observation records of 20 years, and the objective is to undertake a rough estimation of a 100-year flood, or even a 500-year or 1000-year flood, requiring excessive extrapolation and increasing uncertainty.

Typically, the broad public fails to understand risk properly. What is even worse, public policy is often driven by misunderstandings regarding risk. Low probabilities (e.g. for the 100-year flood, i.e. flood with 1% exceedance probability) are commonly, and incorrectly, rounded down to zero, and this encourages development in flood-prone areas. As noted by Tullos (2018), homeowners in such areas may be surprised to learn that the odds of their house being flooded over the 30-year lifetime of their mortgage is unexpectedly high – in fact, some 26% chance (i.e. more than one in four) of experiencing a 100-year event.

Yet, in reality, there is a clear and considerable non-stationarity effect (Milly *et al.*, 2008, 2015). The apparent non-stationarity of streamflow is attributable not only to climate change and variability but also to land use and development. Flood peaks increase because of deforestation, urban sprawl, sealing of ground surface, channel constrictions due to flood walls, flood protection embankments, bridge constrictions, and channel straightening (Vogel *et al.*, 2011). Hence, a 100-year flood for a particular location can be dramatically different from a 100-year flood determined for pre-development watersheds. Even more complicated is coping with a watershed where significant changes have been made over a long period of time.

3. CHANGES IN INTENSE PRECIPITATION AND HIGH FLOOD HAZARD – OBSERVATIONS AND PROJECTIONS

Large floods have been recorded since the dawn of human civilization (and, actually, paleo-floods occurred earlier than that), yet information about very old floods is, at best, fragmentary. There is no doubt that costs related to flood damage have been increasing, worldwide, partly due to the increasing exposure of people and assets (Kundzewicz *et al.*, 2014). Kron *et al.* (2019) reported an increase in the number of large flood events and also in economic losses and insured losses, with careful adjustment for inflation (change in the actual value of the currency units used).

The analysis of change in the frequency and intensity and/or magnitude of observed heavy precipitation records showed significant increases in many (but not all) regions of the world. Anthropogenic warming has likely contributed to a global-scale intensification and frequency of heavy precipitation (IPCC, 2013), and this impact is particularly visible in some regions. For winter, a change to wetter conditions and more extreme precipitation was noted in much of Europe, while drier conditions were detected in the south of the European continent, with a slight increase in the occurrence of extreme events.

A large number of studies of changes in flood hazard were examined by Kundzewicz (2012) and Madsen *et al.* (2014). However, there remains only low confidence in the claim that anthropogenic climate change has affected the frequency and magnitude of river floods. There exists a complex interplay between long-term trends, inter-annual and inter-decadal natural variability, as well as nonlinearities and thresholds in the climate system. Pall *et al.* (2011) offer an example of rigorous attribution of observed changes in flood hazard to anthropogenic climate change. In their model-based study, increasing global greenhouse gas concentrations were found to have considerably increased the risk of rainfall-dominated flood occurrence in some river basins in the UK, as observed during the large inundations in the autumn of the year 2000.

In their study of trend detection in maximum river flow records, Kundzewicz *et al.* (2005) did not find the ubiquitous prevailing direction of change, but rather discovered domination of large inter-annual and inter-decadal variability. Typically, eventual trends are not robust and do strongly depend on the start-year and the end-year of analysis. Moreover, trend detection cannot be a meaningful tool for a short-time series (e.g. extending over just a few decades). The occurrence of a single (or several) extraordinary event(s) may disturb the regularity of the trend. Indeed, long-time series of annual maxima of river discharge show no convincing upward trend (e.g. Kundzewicz *et al.*, 2005). There is no conclusive evidence, so far, for ubiquitous and homogeneous, climate-related, increasing trends at larger spatial scale (e.g. regional or national level) in observed extreme streamflow.

It has not been possible to find ubiquitous flood hazard changes in observation records in Europe, so far. There are no clear larger-scale regions in Europe which uniformly exhibit statistically significant increases in flood discharges. However, Kundzewicz *et al.* (2018b) detected an increasing trend in the number of large floods, even if the year-to-year, as well as the decadal, variabilities are strong.

However, for smaller regions in Europe, apparent increases in extreme streamflow have been found. These include, among others, alpine catchments and some maritime-influenced basins (Madsen *et al.*, 2014). In many cases, individual stations in a country or within larger regions may have positive or negative trends (over some intervals) or no evident trend (see a study from Germany by Hattermann *et al.* (2012)). In some areas, where snowmelt is an important flood generation mechanism, decreases in extreme streamflow and earlier spring snowmelt peak flows have been noted, likely caused by increasing temperature. Blöschl *et al.* (2017) detected a clear climate signal in the timing of river floods at the continental scale in Europe. Earlier spring snowmelt floods were found throughout North-Eastern Europe; delayed winter storms associated with polar warming have led to later winter floods around the North Sea and parts of the Mediterranean coast; and earlier soil moisture maxima have led to earlier winter floods in Western Europe.

The study of climate-driven variability in the occurrence of large floods in North America and Europe carried out by Hodgkins *et al.* (2017), only in minimally altered catchments, demonstrated that the number of significant trends was approximately equal to the number expected due to chance alone. Their finding was that natural variability rather than long-term trends drive the variability of occurrence of large floods.

Ivancic & Shaw (2015) demonstrated that large floods do not necessarily depend on the recent precipitation only. The antecedent watershed wetness can play a very important role, and there are ample examples to support this thesis. The precipitation preceding floods in Poland in May and June of 2010 was not at all extreme, yet the capacity of watersheds was filled with water and, as a result, the size of the flood was very large (exceptional for the season). Clearly, trends in heavy precipitation should not be mistaken for trends in high river flow and flood hazard. Sometimes, heavy precipitation does not lead to high river flow and, the other way around, there is high river flow without very heavy precipitation. When examining links between intense precipitation and high river flow, precipitation data should be segregated, based on concurrent soil moisture, resulting from antecedent precipitation or from snow cover. In terms of projections for the future, 'warmer' may mean 'drier'. Hence, the antecedent state of soil moisture in the catchment can considerably modulate the transformation of precipitation into river discharge.

No doubt that hydrological projections for the future are badly needed to inform water management. However, there are considerable differences in flood hazard projections, as demonstrated in a European study by Kundzewicz *et al.* (2017). Since there is a great deal of uncertainty related to the projections of water-related impacts (Kundzewicz *et al.*, 2018a), hence, Kundzewicz & Stakhiv (2010) posed a question 'Are climate models ready for prime time in water resources management applications or is more research needed?'.

Projections for the future can only be based on mathematical models. Typically, their core concepts are physically based, because it is a plausible assumption that laws of physics will not change in the unknown, and largely unknowable but likely warmer future. Yet, models are calibrated on past data, and no account is taken of prospective changes in catchment characteristics. In addition, typically little is done to normalize the measured record to account for evolving changes in the watershed that influence runoff and flooding as a function of time. The assumption that the concepts hold outside the range of calibration is questionable.

An increase in the time horizon and accuracy of flood predictions and projections remains among essential challenges. This includes forecasting the propensity of the occurrence of water abundance synchronized with the rhythm of oscillation of the atmosphere–ocean system (e.g. ENSO: El Niño – Southern Oscillation; NAO: North Atlantic Oscillation; AMO: Atlantic Multi-decadal Oscillation; PDO: Pacific Decadal Oscillation), cf. Kundzewicz *et al.*, 2019, 2020; Norel *et al.*, 2021).

It is advisable to generate river discharge projections for multi-GCMs (General Circulation Models, also known as Global Climate Models) ensembles and multiple realizations of the same model(s). One of the main problems related to GCMs, in the hydrological context, and which is responsible for a major share in total uncertainty, is the large discrepancy between different GCM projections for the same emission scenarios over some regions of the world. Regions, where GCM projections show high uncertainties, warrant more attention from climate modelers.

More understanding is necessary for the impact of bias-correction schemes, parameter uncertainty, and calibration stability within impact (hydrological) models; and uncertainty is related to extreme value estimation. Since there is still low spatial resolution of GCMs, downscaling is often necessary for watershed-scale analyses. Scale-specific assessments are needed – though using GHMs (Global Hydrological Models) may be acceptable for global/continental overviews, it is not so for the regional-scale impact assessment and adaptation actions. Some experts recommended using several available hydrological models in impact studies, but only those were able to mimic the past observations sufficiently well. In global hydrological studies, existing models are often not validated, i.e. they are not evaluated with respect to the quality of their performance in the historical observation period (cf. Krysanova *et al.*, 2018).

In general, there is a puzzling, and distorting, disconnect between a lack of significant increasing trend in the observation record of annual maximum river discharge (or peak-over-threshold series) that could hold ubiquitously or at least for a larger region and the projections for the future. The latter show increase in the frequency of intense precipitation, reflecting, in qualitative terms, the Clausius–Clapeyron law (suggesting links between climate change and flood risk: 1 °C warming should lead to a 6–7% increase of saturation vapor pressure, hence increase of the potential for intense precipitation), as well as regionally organized changes in flood hazard.

In their study of projections for the future, Hirabayashi *et al.* (2013) found that flood hazard is likely to increase in some regions of the globe and to decrease in others. However, flood hazard projections in a region of concern, such as Europe, are largely uncertain, and various approaches reported in the literature may produce dramatically different results (see Kundzewicz *et al.*, 2017, 2018a).

Some experts (e.g. Koutsoyiannis *et al.* 2008, 2009; Beven, 2011, 2018) take the stance that, at the present stage, projections are a waste of time and money, especially since the climate scenarios are unreliable. Sensitivity analyses of Prudhomme *et al.* (2013) show that we do not actually need climate projections to be precautionary about future change. In fact, because of the general unreliability of GCM-based projections for site-specific engineering design, there is a growing body of literature based on the notion of 'bottom-up' analysis, termed 'decision-scaling', that is being promoted by some of the most prestigious institutions such as the World Bank (Ray & Brown, 2015), UNESCO, and the U.S. Army Corps of Engineers (Mendoza *et al.*, 2018). The basic premise of both works is that the upgrading of existing infrastructure or the design of new infrastructure should be conducted through a series of 'bottom-up stress tests' to determine the degree of existing vulnerabilities to climate and service demands, followed by increasingly more rigorous analytical methods based on risk-analytic concepts that address the relative reliability of various risk management measures.

4. URBAN AND TRANSPORT (MOTORWAYS AND RAILWAYS) DRAINAGE DESIGN

Adapting standards for designing urban and transport (motorways and railways) drainage to climate change faces several difficulties, many of which may have a common source being imperfections, inaccuracies, and ambiguities in the toolbox that is used today. Due to the stochastic nature of rainfall, reliable operation of sewer systems cannot be fully accomplished and failures are bound to happen. Therefore, we limit ourselves to designing a drainage system in such a way that it is ready to accept the maximum (projected) stormwater input with the frequency of occurrence equal to the permissible frequency of flooding.

Obviously, in a newly designed urban or road drainage system, we cannot know the variability of the maximum flows. Hence, we have to estimate their maximum design size, reaching for a design rainfall intensity, via the classic IDF (intensity–duration–frequency) or DDF (depth–duration–frequency) models. The design rainfall intensity is determined on the basis of the calculated time of runoff concentration and the *à-priori* assumed level of rainfall occurrence. Unfortunately, the frequency of design rainfall is not the same as the frequency of surface flooding. There is only a certain arbitrary relationship between the frequency of design rainfall and the frequency of flooding, which cannot be generalized in an analytical manner for all catchments. This relationship is empirical and is a result of engineering experience rather than comprehensive hydrological studies.

Looking to a future, changing climate and wishing to translate the predicted changes in the maximum intensity of local rain into changes in the frequency of overflows from drainage systems, it is convenient for an engineer to have a specific conversion table. Unfortunately, the recent changes to the design standards of stormwater drainage systems in Europe seem to dilute rather than consolidate the relationship between these frequencies.

The European standard (EN 752, 2008) limited the permissible frequency of flooding from sewage systems, or the inability to collect stormwater, to rare frequencies of their occurrence, while adapting to four types of spatial development, i.e. on average, once in 10 years for rural areas and up to once every 20, 30, or 50 years for different

Table 1 | Recommended design frequencies (storm – for use with simple design methods, flooding – for use with complex design methods), according to the recent standard (EN 752, 2008).

	Design storm frequency[a]		**Design flood frequency**[a]	
Location	**Return period (1 in *N* years)**	**Exceedance probability in 1 year (%)**	**Return period (1 in *N* years)**	**Exceedance probability in 1 year (%)**
Rural areas	1 in 1	100	1 in 10	10
Residential areas	1 in 2	50	1 in 20	5
City centers/industrial/ commercial areas	1 in 5	20	1 in 30	3
Underground/railway underpasses	1 in 10	10	1 in 50	2

[a] For those design storms or design floods, no surcharge shall occur.

types of urban areas (Table 1). For the design of new or modernization of existing drainage systems, the standard recommended correspondingly lower rates of design rainfall: from once a year for rural areas to once every 2, 5, or 10 years for urban areas (Table 1), with a condition that gravity channels cannot be overloaded, e.g. no pressurized flow occurs. Certainly, Table 1 for the conversion of design storm rate and the design flooding rate was not perfect, yet it was straightforward and clear for engineering applications.

A recent version of this standard (EN 752, 2017) proposed to make the permissible frequency of flooding from sewerage dependent on the seven-degree scale of the impact of the threat on the environment for defined locations (Table 2). It can be presumed that the exemplary criteria for inundation hazards are deliberately formulated rather vaguely and descriptively, e.g. ‘roads or open spaces away from buildings: $N = 1$ year’, or ‘roads or open spaces near buildings: $N = 5$ years’. At the same time, it is stipulated that the values of permissible frequency of flooding hazards given in Table 2, as an example, can be both increased in the case ‘where the floodwater is moving faster’, and also lowered in the cases of ‘undertaking rehabilitation of existing systems and where achieving the same design criteria for a new system would entail excessive cost’. As sewer systems are designed for the lifetime of 50–100 years, the latter possibility (i.e. lowering the permissible frequency of hazards) is debatable in view of the generally expected increase in the frequency of heavy rainfall events in the future climate. Moreover, this standard (EN 752, 2017) entails a caveat that ‘criteria may largely vary between countries’.

As a result, it is more difficult for an engineer to use the new standard (EN 752, 2017). To manage the risk of sewer flooding, both the permissible frequency of occurrence and the anticipated and estimated effects of flooding, i.e. damage to property, and in particular the impact on human health and safety, should be taken into account. What is worse, there is no clear conversion table for the frequency of the design storm and the frequency of the design flood. In practice, matters are even more complicated, because the real environmental threats caused by flooding from drainage systems can be determined either during their operation or demonstrated by means of hydrodynamic modeling. In the latter case, which is the only possibility at the design stage, other frequencies have to be used. The key problem is how does one calculate the frequencies of a non-stationary climate? In other words, the new standards should have a method for calculating frequencies for infrastructure that will last 50–100 years.

Unfortunately, the European standard (EN 752, 2017) does not contain any indications as to the permissible frequency of surcharges of the sewerage system manholes up to the ground level. In contrast, such values were

Table 2 | Examples of design sewer flooding criteria for standing floodwater, according to the recent standard (EN 752, 2017).

No.	Impact	Example locations	Return period (years)	Probability of exceedance in any year (%)
1	Very small	Roads or open spaces away from buildings	1	100
2	Low	Agricultural land (depending on land use, e.g. pasture, arable)	2	50
3	Low to medium	Open spaces used for public amenity	3	30
4	Medium	Roads or open spaces adjacent to buildings	5	20
5	Medium to high	Flooding in occupied buildings, excluding basements	10	10
6	High	Deep flooding in occupied basements or road underpasses	30	3
7	Very high	Critical infrastructure	50	2

The return period should be increased (probabilities reduced) where the floodwater is moving faster. When undertaking rehabilitation of existing systems and where achieving the same design criteria for a new system would entail excessive cost, a lower value may be considered.

Table 3 | Acceptable frequencies of drainage surcharges damming up to the ground level for calculations checking the operation of the drainage systems according to DWA-A118 (2006).

Lp.	Location	Frequency of overflows (once in *N* years)
1	Rural areas	2
2	Residential areas	3
3	City centers/industrial/commercial areas	More than 5
4	Underground/railway/road and pedestrian underpasses	More than 10[a]

[a] When local security measures are not applied, the frequency of overflows is 50.

previously established in Germany and included in the technical guideline DWA-A118 already in 2006 (Table 3). These German guidelines find practical application also in other countries of Central and Eastern Europe, where approaches to design and construct urban drainage systems primarily established in Germany have often been followed.

5. RIVER FLOOD RISK REDUCTION STRATEGIES

It is recognized that changes in river flood risk may depend (Kundzewicz & Schellnhuber, 2004) on:

1. changes in socio-economic systems (land-use change, increasing exposure and damage potential related to floodplain development and increasing wealth in flood-prone areas, change in flood risk perception);
2. changes in hydrological/terrestrial systems (land-cover change accompanying land-use change: urbanization, deforestation, elimination of natural inundation areas – wetlands and floodplains; river regulation – riverbed straightening and shortening, constructing embankments; damming rivers; changing conditions of transformation of precipitation into runoff by way of increase of impermeable areas; under urban sprawl; watershed management; and structural flood defenses); and
3. changes in climate and atmospheric systems (water holding capacity of the atmosphere, intense precipitation, changing precipitation phase – solid or liquid, seasonality, snowmelt pattern, ice phenomena, and atmospheric circulation patterns).

Over many decades, the USA played the role of the global leader in river flood preparedness, indeed being the pattern for other countries to follow. The Flood Control Act (FCA), passed in the USA in 1936, and subsequent legislation that authorized federal US engagement in structural flood protection have influenced flood protection policy in many countries that followed the US example. Thirty years after the FCA, the National Flood Insurance Act was passed in the USA in 1968, and the National Flood Insurance Program (NFIP) was established. The idea was to identify the 100-year floodplain (with a probability of being flooded of 1% in an average year), as a high-risk area. The flood insurance program discouraged floodplain development, providing incentives for communities that adopted land-use regulations and prohibited future construction below the 100-year flood elevation. However, local governments had ultimate authority on land-use regulations.

A wide array of risk analysis and risk management methods have been developed for flood management that attempts to provide a more uniform and replicable approach to the analysis and consideration of risk–cost-effective flood risk management options. These methods have proven to be relatively effective over the past century, but have come under scrutiny because of climate change and associated non-stationarity and increased uncertainties of the underlying physical phenomena of the generating mechanisms for precipitation, as projected through a myriad of general circulation models.

One cannot directly influence the variability of precipitation, yet one can do a great deal to reduce flood risk. In the EU (European Union) STARFLOOD project, a roster of strategies useful in flood risk reduction were examined (Driessen *et al.*, 2016; Hegger *et al.*, 2016). The fundamental, and deeply rooted, strategies are flood risk prevention measures (keeping people away from destructive water) and structural flood defense measures (keeping destructive water away from people) (Dieperink *et al.*, 2016). The former aim to decrease the consequences of flooding by decreasing the exposure of people and property, via prohibiting or discouraging development in areas at risk of flooding (e.g. via land-use policy, spatial planning, resettling communities with repetitive losses, expropriation policy, and re-allotment policy). The latter aim to decrease the flood damages through infrastructural works (e.g. dikes, dams, and embankments) that increase the capacity of existing channels for water conveyance or the creation of new water storage spaces. Since our efforts to keep people away from destructive water and to keep destructive water away from people sometimes may fail, we also need strategies of flood risk mitigation, flood preparation, and flood recovery (Kundzewicz *et al.*, 2018c).

Flood governance deals with various aspects of relevance to different sectors: natural hazard (here: flood) risk reduction, water resources management (e.g. implementation of the FD of the European Union), and adaptation to climate change (see Lugeri *et al.* 2010).

6. HOW TO ACCOUNT FOR NON-STATIONARITY IN THE DETERMINATION OF DESIGN PRECIPITATION AND DESIGN FLOOD: EUROPEAN PERSPECTIVE

In a non-stationary world, Q_N determined for the 1980s can be considerably different from Q_N determined for the 2020s, and even more so – for future horizons, e.g. the 2040s or the 2070s. One can use the concept of magnification factor to reflect the change in the design flood (Salas *et al.*, 2018).

However, one has to be very careful when attempting to generalize attribution of changes in flood hazard, because there exist various flood generating mechanisms driven by different processes. Mechanisms of changes in flood hazard and flood risk can be really complex, as demonstrated in Wyzga *et al.* (2018).

Noting that climate change has rendered water management more difficult due to uncertainty in future changes of hydrological conditions, Döll *et al.* (2015) advocated for extending the approach of adaptive Integrated Water Resources Management (IWRM) by considering the risk of climate change. They called for embracing the uncertainty of future climate and its impacts in decision-making, by probabilistic assessment of the future water conditions for different scenarios, and 'developing a portfolio of low-regret solutions that reduce vulnerability and can be implemented and modified progressively as future conditions evolve'. Salas *et al.* (2018) reviewed various metrics that may be used for assessing infrastructure investment decisions, including economic risk-based approaches, and planning under the additional uncertainty imposed by non-stationary conditions. In areas with short periods of observation and significant non-stationarity, the reliance on probabilistic assessments of future water conditions may become quite unreliable, and the engineering profession will have to resort to other concepts for decision-making.

Adding safety margins to design flood indices has been traditionally used to cope with risk and uncertainty. However, the unprecedented global economic growth and the prospect of climate change have resulted in a need to plan and design for future 'unknown unknowns' (Mendoza *et al.*, 2018). Much effort has gone into tools and models to produce projections for the future on the basis of multi-model ensembles of climate and impact (hydrological) models. Using multi-model ensembles broadens the ranges of possible future scenarios and associated flood frequency analyses, which are the traditional bases for establishing design floods. As framed by Mendoza *et al.* (2018), 'choosing a particular subset of future scenarios to plan, design, or invest has become an increasingly subjective enterprise, centering on which climate scenarios to consider and what hydrological analytical tools could be employed to deal with these cascading uncertainties. A range of basic questions emerge: How can we justify a particular decision, given all the uncertainties? How do we plan for an action that is neither too early nor too late? How do we convey the resulting analyses, built on a pyramid of uncertainties, to the stakeholders and to political decision makers?'

It is instructive to provide just two examples from overseas, indicating how these issues are tackled in Japan and in the USA in comparison to how European countries approach these issues. Nakamura & Oki (2018) studied paradigm shifts in flood risk management in Japan, a country, whose 20% of the area is flat land, vulnerable to flooding, yet 80% of the national population and 50% of the property are located there. They identified three eras of the modern history of Japan, labeled as changing society (1910–1935), response to megafloods (1935–1970), and response to economic growth (1970–2010) that have largely influenced flood risk management. They informed of developments of design flood in the Tone River basin, where the Tokyo metropolitan area is located. The design flood discharge has increased from 3,750 m^3/s in 1900 to 22,000 m^3/s at present. The development reflected the occurrence of large floods (triggers) that had to be accommodated in planning.

Nakamura & Oki (2018) analyzed 109 river basins in Japan and found 323 revisions of design flood after 1910. They assessed the frequencies of triggers for design flood revision as follows: 34% due to national policy change (e.g. update to the River Act), 28% due to occurrence of a large flood that caused severe damage, 19% due to economic growth (advancement of development or urbanization in the basin), and 4% due to dam construction in the basin. The design flood in 1958 corresponded to the return period of 80–100 years for class A rivers and 50–80 years for class B rivers. After several 'five-year national flood prevention plans', the return periods increased to present (since 2004) values greater than 200 (for class A rivers) and 100–200 (for class B rivers). Nakamura & Oki (2018) note the possibility of another paradigm shift due to climate change and increasing public interest. This can be also related to campaigns against dam construction and intimation that design floods have been overestimated in order to facilitate the construction of dams.

An example of developments taken place in the USA clearly illustrates the science–policy interface. On 30 January 2015, then President of the USA, Barack Obama issued Executive Order (EO) 13690 on Establishing a Federal Flood Risk Management Standard and a Process for Further Soliciting and Considering Stakeholder Input[1], replacing the old Executive Order 11988 (after 38 years of validity). The new document stated that it is the policy of the USA to improve the resilience of communities and Federal assets against the impacts of flooding and to recognize the risks and losses due to climate change and other threats. As per EO 13690, establishing the floodplain results from using one of the following alternative approaches:

1. 'the elevation and flood hazard area that result from using a climate-informed science approach that uses the best-available, actionable hydrologic and hydraulic data and methods that integrate current and future changes in flooding based on climate science. This approach will also include an emphasis on whether the action is a critical action as one of the factors to be considered when conducting the analysis;
2. the elevation and flood hazard area that result from using the freeboard value, reached by adding an additional 2 feet to the base flood elevation for non-critical actions and by adding an additional 3 feet to the base flood elevation for critical actions;
3. the area subject to flooding by the 0.2 percent annual chance flood (i.e. a flood with 500-year return period); or
4. the elevation and flood hazard area that result from using any other method identified in an update to the FFRMS[2].'

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[1] https://obamawhitehouse.archives.gov/the-press-office/2015/01/30/executive-order-establishing-federal-flood-risk-management-standard-and-.

[2] Federal Flood Risk Management Standard.

The Executive Order 13690 was based on pure hazard criteria, not risk-based and only probabilistic through the connection to the base flood elevation. It is also only related to federally funded projects.

However, it turned out that the lifetime of EO 13690 was rather short. On 15 August 2017, President Donald Trump revoked Executive Order 13690 and issued Executive Order 13807 on Establishing Discipline and Accountability in the Environmental Review and Permitting Process for Infrastructure Projects. This change was reversed again by President Joe Biden on 20 January 2021 that is on his first day in office. President Biden rescinded EO 13807 and issued EO 13990 on Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis[3]. On 20 May 2021, President Biden issued EO 14030 on Climate-Related Financial Risk, reinstating EO 13690.

6.1. Climate change adjustments in urban and transport (motorways and railways) drainage design standards

Madsen *et al*. (2014) offered a summary of existing guidelines in European countries, referring to climate change adjustment of design rainfall. They reported on national guidelines on design rainfall in Belgium, Denmark, Sweden, and the UK.

Germany has been one of the European leaders in the development of an engineering toolbox for calculating and modeling of drainage systems and one of the most advanced countries in the field of adapting urban and transport drainage systems to the projected climate changes in the continent. For example, Staufer *et al*. (2010) showed that the current intensity of precipitation with statistical repeatability, e.g. once every 5 years ($N = 5$), average, is likely to occur in the future more than twice as often ($N = 2$) due to the expected climate change. On this basis, for the verification of future sewer overflows and flooding for a German federal state (*Bundesland*) North Rhine-Westphalia in the (Merkblatt No. 4.3/3, 2009) guideline, it was recommended to change the design precipitation frequency in the standards applicable at that time (DWA-A118, 2006; EN 752, 2008). These changes are summarized in Table 4.

Germany is also well known for a very pragmatic approach to adapting the drainage systems calculation toolbox through iterative updating of the current intensities of design rainfalls. In this country, the need to develop a specialist rainfall intensity atlas for the design of drainage systems was early recognized. In response to this need, the project of the KOSTRA Atlas (German: *KOordinierte STarkniederschlags-Regionalisierungs-Auswertungen*) (Bartels, 1997; Malitz & Ertel, 2015) was launched in the 1990s. The KOSTRA Atlas is a result of a comprehensive statistical study of rainfall maxima with a wide range of durations (5–4,320 min) from the entire network of rain gauges in Germany. Importantly, it provides information in high spatial resolution, i.e. it can be used to read the values of the intensity of design rainfall for any location corresponding to a specific cell (of an area of 66.83 km^2) of the regular grid, covering the whole country. Thanks to advanced procedures for the statistical processing of the maximum rainfall depths from the rain gauge network, including spatial interpolation with the use of kriging, the values read in the grid cells of KOSTRA Atlas are provided with confidence intervals. The first edition of the KOSTRA Atlas was originally based on 30-year rainfall records (1951–1980) and since then it has been updated. Its most recent version, called KOSTRA-DWD-2010R (Junghänel *et al*., 2017), is based on 60-year rainfall series (1951–2010). The KOSTRA Atlas is comparable in the quality of the products offered to the engineer with the more recent NOAA Atlas 14 in the USA (Perica *et al*., 2018) or the Polish PANDa Atlas (*Polski Atlas Natężeń Deszczów*) in Poland (Licznar & Zaleski, 2020).

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[3] https://www.federalregister.gov/documents/2021/01/25/2021-01765/protecting-public-health-and-the-environment-and-restoring-science-to-tackle-the-climate-crisis.

Table 4 | Amendments to DWA-A118 (2006) and EN 752 (2008) with regard to precipitation frequency, reflecting future sewerage overloads, according to Merkblatt Nr. 4.3/3 (2009).

		Precipitation frequency (once in *N* years)	
No.	**Land development**	**For verification of surcharge**	**For verification of flooding**
1	Rural areas	3 instead of 2	50 instead of 10
2	Residential areas	5 instead of 3	100 instead of 20
3	City centers, service, and industry areas	10 instead of 5	100 instead of 30

Attempts to adapt the toolbox for designing urban and roads/railways drainage systems have been also undertaken in other European countries. For example, in the UK, the Environment Agency (UK), in its guidelines from 2016 (updated in 2020), recommends increasing the maximum intensity of design rainfall for small and urban catchments, due to climate change, by up to 40% (upper end, the 2080s) (Environment Agency, 2016). In Belgium, Willems (2013) studied the impact of climate change projected up to 2100 on the necessary revision of the design principles of urban drainage systems. He showed that in Flemish conditions, the 10-year design storm intensity can increase up to about 50% by the end of 2100, or systems designed for a 20-year return period of flooding, might flood with four times shorter recurrence interval of – in order of magnitude – 5 years by the end of the century.

The cited studies and recommendations are, however, only peculiarities of a very conservative practice of designing urban and roads and railways drainage systems. Engineers do not so much use recommendations and results published in scientific articles, but are usually obliged to use methodologies codified in national standards and technical guidelines. However, these documents are often obsolete, both in terms of the topicality of the recorded sources of information about the intensity of design rainfall, but also in terms of the very idea of the functioning of drainage systems. Especially, the standards and guidelines for roads and railways drainage are still rooted in the old philosophy of 'collect and drain'. To support these theses, it is enough to briefly review the standards and technical guidelines from a few selected countries, such as Germany, Spain, and Poland.

Even in Germany, being an advanced country in terms of adaptation to climate change, the changes to the design guidelines for roads and railways drainage are slow and limited. The German railway standard for drainage *Richtlinie 836 – Erdbauwerke und sonstige geotechnische Bauwerke planen, bauen und instand halten* (Ril-836, 2019) allows the use of a simple delay coefficient method together with the oldish Reinhold (1940) rainfall model to calculate the maximum runoff of rainwater.

The Reinhold (1940) rainfall model responds to the challenges of designing drainage systems according to the principle of 'collect and drain' and combined the intensity of rain with different frequencies of occurrence and duration up to 150 min with the reference intensity $q_{(15.1)}$ for the time of 15 min and return period of 1 year. This model can no longer be used in the calculation of drainage systems, equipped with devices for retention and drainage of rainwater, for which the duration of rainfall may be of the order of a dozen or even several dozens of hours.

The Ril-836 (2019) standard recommends to change the $q_{(15,1)}$ intensity, in relation to the original values after Reinhold (1940), for various locations in Germany. For example, for Berlin, a change in the intensity of $q_{(15,1)}$ from 94 to 127 $\mathrm{dm}^3\,(\mathrm{s\ ha})^{-1}$ was introduced. Moreover, the Ril-836 (2019) standard indicates that the calculation of the maximum rainwater runoff should be in accordance with the road drainage guideline *Fortschreibung der Richtlinien für die Anlage von Straßen, Teil: Entwässerung* (RAS-Ew, 2005). This guideline indicates the KOSTRA rainfall atlas as the source of reliable rainfall intensity for the dimensioning of drainage systems. For calculating rainwater infiltration systems, Ril-836 (2019) recommends the use of the ATV-DVWK-A 138 (2005) technical guideline, also referring to the KOSTRA Atlas.

In Spain, recent guidelines for calculating roads and railways drainage systems for roads (BOE 60, 2016) and railways (NAP 1-2-0.3, 2021) recommend a consistent approach to adopt design rainfall rates for calculating the maximum rainwater runoff. The precipitation intensity is the product of the corrected average daily precipitation intensity corresponding to the desired frequency C and the so-called storminess coefficient, which – according to the standard for a given rainfall duration – can be calculated on the basis of the storminess index, which expresses the ratio between hourly precipitation intensity and corrected average daily intensity. Both standards (BOE 60, 2016; NAP 1-2-0.3, 2021) contain maps with storminess index values for different areas of Spain. The value of daily precipitation with a frequency of $1/N$ for calculations according to the guidelines should be read from the atlas of daily precipitation (*Máximas lluvias diarias en la España Peninsular*), published in 1999. The current standards of Spanish roads and railways drainage can be justified by the fact that they allow for the assumption of daily precipitation values with a frequency of $1/N$ on the basis of a statistical series of annual maximum daily precipitation (with a series length exceeding 30 years), recorded by rain gauges near the designed drainage systems. The Spanish standards also allow for an alternative calculation of the turbulence coefficient on the basis of a nearby representative IDF curve, if it exists and is accepted by the client. These are certainly options that open the possibility of designing on the basis of more current rainfall rates, but the open question is whether engineers will undertake the burden of additional statistical analysis, instead of using simpler, well-established methods from over 20–30 years ago.

Poland faces considerable conservatism with regard to the modernization of the design toolbox, and especially the updating of the intensity of design rainfall. The tools that can be found in the Polish guidelines for designing the roads and railways drainage system lack competence to adapt to changing climate. Both in the national road drainage standard (PN-S-02204, 1997) and in the guidelines for calculating railway drainage systems published 22 years later (Wytyczne obliczania ilości, 2019), it is recommended to calculate the intensity of the design rain, q, on the basis of an outdated empirical, formula:

$$q = 15.347\frac{A}{t_m^{0.667}}, \tag{1}$$

where A is a constant value taken on the basis of the average annual precipitation in depth H and the probability p of the design rain (see Table 5), while t_m is the rainfall duration time in seconds.

Table 5 | Values of A coefficient in Equation (1) on design precipitation intensity (PN-S-02204, 1997; Wytyczne obliczania ilości, 2019).

	***H* (mm)**			
***p* (%)**	**Up to 800**	**Up to 1,000**	**Up to 1,200**	**Up to 1,500**
5	1,276	1,290	1,300	1,378
10	1,013	1,083	1,134	1,202
20	804	920	980	1,025
50	592	720	750	796
100	470	572	593	627

Formula (1) is a very simple empirical relationship, the origins of which date back to 1926 when local discontinuous records (from 1837 to 1891 and 1914 to 1925) of intense short-duration rains were analyzed for the purposes of modernizing the sewerage system in Warsaw. These results were generalized after the Second World War by Błaszczyk (1954) to the form recommended for use throughout Poland:

$$q = \frac{6.67 \cdot \sqrt[3]{H^2 \cdot C}}{t^{0.67}} \tag{2}$$

where q is the unit rainfall intensity (dm^3 (s ha)$^{-1}$), H is the mean annual rainfall (mm), C is the period of a single exceedance of a given intensity (years), and t is the duration of rain (min).

The design rain intensity in any location in Poland was assumed to depend on a single and easy-to-determine climatic parameter in the form of normal annual rainfall. Later, to further facilitate the use of formula (2), its simpler form (1) with a tabular summary of the numerator values was proposed. Obviously, the simple formula was willingly accepted by the engineers. However, its development was not preceded by comprehensive studies of the design rainfall on rain gauges other than located in Warsaw, even if Poland is a large country (an area of over 312,000 km^2), with spatially variable climates (the range of mean annual rainfall varies from 500 to over 1,000 mm). What is worse, the structure of formula (2) had its roots in rather obsolete Gorbachev's precipitation model (Dębski, 1966), the starting point of which was the speculative concept of the rain-force parameter (the root of the product of precipitation intensity and depth) as a discriminant of rains from clouds formed under the same meteorological conditions.

Obviously, the design rainfall formula (2), developed on the basis of outdated and incomplete rainfall data, without proper statistical analysis and assuming a prior relationship between the annual rainfall depth and maximum rainfall intensities, cannot provide reliable estimates of design rainfall intensity. Comparative studies of empirically determined and verified design rainfall intensities on a network of 100 stations from all over Poland and the rainfall intensities calculated from formula (2), taking into account the average annual rainfalls in depth from the last 30 years was performed by Licznar *et al.* (2018) at the preliminary stage of the PANDa Atlas project. They found that:

1. The intensity of design rainfall does not strongly correlate with the average annual precipitation depth; therefore, the structure of Błaszczyk formula (2) is incorrect and it is not possible to introduce rational systematic corrections to the model.
2. The use of the Błaszczyk formula leads, in a great majority of cases, to a dangerous underestimation of the real values of design rainfall intensity. This underestimation is about 33% over the whole network of 100 analyzed gauges and can even be observed in the case of Warsaw, i.e. the place where the original formula was developed. However, the intensity of rainfall resulting from formula (1) is still widely used when designing roads and railways drainage systems in Poland. In fact, it is often overused, beyond the conditions for which it was developed (rainfall durations from 5 to 180 min). In fact, formulas (1) and (2) are used for much longer durations, e.g. for estimating the necessary volume of storage capacity.

The most recent railway guideline (Wytyczne obliczania ilości, 2019), based on a flawed and outdated Błaszczyk rainfall model (Błaszczyk, 1954), recommends increasing the average annual historical rainfall depth by 3.5%, due to the projected climate change. This reflects the projection of an increase in the average annual rainfall depth for the area of Poland by approximately 3.5% in the time horizon 2050, in relation to the reference period 1971–2000. However, the Błaszczyk model was not based on the data from 1971 to 2000, and the correlation of maximum rainfall intensities with the average annual rainfall depth is not strong. Hence, it is impossible to introduce a systematic correction of formulas (1) and (2) (Licznar *et al.*, 2018).

Finally, engineers using these formulas usually do not have sufficient information about the average annual precipitation depth H, at the project site. Data obtained from nearby rain gauges for various years may differ by much more than the recommended 3.5% correction. At the same time, the recommended increase in the average annual rainfall depth, assuming the average rainfall total for the whole of Poland, $H = 600$ mm, translates into a 2% increase in the calculated intensity of design rainfall. Such a small correction is not only unreliable in relation to the scale of recommended changes in rainfall intensity in other European countries, but is even an order of magnitude smaller than the range of local rainfall intensity confidence intervals read from contemporary rainfall atlases, including the Polish PANDa.

Summarizing the presented review of climate change adjustments in the area of designing urban as well as roads and railways drainage systems in Europe, it can be stated that developed scientific methodologies are already in existence. We know how to project the design rainfall and the band of uncertainty, but we cannot translate them easily into probabilities.

In many European countries, engineers do not have access to or do not use the current information on rainfall intensity for design. It would be very useful to create a common, pan-European rainfall atlas, similar to the KOSTRA or PANDa atlases. Ideally, this action should be a long-term project of adjusting rainfall statistics to changing climatic conditions. It is important that such an atlas could give the possibility of reading the intensity of design rainfall together with confidence intervals due to the small-scale variability of rainfall maxima. Only such a source should be the starting point for introducing corrections due to the projected climate changes. It also seems very important to order and simplify European guidelines as to the recommended permissible rates of flooding and overflows of drainage systems and their unambiguous connection with the frequencies of rainfall assumed for the design.

6.2. Climate change adjustments in design floods

Due to the likely increase in flood risk, despite the huge uncertainty, practitioners and water managers in some European countries and regions are already considering explicitly how to incorporate the potential effects of global change into policies and specific design guidelines via climate adjustments (Kundzewicz *et al*. 2008, 2017).

Interesting development of design floods, to reflect climate change, have been undertaken in the basin of the Rhine, a large international river in Europe (Strategy for the IRBD Rhine, 2015).

Effects of climate change modify the discharge pattern of the Rhine and its tributaries: higher flows are likely to become more frequent. Orientation guidance for flood sensitivity values is given in Strategy for the IRBD Rhine, (2015) for various gauges on the Rhine for a range of characteristic discharges, such as MHQ, HQ10, HQ100, and HQ extreme until 2050. The bandwidths for changes in HQ extreme that may serve as a basis for discussions on possible adaptation measures read: from −20 to +35% at Basel and Maxau, from −15 to +30% for Worms, and from −5 to +20% at Kaub, Cologne (Köln), and Lobith. Even if the width of positive change bands exceeds the width of negative change bands, the uncertainty range is high, especially in upstream gauges on the Rhine.

As a consequence of the great floods of the Rhine in 1993 and 1995, the International Commission for the Protection of the Rhine (ICPR) adopted the 'Action Plan on Floods'[4] for the Rhine that aims at improving flood protection as well as extending and enhancing the floodplains of the Rhine. The plan, consisting of numerous measures, was conceived in phases and was implemented by all riparian countries until 2020, entailing expenses of 12 billion euros.

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[4] https://www.iksr.org/en/international-cooperation/rhine-2020/action-plan-on-floods/.

Objectives for 2020 included the following:

1. Damage risks were to be reduced by 25%, compared to the reference year 1995.
2. Extreme flood stages downstream the impounded sections were to be reduced by up to 70 cm (60 cm due to water retention along the River Rhine and approximately 10 cm due to water retention in the Rhine basin).
3. The population living in the vicinity of the Rhine was to be made aware of the flood risk via maps of flood hazard and risk, indicating the areas at risk. To increase flood awareness, flood risk maps were drafted and spread for the flood hazard areas.
4. Lags of flood forecasting should be distinctly prolonged.

In some European countries and regions, flood design values have been increased by correction factors (safety margins), possibly based on climate change impact scenarios. Madsen *et al*. (2014) offered a summary of existing guidelines in European countries, referring to climate change adjustment of the design flood. They reported on national guidelines on design floods in Norway and the UK. In Belgium and Germany, the existence of regional guidelines on design flood was reported in the province of Flanders (Belgium) as well as in some German federal states (*Bundesländer*), such as Bavaria and Baden-Württemberg (Germany). The pattern of the construction of these guidelines is quite common: the guideline foresees an *N*% increase, with a future horizon of concern either explicitly specified or not. The specific numbers may depend on the location/region and the return period. In some guidelines, design floods depend also on the prevailing flood season and catchment size. The amplitude of climate change allowance in a particular country or region usually corresponds to the increase of peak river flow, resulting from climatic projections for the future (e.g. end of the 21st century).

In the UK, the Environment Agency (2016) avoided estimating probabilities by providing climate change 'allowances', that is predictions of anticipated change (increase) for peak river flow that local planning authorities, developers, and their agents should use in flood risk assessments. In particular, this guidance aids in preparing strategic flood risk assessments, or flood risk assessments for planning applications, or development consent orders for nationally significant infrastructure projects. As stated by the Environment Agency (2016), there may be circumstances where local evidence supports using other data or allowances, e.g. if the impact of climate change on peak river flow is not the same in all river catchments in a river basin district. However, then the Environment Agency may want to check how and why other data were used in plans.

Peak river flow allowances listed in Environment Agency (2016) show the anticipated increases to peak flow by river basin district. The range of allowances is based on percentiles, e.g. the upper-end allowance is based on the 90th percentile (being exceeded by 10% of the projections). The future horizons considered are the 2020s (2015–2039), the 2050s (2040–2069), and the 2080s (2070–2115). The higher the percentile and the more remote the future horizon, the higher the potential increase of the index, above the 1961–1990 baseline. For the upper-end allowance based on the 90th percentile, there is a projected increase by 105 and 85%, respectively, for Southeast and Southwest river basin districts. Even higher allowances are given for extreme flows (H + +), being 120, 105, 95, 90, and 80%, respectively, for Southeast, Southwest, Northwest, Severn, and Thames river basin districts.

7. CONCLUDING REMARKS

There is little doubt that high river discharges and stages have been changing, even if trend detection in flood hazards does not yet consistently show a ubiquitous, and statistically significant, change. Flood hazard impacts may increase, and they might come more rapidly than model projections based on climate scenarios suggest. Hence, the rational expectation is that flood frequencies will be changing (mostly increasing), with associated economic and social consequences. With all these uncertainties, society needs to begin thinking about adaptation investments as a precautionary measure now, as in the case of the Netherlands, where flood safety standards have been very high, because the message should be that we have to prepare without precisely knowing the future flood hazard.

The Dutch have created an incremental adaptive strategy for coping with climate change through a combination of scenarios (different levels of both water regime and socio-cultural conditions) and systematic modeling to define sensitivities of current infrastructure systems to levels of change. The incremental adaptation strategy includes multiple responses that supplement each other, precluding the need to speculate on how much change and when for risk mitigation efforts. This strategy is somewhat unique in that it does not focus on probabilities of change but the physical levels of change. It may well be a window into the future if non-stationarity makes probabilistic analysis much more uncertain.

The spread of projections of hazards and damages associated with destructive water abundance has to be interpreted with caution by decision-makers in charge of natural risk reduction, climate change adaptation, and water resources management. Since it would be naïve to expect the availability of trustworthy quantitative projections of future flood hazards, in order to reduce the risk, one should focus attention on the identification of risk and vulnerability hotspots and improve the situation by reducing risk in such hotspot areas.

Decision-making under uncertainty requires identifying and quantifying the uncertainty involved and then improving a suitable framework for decision-making, including consideration of the risk of action vs. the risk of inaction. The lack of agreement in projections between studies can be interpreted and understood by scientists, but less so by stakeholders in general and practitioners in particular. Despite the caveats typically accompanying large-scale studies, stakeholders in regions where no local hazard projections are readily available view large-scale maps from different sources (e.g. maps in scientific publications) that may strongly diverge in their area of interest. Since they tend to take reported flood hazard projections at face value, they may become confused by noted disagreements.

There is no doubt that it is necessary to prepare for the existing variability of water abundance (to which mankind is not adequately prepared today), but this is not likely to be sufficient for future changes. Current water management practices may simply be inadequate to reduce the adverse impacts of climate change (Kundzewicz *et al.*, 2014). Nevertheless, good adaptation to existing climate and its variability augurs better for adaptation to the future, changed, climate. Robust adaptation procedures, which do not rely on crisp and precise projections of future changes (that can never be obtained), need to be developed. Economic risk-based decision-making is necessary, i.e. search for appropriate levels of infrastructure based on the expected damages avoided vs. the cost of the infrastructure. Under strong and irreducible uncertainty, two alternative courses of action can be envisaged – the precautionary principle (a variation of the min–max concept – to choose the approach minimizing the worst outcome) and/or an iterative and sequential adaptive management approach, based on ensembles and multi-model probabilistic approaches (Kundzewicz *et al.*, 2018a, 2018b).

It is also important to note that engineering design standards serve as the legal basis for infrastructure design, construction, and maintenance. Engineering design standards undergo rigorous and extensive peer review by professional engineering societies. Though they are based on the 'best' peer-reviewed scientific literature, engineering design standards represent a practical subset of a vast body of hydrologic sciences and engineering literature. They are meant to reflect 'best management practices', not necessarily 'best scientific papers'. Hence, looking ahead, it should be recognized that a wide range of new hydrologic analytical techniques that have evolved to deal with the uncertainties of non-stationary climate must be further translated into acceptable and replicable engineering design standards to replace the existing ones that are largely based on empirical methods, such as the 'design precipitation', 'design flood', 'probable maximum precipitation', or 'probable maximum flood'. Complex techniques used for climate adaptation of design rainfalls and most of their application results have to be translated into much simpler rules that could be understood by average engineers, who most probably had never studied climate change. These rules have to be implemented at a wider scale, since climate change is a global phenomenon. Finally, if we insist on implementing adaptation to climate change as a correction, most often increase of design rainfall, we have first to take a careful look at current local rainfall statistics used by engineers in everyday practice that typically need an update. Projection uncertainty of climatic models mixed with an outdated starting point could lead us to nowhere.

The basic problem is that ‘risk analysis’ requires probabilities. Flood frequencies must be calculated for a non-stationary climate. There are many methods, but no agreement on which to use – comparable to the issue that the USA uses LP3, while most of Europe and Japan use GEV for flood frequency analysis. All new engineering standards need a replicable method for calculating flood frequencies. The engineering profession should standardize computations of flood and drought probabilities under an anticipated non-stationary climate. Several promising methods have been developed by research hydrologists. These must be integrated into standard ‘best engineering practices’.

There is a clear gap between results of scientific studies and needs of practitioners in the domain of climate change adjustments in engineering design. Scientific results are publishable but not necessarily actionable. They may provide responses to some scientific questions but may not offer useful answers to burning practical questions. Perhaps both science and practice should try to improve the interface, perhaps each side could take a step backward and listen to what the other party has to say (even if practitioners may not feel particularly interested in non-actionable scientific findings, as long as guidelines, e.g. standards justifying their *modus operandi* are in existence). It would be convenient for a practitioner to get a crisp, scientifically sound number for design, but that is not realistic. One has to deal with a range of values (sometimes a broad range). This calls for the preparation of several variants of plans. Adaptation in stages (with the possibility of add-on effect) is encouraged. Both scientists and practitioners have to live (and cope) with uncertainties, non-stationarities, and non-homogeneities.

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DATA AVAILABILITY STATEMENT

All data used in this paper stem from sources that are rigorously referred to.

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