Decision strategies for handling the uncertainty of future extreme rainfall under the influence of climate change

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ABSTRACT

Several extraordinary rainfall events have occurred in Denmark within the last few years. For each event, problems in urban areas occurred as the capacity of the existing drainage systems were exceeded. Adaptation to climate change is necessary but also very challenging as urban drainage systems are characterized by long technical lifetimes and high, unrecoverable construction costs. One of the most important barriers for the initiation and implementation of the adaptation strategies is therefore the uncertainty when predicting the magnitude of the extreme rainfall in the future. This challenge is explored through the application and discussion of three different theoretical decision support strategies: the precautionary principle, the minimax strategy and Bayesian decision support. The reviewed decision support strategies all proved valuable for addressing the identified uncertainties, at best applied together as they all yield information that improved decision making and thus enabled more robust decisions.

Key words | Bayesian decision support, climate change, minimax strategy, rainfall, the precautionary principle, uncertainty

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INTRODUCTION

It is commonly accepted that anthropogenic climate change will affect the water cycle and thereby extreme rainfall events (Solomon *et al.* 2007). Worldwide occurrences of extensive floods within the last few years indicate that the change is perhaps already ongoing. In Denmark this is manifested as problems in urban areas when the capacity of the existing drainage systems is exceeded as a result of the heavy rainfall events. Adaptation is necessary to cope with a future of more extreme rainfall and instant initiation of adaptation strategies is recommended by many authors (Stern 2007; Arnbjerg-Nielsen & Fleischer 2009; Mailhot & Duchesne 2010). Actually, implementation of adaptation strategies in the urban drainage design can be a good opportunity for the development of new integrated management techniques, but it requires a new paradigm for decision making. Presently, the evaluation of possible adaptation strategies versus 'business as usual' does to a large extent depend on the expected change in the frequency and occurrence of future floods, but these changes depend on region and are very uncertain (Fowler & Hennessy 1995; Rosenberg *et al.* 2010; Kjelstrup *et al.* 2011). Despite scientific agreement on the fact that the occurrence and magnitude of extreme rainfall will increase in mid- to high-latitude regions (Solomon *et al.* 2007), it is very difficult to determine how much and how the change will compare with natural variations. Climate modeling will constantly improve, but we will, on the other hand, never know for certain what the world will be like 100 years from now. No matter what the urban planners will face decision making under uncertainty. This uncertainty also relates to other aspects than climatic changes (Arnbjerg-Nielsen 2011), but the present paper focus on changes in design precipitation due to anticipated anthropogenic climatic changes. We aim at testing three different theoretical decision support strategies, which all intend to improve our understanding of how this climate-related uncertainty affects our decisions. These are the precautionary principle, the minimax strategy, and Bayesian decision support.

RECOGNITION AND QUANTIFICATION OF UNCERTAINTIES

Presently in Denmark, parts of the urban drainage systems are old and renovations or new pipes are necessary within

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the next decade (Danish EPA 2004). Due to the long service life (80–100 years) it is important to ensure that the systems built today can meet the desired level of service in the future. Drainage systems are one of the most expensive parts of urban infrastructure and once the investment is made the costs are non-recoverable. All these aspects have encouraged an increased focus on uncertainty and the presence and influence of uncertainties in urban drainage design is, to some extent, acknowledged in Denmark today. A framework addressing this issue was published by the Danish Water Pollution Control Committee in 2005, mentioning both the uncertainty in the applied rainfall intensities, climate change, city expansion and an increase of the impervious areas during the lifetime of the drainage system (Harremoes *et al.* 2005). A safety factor is introduced to represent the present and future uncertainties on these design parameters. The factor applies to design intensities estimated from historical data. The validity of the approach is not discussed here; instead we refer the reader to Arnbjerg-Nielsen (2011, 2012). Specifically for climate related uncertainty the factor is referred to as a 'climate factor' (CF), and defined as the ratio between the future and present design intensities (Gregersen *et al.* 2011; Arnbjerg-Nielsen 2012). In the perspective of urban drainage design there are many ways of addressing the uncertainty of the changing climate. This study uses the current situation in Denmark, while acknowledging that the choice of strategy differs from country to country and that urban planning and adaptation still are subjects of discussion in the literature (e.g. Arisz & Burrell 2006; He *et al.* 2006; Maharjan *et al.* 2008; Verworn *et al.* 2008; Ntelekos *et al.* 2010).

A broader perspective, centered on the drivers, impacts and responses to climate change is beneficial independent of the preferred adaptation strategy. Figure 1 illustrates the conceptual relation between drivers, impacts and responses. Each area is discussed in the following subsections under separate headings, using the framework for quantification of uncertainties that was introduced by Walker *et al.* (2003). For each identified location of uncertainty, four possible levels exist: statistical uncertainty, scenario uncertainty, recognized ignorance and total ignorance. Statistical uncertainty is associated with a probability. For scenario uncertainty, all possible outcomes are known but not their respective probabilities. In the case of recognized ignorance it is acknowledged that not all possible outcomes are known, whereas for total ignorance the presence of uncertainty is not even recognized.

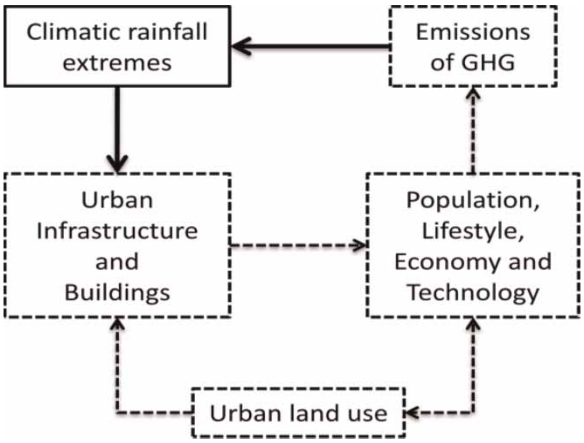

Figure 1 | The conceptual relationship between climatic rainfall extremes and the urban area and its population. Solid lines indicate the main focus of this paper. GHG: greenhouse gases.

Urban infrastructure and buildings

The urban engineer makes assumptions about rainfall input and runoff parameters. Furthermore, statistical uncertainty is present when testing if the proposed system fulfilled the demands related to an acceptable frequency of failure. In relation to adaption, as a response to a climate-change induced increase of this frequency, cost–benefit evaluations become important. Uncertainty is present in all these phases and the highest level is evaluated to be scenario uncertainty.

Urban land use

The vulnerability of the urban landscape to exposure to increased risk of floods depends to a high degree on the technical and social layout of the city. The urban land use is a key parameter to establishing resilient urban complexes, but prioritizing between different land uses may be difficult and perceptions of good layouts change over time. New city paradigms that probably are beyond our imagination today will develop and the highest level of uncertainty is therefore evaluated to be recognized ignorance.

Population, lifestyle, economy and technology

The population is constantly under development and so are their preferences, technological knowledge and economy. On top of this comes the fact that the choices of the population are not always rational. Predictions within these four areas are consequently associated with an uncertain level of recognized ignorance.

Emissions of GHG

The emissions are directly linked to the size of the population and their behaviour. The Intergovernmental Panel on Climate Change (IPCC) has addressed the issue of uncertainty by developing different scenarios for the development of the world in relation to population growth, globalization, technological innovation, economic growth and environmental concern (IPCC 2000). The IPCC does not point toward one scenario being more likely than the others, but assigns all of them an equal probability of occurrence. This therefore seems to be a classical example of scenario uncertainty, but the true development of the world will most likely not follow any of the scenarios. The level of uncertainty is therefore recognized ignorance.

Climatic rainfall extremes

Several extrapolation methods exist that can help in describing how the rainfall extremes are affected given that a specific scenario for the GHG emissions is chosen. These include: climate model simulations, downscaling and extrapolation of trends in observed extreme rainfall. Big challenges still exist for all methods and the associated level of uncertainty level ranges from statistical to recognized ignorance (Willems *et al.* 2012).

In summary, it can be concluded that the highest and most intangible uncertainty is associated with the future preferences and choices of the population, which will affect both the future use of urban land, the requirements of the functionality of the city, but also the forcing of our climate and the resulting climate extremes that the city design should be able to cope with. It must also be acknowledged that no socio-economic model will be able to predict the preferences and potential irrational choices of the future population and that the corresponding uncertainty therefore prevails. Decision strategies that recognize this are therefore necessary.

APPLICATION OF DECISION THEORIES IN URBAN DRAINAGE DESIGN

The decision that should be made in relation to adaptation to climate change can be divided into two phases: the first choice is between adaption and inaction. If adaptation is selected, the next decision is how and how much. By its basic definition, the CF approach itself does not imply a specific procedure estimation of the future design intensities. The most well known methods are among others reviewed by Willems *et al.* (2012). As discussed above, the uncertainty in the CF cannot be quantified, independent of the estimation method, which is indeed the motivation for studying how uncertainty can affect decisions. A constant climate corresponds to $CF = 1$, whereas we in Denmark today apply $CF = 1.4$ for a 100 year-event when new urban infrastructure is designed (Arnbjerg-Nielsen 2012). However, recent studies point towards a higher factor (e.g. Gregersen *et al.* 2011). $CF = 2$ is perceived as a maximum, not because model prediction does not support a higher value, but because a factor above two from expert knowledge is judged to represent a situation in which the change in extreme rainfall should no longer be handled by pipe enlargements alone. The application of the three decision support strategies focuses on the choice of CF using Denmark as a case study. The magnitude of changes in rainfall extremes is expected to vary greatly even within Europe (Larsen *et al*. 2009).

The precautionary principle

The precautionary principle addresses the subject of risk and uncertainty within the framework of decision making, but on an ethical and philosophical level, which leads to guidelines and not direct solutions. It is widely acknowledged and recommended by, among others, the European Commission (European Commission 2000). The essence of the principle is that we need to act on potential environmental or human risks despite a prevailing uncertainty regarding the severity. Consequently, uncertainty becomes a motivation; because we don't know all possible outcomes, precautionary action is necessary. An important argument is that when the effect is delayed or irreversible, strong scientific evidence is only obtained when it is already too late (Harremoes *et al.* 2001). The principle further includes the perspective of future generations; something other decision theories tend to ignore or de-emphasize (Stern 2007). Naturally there are also arguments against; Sunstein (2005) reviews and discusses some of these. In the light of the uncertainties identified in the previous section, the precautionary principle will lead to a choice of action. The interesting question is how strong and expensive the adaptation should be. Does the precautionary principle actually lead us to choose a CF that represents the worst case of our selected range despite, or as a consequence of, the many locations of recognized ignorance? To elaborate on this the following pros and cons should be taken into consideration:

- *The potential harm of too small sewers:* this harm varies from inconvenience and economic loss to a higher rate of illness and death. Economic loss is both due to flooding and situations in which the sewer pipes and basins must be replaced before the technical lifetime is expired.

- *The potential harm of too large sewers:* a waste of quite significant amounts of money and resources.
- *The advantage of too large sewers:* the present Danish design criteria imply that drainage systems should be able to handle extreme rainfall intensities with return periods of up to 10 years. For more extreme events, flooding of the surface will occur, but if the sewers are 'too large' the cost associated with these floods will be eliminated or minimized.
- *Perspective of the future generation:* the consequence of too small sewers will increase gradually as the climate changes; the most severe impact is therefore on the future population. We do, however, not know the preferences of the future population that we are trying to protect. Their requirements to the city design are likely to have changed substantially. Too large sewers are, on the other hand, not assumed to induce any direct harm, assuming that the usual design criteria are still fulfilled.
- *Other possible adaption strategies:* enlarging the capacity of the drainage system is a rigid solution. More flexible adaptation could be adopted in the future, such as: local infiltration of rainwater, improved contingency plans, real-time-control and changes of city layout.
- *The drawback of adaptation in general:* adaptation has cost and the question is always if these resources could have been used for better purposes, measured by the increase in utility or social welfare.

The conclusion is that the precautionary principle advocates a strategy with a relatively high degree of adaptation measures, without recommending a specific value. Most importantly, the principle supports further research, careful evaluation of new knowledge and an acknowledgement of all involved uncertainties, including those that are difficult to quantify.

The minimax strategy

The minimax strategy has evolved from game theory and is especially useful to explore the action of two opposite actors, whose benefits/costs depend on the action of the other player. Uncertainty is introduced as the fact that the first player does not know the move of the opposite player, not even in terms of a probability. Each player will therefore act in a way that minimizes his potential loss. The following example is adapted from Clarke (2008), in which the two actors are a political adaptation strategy and the future state of the world, see Table 1. Looking at the human's choice, adaptation has the highest potential cost, in the case where the catastrophe happens despite the preventive measures. As a consequence the minimax strategy will deselect the adaptation and result in inaction.

The example cannot be transferred directly to the adaptation of urban drainage systems; if the adaptation is based on a CF that turns out to be too small, it will still reduce the extent of the resulting flooding. Say we adapt using a CF of 1.4 but the true climate change corresponds to a factor of 2. Our adaptation cost will then be associated with a factor of 1.4, whereas the cost of climate-change-related damage will both depend on the climate change that we prepared for ($CF = 1.4$) and the true climate change ($CF = 2$). The applied notation is: *cost of damage* ($CF_{applied} = 1.4$ given that $CF_{true} = 2$). If we prepare for a climate change that never occurs we will prevent some of the flooding that today is accepted in terms of the desired level of service. The minimax matrix for all possible situations is given in Table 2, but this time it is not evident which CF the strategy will point towards. In order to make the choice, the costs and benefits of a range of possible outcomes must be calculated.

Using the municipality of Roskilde as an example, 15 million DKK is spent every year for urban drainage rehabilitation and maintenance, while the estimated Expected Annual Damage (EAD) due to flooding is 7.3 million DKK (Arnbjerg-Nielsen & Fleischer 2009). It is assumed that adaptation aims at maintaining exactly the same EAD as under the current climate. If the CF is underestimated, then the EAD will increase over time, and vice versa.

The extra replacements of pipes are assessed to be 1.5 and 9.0 million DKK annually for a CF of 1.4 and 2.0, respectively, based on an evaluation of which pipes must be replaced before their technical lifetime is exceeded. In case the actual climate impact is smaller than the anticipated impact, the EAD will rapidly decrease to a new and lower value. In the case of Roskilde the change in EAD is assessed to be:

EAD $(2|2) =$ EAD $(1.4|1.4) =$ EAD $(1|1)$:	0 million DKK
EAD $(1.4|1)$:	–0.2 million DKK
EAD $(2|1)$:	–0.5 million DKK
EAD $(2|1.4)$:	–0.2 million DKK

Table 1 | Minimax matrix for an adaptation strategy and the future state of the world, modified from Clarke (2008). The highest possible cost is marked in italic and the minimax choice is no adaptation

	Nature		
Human	**No catastrophe**	**Catastrophe**	**Catastrophe despite adaptation**
No adaptation	0	Cost of catastrophe	Cost of catastrophe
Adaptation	Cost of adaptation	Cost of adaptation	*Cost of adaptation + cost of catastrophe*

Table 2 | Minimax matrix for the choice of climate factor in urban drainage design. The cost is a function of both the sewer capacity (determined by the humans) and the magnitude of the extreme rainfall (determined by nature). The notation *x*|*y* should be read as *x* given *y*

	Nature		
Human	**CF = 1**	**CF = 1.4**	**CF = 2**
CF = 1	0	Cost of damage (1|1.4)	Cost of damage (1|2)
CF = 1.4	Cost of construction (1.4) − saved damage (1.4|1)	Cost of construction (1.4)	Cost of construction (1.4) + cost of damage (1.4|2)
CF = 2	Cost of construction (2) − saved damage (2|1)	Cost of construction (2) − saved damage (2|1.4)	Cost of construction (2)

If too little adaptation occurs, it is assumed that the EAD will increase gradually over time as described by Arnbjerg-Nielsen & Fleischer (2009). Two key assumptions are: (1) climate change happens gradually during the technical lifetime of the system; and (2) the relationship between the return period and the cost of damage is modeled by a log-linear relation. Using this approach the EAD (2|1) in year 2100 has increased to 120 million DKK.

The Net Present Value can now be calculated for each of the nine scenarios presented in Table 2. The results are presented in Table 3.

Table 3 shows that adaption is better than inaction, because even though the effect of climate change is underestimated the adaption still has an effect and hereby reduces the associated damage costs. Looking at the total matrix, the minimax choice points towards CF = 2. It cannot be concluded that an even larger CF thereby will be the minimax choice, if the matrix is expanded further. Factors above this value could be associated with very high costs because complete redesign of the city may be necessary. Finally, note that the choice also depends on the chosen cost estimation method. The results in Table 3 are rough estimates, given only to illustrate the application of the minimax strategy.

Table 3 | Minimax matrix for the choice of climate factor in urban drainage design. The fabricated costs are given as a NPV in mio DKK for a project period of 90 years and with a discounting rate of 3%. The two highest possible costs are marked in italic.

	Nature		
Human	**CF = 1**	**CF = 1.4**	**CF = 2**
CF = 1	0	360	*1140*
CF = 1.4	40	45	*840*
CF = 2	265	275	280

Bayesian decision theory

The Bayesian decision theory provides the means for updating our current knowledge (K) when new information, in terms of observations (O), becomes available. It should be noted that deciding on a given value for the CF actually is equal to believing that the chosen value has the highest probability of occurring. As argued earlier, the scientific background does not provide a basis for this, a high degree of subjectivity can therefore not be avoided.

The starting point of the Bayesian decision theory is Bayes' Theorem:

$$P(K|O) = \frac{P(O|K)P(K)}{P(O)} \quad (1)$$

P(K) represents the current knowledge expressed as a probability density function. This is also known as the 'prior probability', because it represents the situation before the information about O is taken into account.

P(K|O) is the updated knowledge also known as the 'posterior probability', because this probability has been estimated from O, it is said to be conditional.

P(O|K) is the likelihood of observing *O* when *K* is true.

P(O) is the probability of *O*, it must be included in the calculation of *P(K|O)* as a means of normalization, because the sum of all posterior probabilities, per definition, must be one.

Bayes' Theorem can, among others, be applied when *P(K)* is a probability distribution in which the parameters are updated using the information about *O*. To obtain a mathematical solution the parent distribution for these parameters should be known. A suitable parent distribution can be derived from statistics (Thyregod 1998). Common for all applications of Bayes' Theorem is that if additional information becomes available the previous posterior probability can replace the prior probability in Equation (1), and an updated posterior probability can be found.

A specific and relevant example of application concerns the occurrence of extreme floods. Picture a Danish residential area that was built in 1990 in the neighborhood of a creek. At the time of construction it is expected that floods will occur on average once in 50 years, potentially causing flood damage to nearby houses. The prior probability of flooding in a given year follows a Poisson distribution that has one parameter λ, the rate of flooding [years^{-1}]. As parent distribution a Gamma distribution with scale parameter (α) and shape parameter ($1/\beta$), is applied. An initial estimate of the uncertainty on λ is also needed. Detailed calculation procedures are given by Thyregod (1998). Assuming that the residential area is flooded in 1998, 2007 and 2010, Table 4 shows the corresponding update of λ. The probability that the true rate of flooding is higher than the originally accepted rate of flooding (1/50 years^{-1}) is also given. The choice of time window for flood risk evaluation is somewhat arbitrary; 5 years are used here to illustrate the approach. If only a single update was made at the end of the period, the final conclusions would identical. In relation to decision support, a critical level of p could be decided. Once the evidence is strong enough to conclude that the true rate of flooding is larger than the design value, adaptation is initiated.

DISCUSSION

The three decision strategies discussed above represent three very different, but equally important, perspectives of decision making. The precautionary principle is an excellent point of origin when addressing a certain problem that involves elements of environmental or human risk. This will ensure that areas of recognized ignorance are identified and that the ethical perspective of the evaluated issue is taken into consideration. In addition, the importance of the associated costs is not disregarded, but it must be recognized that the principle provides guidelines and not direct solutions. The minimax strategy illustrates a quite different perspective that is related to a fundamental psychological response to uncertain outcomes, in the case where no probabilities are available. This shows why the uncertainty related to climate change often leads to inaction. However, when the minimax strategy is applied to adaption policies for urban drainage design, inaction is not identified as the obvious choice. It is though important to emphasize that in many cases the involved actors will try to guess or estimate the move of 'opponent', leading to 'perceived probabilities' and perhaps a choice of strategy that is different from the minimax choice. Bayesian decision strategy is a purely statistical way of updating probabilities when new information becomes available and thus provides valuable information about when critical assumptions no longer are met. In the meanwhile, the strategy does not provide a conclusion on the appropriate solution. The uncertainty of climate change is not the only challenge within the area of urban drainage design. The presented strategies could also be used to address uncertainty in other urban design parameters.

Table 4 | Application of Bayes' Theorem, where λ is the rate of flooding [years^{-1}] and $p = P(\lambda > 1/50)$

	1990–1995 **No. of years = 5** **No. of floodings = 0**	**1995–2000** **No. of years = 5** **No. of floodings = 1**	**2000–2005** **No. of years = 5** **No. of floodings = 0**	**2005–2010** **No. of years = 5** **No. of floodings = 2**
Prior	Posterior	Posterior	Posterior	Posterior
$\lambda = 0.02$	$\lambda = 0.014$	$\lambda = 0.056$	$\lambda = 0.045$	$\lambda = 0.1$
Risk 1:50	Risk 1:70	Risk 1:18	Risk 1:22	Risk 1:10
$p = 0.26$	$p = 0.21$	$p = 0.74$	$p = 0.69$	$p = 0.98$

CONCLUSION

There are several uncertainties associated with the present urban drainage design, but the greatest is related to the future development of the design parameters. Looking at future rainfall extremes, the existing extrapolation methods suffer from different limitations, but the highest uncertainty is associated with the future preferences of the population. Identification of strategies, which can guide decision making under uncertainty is therefore essential. In terms of the three strategies discussed in this paper, all proved to be valuable for decisions on inaction vs. adaption, especially Bayesian decision theory which also includes a perspective about timing. Regarding the following decision about the degree of adaption the effect of uncertainty on the optimal choice is well illustrated by the minimax strategy, which hereby provides an extra dimension to the ordinary cost–benefit analysis. By all means the three strategies should at best be applied together as they all enlighten different angles of the necessary debate.

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