Managing the flooding system’s resiliency to climate change

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An increasing lack of stationarity in environmental phenomena and hence in the predictability of loading and effects makes it necessary to modify the traditional approach for planning and risk assessment of flood mitigation. The traditional approach attempts to manage the flooding system with the use of predictive/optimisation methods. These use the ‘most likely’ or average future projection to identify a singular, optimal adaptation strategy. Because the planning and risk management in this method is often decoupled from the dynamics and uncertainty of the flooding system, this is a rather risky approach. This paper argues that responsible climate adaptation requires an alternative approach that attempts to assess and manage the resiliency of the flooding system for long-term future change. The aim of such an approach is to keep the system within a configuration of states that gives at least acceptable functioning despite the occurrence of possible changes.

The paper proposes an options planning and assessment process for managing the resiliency of the flooding system to climate change. This process explicitly acknowledges the uncertainty in future climate conditions by introducing and implementing flexibility (real options) into the designed components of the flooding system.

I. INTRODUCTION

The likely changes in climate, even within fairly short timescales, pose both a challenge and an opportunity to decision makers engaged in flood risk management by introducing greater unpredictability in the drivers of future risk, in particular for rainfall extremes (IPCC, 2007). This unpredictability necessitates the acceptance that historic data cannot now provide the means to make probabilistic projections of rainfall extremes for the future. It also involves the acceptance that the uncertainty cannot be entirely reduced by carrying out more climate research. These changes to the presumption of stationary and well-specified design and operational assumptions, which have been fundamental to providing sustainable flood risk management in the past, severely limit the effectiveness of the traditional approaches that have been used.

Traditional approaches attempt to manage the flooding system with the use of predictive/optimisation methods. The predictive/optimisation methods use projections of future change as the starting point (the driver) to identify adaptation strategies, and this is followed by analysing the cause–effect chain using a pressures–state–impact–response framework (Kwadijk et al., in press). It presumes that it is possible to define a singular optimal adaptation strategy according to the ‘most likely’ or average future projection. In reality, the result of such analyses is strongly dependent on the chosen future projection and the assumptions concerning the uncertainties related to these issues. Furthermore, as soon as new knowledge on future change becomes available, the system boundary conditions alter and may lead to other ‘optimal’ decisions on adaptation strategies. As an example related to water management in the Netherlands, one climate scenario was taken as a best estimate and other possible future conditions have been ignored. With this approach, the use of the related predictive/optimisation method is rather risky, because its planning and risk management procedures are typically decoupled from the dynamics and uncertainty of the system – i.e. the climate change drivers.

Rather than taking a traditional approach, responsible climate adaptation requires an alternative approach that attempts to assess and manage the resiliency of the flooding system for long-term future change. The aim of this approach is to keep the system within a configuration of states that give at least acceptable functioning despite the occurrence of possible changes (Walker et al., 2002). This means that the approach acknowledges that projections are ‘always wrong’ and that it is necessary to plan for a range of possible future conditions.

There are number of different definitions of resilience, and each emphasises different aspects (e.g. Brand and Jax, 2007). This paper focuses on the socio-ecological definition of resilience (Folke, 2006). Socio-ecological resilience refers to the system’s ability to maintain or go back to a state of dynamic stability; that is, stability in the face of perturbations and change. There are two aspects to this system ability: robustness and adaptive resilience. Robustness refers to the inherent or antecedent conditions that allow the system to absorb perturbations and change, whereas adaptive resilience refers to the adaptive processes that facilitate the ability of the system to reorganise into a possible adaptation following change.
The general meaning of resilience in this paper is taken from Norris et al. (2008) as the ability or process that links a set of system capacities to the preservation or enhancement of system functioning. This concept recognises implicitly that resilience emerges from a set of system capacities that together provide a strategy to ensure dynamic stability. De Graaf et al. (2009) distinguish between four system capacities: threshold/resistance capacity; coping capacity; recovery capacity; and adaptive capacity.

(a) Threshold/resistance capacity is the capacity to build up a threshold to prevent the risk event. Examples of threshold/resistance capacity measures are building higher and stronger embankments and implementing additional flood storage.

(b) Coping capacity is the capacity to reduce the (negative) effects in case a risk event exceeds the threshold. Examples of coping capacity measures are undertaking damage-reducing measures and the presence of effective emergency and evacuation plans.

(c) Recovery capacity refers to the capacity to recover quickly and effectively from the (negative) effects of a risk event above the threshold. Examples of recovery capacity measures include insurance, disaster funds and the availability of reconstruction plans and effective communication.

(d) Adaptive capacity is the capacity to adjust adaptively to future change. Examples of adaptive capacity measures are building in flexibility and reversibility in infrastructure and making financial and spatial provisions to allow for adaptations.

Vulnerability occurs when the system capacities are not sufficient to maintain required levels of resilience, resulting in persistent malfunction; i.e. when the system cannot meet the imposed acceptable levels of functioning over a longer time period (Norris et al., 2008).

Of the many potential factors and mechanisms that affect resilience this paper focuses on the technical characteristics of the flood risk management infrastructure and the processes for climate adaptation. It addresses two out of the four capacities above: (a) increasing threshold/resistance capacity by upgrading pipes and implementing additional storages; and (b) increasing adaptive capacity by building in flexibility in infrastructure. This selection is based on the presumption that threshold/resistance capacity and adaptive capacity measures are more effective in dealing with future change than coping capacity and recovery capacity measures.

In the paper, section 2 provides a case for the operationalisation of resilience as a process to ensure dynamic stability. The approach uses real options analysis for assessing resilience. In order to test this approach the paper compares two kinds of approaches for adapting the flooding system to climate change: adopting a robust compared with an adaptively resilient approach. The characteristics of these approaches are discussed in section 3. Section 4 provides a five-step procedure for identifying both the least-cost robust system design and adaptively resilient system design. This procedure is then applied to a semihypothetical case study, which is taken from an urban drainage system in Porto Alegre, Brazil. Finally, the results are discussed in view of the use of the procedure and model to investigate different resilience mechanisms and some preliminary conclusions are drawn.

2. OPERATIONALISING RESILIENCE IN THE CONTEXT OF FLOOD RISK MANAGEMENT

For the operationalisation of resilience as a process to ensure dynamic stability it is necessary to specify resilience ‘of what, for what, to what’ (Carpenter et al., 2001) and to identify appropriate resilience indicators for the ability of interest. The ‘of what, for what, to what’ part links the resilience of some specified system attribute, for some specified functioning, and in response to an identified set of perturbations or changes.

This paper focuses on the resilience of the flooding system to gradual changes in extreme rainfall, with respect to its hydraulic functioning. Indicators of resilience describe the ability of the system to maintain or go back to a state of dynamic stability. This is described by relevant boundary conditions in which imposed acceptable levels of functioning are not exceeded. Acceptable functioning of the flooding system is determined by meeting the standard for flood protection despite the occurrence of possible climate changes. This requirement thus includes the need to have a climate-proofed flooding system (Kabat et al., 2005).

From a socio-ecological resilience perspective, the resilient system property is invariant across any of the alternative climate change sequences that define future possible response trajectories. For these climate change sequences it is required that some designed components of the system also change in order to prevent persistent malfunction. The precise response trajectory followed by the system in response to any specified adaptation strategy will be contingent upon the particular climate future that occurs. This means that it is required to construct models of the relationship between the various alternative adaptation strategies and the corresponding system responses to various alternative climate change sequences, in particular including the impact on hydraulic functioning. Brinsmead and Hooker (2005) therefore argue that real options analysis methods, which take account of uncertain contingencies, would be able to inform a quantitative assessment of resilience.

Real options analysis allows the calculation of the net present value of acquiring options that can be exercised in response to a future contingency. That is, of acquiring resilience. To calculate the option value, it is necessary to explore all possible trajectories under which exercising the option is worthwhile. In this sense, a surrogate value for a specified management strategy is given by the (probabilistic expected) net present value of acquiring resilience. The best management strategy is then the most valuable option available under those conditions.

In order to test the proposed approach to operationalising resilience this paper compares the economic effectiveness of two kinds of approaches for dealing with climate change: selecting a robust approach or selecting a more adaptively resilient approach.

3. APPROACHES FOR ADAPTING TO CLIMATE CHANGE

There are two kinds of approaches that are used in practice for adapting the flooding system to climate change: a robust and an adaptively resilient approach. Both approaches acknowledge there is uncertainty regarding the risk events, but these differ in the way the impacts are managed over time. Figure 1(a) and (b) shows the consequential saw-tooth effect in flood probability/risk and associated functioning, as part of taking both a robust
and an adaptively resilient approach. These two approaches have recently been recommended for different aspects of flood management in the UK (Defra, 2006), and it is also used for the long-term strategy for flood protection in the Netherlands (Ministerie van Verkeer en Waterstaat, 2008).

3.1. An adaptively resilient approach

An adaptively resilient approach, also called a managed adaptive approach, allows for adaptation in the future, leading to incremental responses. This approach assumes an iterative process that includes the formulation of acceptable standards, models and plans that are to be monitored and assessed in a semicontinuous learning process. It allows for responses to be reviewed, and further or modified responses to be delivered in the future, as improved information becomes available (Ingham et al., 2007). In this sense, an adaptively resilient approach confers the ability, derived from keeping options open, to adjust adaptively to possible changes without having to predict them with any certainty. This paper argues that an adaptively resilient approach requires a number of complementary mechanisms: both active and passive modes of response, and ongoing, active learning on the part of the decision makers. These mechanisms are summarised in the following sections.

3.1.1. Active modes of response. Active modes of response, by building real options into the physical/technical system (De Neufville, 2003), provide the flexibility to manage future uncertainties by changing the actual design of the physical/technical system as the uncertainty is resolved. Real options originated in the field of finance, but they are applied to physical/technical systems (Myers, 1984). In particular, a real option refers to designed components of a system that provide ‘the right, but not the obligation’ to decision makers to redirect its evolution in a way that either avoids downside consequences or exploits upside opportunities of uncertainty. This means that the economic returns from an option are asymmetric – the greater the uncertainty of the infrastructural project, the greater the value of the opportunity, and the greater incentive to wait and keep options open rather than implement it at once. Real options thus constitute attractive additions to the system design, because they offer the prospect of high gains with low regret. In this sense, building real options into the physical/technical system provides

![Diagram](attachment:image.png)
a buffer against entrapment (Walker, 2000), in which resources can be wasted on inflexible and unadaptable responses.

3.1.2. Passive modes of response. Because of the delay in implementing structural responses, decisions to undertake real options have to be made before the future uncertainty is fully resolved. This means that these decisions may still be affected by future change, in particular when reaction times for adjusting to future change are relatively lengthy, such as for large-scale structural responses (e.g. 10–20 years from initial planning to operation). To protect the system design against this uncertainty it is recommended here that a headroom methodology (Ingham et al., 2007) is taken, which is a form of passive response to uncertainty. Headroom is the excess capacity added on to the ‘design capacity’ to allow for future uncertainties that cannot be resolved at the present time. Introducing this excess capacity into the physical/technical system will help ensure that the acceptable level of flood risk can be achieved. The headroom methodology is thus designed to convert the sources of uncertainties into a headroom allowance in terms of the residual performance available over and above the ‘design performance’. Headroom may be expressed in time units; how long, following the implementation of a response, the performance again becomes unacceptable (Ashley et al., 2008). Note that the belief in ‘optimisation’ of system performance has virtually eliminated the headroom from recently constructed engineering infrastructure, putting at risk the likely widespread failure in the near future of drainage systems designed to specified return periods in accordance with codes of practice and standards (Leeds City Council, 2008).

3.1.3. Ongoing learning. At the core of the adaptively resilient approach is the ongoing (active) learning process. Learning about the future parameters that were uncertain ensures that real options can be implemented at the correct time, so that society obtains full economic value from the physical/technical system. Hence, commitment to ongoing learning is the most important factor influencing economic benefits likely to arise from the proper timing of responses. As with the response modes, learning on the part of decision makers (and others) can be both active and passive. Active learning is when the decision-maker can learn from experience, which involves undertaking experimentation. For example, the decision maker may test a range of different structural and non-structural responses to see what is involved in each option and what the effectiveness is. Such testing supports the possibility for feedback to update and revise the system, thus enhancing adaptive resilience. Observing current climate events to gain better scientific information about future climate evolution is another example of active learning processes. Passive learning is when learning is exogenous to the decision maker’s actions, so that just the passage of time reduces uncertainty. It involves the arrival of new information over time, which allows decision makers to respond to changing risks. Passive learning thus corresponds to reactive adaptation. Note that passive processes are generally inferior (in terms of effectiveness) to active processes in cases in which the decision maker can influence the amount of new information.

3.2. A robust approach
A robust approach, with a one-off intervention, applies to the implementation of adaptation that comprises large-scale responses with high initial capital cost, such as large embankments, increasing the capacity of major sewer pipes, or similar irreversible responses. To respond to future uncertainty, a robust approach must be able to cope with any predicted future. Consequently, this approach will lead to a robust system design, which can deal with the ‘worst-case’ projection of future change. The main risk of adopting a robust approach is only that it may provide significant inertia against future abandonment (due to sunk cost effects, etc.) if the solution later proves to be inadequate or not amenable to future adaption to changing risk.

4. OPTIONS PLANNING AND ASSESSMENT PROCESS
This section provides a brief explanation of an options planning and assessment process that can inform decision making on climate adaptation, although other methods have also been proposed (Ingham et al., 2007; Hall and Harvey, 2009; Harvey et al., 2009; Kwadijk et al., in press). The options planning and assessment builds upon the procedures described by Zhang et al. (2009) and Wang and De Neufville (2004). These divide the process into five phases as shown in Figure 2.

The options planning and assessment process explicitly acknowledges the uncertainty in future climate by introducing and implementing flexibility (real options) into the designed components of the flooding system (when adopting an adaptively resilient approach). There exist different design solutions to embed this flexibility into the flooding system. This implies that cost-effective system design is complex due to the number of design variables and their interactions, coupled with various considerations of technical and real option constraints.

The use of evolutionary optimisation techniques, such as genetic algorithms, offers the potential of identifying both the least cost robust system design and adaptively resilient system design, subject to different requirements. Genetic algorithms can be used to select the set of response options and the rules for their implementation as part of an integrated simultaneous procedure. In this way, evolutionary optimisation allows the delivery of explicit plans for the implementation of responses according to the contingencies that arise, which is termed the contingency plan. The contingency plan is calculated so as to minimise the net present value of life-cycle cost for the system design, while meeting imposed acceptable levels of functioning along all possible sequences of climate change.

Climate change uncertainty is handled in the options planning and assessment process by means of a trinomial tree, which is a time-discrete representation of the climate evolution over a small number of periods. The trinomial tree simplifies the stochastic process that the uncertain climate parameter follows by stating that it can only move up, mid, or down during a period of time leading to a new value of the climate parameter, as shown in Figure 3. Depending on this value, a decision is made to reconfigure the system design to the new information obtained about the climate state. In the process, adaptation decisions are triggered by unacceptable changes in the system functioning.

5. APPLICATION TO A SEMIHYPOTHETICAL CASE STUDY
The options planning and assessment process has been applied to a semihypothetical case study of an existing drainage system in Porto Alegre, Brazil. The drainage network consists of nine
pipes, ten nodes (including five possible storage nodes) and 11
subcatchments (Figure 4).

The objective function involves the identification of the contingency plan to minimise the net present value of life-cycle cost for the system design, while meeting the imposed acceptable level of functioning along all possible sequences of climate change. Acceptable functioning of the flooding system is determined by meeting the standard for flood protection, in this case no surface flooding for a design storm with a 1 in 10-year recurrence interval. This has been selected as illustrative and, in practice, more storm events would need to be investigated, together with time-series rainfall.

The peak intensity for the 10-year storm is some 59 mm/h, for the critical duration of 30 min. However, as a result of climate change effects, there is uncertainty about the peak intensity for future time periods.

Because the arrival of new information about climate change typically requires more than one decade, it is assumed that there are only three time periods of 20 years in which responses can be implemented. A trinomial tree model is used to represent the decision to implement responses in the different time periods. Three time periods in the trinomial tree result in nine sequences of climate change.

For these alternative sequences of climate change it is required that the designed components of the system also change in order to prevent persistent malfunction. Associated with the designed components are the design variables, which define the system configurations. The most important design variables for this application are given in Table 1.

If a robust approach is adopted, the design variables have to be considered fixed over the time horizon. That is, the system design cannot evolve after the initial implementation of a configuration. With an adaptively resilient approach, however, the variables is allowed to vary between practical upper and lower bounds. Table 2 presents the ranges for the different design variables. The ‘step’ in Table 2 corresponds to the increment that is (arbitrarily) used in the analysis.

Whereas calculating the life-cycle costs for the robust system design is straightforward using net present value techniques, the life-cycle cost for the adaptively resilient system design depends on the particular climate future that occurs and the resulting capacity increments. To obtain just one life-cycle cost for the adaptively resilient system design, the expected cost of the set of response options is averaged over all sequences of climate change based on the probabilities derived from the stochastic process (as represented in Table 3). The derivation of the probabilities falls outside the scope of the current paper.

Four life-cycle cost types are identified:

(a) Initial capital cost: this corresponds to the investments to implement the first configuration in the development path. These costs do not include the price of the embedded options, because these have been ignored up to this point.
(b) Operating cost: this comprises the costs of operating, repairing, cleaning and maintaining the configuration.
(c) Damage cost: this relates to the damage costs from flood events and climate change.
(d) Evolution cost: this corresponds to the necessary investments to implement the next step of the development path.

In this example, the operating costs have been considered as zero. The damage costs are set at a very large value, which ensures that configurations that do not meet the standard for flood protection do not get selected in the optimisation. Furthermore, the following cost functions are defined based on Allasia (2002):
Where $K$ is the maximum hydraulic conductivity from Manning’s equation. The Brazilian currency (R$) is used for the cost functions, and all costs are discounted using a discount rate of 6%.

### 5.1. Results

Using the above input parameters, the probabilistic expected net present value of life-cycle costs obtained for adopting an adaptively resilient approach is R$3.55 million. The results for a robust approach give a deterministic net present value of R$3.91 million, based on the worst-case projection of climate change. As such, the difference between the optimal value of the adaptively resilient system design and that of the robust system design amounts to approximately R$0.36 million. In options theory, this is called the flexibility value. For this case study the flexibility value represents more than 9% of the result of the robust approach. Note, however, that the flexibility value is sensitive to the planning horizon and discount rate, as shown in Figure 5.

Besides giving an estimate of the flexibility value, the options planning and assessment process provides the contingency plan associated with taking an adaptively resilient approach. This is illustrated in Table 3 and Figure 6. The contingency plan is to build configuration A1 in the first time period whatever the peak intensity is. Configuration A2 is built in the second period if the peak intensity goes up for period 2, or in the third period if the peak intensity goes midway for period 2 and up further for period 3. In the third period, configuration A3 is built only in case the intensity increases for period 2 and again for period 3.

The key technical characteristics of the different configurations of the adaptively resilient system design are shown in Table 4, along with the technical characteristics of the existing and robust system design.
6. DISCUSSION

The two approaches presented in the semihypothetical case study characterise an adaptively resilient and robust approach for dealing with climate change. The difference between the approaches is apparent in the level at which flexibility is implemented into the options planning and assessment process. Whereas a robust approach will function without any assessment and significant real adjustment of management, the process associated with an adaptively resilient approach is more flexible and open to assessment/learning and feedback and hence necessitates much more engagement by the decision maker. This paper has studied the (economic) potential of passive learning related to the effects of climate change, which is considered to be perhaps the most important mechanism affecting the resiliency of flooding systems. Modelling results suggest that if there is the possibility that adaptation decisions can take account of learning about future climate parameters that were uncertain at the start of the investment process, climate adaptation costs could be reduced by between 5% and 17% compared with when no learning takes place (i.e. taking a robust approach). Such cost savings arise from avoiding potentially irreversible investments that are found subsequently to be needed no longer. Based on these preliminary results, it can be concluded that the promotion and adoption of ongoing learning on the part of decision makers biases climate adaptation policy towards an adaptively resilient rather than a robust approach, by offsetting the consequences of irreversibility, thus also saving money in a different form of optimisation than is currently adopted.

7. CONCLUSION

Along with a number of external drivers, the factors influencing the flooding system have changed fundamentally from a relatively stable, predictable system (quasistationary) with only slowly changing external drivers to an unpredictable system subject to a lack of stationarity (Milly et al., 2008). The traditional paradigm for planning and risk assessment of flooding systems appears to be incapable of credibly addressing unpredictability and non-stationarity in future risk drivers, like climate change. In a non-stationary world, it is rather risky to plan for a single projected future, as was done with the use of traditional approaches. Instead, responsible climate adaptation must acknowledge and act on the full range of uncertainty in climate change projections. When the probability and specifics of a future external driver are difficult to define, the enhancement of system resiliency is a rational adaptation strategy. The aim of such an approach is to keep the system within a configuration of states that gives at least acceptable functioning despite the occurrence of possible changes. The shift to an adaptively resilient approach will require cultural changes in regimes, institutions, decision makers and professional actors. It will also require changes in the planning and risk assessment procedures for the flooding system. This paper has highlighted a specific example of an options planning and assessment process that explicitly acknowledges the uncertainty in future climate by introducing and implementing flexibility (real options) into the designed components of the flooding system. This process can enable decision makers to adapt the physical/technical system to deal with a wide range of possible climate changes. At the same time, it can save costs on adapting to climate change compared with a robust approach.

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Table 4. Technical characteristics of the existing, resilient and robust system design

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