Transient scenarios for robust climate change adaptation illustrated for water management in

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Transient scenarios for robust climate change adaptation illustrated for water management in The Netherlands

M Haasnoot[1,2,6]**, J Schellekens**[1]**, J J Beersma**[3]**, H Middelkoop**[4] **and J C J Kwadijk**[1,5]

[1] Deltares, Delft, The Netherlands
[2] Delft University of Technology, The Netherlands
[3] Royal Netherlands Meteorological Institute (KNMI), The Netherlands
[4] Utrecht University, The Netherlands
[5] Twente University, The Netherlands
[6] Author to whom any correspondence should be addressed.

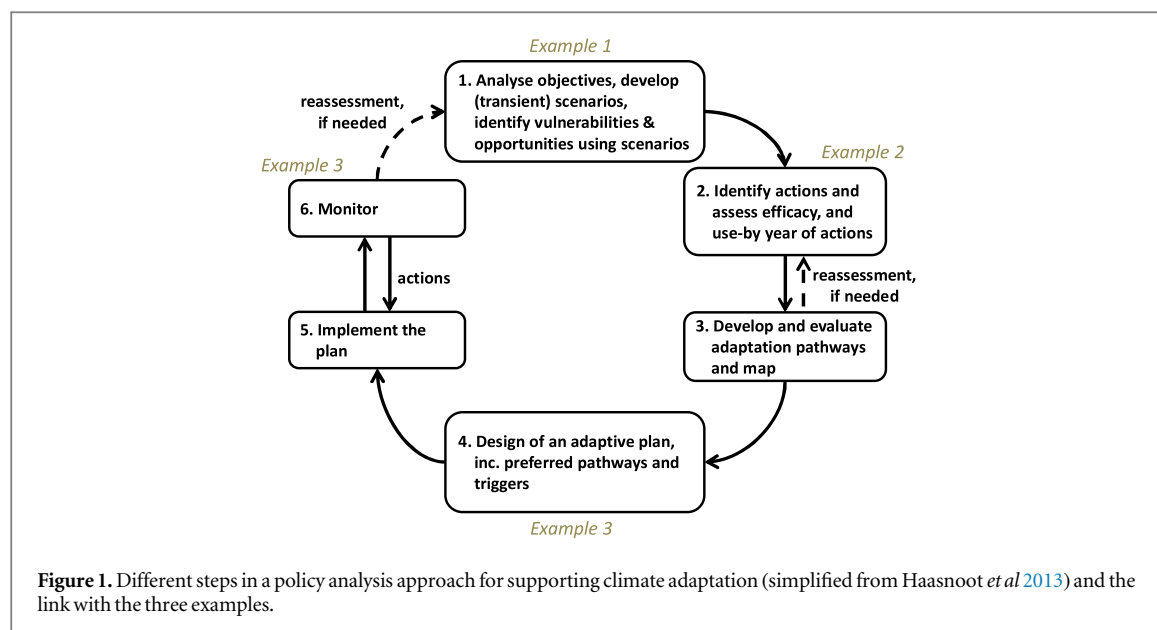**E-mail:** marjolijn.haasnoot@deltares.nl

Abstract

Climate scenarios are used to explore impacts of possible future climates and to assess the robustness of adaptation actions across a range of futures. Time-dependent climate scenarios are commonly used in mitigation studies. However, despite the dynamic nature of adaptation, most scenarios for local or regional decision making on climate adaptation are static 'endpoint' projections. This paper describes the development and use of transient (time-dependent) scenarios by means of a case on water management in the Netherlands. Relevant boundary conditions (sea level, precipitation and evaporation) were constructed by generating an ensemble of synthetic time-series with a rainfall generator and a transient delta change method. Climate change impacted river flows were then generated with a hydrological simulation model for the Rhine basin. The transient scenarios were applied in model simulations and game experiments. We argue that there are at least three important assets of using transient scenarios for supporting robust climate adaptation: (1) *raise awareness* about (a) the implications of climate variability and climate change for decision making and (b) the difficulty of finding proof of climate change in relevant variables for water management; (2) assessment of *when to adapt* by identifying *adaptation tipping points* which can then be used to explore adaptation pathways, and (3) *identification of triggers* for climate adaptation.

1. Introduction

Scenarios are descriptions of alternative hypothetical futures based on coherent and internally consistent assumptions that reflect different perspectives on past, present and future developments (e.g. Van Notten 2005, Lempert 2013, Van Vuuren *et al* 2014). Scenarios are particularly used to explore potential ranges of outcomes due to uncertainties; for example to explore different futures, to assess impacts of changes in boundary conditions, and to identify policy actions and assess their robustness across a range of possible future conditions. Many of such future studies are done to evaluate climate adaptation strategies.

Climate change scenarios combine emission scenarios and resulting climate effects. Since their first use

in the 1980s they have largely evolved. In the first generation of climate change studies, analysts used GCMs to simulate an equilibrium response of the climate system under an increased but constant atmospheric carbon dioxide concentration. The second generation studies performed transient climate change experiments that included dynamics resulting from ocean-atmosphere interactions and more recently, ocean-atmosphere-biosphere interactions. This firstly occurred using linearly increasing GHG concentrations, and later using the SRES emission scenarios (Nakicenovic and Swart 2000) as input to the climate models. The third, recently developed, scenario generation (Moss *et al* 2010) includes shared socio-economic development pathways that describe socio-economic storylines for emissions (Nakicenovic *et al* 2014);

Figure 1. Different steps in a policy analysis approach for supporting climate adaptation (simplified from Haasnoot *et al* 2013) and the link with the three examples.

representative concentration pathways that describe trajectories of GHG concentrations with radiative forcing endpoints (Van Vuuren *et al* 2011); and shared policy assumptions that give mitigation and adaptation actions (Kriegler *et al* 2012). These new scenarios all include the word pathways emphasizing that they explicitly consider the trajectories that are taken over time to reach the future GHG concentrations or radiative forcing (Moss *et al* 2008).
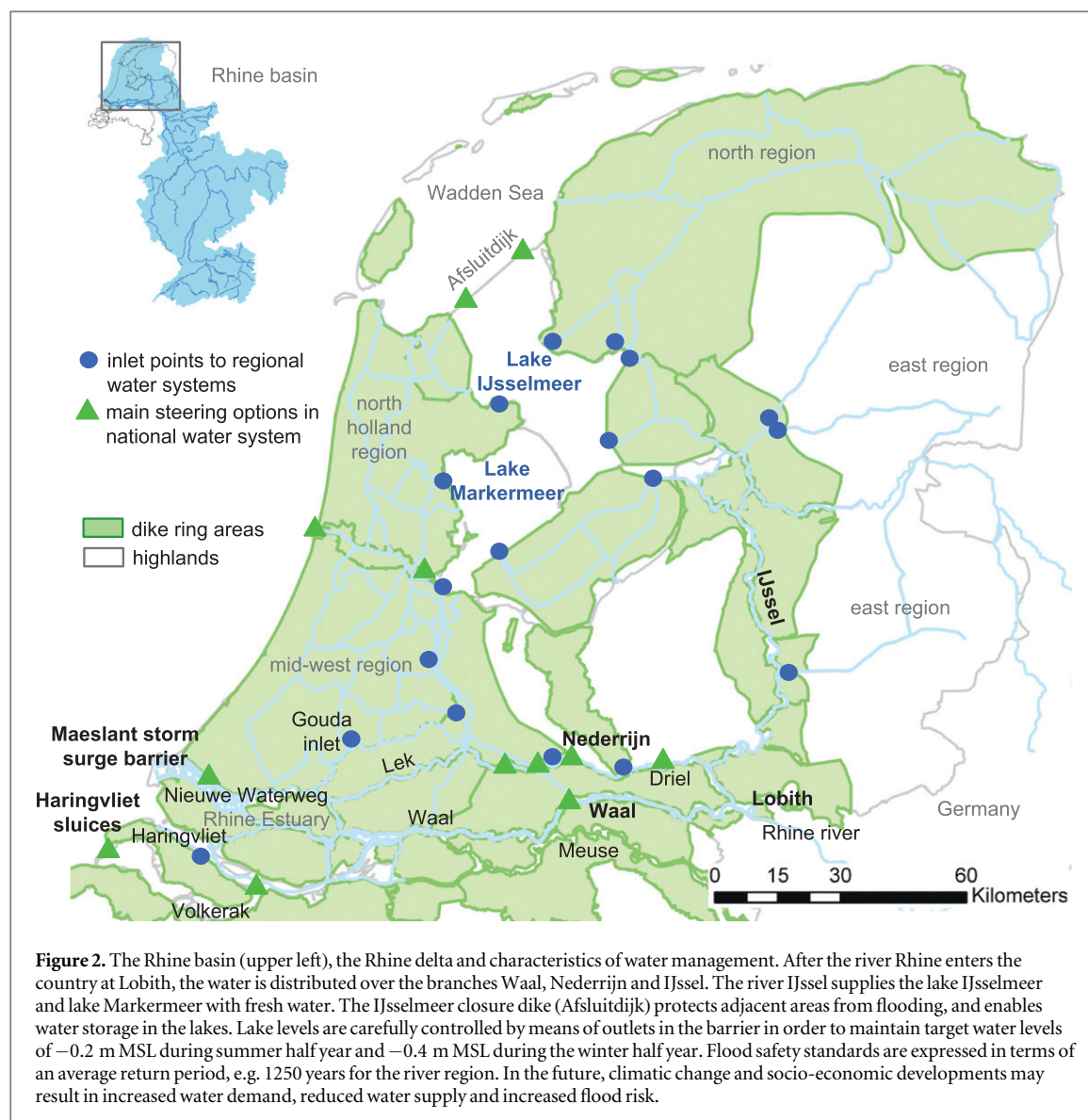
At the global scale climate scenarios thus include time-series that describe both dynamics and interactions within the climate system, as well as mitigation policies over time. Local or regional-scale climate impact assessments or policy studies generally use climate change and socio-economic developments as external—uncontrollable boundary conditions for the assessments. Unlike the global assessments in regional or local studies there is no feedback from the mechanisms occurring within the domain of assessment to these external controls. Moreover, with a few exceptions (e.g Haasnoot *et al* 2012, Groves *et al* 2014), scenarios to support decision making for local or regional climate adaptation are still static in the sense that they describe a future—2050 and/or 2100—end-point situation of climate and socio-economic boundary conditions (see e.g Haasnoot and Middelkoop 2012 for a review). Future climate changes are then often based on incrementally changed baseline climate time-series, and estimates of changes in probabilities or magnitudes of extreme events. The transient pathway of the dynamic interaction between impacts and adaptation from the present day situation into the future is not considered.

In this paper, we argue that transient (i.e. time-dependent) scenarios are valuable for local or regional climate adaptation assessment, and describe three possible assets of using transient scenarios in decision making on climate adaptation. Transient scenarios for

climate adaptation describe developments over time that cannot be influenced by the actor(s) under consideration. The use of transient scenarios fits well with the increasing interest to explore sequences of (portfolio of) actions—adaptation pathways—to develop an adaptive plan under conditions of severe uncertainties (Haasnoot *et al* 2012, Ranger *et al* 2013, Barnett *et al* 2014, Rosenzweig and Solecki 2014, Wise *et al* 2014). In this study, transient scenarios describing the relevant boundary conditions for a case on water management in the Netherlands were developed. We focus on long-term (50 to 100 years) water management since this is an important policy domain in climate change adaptation, and can inspire other domains that need to adapt as well. We demonstrate how these transient scenarios can be used for (1) *awareness raising* about climate (change) uncertainties, (2) *assessment of when to adapt*, and (3) identification of *triggers for climate adaptation*. This paper first describes the approach for developing transient scenarios, presents their application in three examples, and concludes with thoughts on the added value of using transient scenarios for supporting climate adaptation decision making.

2. Method

Experiments were setup for three examples illustrating the potential use of transient scenarios in climate adaptation decision making. The examples are related to different steps of a policy analysis, such as the dynamic adaptive policy pathways approach (DAPP Haasnoot *et al* 2013, figure 1). Transient scenarios are developed in step 1 and are firstly used for raising awareness of the implications of uncertainties in climate change and climate variability for decision making, the difficulty of detecting climate change

Figure 2. The Rhine basin (upper left), the Rhine delta and characteristics of water management. After the river Rhine enters the country at Lobith, the water is distributed over the branches Waal, Nederrijn and IJssel. The river IJssel supplies the lake IJsselmeer and lake Markermeer with fresh water. The IJsselmeer closure dike (Afsluitdijk) protects adjacent areas from flooding, and enables water storage in the lakes. Lake levels are carefully controlled by means of outlets in the barrier in order to maintain target water levels of −0.2 m MSL during summer half year and −0.4 m MSL during the winter half year. Flood safety standards are expressed in terms of an average return period, e.g. 1250 years for the river region. In the future, climatic change and socio-economic developments may result in increased water demand, reduced water supply and increased flood risk.

trends in extreme values, and consequently the need for an adaptive plan to manage uncertainties about the future (example 1). In step 2, the transient scenarios are used to identify the moments of adaptation tipping points (ATPs) (use-by years) of the status quo and possible adaptation actions (example 2). Based on this, potential pathways—sequences of adaptation actions—can be constructed, evaluated and presented in a pathways map (see Haasnoot *et al* 2013 for an example; step 3), and subsequently one or more preferred pathways can be selected as input for an adaptive plan that includes short term actions to do the necessary short term adaptations and to prepare to keep options open to further adapt in the future if needed. In step 4, signposts variables and related trigger values are identified for these transient scenarios (example 3). These early warning signals can help water managers to decide when to start implementing (next) actions of an adaptation pathway or when reassessment of the adaptive plan is needed (step 6).

The experiments were applied to the lower Rhine delta in the Netherlands (figure 2) and to a (fictitious) highly stylized river reach based on this delta. Experiments were carried out in consultation with a range of different groups, varying from graduate students to professional water managers. At that moment these water managers were working on the Delta Programme, a nation-wide study to prepare the Netherlands for climate change and sea level rise, taking into account socio-economic developments as well. The transient scenarios were used as input for integrated assessment metamodels (IAMM), one for the highly stylized river reach (Haasnoot *et al* 2012), and one representing the entire lower Rhine delta (Haasnoot *et al* 2014).

2.1. Transient climate change scenarios
The applied transient climate change scenarios consist of daily time-series of the period 2001–2100 for three relevant boundary conditions of the Rhine delta: (1)

the Rhine discharge at Lobith, (2) precipitation and (potential) evaporation for six regions in the Netherlands and (3) sea levels at two key locations along the Dutch coast.

To construct the time-series daily weather information on temperature, precipitation and evaporation, and sea water levels for 1961 to 1995 were used as reference period (Rhine are derived from the so called CHR-OBS data, see Görgen *et al* 2010; sea level at Dutch coast: https://www.watergegevens.rws.nl/; Dutch stations: www.knmi.nl). Using the 1961–1995 reference period two synthetic time-series of 1000 years of daily temperature and precipitation were generated for the Rhine basin (figure 2, top-left) with a rainfall generator specifically developed for this basin[7] (Beersma 2002). The same (resampled) 1000 year sequences of historical dates were used to get daily time-series of precipitation and evaporation in the Netherlands that are consistent with those for the Rhine basin. The two 1000 year time-series were split into time-series of 100 years, resulting in an ensemble of 20 members. These 20 members are equally plausible and only differ as a result of natural climate variability. They serve as the baseline for an ensemble of transient time series in which all members have the same climate forcing but in which the members differ again as a result of natural variability. In this way we derived 60 transient precipitation and temperature time-series (20 for the no climate change scenario, 20 for the G scenario and 20 for the W+ scenario).

Transient climate change scenarios were constructed by gradually transforming each ensemble member according to two so-called KNMI'06 climate change scenarios of the Royal Netherlands Meteorological Institute; a moderately warm scenario with a temperature rise of 1 °C in 2100 and a warm scenario with a rise of 2 °C (respectively denoted as G and W+; Van den Hurk *et al* 2007). The KNMI'06 scenarios represent an equilibrium and thus stationary climate for two projection 'years' (being 2050 and 2100). The monthly changes for these scenarios were used to adapt the synthetic 100 year sequences according to a classical delta-method (see e.g Lenderink *et al* 2007, Te Linde 2007), in which each daily value of the time-series is perturbed with the scenario-dependent change for that specific calendar month. To make these perturbed time-series transient for the period 2001 to 2100, the transformation coefficients for 2050 were linearly scaled between 2001 and 2100.

Each time-series was were used as input for a river basin model HBV (Bergström and Forsman, 1973,

Lindström *et al* 1997) for the Rhine basin[8] upstream of Lobith (Berglöv *et al* 2009) yielding transient climate impacted daily river flows for the Rhine at Lobith (figure 2). Figure 3 shows the yearly discharge maxima of four of these transient scenarios. Note that, for the experiments in example 1 the ensemble of transient time-series of the river discharges was constructed slightly differently: first equilibrium discharge time-series for each equilibrium climate change scenario were simulated with the HBV model (Te Linde *et al* 2010) and in a second step these equilibrium discharge time-series were made transient by applying a classical delta method to the discharge time-series and again linearly interpolating the monthly deltas (Haasnoot *et al* 2012).

Sea level time-series along the Dutch coast were obtained through a (balanced) bootstrap technique (Efron and Tibshirani 1994). By sampling with replacement complete years from the 35 yr reference period, ten 100 yr series were constructed in which the day-to-day persistence is essentially preserved. These time-series were transformed into transient sea level time-series both for the upper and lower estimate of the sea level rise for each of the two selected KNMI'06 climate scenarios. To account for nonlinearity as a result of accelerated sea level rise as described in the KNMI'06 scenarios, sea level was increased linearly between 2001 and 2050 and between 2051 and 2100, with a higher rate in the latter period.
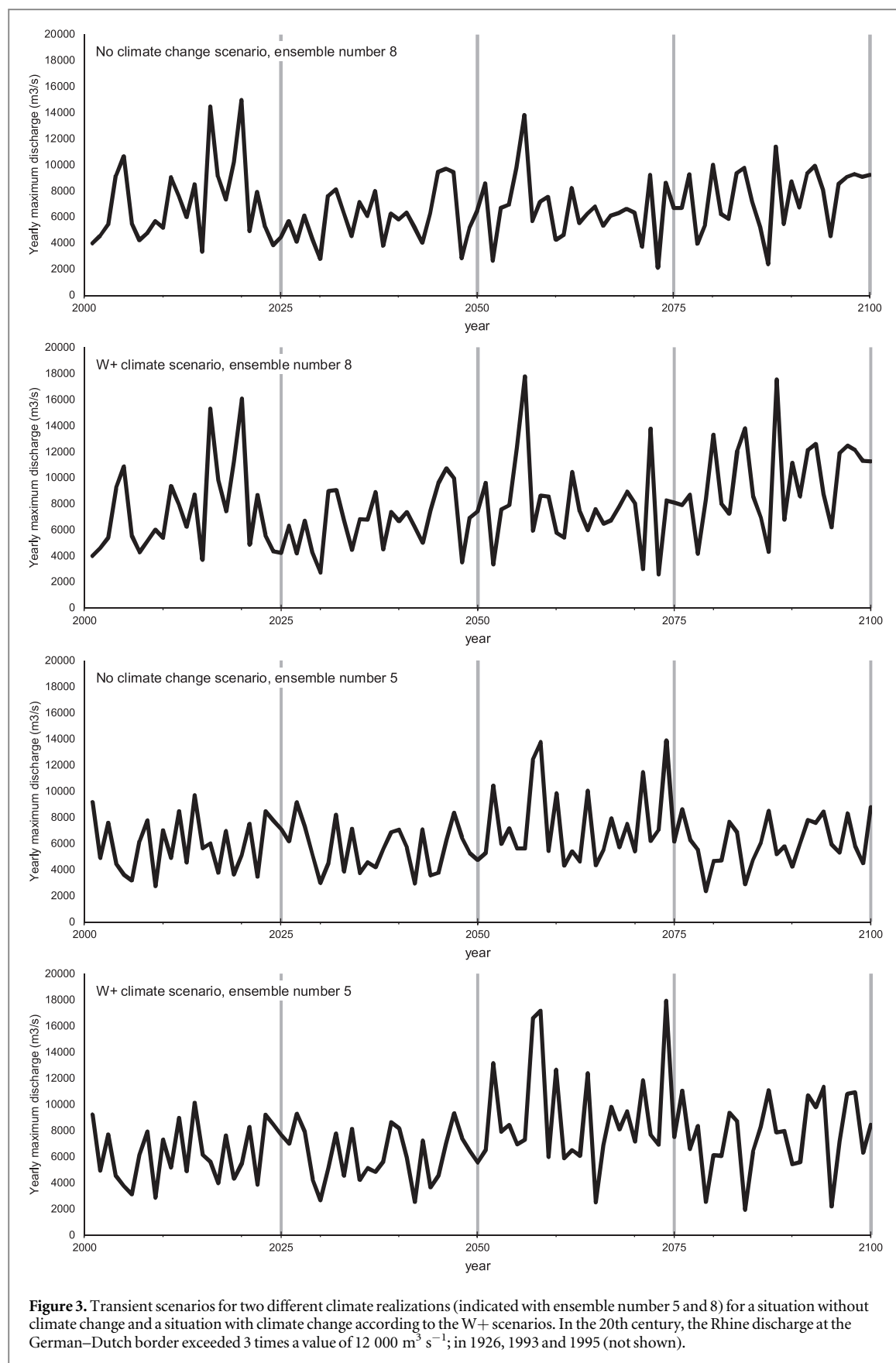
Appendix A describes which (combinations of) transient scenarios are used in the experiments.

2.2. Three examples on using transient scenarios in climate adaptation decision making

Table 1 presents the characteristics of the three examples. The results are presented in the next section. In example 1 the scenario ensemble for the Rhine river discharge was used. Two types of experiments were done in this example. First, participants were informed on historical extreme discharge events and possible future climates that may result in more extreme low and high flows. Then, they were shown a 100 year ensemble member in subsequent 25 year periods (2001–2025; 2001–2050 etc). For this experiment, we selected four time-series that differ in climate variability (one with peaks in the beginning and one with no peaks in the first 50 years) and climate change (a lower and an upper estimate). Appendix B presents the selected time-series in combination with the other ensemble members. After each period, participants were asked whether or not they would take flood risk actions. A second experiment was done with the simulation game Sustainable Delta (Deltares, online

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[7] The rainfall generator for the Rhine basin makes use of time-series resampling (more specifically nearest-neighbour resampling) of daily meteorological data. For the time-series generated with this version of the rainfall generator for the Rhine basin (Beersma 2002) the precipitation and temperature data from 1961 to 1995 serves as the reference period.

[8] Actually there is not a single precipitation and temperature time-series for the whole Rhine basin but there are 134 of such time-series representing the 134 subbasins of the HBV model for the Rhine. All of these 134 time-series are transient, representing 2001–2100 and constructed in the way described in the main text.

Figure 3. Transient scenarios for two different climate realizations (indicated with ensemble number 5 and 8) for a situation without climate change and a situation with climate change according to the W+ scenarios. In the 20th century, the Rhine discharge at the German–Dutch border exceeded 3 times a value of 12 000 m^3 s^{-1}; in 1926, 1993 and 1995 (not shown).

Valkering *et al* 2012). In this game a group of participants had the assignment to develop a water management plan for the fictitious river stretch. As the future unfolded stepwise, the participants experienced

changing boundary conditions and impacts in the delta (e.g., floods, droughts, socio-economic development) as a result of one of the transient scenarios, while they did not know whether or not it was driven

Table 1. Overview of the examples and their characteristics.

	Example 1	Example 2	Example 3
Purpose of the example	Awareness raising about the implication of climate change and climate variability for decision making and the difficulty of detecting climate change trends.	Assessing when to adapt to climate change.	Identification of triggers for climate adaptation in order to monitor when the next action of an adaptation pathway needs to be implemented.
Approach	Workshop setting: (a) Asking questions about response after showing a river discharge time-series for Rhine, (b) Playing a serious game wherein participants need to make a water management plan for stylized river branch.	Model-based performance over time of status quo and promising policy actions is used to identify moments of adaptation tipping points for all transient scenarios. This results in a range of the use-by years of the status quo and of adaptation actions.	Time-series analysis. Possible trigger values for river discharge were applied to each ensemble member to assess when their value would be outside the range of the baseline members without climate change.
Transient scenarios	Ensemble of 10 realizations for each climate (change) scenario for river discharge for the period 2001–2100. Rainfall generator (RG) for the Rhine basin (Beersma 2002; time-series number 1.7) input for the river basin model. The time series of river discharges made transient by linear scaling in time.	Ensemble of 10 realizations for each climate (change) scenario for river discharge, precipitation and evaporation and 20 realizations for sea level rise (10 for the lower and 10 for the upper estimate). All realizations cover 2001–2100. Transient scenarios constructed by linear perturbation of RG time-series number 1.7 used as input for the river basin model to generate the transient changing river discharges, and bootstrapping sea levels for the same reference period as used in the RG. Transient linear perturbation synthetic sea level series.	River discharge ensemble of 20 100-year realizations for each climate (change) scenario (RG time-series number 1.7 and 1.9 were used). Developed in the same way as in example 2.
Models used	RG for the Rhine basin, Integrated Assessment Meta Model (IAMM) for the stylized river.	RG and river basin model for the Rhine basin, IAMM for the Rhine delta.	RG and river basin model for the Rhine basin.
Participants	Students, water professionals, water policy makers	Policy analysts of the Dutch Delta Programme	Policy analysts of the Dutch Delta Programme
Policy analysis part	Scoping phase. Awareness raising on the need for an adaptive plan for dealing with uncertainties about the future.	Identifying and screening of promising adaptation actions and pathways.	Identification of triggers to include in a monitoring section of an adaptive plan.

by an underlying changing climate. Based on their experience and societal responses, participants decided whether or not to implement adaptation actions. The IAM model for stylized river (Haasnoot *et al* 2012) returned direct feedback to the participants on the impacts of the transient scenario and their policy actions.

For the second example, impacts of transient scenarios were assessed to identify whether or not and when adaptation is needed in the Rhine delta using the IAM model for the Rhine delta (Haasnoot *et al* 2014) that was driven by all climate related boundary conditions. The performance of the reference case (which assumes no adaptation) was evaluated for different scenarios against a-priori specified objectives. When a mismatch arises between the objectives and the time-dependent performance, an adaptation tipping point (ATP Kwadijk *et al* 2010) occurs and new actions are needed to achieve objectives again. This analysis

yielded for each ensemble member a moment that an ATP occurs, i.e. the 'use-by' year of the status quo depending on how the future unfolds. Taking into account a lead time for implementation of action(s), decision makers can assess when they need to adapt. Likewise, after implementation of actions a new ATP might occur after a period of time. Therefore, similar assessments were done for a range of adaptation actions.

The third example addresses the identification of early warning signals for adaptation. Here, the river discharge was used as a signpost, i.e.—the information that one needs to monitor to assess the need for adaptation (Dewar *et al* 1993, Walker *et al* 2001). We then searched for threshold values for this signpost (referred to as triggers Walker *et al* 2001). Comparing observed values of signposts with their pre-specified trigger-values, enables one to decide whether adaptation decisions need to be taken (Hermans *et al* 2014).

Although climate change can best be monitored early in the impact chain, for example by measuring temperature change, in practice adaptation actions are generally based on the (potential) impacts later in the impact chain that are closer to objectives, such as impacts potential casualties, flood damage, and loss of habitats. In the Rhine delta, the river discharge is a signpost that is closely related to water management objectives. Different trigger values, frequencies of occurrence and time slices were investigated and evaluated. A signal is given if the value for the scenario realization is outside the range obtained from the realizations without climate change. Ideally, a trigger value gives a justified and reliable signal for adaptation as soon and clearly as possible without false positive alarms.

3. Results of three example applications on long-term water management in the Netherlands

3.1. Example 1: raising awareness

The third transient scenario in figure 3 was shown step by step to the participants. After showing the period until 2025 and also after extending it to 2050, almost all participants responded that they would not take actions. After extending it to the year 2075 all participants responded that they would take action(s) immediately, as two peak discharges occurred. At some occasions, participants identified a trend in the river discharges that was attributed to climate change (between 2040 and 2060). After showing the entire time-series participants were surprised—even disappointed—not to see any peak discharges in the last period. Some participants then concluded that they had invested in adaptation too late (i.e. after the peak flows) and/or mis-invested as the damage already had occurred.

Next, the first 50 years of all four transient scenarios were shown to discuss the influence of climate variability and climate change on implications for decision-making. The first two time-series present (in 2016 and 2020) a similar situation to the major peak flows that subsequently occurred in the Netherlands in 1993 and 1995, triggering large-scale evacuation. Such a situation might offer a window of opportunity to implement rigorous anticipatory measures for a future where climate change may result in a larger occurrence of such events. However, events might occur at any time, as shown by the entire ensemble. All realizations are equally likely; 'early warning' peak discharge events might not occur before a major event takes place, while conversely, extreme peak events might not do so in the second half of the century. Such sequential issues are independent from a change in underlying climate. Accordingly, different adaptation pathways arose for the graphs shown in figure 3. Without extreme events the sense of urgency for adaptation

may disappear. However, when peak discharges occur the impacts may be high. The time-series in figure 3 also show that for the nearby period the differences between the realizations with and without climate change are remarkably small: only on the long term the differences become visible (for the W+ scenario). Moreover, the first 50 years of the time-series at the bottom demonstrate that it is possible that climate change is happening, but that we do not see this in the occurring discharges.

In the experiments with the simulation game, the transient scenarios presented in figure 3 were played many times (>50 times). Although all sessions evolved quite differently due to the various backgrounds of the players and differences in negotiation results during the game, we did see some general steps in how the future unrolled in the game sessions. In most sessions with the transient scenario W+ ensemble member 8 (the second in figure 3) moderate actions were taken at time zero as the participants realized something needed to be done. Still, actions were limited to avoid spending too much money and due to the large variety in preferences for certain actions; the more far-reaching actions failed to get support for implementation during negotiations between the participants. At the next evaluation moment—after simulation of the first 20 years with the actions implemented—two peak discharges that caused flooding had occurred. Participants were then—surprised by these events—willing to implement major flood reduction measures. In the following simulation periods no flood events occurred; sometimes drought damage occurred as taken measures primarily targeted at flood reduction. Although participants then were satisfied about their actions, once we showed the discharges of other transient time-series they realized that they might have been lucky that in their realization no further major peak event had occurred.

In both experiments, despite the intention to act pro-actively and to anticipate on the future, adaptation actions were often determined *in response* to extreme events. Remarkably, even water policy professionals tended to respond reactively instead of proactively. For example, in a session with policy analysts involved in the Dutch Delta Programme, participants were confronted with W+ ensemble number 5 (fourth series in figure 3). After two periods of 25 years, without any severe impacts of flooding, one of the participants stated that nothing was happening, concluding that no measures needed to be taken. They were subsequently surprised by the two peak events in the period of 2055–2060, and then started to take rigorous measures. Some of the participants became quite frustrated by this scenario, even though it contained a plausible combination of a longer period without major events followed by events that well fall within the current design standards. Participants were often focused on the peak discharges, as these result in the most severe impacts in this case and they tended have
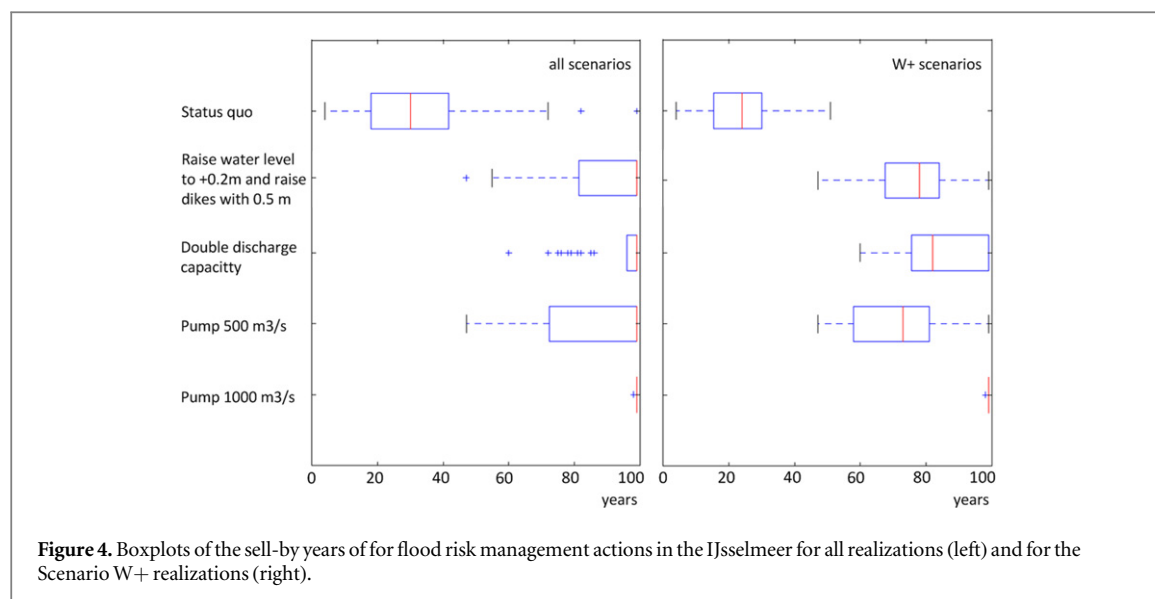
Figure 4. Boxplots of the sell-by years of for flood risk management actions in the IJsselmeer for all realizations (left) and for the Scenario W+ realizations (right).

less eye for the impacts of low flows. Only if they were satisfied about flood risk, focus was shifting towards drought risk management and impacts on nature.

These sessions raised the awareness that people—including water managers—tend to try to identify trends in the single transient scenario that they experience during a thought experiment—and what they will experience in the future. The occurrence of extreme peak flow events during a session was often seen an indicator that climate is changing, or in the evaluation after the game session the used discharge series was thought to be a realization with climate change. However, maximum yearly discharge is highly variable, as is natural climate variability and thus difficult for detecting trends, especially in a single realization. In contrast, the occurrence of low flow periods is less variable, and would be a better indicator of an underlying changing climate. However, due to peoples focus on floods, this indicator is generally overlooked.

With these experiments participants became aware that both climate change and climate variability are relevant for decision making. The willingness to take measures was remarkably driven by the occurrence of floods, and resulted in a responsive instead of anticipatory strategy. Also, participants were unable to see whether the transient scenario was with or without climate change, which they attempted to detect from the evolving time-series of river discharge, and in particular from the extremes.

3.2. Example 2: assessing when to adapt with ATPs

Here, we illustrate the use of transient scenarios for identifying when to adapt for flood risk management in the Lake IJsselmeer in the Rhine delta. For this example the transient scenarios for sea level, precipitation and evaporation and river discharge were applied. The water levels in the Lake IJsselmeer are regulated to maintain summer and winter target levels by draining under gravity through the IJsselmeer closure dike

(Afsluitdijk) into the Wadden Sea. As a result of climate change and sea level rise, it may be more difficult to maintain target water levels in winter and thus to ensure safety against flooding. Sea level rise will limit the period to drain water to the Wadden Sea under gravity during low tides and more precipitation in winter will increase the inflow of water both directly and through the Rhine river into the lake. Two main alternatives for flood risk management are available: (1) maintaining the current target water levels through additional gravitational discharge capacity or pump capacity, or (2) increase water levels to enable continuation drainage by gravity. Allowing the target water level to rise to +0.2 m MSL in winter would sustain lake drainage under gravity, but should be combined with an increase of the heights of the embankments along IJsselmeer. An ATP for the flood risk policy in the IJsselmeer is assumed to occur when a large event (which increases the lake level to more than 0.3 m MSL, causing flooding of surrounding areas) occurs, or when three small events (minor lake level increase to 0.1 m–0.3 m MSL), occur consecutively within a few years.

The timing of the ATPs (i.e. the use-by years) for all ensemble members of the reference, G and W+ scenarios were identified using modelling results.

Figure 4 shows boxplots of use-by years of the status quo and various adaptation actions for all 50 transient realizations and for the W+ climate change ensemble. For some actions the time span of the sell-by date is large, while for others there is little difference between the scenarios. The current situation without any adaptation actions reaches an ATP after ~55 years (median) in the transient scenarios without climate change, after ~30 years in Scenario G and after ~25 years in Scenario W+. This gives an indication on when adaptation is needed. Doubling the gravitational discharge capacity delays an ATP in most of the realizations, but not for many of the W+ realizations

(median ~80 years) or for several outliers in the realizations without climate change (earliest after 60 years). Additional pumping capacity of 500 m^3 s^{-1} is not sufficient to prevent outliers which may result in an ATP after ~55 years at earliest. A risk aversive policy maker could implement a pumping station with a higher capacity (e.g., 1000 m^3 s^{-1}); in that case water levels will rarely exceed the threshold value for the tipping point, even in the W+ scenario with the largest sea level rise. Allowing the target water level to rise to +0.2 m MSL in winter and increase the levee heights for example by 0.5 m, an ATP is reached after ~80 years in W+ (median value for all realizations). Based on the ATP's an adaptation pathways map was generated for flood risk management in the IJsselmeer (figure 45 in Haasnoot 2013).

3.3. Example 3: identification of triggers for climate adaptation

In this example the transient scenarios were used to evaluate trigger values for the river discharge on their performance as 'early warning' signal (as a signpost) that climate change is affecting river discharge and that adaptation is needed. Using twenty transient realizations for river discharge for each climate scenario we explored various types of triggers, such as threshold values, mean values and return flows.

The timing of the signal for the evaluated trigger values is given in table 2. Figures 5 and 7 present the results over time. For some triggers the bandwidth is very large illustrating the large influence of climate variability. For example, the 1:10 year discharge has a large variability and varies thus largely between the different ensemble members for the same climate change and also within one ensemble member. For the number of days that the discharge is below 1200 m^3 s^{-1} the natural variability is much less apparent. The values for the G scenario do not deviate enough from the ensemble for the current climate to detect a climate-induced change in river flow. Only for the number of days the Drought Committee will be active some deviation is shown for the G scenario, but not enough to get a clear signal for climate adaptation. The values for the average discharge in the summer half year and the discharge deficit deviate well from the values for the ensemble for the current climate. These trigger values may thus be good indicators for the need of climate adaptation.

In reality, we will experience only a single future (comparable to one ensemble member in our study). Therefore, it is useful to know the spread of the timing of the signal and also whether there may be false warnings. To quantify the signal's timing and to get an idea of the chance a trigger value will timely give a signal, the number of ensemble members that are outside the range of the ensemble of the current climate was calculated (table 2, figure 6). In correspondence with the above, the trigger values do not give a signal in many of the ensemble members of the G scenario. For the W+ scenario, figure 6 shows that in general farther away into the future and hence with increasing climate change, more ensemble members give a signal. The average discharge for the summer half year seems the best trigger with respect to sharpness and reliability. Already around 2024 half of the ensemble members are outside the reference range and would thus give a signal. This will be in time to take decisions on the next actions in the adaptation pathways as it is well before the ATP as described by the Dutch Delta Programme (Delta Programme 2015). The 1:10 year low flow varies greatly and is neither sharp nor reliable and may confuse decision makers in the sense that they get a signal and later this signal is gone. The number of days the Drought committee will be active has a stable signal but the signal manifests itself much later than the average discharge during the summer half year.

The triggers values for high flows (figures 7 and 8) do not show a clear signal despite a clear trend of the ensemble mean. Even the average value for the wet season does not appear to be a good trigger. Only the number of days the flow is above 6000 m^3 s^{-1} gives a signal in a lot of ensemble members, but triggers very late in the century and probably too late to adapt.

4. Discussion

Recently Hall *et al* (2014), recommended combining two traditional approaches for knowledge on flood regime changes: (1) data-based detection of changes in observed flood events and (2) scenarios and modelling. Using transient scenarios to identify adaptation signals as described is this paper is an example of such a combination.

Transient scenarios allow for taking into account both climate variability and change which is important for assessing the implications of dynamic interactions between impacts and policy response and thus for adaptation decision making over time. Transient scenarios are thus a prerequisite for assessing path-dependency of decisions. The example experiments allowed for including this interaction, and demonstrated the difficulty of taking anticipatory measures if extreme discharges do not occur—as a consequence of natural variability. Even managers who by profession are responsible for long-term management strategies tended to act responsive. By exploring many realizations with policy makers the awareness has raised that the future should be considered as one member out of a potential ensemble: as we do not know which member will occur, we have to explore and prepare for the entire ensemble.
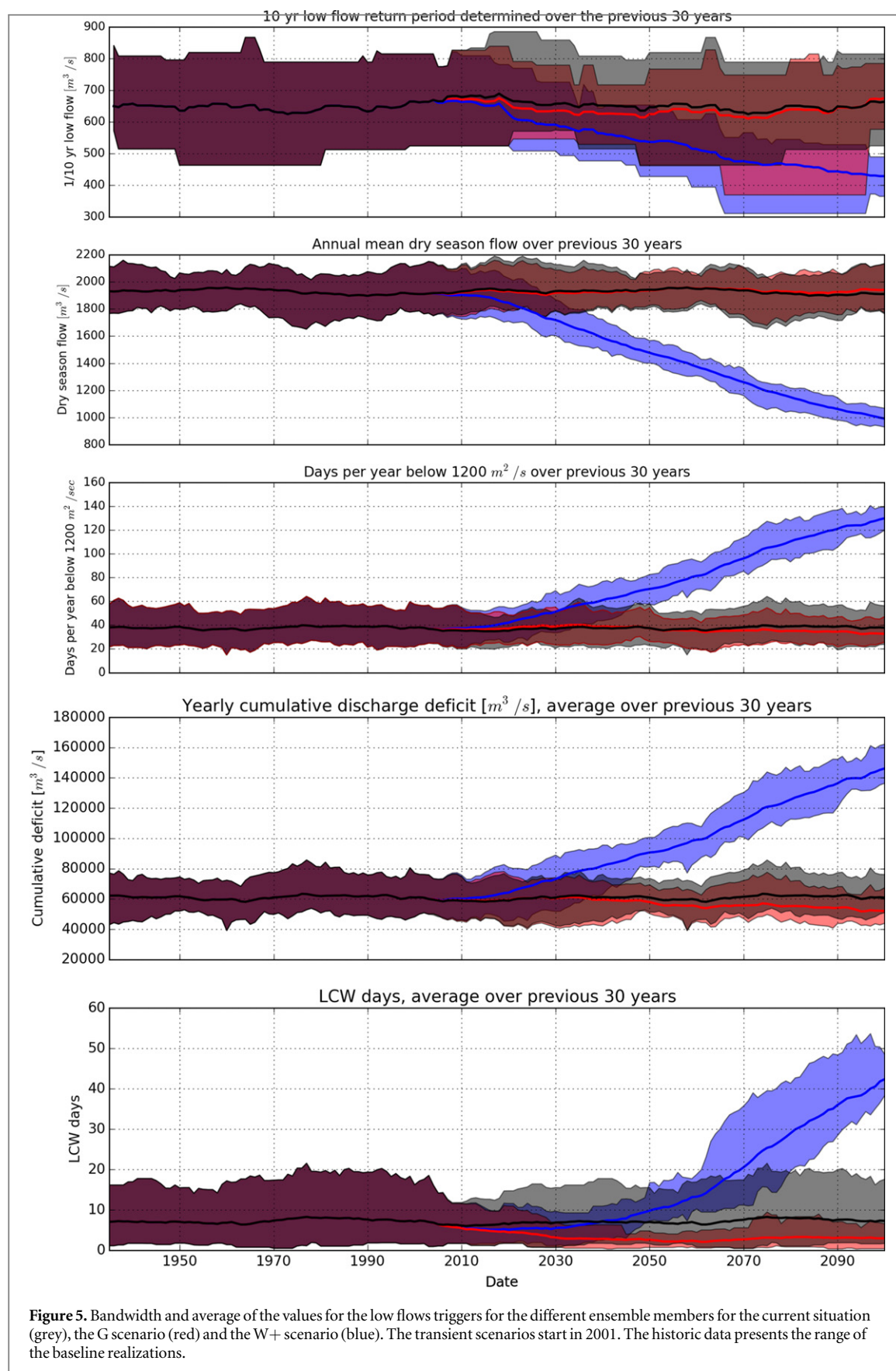
Exploration of the role of climate variation and climate change thus requires ensembles of scenarios with dynamic interaction between the physical river system and water management adapting the system during a simulation. Because long model computing times are undesirable in these interactive applications, fast

Table 2. Signposts and trigger values for low flows and high flows. Performance is related to when the signposts give a signal that climate change may have an impact on the river discharge. Earliest is defined as the year that one realization is outside the range of the baseline (no climate change) realizations, average the year that 50% of the realizations are outside the range and latest the year that all realizations are outside the range.

Signpost river discharges	Trigger values for Low flows	Signal G scenario Earliest/average/latest	Signal W+ scenario Earliest/average/latest	Trigger values for High flows	Signal G scenario Earliest/average/latest	Signal W+ scenario Earliest/average/latest
Threshold value	# days below 1200 m^3 s^{-1}	2014/-/-	2003/2029/2050	# days above 6000 m^3 s^{-1}	2003/2088/-	2003/2043/-
Mean value	Mean in dry season (July–October)	2003/-/-	2003/2024/2036	Mean in wet season (December –March)	2030/-/-	2030/-/-
Return flow past 30 years	1/10 year low flow	2019/-/-	2020/2078/2096	1/10 year peak flow	2017/-/-	2016/2050/-
Discharge deficit[a]	Sum of difference 1800 m^3 s^{-1}	2003/-/-	2005/2029/2046	N.A.	N.A.	N.A
Committee active[b]	# times Drought Committee will be active	-/-/-	2049/2065/2079	N.A.	N.A.	N.A

[a] Discharge deficit = difference between a threshold value (1800 m^3 s^{-1} at Lobith) and the average discharge in a 10 day period summed for the whole year if the discharge is below that threshold (instead of summer half year that has been used by (Beersma *et al* 2004).
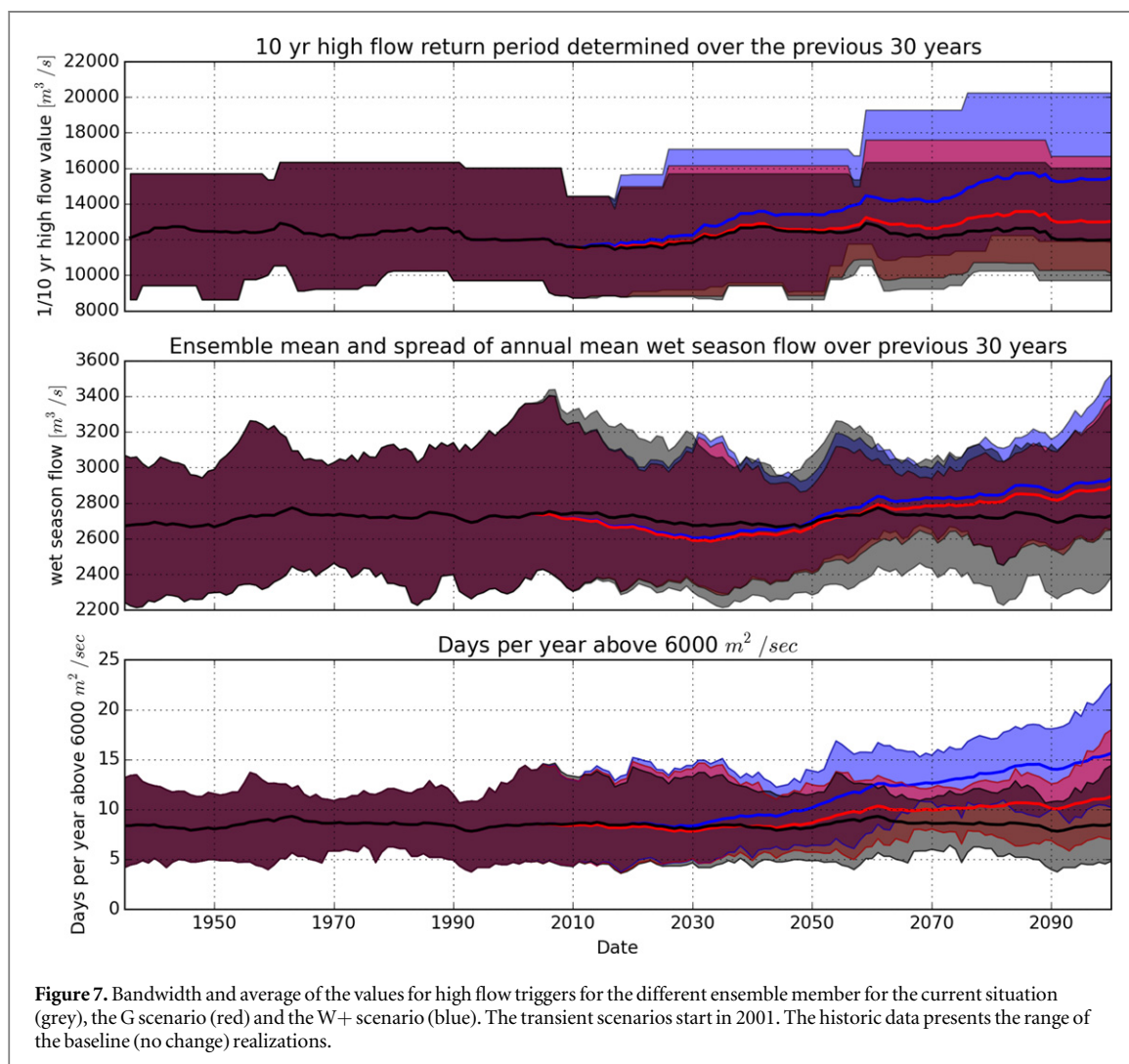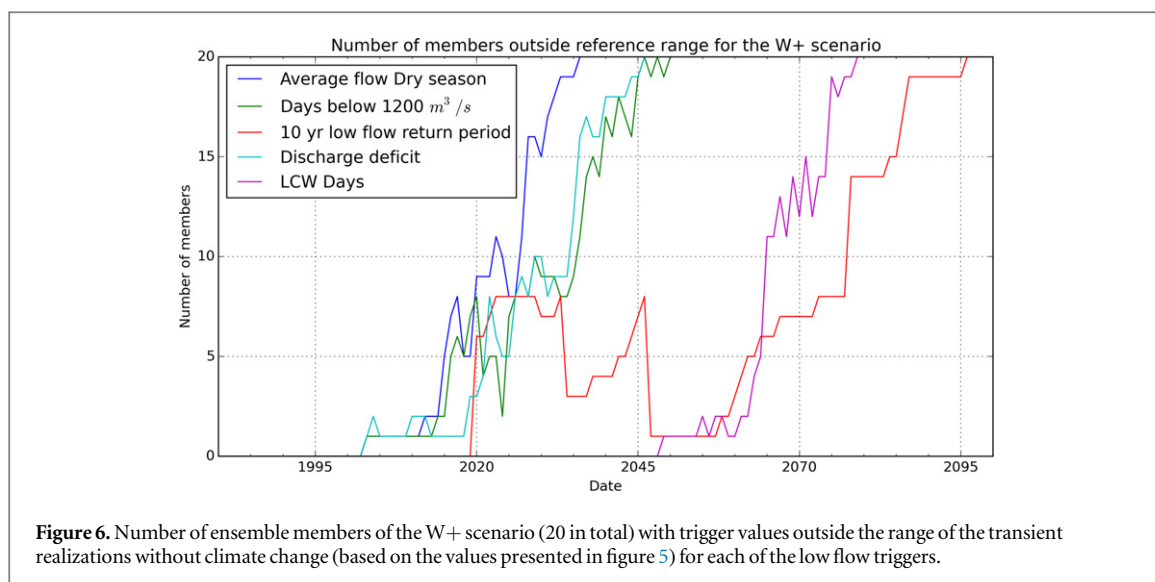
[b] In the Netherlands the Drought committee is active to advice on water management actions if the river discharge is lower than 1400 m^3 s^{-1} in May, 1300 m^3 s^{-1} in June, 1200 m^3 s^{-1} in July, 1100 m^3 s^{-1} in August, 1000 m^3 s^{-1} in the other months (LCW 2012).

Figure 5. Bandwidth and average of the values for the low flows triggers for the different ensemble members for the current situation (grey), the G scenario (red) and the W+ scenario (blue). The transient scenarios start in 2001. The historic data presents the range of the baseline realizations.

integrated meta-models are becoming increasingly adequate tools for this purpose (Haasnoot *et al* 2014).

Using transient scenarios supports assessing the moment *when* adaptation should be undertaken,
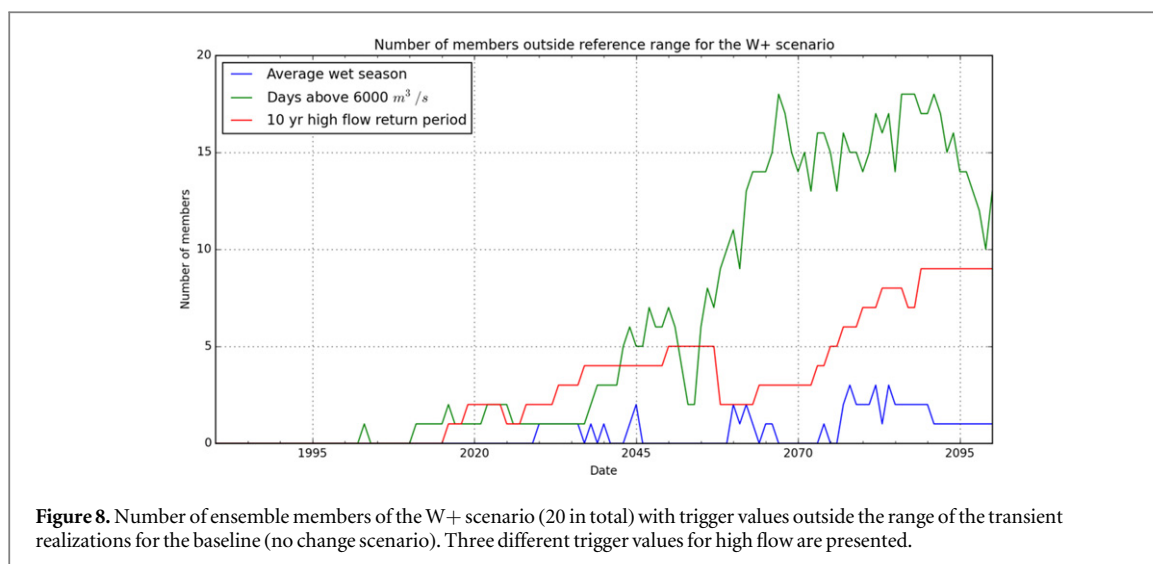
along with an estimate of the uncertainty bandwidth around this timing. With a large ensemble of scenarios it would also be possible to assess probabilities of the timing of ATP. This way, characteristics of two

Figure 6. Number of ensemble members of the W+ scenario (20 in total) with trigger values outside the range of the transient realizations without climate change (based on the values presented in figure 5) for each of the low flow triggers.

Figure 7. Bandwidth and average of the values for high flow triggers for the different ensemble member for the current situation (grey), the G scenario (red) and the W+ scenario (blue). The transient scenarios start in 2001. The historic data presents the range of the baseline (no change) realizations.

bottom-up vulnerability approaches for climate adaptation would be combined: the ATP approach (Kwadijk *et al* 2010) and the decision scaling approach (Brown *et al* 2012, 2011, García *et al* 2014).

The experiments clearly demonstrated the large influence of internal climate variability on the

occurrence of extremes, especially for the high flows, when compared to the role of climate change. This confirms the results by Van Pelt *et al* (2014) who showed that 30% of the variance of the basin-average winter precipitation could be explained by internal climate variability, and the results of Haasnoot *et al*

Figure 8. Number of ensemble members of the W+ scenario (20 in total) with trigger values outside the range of the transient realizations for the baseline (no change scenario). Three different trigger values for high flow are presented.

(2012) who concluded that on the short to midterm (<50 years) climate variability rather than climate change appears to be important for taking decisions in water management. Likewise, changes in water management adaptation in the Rhine delta over the past century was mostly driven in a responsive way to extreme flood or drought events and changing socio-economic developments, instead of anticipating to a changing future (Haasnoot and Middelkoop 2012, EEA 2014).

In this study's scenarios natural climate variability was implicitly assumed to the same as under present-day's climate, due to the application of the classical delta-method (which transforms all quantiles equally and thus leaves the internal variability unchanged). Regarding the importance of natural variability in decision making apparent from our experiments, transient approaches should allow for (transient) scenario's that include changes in internal climate variability along with changes in the mean climate. Within our approach this is possible by applying a non-linear delta-method such as e.g. the advanced delta change method (Pelt *et al* 2012) in a way that preserves the transient (in time) nature of the climate change scenarios. Such an ensemble could also be derived from different climate models, such as generated within Coupled Model Intercomparison Project Phase 5 (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/).

Furthermore, for the sake of simplicity of the experiments, the scenarios explored by the experiments mainly comprised transient time series of climate boundary conditions. Socio-economic boundary conditions are very likely to change as well, and may equally well trigger adaptation. Examples include rapid population growth, increasing economic pressure on and value of land, and changing societal attitudes and values. The latter is often not included but it is an important driver for changing priorities and objectives, investment opportunities, and acceptance of risk, which all may lead to water management

adaptation even in the absence of climate change or extreme events. A subsequent step in scenario analysis should be to include such socio-economic changing boundary conditions as well.

Using our method of experiments with the fast and integrated model driven by an ensemble of time-transient boundary conditions and dynamic responses leads to a different approach to assess flood risk. In the first place, each scenario run—which here is a 100 year adaptation pathway—results in a final cost estimate of floods when these occurred. This can be converted to an annual average cost or averaged 'risk'. Secondly, by establishing a large number of pathways using a large ensemble of transient (time-dependent) climate and socio-economic boundary conditions, a risk estimate can be obtained from the average damage resulting from all scenarios. However, our approach also indicates that the concept of minimizing risk as key objective in water management is not a matter of simple calculation of 'probability times damage'. In our scenarios, both flooding probability and potential damage vary over time; they increase under increasingly changing climate and with expanding socio-economic development in flood-prone areas, but also depend on measures taken in the course of time. In addition, social changes might also lead to a change in risk acceptance, and a different balancing of flood risk against cost of protection or other ecosystem services of rivers. The adaptation pathway method and use of an ensemble of transient scenarios will allow river management to explore these issues.

Identifying, evaluating and using a signpost variable for climate adaptation has received little attention in literature so far (e.g Lempert and Groves 2010, EEA 2014, Groves *et al* 2014). Although other policy domains have experience in identifying and using signposts for robust decision making under uncertainty (Dewar *et al* 1993, Walker *et al* 2001, Kwakkel *et al* 2010, Hamarat *et al* 2013), a stepwise approach for developing and evaluating signposts and triggers for

adaptive management under climate change seems to be missing (also confirmed by Hamarat *et al* 2014). Signposts and trigger values function as 'early warning' signals that objectives are not or will not be achieved anymore through underperformance of the system and should trigger adaptation actions. However, signposts are often related to extreme—rare—events and thus difficult for application as early warning signals. Moreover, our experiments suggest that actions by decision makers often triggered by (the occurrence of (extreme) events, that are falsely identified as being a signpost for climatic change. A climate signal can be best monitored in climate variables as early as possible in the impact chain. But these signals may be less noticeable and convincing for policy makers and society to start acting. An advantage of using in our experiments the average river summer discharge as a trigger is that this signal arises earlier in the impact chain than policy-relevant impacts, it is less sensitive to extremes and is at the same time sufficiently directly related to policy objectives that it may trigger actions. In practice, several signposts and related trigger values could be used to obtain a fingerprint of the changes (as is done for impacts on species by Parmesan and Yohe 2003): several triggers indicating that adaptation is needed is more convincing than only one trigger value giving a signal.

5. Conclusions

In this paper, we demonstrated the value of transient scenarios for local to regional scale climate adaptation by means of three examples for water management. The examples showed how transient scenarios can be used for assessing when to adapt and to explore adaptation pathways, defining triggers for adaptation, and raising awareness about adaptation over time. In considering timing of adaptation actions transient scenarios help to include both climate change and natural variability making it possible to consider also impacts of (changes in) the temporal sequences of extremes such as multiyear droughts.

From a policy perspective it seems evident to select triggers for adaptation that are related to norm or design values, objectives or acceptability values, since these are the values upon which the policies are evaluated. However, instead of events that come close to critical design values, our results show alternative indicators (i.e. average flow in summer half year)—not necessarily policy related—that can be used additionally to trigger adaptation action. To avoid missing the signal—that may be the result of 'bad luck' due to natural variability or may result from a different climate change as expected, e.g. because it occurs in a different season than predetermined by the trigger value, several signposts and related trigger values could be monitored to get a fingerprint of the climate change signal to trigger climate adaptation.

We expect that other policy fields can benefit from our examples as well, especially fields that are sensitive to climate variability which is true for many climate adaptation cases.
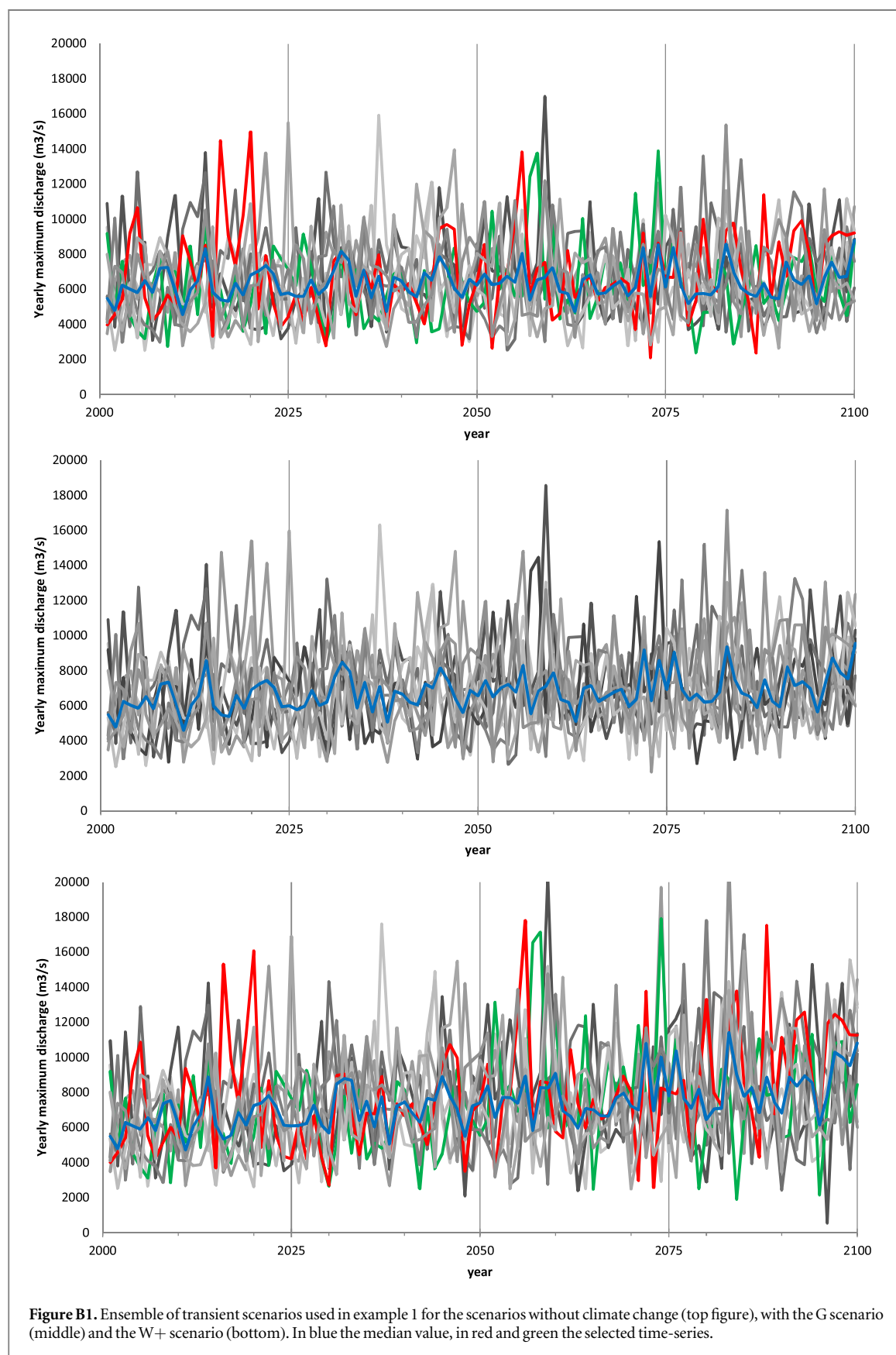
Appendix A. Combinations of transient scenarios are used in the experiments.

		Total number of ensemble members	Ensemble members from rainfall generator time-series number 1.7	Ensemble members rainfall generator time-series number 1.9
Example 1	No climate change	10	10 river discharges	
	G scenario	10	10 river discharges	
	W+ scenario	10	10 river discharges	
	All scenarios	30		
Example 2	No climate change	10	10 river discharges, 10 sea levels	
	G scenario	20	10 river discharges, precipitation and evaporation that are combined with 10 sea levels lower estimate 10 sea level upper estimate	
	W+ scenario	20	10 river discharges, precipitation and evaporation that are combined with 10 sea levels lower estimate 10 sea level upper estimate	
	All scenarios	50		
Example 3	No climate change	20	10 river discharges	10 river discharges
	G scenario	20	10 river discharges	10 river discharges
	W+ scenario	20	10 river discharges	10 river discharges
	All scenarios	60		

Appendix B.

The figure below shows the ensemble of transient scenarios used in example 1 for the scenarios without climate change (top figure), with the G scenario (middle) and the W+ scenario (bottom). In blue the median value, in red and green the selected time-series.

Figure B1. Ensemble of transient scenarios used in example 1 for the scenarios without climate change (top figure), with the G scenario (middle) and the W+ scenario (bottom). In blue the median value, in red and green the selected time-series.

References

Barnett J, Graham S, Mortreux C, Fincher R, Waters E and Hurlimann A 2014 A local coastal adaptation pathway *Nat. Clim. Change* **4** 1103–8

Beersma J J 2002 *Rainfall Generator for the Rhine Basin: Description of 1000-year Simulations* (De Bilt, The Netherlands: KNMI)

Beersma J J, Buishand T A and Buiteveld H 2004 *Droog, Droger, Droogst (Dry, Drier, Driest)* (De Bilt: Koninklijk Nederlands Meteorologisch Instituut)

Berglöv G, German J, Gustavsson H, Harbman U and Johansson B 2009 Improvement HBV model Rhine in FEWS *Final Report* SMHI Hydrology, Tech. Norrkoping, Sweden

Bergstrom S and Forsman A 1973 Development of a conceptual deterministic rainfall-runoff model *Nordic Hydrology* **4** 147–70

Brown C, Ghile Y, Laverty M and Li K 2012 Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector *Water Resour. Res.* **48** W09537

Brown C, Werick W, Leger W and Fay D 2011 A decision-analytic approach to managing climate risks: application to the upper great lakes1 *JAWRA J. Am. Water Resour. Assoc.* **47** 524–34

Delta Programme2015 *Working on the Delta: The decisions to keep the Netherlands safe and liveable* Ministry of Infrastructure and the Environment, Ministry of Economic Affairs

Deltares, online. Sustainable Delta Game (http://deltagame.deltares.nl)

Dewar J A, Builder C H, Hix W M and Levin M H 1993 *Assumption-Based Planning: A Planning Tool for Very Uncertain Times Report* MR-114-A, RAND, Santa Monica

Efron B and Tibshirani R J 1994 *An Introduction to the Bootstrap* (London: Chapman and Hall)

EEA 2014 National adaptation policy processes in European countries *EEA Report No* 4/2014

García L E, Matthews J H, Rodriguez D J, Wijnen M, DiFrancesco K N and Ray P 2014 Beyond downscaling: a bottom-up approach to climate adaptation for water resources management *AGWA Report* 01 World Bank Group, Washington, DC

Görgen K *et al* 2010 Assessment of climate change impacts on discharge in the Rhine River Basin: results of the RheinBlick2050 project *CHR Report No.* I-23 CHR, Lelystad, Netherlands p 211

Groves D, Bloom E, Lempert R, Fischbach J, Nevills J and Goshi B 2014 Developing key indicators for adaptive water planning *J. Water Resour. Plan. Manag.* **141** 05014008

Haasnoot M 2013 *Anticipating Change: Sustainable Water Policy Pathways for an Uncertain Future* Twente University, Enschede

Haasnoot M, Kwakkel J H, Walker W E and ter Maat J 2013 Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world *Glob. Environ. Change* **23** 485–98

Haasnoot M and Middelkoop H 2012 A history of futures: a review of scenario use in water policy studies in the Netherlands *Environ. Sci. Policy* **19–20** 108–20

Haasnoot M, Middelkoop H, Offermans A, Beek E V and van Deursen W P A 2012 Exploring pathways for sustainable water management in river deltas in a changing environment. *Clim. Change* **115** 795–819

Haasnoot M, van Deursen W P A, Guillaume J H A, Kwakkel J H, van Beek E and Middelkoop H 2014 Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways *Environ. Model. Softw.* **60** 99–120

Hall J *et al* 2014 Understanding flood regime changes in Europe: a state-of-the-art assessment *Hydrol. Earth Syst. Sci.* **18** 2735–72

Hamarat C, Kwakkel J H and Pruyt E 2013 Adaptive robust design under deep uncertainty. *Techno. Forecast. Soc. Change.* **80** 408–18

Hamarat C, Kwakkel J H, Pruyt E and Loonen E T 2014 An exploratory approach for adaptive policymaking by using multi-objective robust optimization *Simul. Modelling Pract. Theory* **46** 25–39

Hermans L M, Haasnoot M and Kwakkel J H 2014 Next stop, implementation: collaborative monitoring to inform adaptive policy-making and implementation *Proc. ICWRS* (*Bologna, Italy, 4–6 June 2014*) IAHS publication 363 (doi:10.5194/piahs-364-374-2014)

Kriegler E, O'Neill B C, Hallegatte S, Kram T, Lempert R J, Moss R H and Wilbanks T 2012 The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways *Glob. Environ. Change* **22** 807–22

Kwadijk J C J *et al* 2010 Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands *Wiley Interdiscip. Rev. Clim. Change* **1** 729–40

Kwakkel J H, Walker W E and Marchau V A W J 2010 Adaptive airport strategic planning *Eur J. Trans. Infr. Res.* **10** 227–50

LCW 2012 *Handreiking Watertekort en Warmte - Scenario's* Ministerie Verkeer en Waterstaat

Lempert R J and Groves D G 2010 Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west *Technol. Forecast. Soc. Change* **77** 960–74

Lempert R J 2013 Scenarios that illuminate vulnerabilities and robust responses *Clim. Change* **117** 627–46

Lenderink G, Buishand A and van Deursen W P A 2007 Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach *Hydrol. Earth Syst. Sci.* **11** 1145–59

Lindstrom G, Johansson B, Persson M, Gardelin M and Bergstrom S 1997 Development and test of the distributed HBV-96 hydrological model *J. Hydrol* **201** 272–88

Moss R H *et al* 2008 *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies (Technical Summary)* Intergovernmental Panel on Climate Change

Moss R H *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747–56

Nakicenovic N, Lempert R J and Janetos A C 2014 A Framework for the development of new socio-economic scenarios for climate change research: introductory essay. *Clim. Change* **122** 351–61

Nakicenovic N and Swart R 2000 *IPCC Special Report on Emissions Scenarios* (Cambridge: Cambridge University Press) p 570

Parmesan C and Yohe G 2003 A globally coherent fingerprint of climate change impacts across natural systems *Nature* **421** 37–42

Pelt S C, van Beersma J J, Buishand T A, Hurk B J J M van den and Kabat P 2012 Future changes in extreme precipitation in the Rhine basin based on global and regional climate model simulations *Hydrol. Earth Syst. Sci.* **16** 4517–30

Pelt S C, van Beersma J J, Buishand T A, Hurk B J J M van den and Schellekens J 2014 Uncertainty in the future change of extreme precipitation over the Rhine basin: the role of internal climate variability *Clim. Dyn.* **44** 1789–800

Ranger N, Reeder T and Lowe J 2013 Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the thames estuary 2100 Project *EURO J. Decis. Process* **1** 233–62

Rosenzweig C and Solecki W 2014 Hurricane Sandy and adaptation pathways in New York: lessons from a first-responder city *Glob. Environ. Change* **28** 395–408

Te Linde A 2007 Effect of climate change on the discharge of the rivers Rhine and Meuse *Applying the KNMI 2006 Scenarios Using the HBV model* (No. Q4286) WL | Delft Hydraulics, Delft, The Netherlands

Te Linde A H, Aerts J C J H, Bakker A M R and Kwadijk J C J 2010 Simulating low-probability peak discharges for the Rhine basin using resampled climate modeling data *Water Resour. Res.* **46** W0351

Valkering P, van der Brugge R, Offermans A, Haasnoot M and
    Vreugdenhil H 2012 A perspective-based simulation game to
    explore future pathways of a water-society system under
    climate change *Simul. Gaming* **44** 366–90

Van den Hurk B *et al* 2007 New climate change scenarios for the
    Netherlands *Water Sci. Technol.* **56** 27

Van Notten P W F 2005 *Writing on the Wall: Scenario Development
    in Times of Discontinuity* University of Maastricht,
    Maastricht

Van Vuuren D P *et al* 2011 The representative concentration
    pathways: an overview *Clim. Change* **109** 5–31

Van Vuuren D P *et al* 2014 A new scenario framework for climate
    change research: scenario matrix architecture *Clim. Change*
    122 373–86

Walker W E, Rahman S A and Cave J 2001 Adaptive policies,
    policy analysis, and policymaking *Eur. J. Oper. Res.* **128**
    282–9

Wise R M, Fazey I, Stafford Smith M, Park S E, Eakin H C,
    Archer Van Garderen E R M and Campbell B 2014
    Reconceptualising adaptation to climate change as part of
    pathways of change and response *Glob. Environ. Change* **28**
    325–36