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Computer assisted dynamic adaptive policy design for sustainable water management in river deltas in a changing environment

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Abstract: Sustainable water management in a changing environment full of uncertainty is a profound challenge. To deal with uncertainties, dynamic adaptive policies can be used. Such policies can change over time in response to how the future unfolds, to what we learn about the system, to changes in environment, and to changes in societal preferences. This paper presents a model driven approach that supports the development of dynamic adaptive policies, and illustrates the approach using a hypothetical case. The key idea of the approach is that the dynamic behavior of a fast and simple Integrated Assessment Meta Model (IAMM) is explored across a wide variety of uncertainties. Next, the performance of a set of candidate policy actions is assessed across these uncertainties. This provides insight into the sell-by date of the various actions, and thus when to modify or replace the action. From this, we deduce a logical sequencing of actions, constituting potential pathways. The performance of these pathways is in turn assessed, and iteratively improved. The hypothetical case is inspired by a river reach in the Rhine delta of the Netherlands. Like in the real world, this case is characterized by uncertainties about the future (e.g. climate change, socio-economic developments, and natural variability), uncertainties about the system (e.g. chance on dike failure in relation to high water levels), and uncertainties about societal preferences (e.g. weight society gives to nature). Using a rule induction algorithm, we identify the vulnerabilities and opportunities presented by each pathway. We modify the pathways to address these opportunities and vulnerabilities through capitalizing and defensive actions. With the results it is possible to make an informed decision on a dynamic adaptive policy in a changing environment that is able to achieve the intended objectives despite the multitude of uncertainties present.

***Keywords**: exploratory modelling, adaptation pathways, uncertainty, water management*

1 INTRODUCTION

Water management decisions should bring solutions that will sustain for several decades, implying that they should be adequate even in case of changes in pressures. However, uncertainties about the future and the system make the decision less straightforward. In the wider planning literature a wide spectrum of approaches exists that can be used in the development of adaptive policies. On the one hand [Swanson et al., 2010], these approaches emphasize the need for a more thorough integrated forward-looking analysis of the uncertainties through techniques such as Exploratory Modeling and Analysis (EMA) [Agusdinata, 2008, Bankes, 1993], and scenarios in various forms [Bradfield et al., 2005, Varum et al., 2010]. On the other hand, because of the limited capability of these techniques for anticipating rare events [Goodwin et al., 2010], there is a growing interest in flexibility and adaptability in plans in which a strategic vision of the future is combined with short-term actions and a framework that can guide future actions [Albrechts, 2004, Walker et al., 2001]. This interest in flexibility and adaptivity is partly motivated by a desire to avoid lock in, while transitioning to more sustainable water management. One of the central challenges of these approaches is to design the adaptive policy in light of a multiplicity of futures, and uncertainties about the system. Another challenge is the multiplicity of candidate actions that could be part of the policy. Such analyses can become quite complex. Computational models can be of support in addressing both challenges.

Our particular approach combines the strong features of the concepts of adaptation pathways (AP) [Haasnoot et al., 2012] and adaptive policy making (APM) [Kwakkel et al., 2010a, Walker et al., 2001]. We use Exploratory Modelling Analysis (EMA) to support the development of adaptive policy pathways computationally [Bankes, 1993]. We illustrate this application through a simplified example case based on Haasnoot et al. [2012]. This paper presents a model driven approach that supports the development of dynamic adaptive policies, and illustrates the approach using a hypothetical case. The key idea of the approach is that the dynamic behaviour of a fast and simple Integrated Assessment Meta Model is explored across a wide variety of uncertainties with computational support of EMA. In section 2, we elaborate on the combination of AP and APM, and how EMA can facilitate the resulting process. Section 3 contains the illustrative case. Closing remarks are presented in section 4.

2 AN APPROACH FOR DESIGNING DYNAMIC ADAPTIVE POLICIES

The combined approach of APM and AP, called adaptive policy pathways, includes the strong elements of both. In short this integrated approach includes: *transient scenarios* representing a variety of relevant uncertainties; different *types of policy actions* to handle vulnerabilities and opportunities; *adaptation pathways* describing an assembly of promising actions; and a *monitoring system* with related actions to stay on track of a preferred pathway. We first describe the different steps in the approach, and then explain the role of a computational model in these steps.

The first step is to *describe the study area*. This includes a specification of and related societal issues related to it (e.g. agriculture, flood risk, nature). This description can be used to identify the objectives, constraints in the current situation, and potential constraints in future situations. This results in a definition of success, which is a specification of the desired outcomes in terms of indicators and targets. The definition of success is used in subsequent steps to identify problems, and to evaluate the performance of policy actions and policy pathways. The description of the study area should also include a specification of the uncertainties that are relevant for decision making. These uncertainties are not restricted to uncertainties about the future, but can also cover uncertainties related to data, or models that are being used [Kwakkel et al., 2010b].

The next step is the *problem analysis*. In this step, the specified uncertainties are used to generate an ensemble of plausible futures in the form of transient scenarios. Next, using the condition for success, the possible ways in which problems can arise are identified. This determines if and when policy actions are needed. During the problem analysis, attention should also be given to the identification of opportunities and vulnerabilities. Opportunities are developments that can help in achieving the objectives, while vulnerabilities are developments that can harm the extent to which the objectives can be achieved.

In step 3 policy actions are defined for addressing the identified vulnerabilities and seizing the identified opportunities. To assemble a rich set of possible actions, we distinguish between four types of actions: shaping actions, mitigating actions, hedging actions, and capitalizing actions [Kwakkel et al., 2010a]. The aim of this step is to assemble a rich set of possible actions. In subsequent steps these actions are used as the basic building blocks for the assembly of adaptation pathways.

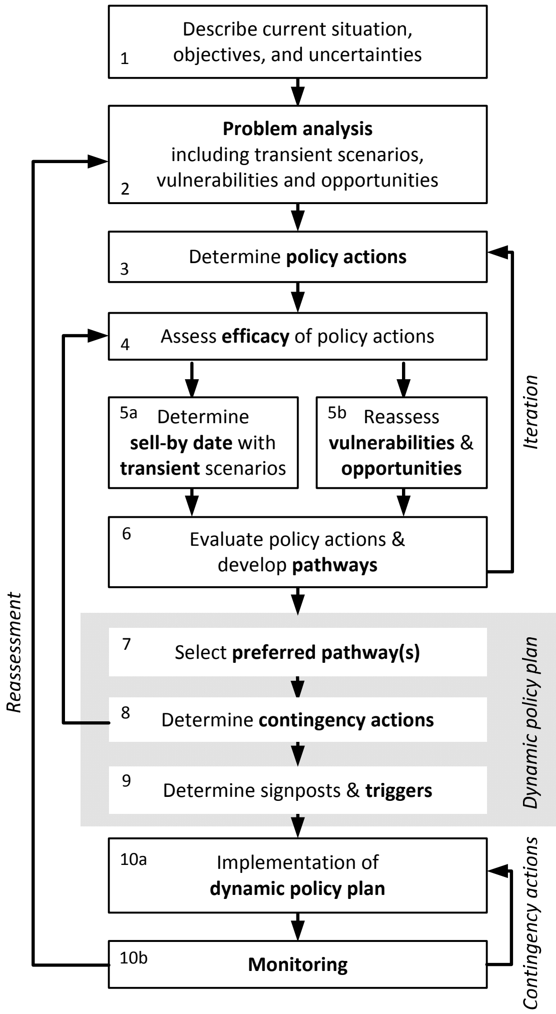

Figure 1. The adaptive policy pathway approach

Step 4 is the assessment of the efficacy of each of identified policy actions. This can be done by performing an impact analysis for each policy action across the ensemble of transient scenarios. The efficacy of each of the policy actions is assessed in light of the definition of success. The sell-by date is reached when a policy action no longer meets the condition for success. The sell-by date thus indicates how long a particular action in isolation is sufficient in meeting the definition of success. Furthermore, the previously identified vulnerabilities and opportunities need to be reassessed. For each action, one needs to assess whether the action was able to reduce or remove a specified vulnerability; whether the action was able to utilize the opportunities; and whether action created new opportunities and/or vulnerabilities.

The development of adaptation pathways is the next step. It is conceivable that the reassessment of the vulnerabilities and opportunities of the assessment of the sell by date triggers an iterative process wherein new or additional policy actions are added to the set of possible actions. Once the set of actions is deemed adequate, pathways can be designed. A pathway consists of a concatenation of policy actions, where a new policy action is activated once its predecessor is no longer able to meet the definition of success. Pathways can be assembled in different ways. For example, analysts could explore all possible routes with all available policy options. Each of these routes can then be evaluated on its performance. However, this could result in the evaluation of a very large number of pathways. Using common sense and basic criteria such as the urgency of actions, the severity of the impacts, and the desire to keep options open, can be used to assemble a set of promising pathways.

The next step is to evaluate the candidate pathways in the same way as the individual policy actions were previously evaluated. Each of the pathways is evaluated across the ensemble of transient scenarios and its performance is confronted with the definition of success. Based on this evaluation, a manageable number of preferable pathways can be selected. Preferred pathways can be improved through contingency planning. Contingency planning requires the specification of corrective, defensive and capitalizing actions, and their associated monitoring system with trigger values [Kwakkel et al., 2010a]. This monitoring system specifies what to monitor and when a specific contingency action is activated. In light of the final adaptation map, a plan for action can be made. This plan for action specified which actions are to be taken immediately, which developments need to be monitored, when contingency actions will be implemented, and when a shift to a different policy action will take place.

The outlined approach requires the repeated assessment of policy actions, contingency actions, pathways, and doing nothing over an ensemble of transient scenarios. One method that can be used to facilitate this is Exploratory Modeling and Analysis (EMA). EMA is a research methodology that uses computational experiments to analyze complex and uncertain systems [Agusdinata, 2008, Bankes, 1993]. EMA is motivated by the fact that for many systems of interest, the construction of a model that may be validly used as surrogate is simply not possible. [Cambell et al., 1985, Hodges et al., 1992]. For such systems, a methodology based on consolidating all known information into a single model and using it to make best estimate predictions can be highly misleading. However, the available information is consistent with a set of models, whose implications for potential decisions may be quite diverse. A single model run drawn from this potentially infinite set of plausible models is not a “prediction”; rather, it provides a computational experiment that reveals how the world would behave if the various guesses any particular model makes about the various unresolvable uncertainties were correct. By conducting many such computational experiments, one can explore the implications of the various guesses. EMA is the explicit representation of the set of plausible models, the process of exploiting the information contained in such a set through a large number of computational experiments, and the analysis of the results of these experiments. EMA is first and foremost an alternative way of using models, knowledge, data, and information. Many well established techniques, such as Monte Carlo sampling, factorial methods, and optimization techniques, can be usefully and successfully employed in the context of EMA [Agusdinata, 2008, Kwakkel, 2010, Lempert et al., 2003, Miller, 1998]. EMA can be used to support the outlined policy design approach by generating the ensemble of transient scenarios, by exploring the performance of actions over this ensemble while accounting for uncertainties about the models to be used, and by analyzing the performance of the actions using various machine learning techniques.

3 ILLUSTRATION OF THE APPROACH FOR A HYPOTHETICAL CASE

3.1 The study area and problem analysis (step 1 to 3)

To illustrate the outlined approach, we use a hypothetical case study, called the Waas. The case is inspired by a river reach in the Rhine delta of the Netherlands (the river Waal). The river and floodplain are highly schematized, but have realistic characteristics. The river is bound by embankments, and the floodplain is separated into five dike rings. A large city is situated on higher grounds in the south-east part. Smaller villages exist in the remaining area, including greenhouses, industry, conservation areas, and pastures. In the past, two large flood events occurred resulting in considerable damage to houses and agriculture.

Drought events limited the navigation through the river and reduced the available of the river for shipping. This demonstrated that the system has not been adequately managed. In the future, climate change and socio-economic developments may increase the pressure on the available space and potential future damages, so additional strategies are needed.

Table 1: Overview of uncertainties

Name	Short description
Climate change	For river discharge and precipitation, 30 realizations of three climate change scenarios are considered.
Land use	Land use will change in the coming 100 years. Six alternative land use scenarios are considered, including slow or fast urbanization, sustainable growth, more nature, urbanization followed by deurbanization, and no change.
Fragility of the dikes	There is uncertainty about the fragility of dikes. Four alternative fragility functions are considered
Damage functions	There is parametric uncertainty about the damage functions used to calculate the damage from flooding and the damage to shipping. A bandwidth of plus and minus ten percent is considered
Policy uncertainty	One of the candidate policy options includes upstream collaboration. The effect of this on the discharge is uncertain. A wide bandwidth is taken into account.

The objective is to limit the flood damage and ensure navigation. A wide variety of relevant uncertainties have to be taken into account in sustainable water management.
gives a high level overview of the uncertainties that are taken into consideration.

In order to explore how the situation will evolve in the future if no action is taken and to assess the efficacy of various actions, a fast and simple impact assessment model has been used. This model is implemented in PCRaster, a grid-based spatial analysis tool for dynamic modeling [van Deursen, 1995]. The model was checked for internal consistency and plausibility of the outcomes by expert judgment. Discharges arising from the transient climate scenarios are translated into water levels using stage discharge relations for each grid cell along the river Waas. These relations were derived from modeling results using a 1D hydrodynamic model (SOBEK) for the river Waal in the Netherlands. The water levels are translated into a 2D surface, and compared with the dike heights derived from the elevation map. Subsequently, the model calculates the probability of dike failure caused by piping or by wave overtopping by examining the difference between dike level and water level [Van Velzen, 2008]. In the case of a dike failure, the water level is considered to be equal to the river water level in the whole dike ring. Damage due to the flooding of dike rings is a function of the water depth using damage relations for the Netherlands given in [De Bruijn, 2008]. The maximum potential damage and the shape of the damage curves are derived from the HISSM model [Kok, 2005]. Cause-effect relations for shipping, describing the water depth and the suitability for shipping were derived from the SHIPS@RISK model [Middelkoop et al., 1999] resulting in the total proportion of navigable time (%) given the operating ship type. To model the impact on ecology, ecologically-relevant flood durations are used to distinguish different ecozones with different riparian vegetation types [Haasnoot et al., 2005]The effect on each ecozone is transformed into an diversity index for ecology by multiplying the relative area by a weighting factor. The sum of these weighted areas is then scaled to an index between 0 and 1. The weighting factor is 6 for the rarest zone and 1 for the most common zone. For more details on the mode, see Haasnoot et al. [2012].

The Waas model is connected to the exploratory modeling workbench. The exploratory modeling workbench [Kwakkel, 2012] is a suite for performing exploratory modeling written in the Python programming language [van Rossum, 1995]. It is responsible for generating the computational experiments, running the experiments, and storing the results for each experiment. This workbench supports parallel computing to reduce computational time. In order to connect the Waas model to this workbench, an interface has been programmed in Python. This interface produces the correct binding files based on the specified computational experiment and parses the output files. 1000 computational experiments were generated using Latin Hypercube sampling. Each of these experiments constitutes a single transient scenario for the future development of the specified uncertainties.

Table 2 shows an overview of the policy actions that are being explored. We distinguish between actions aimed at flood management, and actions aimed at addressing the problems of low flows. The low flow affect the potential time that ships navigate through the river. The uncertainty about damage functions affects the impact of the floating home option and thus is a form of policy uncertainty. Similarly we use a bandwidth for the effect of upstream collaboration.

Table 2. Overview of candidate policy actions

Name	Description
DH500	Dike height rise to cope with the 1:500 discharge, based on measurements
DH1000	Dike height rise to cope with the 1:1000 discharge, based on measurements
DH1.5	Dike height rise: adapting to 1.5 times the second highest discharge ever measured ('rule of thumb measure')
RfRl	'Room for the river' - Large scale: with extra side channels, the river has more space after a threshold discharge is exceeded
RfRs	'Room for the river' - Small scale: with extra side channels, the river has more space after a threshold discharge is exceeded
CopU	Upstream cooperation: discharges are reduced to 14.000
FloatH	Floating houses: resulting in damage functions with 10 times less damage
FaC	Fort cities: extra embankments around the cities
Mound	All cities are raised by 4 m, resulting in houses on a area of elevated ground
SmallS	Use small ships (300 ton) to ensure navigation at low discharges
MediumS	Use medium size ships (3000 ton) to ensure navigation at low discharges
SmallD	Small-scale dredging for navigating at lower discharges
LargeD	Large-scale dredging for navigating at lower discharges

3.2 Efficacy of policy actions and development of adaptation pathways (step 3 to 6)

In order to assess the sell-by date of each of the policy actions, we used the following approach. For the flood management actions, we calculated the cumulative flood damage from year 4 onwards (as we assume 4 years of Implementation time). As the sell-by year, the first year in which the cumulative damage exceeds 2500 is used. If for a specific computational experiment, this value is not reached over the duration of the simulation, a sell-by year of 100 was used. For the low flow policy actions, we considered the percentage of non-navigable time. If for four years in a row, this percentage was equal to or higher than 2%, the last year of this four year sequence was used. If no such four year sequence occurred, a sell by year of 100 was used. This resulted in a sell-by year for each policy action for each simulation (Figure 2).

Figure 3 shows the adaptation map for the low flow actions. This map is generated from the sell-by year analysis. The minimum value of the sell-by year for each action denotes the earliest point in time at which the decision makers need to consider shifting to another policy action. This point is denoted by a 'transfer station' and the start of a dashed line. The dashed line indicates that more and more ensemble members meet the sell by date. The dashed line ends with a 'terminal station'. The terminal station corresponds to the maximum sell by year for an action as encountered across the ensemble. Figure 4 shows an adaptation map for the flood management actions. Here, the transfer stations are based on respectively the first and third quartile of the sell by year for each action. This maps is quite a bit more complicated and shows a large number of possible routes. It also shows some crucial points in time at which multiple actions are expected to reach a transfer point. The first of these is encountered at around 20 years into the future, a second one is encountered at around 35 years into the future, and a third one is encountered at close to sixty years into the future. For the flood risk map, we did not include actions with a low sell by date.

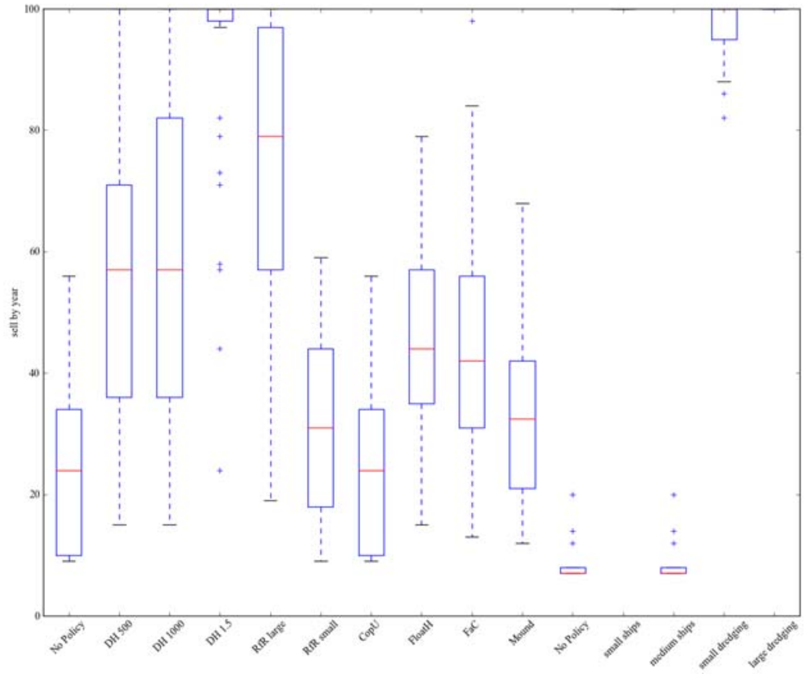

Figure 2. Boxplot of the sell by year for each policy action

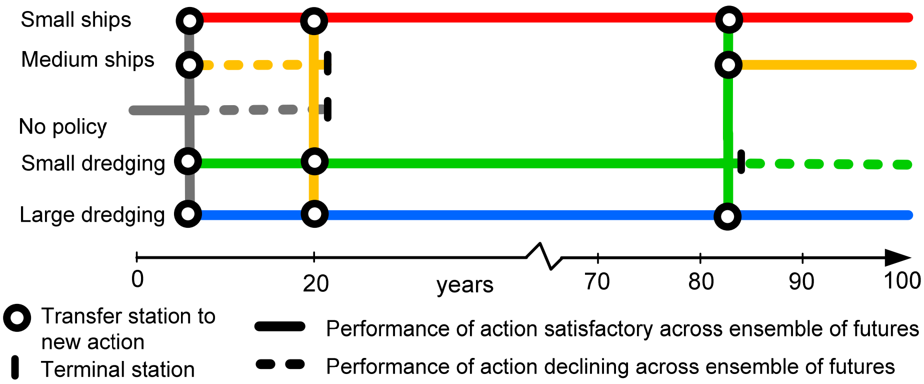

Figure 3. An adaptation map for the low flow policy actions. The terminal station is based on the maximum value of the sell by year for the action. The dashed lines start from the minimum sell by year encountered across the ensemble of plausible futures for each action.

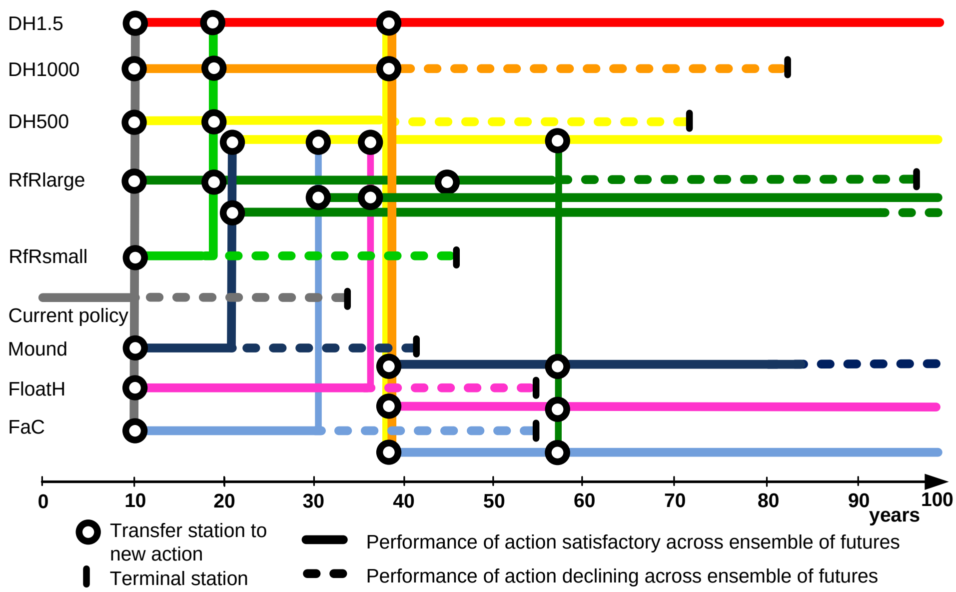

Figure 4: An adaptation map for flood risk. The terminal station is based on the third quartile value of the sell by year for the action. The dashed lines start from the first quartile for the sell-by year for each action.

3.3 Towards a dynamic policy plan (steps 7 – 9)

The identified maps present a wide variety of possible adaptation paths. The next steps for translating the map into a plan for action would be to identify possible developments that can be monitored. In this case, land use is the most obvious candidate development, because it changes slowly. River runoff, given its intrinsic natural variability, is a more difficult phenomenon to monitor, implying that shifting from one action to the next in case of flood risk actions cannot be tied directly to river runoff. Alternatively, the performance of the specified pathways could be explored over an ensemble of transient scenarios, and using rule induction algorithms, the combination of uncertainties responsible for negative outcomes, can be identified and used to specify additional contingency actions and signposts. One obvious contingency action is the need for spatial reservations to keep open the possibility to shift to room for the river in the future. This would result in a modified map that would form the basis for designing the plan for action.

4 CONCLUDING REMARKS

Water management decisions should result in satisfying outcomes in the future that manifests itself, as it involves large investments with a long life time, and can have large societal impacts. However, during the decision making, this future is still highly uncertain. Decision making is further complicated by additional uncertainties about the system under study, the models that can be used, etc. To support this decision making, in the wider planning literature, a wide spectrum of approaches exists that all emphasize the need for flexibility and adaptability of the decisions to the changing future. Still, the design of such decisions requires exploring the multiplicity of futures and evaluating a wide variety of candidate solutions and combinations of solutions over this same multiplicity of futures. We have presented an approach that combines the strong features of the concepts of adaptation pathways [Haasnoot et al., 2012] and adaptive policy making [Kwakkel et al., 2010a, Walker et al., 2001], discussed, and illustrated how this synthesis can use computational support for the development of water management plans.

Future research will elaborate this case in more detail. First, the final three steps are only tentatively sketched and have not been carried out yet. Moreover, in case of the flood management strategies, there is a large number of possible routes over the presented adaptation map. In future work, investigating methods and techniques that can help in relatively quickly identifying the most promising paths is necessary. Another important avenue for research is to translate the presented concepts and approach from the illustrative show case to a real world case.

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