Modeling flood protection as an upstream-downstream problem - using the Rhine as example

Eva Ebenhöh
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Abstract
The model description starts with a model overview, followed by a discussion of design concepts and then more detailed information on initialization, input, and some of the relevant processes in the model. It concludes with a discussion of some results of the model in various model settings.

1 Introduction
The rhine flood protection model presented here is an application to a modeling framework which is used to compare different water management regimes. The model description follows the ODD (Overview, Design, Details) protocol for describing individual and agent-based models (Volker Grimm et al. [2006]). It is written to be comprehensive enough to allow replication of the model structure and its first results. The main reason for writing this model as an application to a more general modeling framework is that agent decision making is supposed to be modular in the sense that alternative decision making can easily be incorporated.

2 Overview
Agents located along one of a number of rivers create dikes and retention sites in order to deal with unpredictable high water levels. While retention sites store water away from the river until the water levels are safe again, dikes increase the potential maximum discharge of a river segment and thus the highest possible water level in the next segment. Thus, upstream agents can create positive (retention) or negative (dikes) effects for downstream agents. At the same time, dikes have a higher cost-effectiveness than retention site, so that there is the incentive to create the negative external effects. This principal social dilemma is shown in Table 1.
<table>
<thead>
<tr>
<th>Measure</th>
<th>Cost-Effectiveness</th>
<th>External Effect on downstream sub-basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dikes</td>
<td>high</td>
<td>negative</td>
</tr>
<tr>
<td>Retention</td>
<td>low</td>
<td>positive</td>
</tr>
</tbody>
</table>

*Table 1:* Dikes with a higher cost-effectiveness than retention sites create negative external effects, while retention sites create positive external effects. The agents thus face a social dilemma, which can be resolved in different ways.

### 2.1 Purpose

The model is exploratory in the sense that it allows to investigate a number of different aspects in a social situation in which upstream agents create negative external effects for downstream agents. The objective is to investigate the dynamics of different decision making processes in a simplified but realistic decision environment of medium complexity. It should be possible decision makers involved in real world flood protection to confirm both agent decision making and behaviour of the environment.

Environmental structure is not fixed but can be tuned to represent an abstract set of river systems or a particular river, in this case the German and Dutch part of the Rhine. By this design it is intended to investigate the impact of different environmental structures on the same kind of decision making.

### 2.2 State variables and scales

#### 2.2.1 RiverSubbasin

A river consists of a number of instances of `RiverSubbasin`. A `RiverSubbasin` is characterized by the following attributes:

- exactly one inflow, which may be a random or pre-set inflow or an instance of `RiverSubbasin`
- any number of tributaries, which are random or preset inflows¹
- zero or one outflows, which is an instance of `RiverSubbasin`. If a `RiverSubbasin` has no outflow it is the river’s mouth and the outflowing water is no longer considered inside the boundaries of this model.
- a length, given in kilometers
- a safety margin, as a number between 0 and 1, defining the water level in relation to the dike limit, at which retention sites are used.

¹It may be useful to allow instances of `RiverSubbasin` as tributaries.
• a number indicating how many downstream instances of RiverSubbasin to take into account when deciding whether or not to use the retention sites. Result of this is that retention sites may be used when the RiverSubbasin itself is not threatened but the next downstream RiverSubbasin is.

• one or more subsequent segments, which are instances of RiverSegment. A RiverSegment is characterized by the following attributes:
  – one inflow
  – zero or one tributaries
  – the highest water level observed so far, given in cubic meters per second
  – a boolean indicating whether or not this segment is currently threatened.\(^2\)
  – a length, given in kilometers
  – a dike height, given in cubic meters per second
  – a maximum possible dike limit, given in cubic meters per second. This is used to create limits to building dikes, as in a part of the lower Rhine, where the the cities are so close to the river, that they can not be further protected by dikes.
  – a retention capacity, given in cubic meters per second\(^3\)
  – a boolean indicating whether or not the segment has natural barriers like mountains, which channel the water that overflows the dikes still into the next segment. Otherwise, this water is subtracted from the discharge.

The configuration for the Rhine model is shown in Figure 1, the parameters are also given in Table 2 in 4.1.

2.2.2 Participant

According to the model framework, agents are called Participant. Each agent has the Role of FloodprotectionManager and is responsible for exactly one instance of RiverSubbasin. Objective of an agent is to prevent

\(^2\)Currently, this is defined by comparing the highest observed water level and the current safety measures including upstream retention. Potentially, the way to define whether a RiverSegment is threatened can be done in different ways.

\(^3\)A retention site usually has a defined amount of water which can be stored. Assuming a floodwave peak to have the length of a day, the maximum effectiveness on the discharge is calculated by dividing the amount [cubic meters] by 86400 seconds, which is the number of seconds per day. However, retention sites are usually less effective than that. A possibility for lower effectiveness, given as a double between 0 and 1 is already included in the model, but not used so far.
Figure 1: The model of the rhine consists of three sub-basins. Upper and Lower Rhine consist of three segments each, the Dutch Rijn only of one segment. For some input data, Mosel and Lahn are separated and then the Lower Rhine is divided into four segments, the second segment defined by the Lahn is only 20 kilometers long, and correspondingly, the first segment is 20 kilometers shorter.
dike overflows. In the beginning and in each time step (see subsection 2.3 on scheduling), an agent with the Role FloodprotectionManager obtains money in order to build dikes and retention sites and is informed about new possible actions. They observe their own and other sub-basins’ maximum observed discharge, dike heights and retention capacities. They can assess cost and potential effect on the maximum water level of possible actions (see below) and decide on one action, corresponding to one flood protection measure, per round.\footnote{Not used, but intended for further model uses, are agent traits like cooperativeness, conformity, and fairness, respectively defining the agents inclination to behave in a group optimal as opposed to individually optimal way or to gain social utility out of others’ approval of their own behaviour, its inclination to follow group norms, and its adversity to create negative external effects for others. These values are random numbers between 0 and 1.}

2.2.3 Action

An instance of Action is either a decision to raise a dike or to build a retention site.\footnote{A problem are dike relocation measures. These do not have the water storage effect of true retention sites but potentially still slow down the wave, so that the peak is lessened somewhat. At the moment, these measures are treated as raising a dike, but the difference will become important, when environmental criteria are used for decision making.}

RaiseDike is located in a RiverSegment. Correspondingly the length is set to twice the length of the RiverSegment. Raising a dike is not instantaneous but takes a number of time steps to finalize. There is a minimum effect by which a dike is raised, if it is raised at all. Alternatively, a dike can be raised to guard against the current highest water level, taking retention measures already planned and built since this highest water level occurred into account. The cost for a dike of the minimum effect is set as the default cost. It is assumed that half this price is a fixed price and the other half corresponds to the actual dike height. The equation for the cost per kilometer of a dike is thus:

\[
\text{cost} = \frac{1}{2}(\text{defaultCost} + \frac{\text{dikeEffect}}{\text{minimumEffect}} \text{defaultCost})
\]

RetentionAction is located in a RiverSegment. Creating a retention site also takes time. A retention measure is characterized by an amount of water that can be stored in cubic meters, an effectiveness between 0 and 1, a chance of failure between 0 and 1, a year of failure within the time it takes to build the retention site, and a cost. The end effectiveness of a retention site is calculated to be the storage amount divided by 86400 seconds (a day) multiplied by the effectiveness. When a retention site is used, this end effectiveness is subtracted from the
discharge of a RiverSegment. A measure to create a retention site can fail and when it does, it fails in a certain year after the initial decision. The cost of pre-defined retention sites is fixed for each cubic meter of storage amount, the cost for retention site possibilities created in the model can vary (see 4.2).

2.2.4 Institution

Agent decision making is enabled and constrained by instances of Institution. So far, institutions are used only as constraints, because they all are of the form: Agents must not do Action X if Condition Y.⁶ Which of the following institutions are in effect depends on the model setting. Comparing effects of these different institutions and evaluative criteria (see below) is the main objective of the model.

**Don’t raise dikes**  Agents must not choose a RaiseDike Action.⁷

**Don’t raise dikes in not threatened segments**  Agents must not choose a RaiseDike Action for a RiverSegment that is not threatened.

**Don’t raise dikes in segments in which currently a dike is built**  Agents must not choose RaiseDike in a RiverSegment for which previously a RaiseDike Action has been chosen that is not yet finalized.

**Don’t build retention sites if no downstream segment is threatened**  Agents must not choose RetentionAction in a RiverSegment when it is not threatened and no downstream instances of RiverSegment in the same RiverSubbasin are threatened.

**Don’t build retention sites if no downstream subbasin is threatened**  Agents must not choose RetentionAction in a RiverSegment when it is not threatened and no downstream instances of RiverSegment in this or any downstream instances of RiverSubbasin are threatened.

**Don’t decide measures which cost more than you can afford**  Agents must not choose an Action which costs more than their accumulated resources minus obligatory payment for already chosen actions.

2.2.5 Evaluative Criterion

Evaluative criteria are used to choose from the possible actions, which were not ruled out by the institutions, those that fit the criterion best.

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⁶No sanctions are implemented yet, all institutions are implemented as norms, which are simply followed by the agents. However, it should be possible for them to reject an institution and suffer the consequences, if there are consequences at all.

⁷This corresponds to the implementation of the EU Flood Directive in the model.
The only EvaluativeCriterion defined is CostEffectiveness, but with three different ways to calculate the cost-effectiveness of a measure, the first comparing only expected effect and cost. The other two taking effects on downstream segments into account, either only in the sub-basin the agent is concerned with or in the total downstream river basin. The equations are given in 4.3.3.

2.3 Process overview and scheduling

The environmental variable of interest is the peak water level of a year. Thus, a time step in the model is considered to be a year. The water peak level is processed through the river system.

Before the first year, an initialization phase takes place, in which the river, participants, and possible actions are created according to the setting in which the model is about to run (see 4.1. Each model year consists four processes called start, participant, environment, and data, as well as an optional collective choice process, which is not yet implemented. The processes are shortly described and the location of several important processes within this general schedule are displayed in Figure 2. More detailed descriptions of agent decision making, effects of actions, and water level processing are given in 4.3.

2.3.1 Start

New possible actions are generated and old ones adapted. Money is handed to the decision makers.

2.3.2 Participant

As shown in Figure 4, agents choose flood protection measures according to their institutions and evaluative criteria from among their possible actions, if they perceive the need for action. For a more detailed descriptions, see 4.3.1. Using different institutions and evaluative criteria makes up different model settings.

2.3.3 Environment

Agents’ decisions and water levels need to be processed. When participants decide on actions, their announcement effects are take place, each year in which an action is not finished, its round effects happen, and when they are finalized, the end effects take place. This is described in more detail in 4.3.2.

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8The sequence is a leftover of earlier models. It seems more logical to let the environment act first and the agents after that.
This is done here in order to make sure that the tributaries discharges are calculated before the main river. See extra graphic on agent decision making for filterActions and evaluateActions.

This is done here and not in announceChosenActions in order to synchronize agent decision making. Note that this is called 1 plus the number of time steps it takes to complete a measure.

See extra graphic on agent decision making for filterActions and evaluateActions.

Figure 2: Each time step equals one year and consists of four model steps that are called setup, player, game, and data.
Figure 3: Agent decision making uses institutions, heuristics, and evaluative criteria as filters to decide on an action out of a number of possible actions.

The water level is processed through the segments of the river system, taking retention sites, dike heights, and discharges of tributaries into account. This is described in more detail in 4.3.4.

2.3.4 Data

All charts for displaying environmental and agent data collect their data now. There are charts for discharge, dike level, and retention amounts for each RiverSubbasin, a chart for floods, and a chart for all relevant discharges. Decisions of agents are currently printed out as text.

2.3.5 Meta Decisions (optional)

If agents move their problem on the collective choice level, that is to either think about new evaluative criteria and institutions, or whether or not to follow existing institutions on their own, or to communicate on joint strategies, this is done in a meta decision phase.

3 Design concepts

3.1 Emergence

At this level, no emergence of collective behaviour, which is not directly observable on the individual level takes place. A lag in dike building is observable, which is due to the fact that agents react on rising water levels only after their occurrence, which occur in their bucket due to decreased flooding in upstream buckets.
3.2 Adaptation
Agents react on flooding with floodprotection measures, but have no further adaptive capabilities.

3.3 Prediction
Agents cannot predict water levels.\(^9\)

3.4 Sensing
Agents sense the peak water level and the level that can be safely processed through the segments of their RiverSubbasin and potentially a number of downstream instances of RiverSubbasin.

3.5 Interaction
No interaction occurs. In later models, however, interaction will occur during communication in meta decisions and through network effects of connected agents.

3.6 Stochasticity
Depending on the initialization, water levels of inflows and tributaries are either calculated using pseudo random numbers or taken from data charts. See subsections 4.1 and 4.3 for further specification. For further submodels it may become relevant that the agent traits, like cooperativeness, fairness, and conformity, are also subject to a random number generator.

3.7 Collectives
No collectives exist. In later models, collectives will be defined by joint strategies for a whole river basin.

3.8 Observation
An observer can observe agents’ decisions but not their reasoning, as well as discharges, floodings and retention in all instances of RiverSubbasin, but again not the reasons for using or not using retention.\(^{10}\)

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\(^9\)This should be different, because real world water managers try to ascertain an underlying distribution of yearly peak water levels on the basis of historic water levels. This is used to define safety standards. In the model, however, this is not yet incorporated.

\(^{10}\)Making reasons observable is, however, possible in principle, and may be useful for model validation.
<table>
<thead>
<tr>
<th>Segment</th>
<th>Inflow or Tributary</th>
<th>Dike</th>
<th>max Dike</th>
<th>Retention Capacity</th>
<th>Length</th>
<th>natural Dike</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[m$^3$/sec]</td>
<td>[m$^3$/sec]</td>
<td>[m$^3$/sec]</td>
<td>[km]</td>
<td></td>
</tr>
<tr>
<td>upper Rhine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Rhine (Basel)</td>
<td>5000</td>
<td>20000</td>
<td>756</td>
<td>256</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>Neckar</td>
<td>6000</td>
<td>20000</td>
<td>0</td>
<td>50</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>Main</td>
<td>7200</td>
<td>20000</td>
<td>0</td>
<td>66</td>
<td>no</td>
</tr>
<tr>
<td>lower Rhine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>upper Rhine</td>
<td>8000</td>
<td>8000</td>
<td>0</td>
<td>54</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>Lahn/Mosel</td>
<td>10000</td>
<td>10000</td>
<td>0</td>
<td>110</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>Sieg/Ruhr/Lippe</td>
<td>13300</td>
<td>20000</td>
<td>0</td>
<td>142</td>
<td>no</td>
</tr>
<tr>
<td>Dutch Rijn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>lower Rhine</td>
<td>15000</td>
<td>20000</td>
<td>0</td>
<td>148</td>
<td>no</td>
</tr>
</tbody>
</table>

Table 2: Parameters for the initialization of the model corresponding to data from the Rhine.

4 Details

4.1 Initialization

The current version of the model is initialized to reproduce the situation of the Rhine. The Rhine, in this model consists of three instances of RiverSubbasin, the upper Rhine, the lower Rhine, and the Dutch Rijn. Initial parameter values for these sub-basins are given in Table 2. There are retention sites only in the first segment of the upper Rhine, amounting to 756 m$^3$/sec (IKSR [2007]).

In addition, default parameters for all parameters mentioned in the model description can be obtained from Table 3.

4.2 Input

Suggested flood protection measures (IKSR [2007]) are used as initial possible actions, given in Table 4. Raising dikes is always possible, as long as the maximum dike height in a given segment has not been reached. New retention sites are generated using a random retention site generator. Each round this creates retention sites with a probability of 0.1 for each subbasin, and with random location within the segments of the RiverSubbasin and

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11 Already existing retention sites of Altenheim (17.6 Mio m$^3$), Kulturwehr Straßburg/Kehl (37.0 Mio m$^3$), Moder (5.6 Mio m$^3$), and Daxlander Au (5.1 Mio m$^3$) amount to a total retention amount of 65.3 Mio m$^3$. Divided by 86400 seconds this results in about 756 m$^3$/sec.
<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Default Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>safety</td>
<td>0.9</td>
<td>m³/s</td>
<td></td>
</tr>
<tr>
<td>number of downstream sub-basins to take into account for retention</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>start assets</td>
<td>200.000</td>
<td>Euro</td>
<td></td>
</tr>
<tr>
<td>yearly assets</td>
<td>10.000</td>
<td>Euro</td>
<td></td>
</tr>
<tr>
<td>years to complete a measure</td>
<td>15</td>
<td>time steps</td>
<td>(source: Ask Rita)</td>
</tr>
<tr>
<td>minimum effect for raising dikes</td>
<td>500</td>
<td>m³/s</td>
<td></td>
</tr>
<tr>
<td>cost for raising a dike by this minimum effect</td>
<td>500</td>
<td>Euro/km</td>
<td>(source: Ask Rita)</td>
</tr>
<tr>
<td>default effectiveness of retention sites</td>
<td>0.5 or 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>default chance of failure of retention sites</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>default year of failure of retention sites</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cost for pre-defined retention sites</td>
<td>4</td>
<td>Euro/m³</td>
<td>IKSR [2001]</td>
</tr>
</tbody>
</table>

*Table 3:* Default values of all parameters mentioned in this model description.
<table>
<thead>
<tr>
<th>Name</th>
<th>Segment</th>
<th>Amount</th>
<th>Effectiveness</th>
<th>Resulting Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[m³]</td>
<td>[m³/sec]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erstein</td>
<td>0</td>
<td>7800000</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>Söllingen</td>
<td>0</td>
<td>12000000</td>
<td>1</td>
<td>139</td>
</tr>
<tr>
<td>Flotzgrün</td>
<td>0</td>
<td>5000000</td>
<td>1</td>
<td>58</td>
</tr>
<tr>
<td>Kollerinsel</td>
<td>0</td>
<td>6100000</td>
<td>1</td>
<td>71</td>
</tr>
<tr>
<td>Breisach +</td>
<td>0</td>
<td>34600000</td>
<td>0.5</td>
<td>200</td>
</tr>
<tr>
<td>Freistett +</td>
<td>0</td>
<td>39200000</td>
<td>0.5</td>
<td>227</td>
</tr>
<tr>
<td>Elisabethenwörth</td>
<td>0</td>
<td>23700000</td>
<td>0.5</td>
<td>137</td>
</tr>
<tr>
<td>Waldsee</td>
<td>0</td>
<td>9000000</td>
<td>0.5</td>
<td>52</td>
</tr>
<tr>
<td>Bodenheim + Ingelheim</td>
<td>2</td>
<td>11200000</td>
<td>0.5</td>
<td>65</td>
</tr>
<tr>
<td>Köl-Langelf</td>
<td>2</td>
<td>4530000</td>
<td>0.5</td>
<td>26</td>
</tr>
<tr>
<td>Worringer Bruch</td>
<td>2</td>
<td>29500000</td>
<td>0.5</td>
<td>170</td>
</tr>
<tr>
<td>Orsoy–Rheinbogen</td>
<td>2</td>
<td>34090000</td>
<td>0.5</td>
<td>197</td>
</tr>
<tr>
<td>Lohrward</td>
<td>3</td>
<td>17350000</td>
<td>0.5</td>
<td>100</td>
</tr>
</tbody>
</table>

**Tabelle 4:** Parameters for the initialization of possible retention sites corresponding to data from the International Commission for the Protection of the Rhine (IKSR) (IKSR [2007]) Suggested dike relocation measures are not used as retention sites in the model. Some smaller retention sites have been combined to one, for instance “Freistett +” consists of Freistett, Bellenkopf, and Wörth/Jockgrim.

random retention amounts (according to a Gaussian distribution with mean 10 Mio cubic meters and standard deviation of 4 Mio cubic meters) and random cost (according to a Gaussian distribution with mean 4 Euro per cubic meter and standard deviation of 0.5 Euro per cubic meter). In the data I have, a floodplain costs 3.5 Euro per cubic meter and technical retention 4.5 Euro per cubic meter (IKSR [1998, 2001]).

In addition to these input parameters there are two different ways to generate the yearly peak discharges as described in the next two paragraphs.

### 4.2.1 Random discharges

Yearly peak water levels are calculated using a pseudo random number generator and Gaussian distribution with means and standard deviations according to Table 5, which were obtained by using the maximum discharges from a Rhine rain generator (source: Ask Gert), taking three quarters of the maximum as mean and one eighth as the standard deviation. This creates much higher discharges compared with real historic data, which is useful,
<table>
<thead>
<tr>
<th>River</th>
<th>Mean Discharge ( \text{[m}^3\text{ sec]} )</th>
<th>Standard Deviation ( \text{[m}^3\text{ sec]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhine (Basel)</td>
<td>3817</td>
<td>636</td>
</tr>
<tr>
<td>Neckar</td>
<td>2017</td>
<td>336</td>
</tr>
<tr>
<td>Main</td>
<td>1507</td>
<td>251</td>
</tr>
<tr>
<td>Lahn</td>
<td>1380</td>
<td>230</td>
</tr>
<tr>
<td>Mosel</td>
<td>3127</td>
<td>521</td>
</tr>
<tr>
<td>Sieg/Ruhr/Lippe</td>
<td>1732</td>
<td>289</td>
</tr>
</tbody>
</table>

*Table 5:* Parameters for the random discharges of the inflow into the upper Rhine and the tributaries of the Rhine. (source: Ask Gert)

in order to see flooding and the need for floodprotection measures in the model.

4.2.2 Discharges generated by rain generator models

Alternatively, discharges generated by rain generator models are used as input to the model. These were obtained by calculations by KNMI using HBV for tributaries and the discharge in Basel and calculating the wave along the Rhine using SYNHP and SOBEK (source Ask Rita).

4.3 Submodels

4.3.1 Agent Decision Making

Decision making is shown in Figure 4 and is done in three steps: (1) all actions ruled out by an institution followed by this agent, are deleted from this round’s list of possible actions, (2) all actions ruled out by an evaluative criterion, that is all actions which are expected not to fulfill a minimum set by an evaluative criterion, are deleted from this round’s list of possible actions, (3) remaining actions are ranked, all actions not on the first rank are deleted. This is done with subsequent evaluative criteria until there is only one action left.

4.3.2 Actions and Effects

Decisions of agents are processed by calling their announcement, round, and end effects at the appropriate times as indicated in Figure 2 and explained below. Each instance of Action has a vector of Effect which define announcement, round, and end effects, as given in Table 6. RaiseDike defines PaymentPerCycle and RaiseDikeEffect, RetentionAction defines PaymentPerCycle and RetentionEffect.
Figure 4: Agent decision making is done in three steps involving first institutions, and in the second and third step evaluative criteria.
1. When an instance of Action was announced in this year, its announcement effects are called.
   This includes the setting of expectations that a measure will raise the protection in a segment and, if it is a retention site, also in all downstream segments. Also, the payment obligation of the responsible agent is set.

2. The round effects of all announced instances of Action are called.
   This includes the yearly payment of the cost of the measure divided by the number of years it takes to complete the measure plus one. Payment reduces the resources of agents but also the obligation. Also, this includes checking whether a retention site fails to be build. If so, it is reduced from the list of chosen actions and the payment obligation of the responsible actor is adapted.

3. All instances of Action are checked, whether they are finalized, according to the time at which they were decided and the number of years it takes for them to be completed (current year equals initial year plus number of years to build the measure). Of these finalized actions the end effects are called.
   This includes building the dike or retention site, and thus altering the corresponding segment. Also, in case of a retention site, the expectation about future protection is reduced again and the maximum observed discharge is also reduced by the effect of the measure.

<table>
<thead>
<tr>
<th>Effect name</th>
<th>Announcement Effect</th>
<th>Round Effect</th>
<th>End Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaymentPerCycle</td>
<td>increase obligation</td>
<td>decrease obligation</td>
<td>raise dikelim and reset</td>
</tr>
<tr>
<td>RaiseDikeEffect</td>
<td>set expectation</td>
<td></td>
<td>expectation</td>
</tr>
<tr>
<td>RetentionEffect</td>
<td>add to expectations</td>
<td>check failure</td>
<td>increase retention effect and</td>
</tr>
</tbody>
</table>
<pre><code>                                                                  | reduce expectations          |
</code></pre>

Table 6: Actions define effects, which in turn determine what happens after actions have been chosen. RaiseDike defines PaymentPerCycle and RaiseDikeEffect, RetentionAction defines PaymentPerCycle and RetentionEffect.
### 4.3.3 Different ways to calculate cost-effectiveness

Three different ways to calculate the cost-effectiveness of measures has been implemented and can be contrasted in the model.

**Cost-Effectiveness** Rules out measures with a negative ratio of effect (in cubic meters per second) to cost. Ranks the possible actions according to the cost-effectiveness $ce$ calculated as:

$$ce = \frac{\text{expectedEffect}}{\text{cost}}$$  \hspace{1cm} (2)

**Sub-basin Cost-Effectiveness** Rules out measures with a negative cost-effectiveness. Ranks the possible actions according to the cost-effectiveness $ce_{\text{subbasin}}$ calculated as

$$ce_{\text{dike\_subbasin}} = \frac{\text{expectedEffect}}{\text{cost}} \times \frac{\text{lengthOfDike}}{\text{lengthOfSubbasin}}$$  \hspace{1cm} (3)

$$ce_{\text{retention\_subbasin}} = \frac{\text{expectedEffect}}{\text{cost}} \times \frac{\text{lengthOfThreatenedSegments}}{\text{lengthOfSubbasin}}$$  \hspace{1cm} (4)

with $\text{lengthOfThreatenedSegments}$ taking into account the length of all segments downstream within the same sub-basin, including the segment of the measure.

**Whole basin Cost-Effectiveness** Rules out measures with a negative cost-effectiveness. Ranks the possible actions according to the cost-effectiveness $ce_{\text{wholebasin}}$ calculated as

$$ce_{\text{dike\_wholebasin}} = \frac{\text{expectedEffect}}{\text{cost}} \times \frac{\text{lengthOfDike}}{\text{lengthOfDownstreamRiver}}$$  \hspace{1cm} (5)

$$ce_{\text{retention\_wholebasin}} = \frac{\text{expectedEffect}}{\text{cost}} \times \frac{\text{lengthOfThreatenedSegments}}{\text{lengthOfDownstreamRiver}}$$  \hspace{1cm} (6)

with $\text{lengthOfThreatenedSegments}$ taking into account the length of all segments downstream from the measure, also in downstream sub-basins, including the segment of the measure.

### 4.3.4 Water Level Processing

Processing the water level through the river system is described in the following and displayed in Figure 5.

1. The initial inflow and inflows from tributaries are calculated or taken from corresponding charts.
If in any of the considered segments, which may also be in downstream sub-basins, the discharge is within the safety margin of the dikelimit, possibleOverflow is set to TRUE.

IF discharge\leq \text{dikelimit} \\
IF naturalDike \\
IF no more segments

IF more segments

calculateSegmentInflow \\
\text{discharge}=\text{upstream}+\text{tributary}

IF possibleOverflow

useSegmentRetention \\
\text{discharge}=\text{discharge}-\text{retention}

IF discharge\geq \text{dikelimit} \\
IF more segments \\
IF NOT naturalDike

calculateSegmentOverflow \\
\text{overflow}=\text{discharge}-\text{dikelimit}

calculateSegmentOutflow \\
\text{outflow}=\text{discharge}

Figure 5: Each sub-basin first determines whether or not there may be an overflow. Then, for each segment, the water level is calculated, potentially altered by retention sites and dike overflow in this segment.
2. All instances of RiverSubbasin beginning upstream calculate their total inflow (inflow plus all tributaries). If the inflow is within a specified safety margin of the dike limit, for this or a specified number of downstream instances of RiverSubbasin, all retention sites are used. That is, beginning from the first segment (if there are any) the inflow and tributaries of that segment are reduced by the retention effects to calculate the discharge. If the water level is still above dike height, the amount which is above dike height floods this segment and the discharge into the next segment is set to be the dike limit. This is followed through all segments resulting in a certain discharge at the end of the RiverSubbasin. This discharge is used as the inflow to the next downstream RiverSubbasin, which calculates in the same manner.

5 Results

Six different settings are contrasted, which differ from each other in the institutions and evaluative criteria used. They differ along two dimensions. The first is called central versus fragmented. In the central regime, the EU Flood Directive is in effect, preventing dikes from being raised. In the fragmented setting, no such institution exists. The second dimension is called cooperative versus uncooperative. In the cooperative setting, building retention sites for downstream sub-basins is allowed and the calculation of measures’ cost-effectiveness includes downstream sub-basins that are threatened. In the uncooperative setting this is not allowed and the calculation of measures’ cost-effectiveness does not include downstream sub-basins. The remaining two settings contrast the use of the cooperative institution, that it is allowed to build retention sites, if only downstream sub-basins are threatened, and the evaluative criterion, which calculates the cost-effectiveness for the whole basin instead of only the sub-basin. The settings are displayed in Table 7.

In all settings flooding occurs in the upper and lower Rhine in years 3 and 32 leading to flood protection actions in these two sub-basins. In the central settings (CC and CU) dikes are prevented by the EU Flood Directive. In the cooperative settings (CC, FC, and FCE), dikes are not as cost-effective as retention sites, because downstream sub-basins that are threatened are taken into account and the lower Rhine is threatened. Only in the Fragmented-Uncooperative setting and the Fragmented-Cooperative-Institution setting dikes are built.

The higher the retention capacities in the upstream sub-basins, the lesser are the discharges in the Dutch Rijn. Although, the Dutch Rijn is never threatened, it profits from the retention upstream.

Other variables to compare the settings are total cost, the year in which the safety standard is reached, and the total retention in the two upper sub-basins. These are compared in Table 8.
Table 7: Six settings are contrasted, called Central-Cooperative (CC), Fragmented-Cooperative (FC), Central-Uncooperative (CU), Fragmented-Uncooperative (FU), Fragmented-Cost-Effectiveness (FCE), and Fragmented-Cooperative-Institution (FCI).

<table>
<thead>
<tr>
<th>Setting</th>
<th>EU Flood Directive</th>
<th>Whole Basin Cost-Effectiveness</th>
<th>Cooperation Allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>CU</td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>FU</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCI</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: The six settings can be compared according to some global variables hinting at different system performance.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>1455</td>
<td>729</td>
<td>68</td>
<td>2848</td>
<td>1708</td>
</tr>
<tr>
<td>CU</td>
<td>1411</td>
<td>684</td>
<td>67</td>
<td>2848</td>
<td>1579</td>
</tr>
<tr>
<td>FC</td>
<td>1455</td>
<td>729</td>
<td>68</td>
<td>2848</td>
<td>1708</td>
</tr>
<tr>
<td>FU</td>
<td>1590</td>
<td>1319</td>
<td>126</td>
<td>756</td>
<td>3406</td>
</tr>
<tr>
<td>FCE</td>
<td>1455</td>
<td>729</td>
<td>68</td>
<td>2848</td>
<td>1708</td>
</tr>
<tr>
<td>FCI</td>
<td>1455</td>
<td>729</td>
<td>126</td>
<td>756</td>
<td>2788</td>
</tr>
</tbody>
</table>

Table 8: The six settings can be compared according to some global variables hinting at different system performance.
Figure 6: Results for the upper and lower Rhine and the Dutch Rijn in the setting CC.
Figure 7: Results for the upper and lower Rhine and the Dutch Rijn in the setting CU.
Figure 8: Results for the upper and lower Rhine and the Dutch Rijn in the setting FC.
Figure 9: Results for the upper and lower Rhine and the Dutch Rijn in the setting FU.
Figure 10: Results for the upper and lower Rhine and the Dutch Rijn in the setting FCE.
Figure 11: Results for the upper and lower Rhine and the Dutch Rijn in the setting FCI.
References


