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Simulating Stakeholder Support in a Policy Process: An Application to River Management

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The authors present an agent-based model representing a policy process among stakeholders of river management. For evaluating the different river management alternatives, the agent-based model is coupled to an integrated river model that describes the impacts of river management, such as flood risk, nature development, and costs. The model is applied to the case of the ongoing Dutch river management project "Grensmaas." The authors analyze stakeholder support and reconstruct the observed policy outcomes of the Grensmaas project over the past 15 years to provide a first validation of the model. They then assess how stakeholder support and the policy outcome might change when stakeholders would change their preference structures or take climate change into account. They argue that the main virtue of the developed modeling framework lies in its application within participatory processes, to support stakeholders to reflect on their goals and uncertainty perspectives in a social context.

Keywords: Agent based modeling, participatory processes, stakeholders, river management

1. Introduction

Agent-based modeling (ABM) is a promising technique for interpreting actor perspectives and simulating actor behavior in policy-relevant research. In particular, agent-based models may be incorporated into integrated assessment (IA) modeling frameworks for a better representation of stakeholder behavior [1], for example, in IA models of climate change [2] and land-use development [3]. Such model frameworks may be used to explain actions of actors from their perspectives, expressed in terms of their goals and beliefs, and show the implications of these actions on the environment and for other stakeholders. Moreover, the models could be used to investigate stakeholder-environment interaction by simulating changing perspectives and behavior in response to environmental change. Finally, the models could aid to investigate stakeholder-stakeholder interaction by modeling processes such as co-operation and competition [4]. The ABM approach is especially relevant in combination with participatory methods. Stakeholders could be involved in the model design to ensure that the model captures the issues of relevance and the subjective stakeholder perceptions. Furthermore, agent-based models can be used to structure participatory processes, supporting social learning by making viewpoints among stakeholders explicit [5].

In this article, we aim to apply the approach of ABM for a case study of river management. We focus on the river engineering project "Grensmaas," which is currently ongoing in the Dutch province of Limburg. The Grensmaas

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project was initiated in 1997 to achieve three main goals [6, 7]: (1) reduction of flood probability to 1/250[1] for inhabited areas, (2) the development of a minimum of 1000 ha of riparian nature, and (3) the extraction of a minimum of 35 million tons of gravel for national use. To this end, measures are planned to widen the Meuse to the north of the city of Maastricht over a length of some 40 km. The Grensmaas project affects many stakeholders with a variety of interests. The main stakeholder groups of the Grensmaas project are the inhabitants of the region, farmers, nature organizations, and the gravel-extracting companies. It is an explicit aim of the project organization to involve these stakeholders as much as possible in the policy process to develop an integrated strategy and a broad societal interest and support.

The policy process of the Grensmaas project can be characterized as long and complex, involving many uncertainties and conflicting interests. It dates back to the early 1990s, when the first plan for riverbed widening was formulated, and has continued up until the present date. During this period, the river management plan was continuously adapted under the influence of changing goals and an increasing number of stakeholders in the policy process. Given the complexity of this policy process, a policy maker may ask himself or herself the following questions. Does the policy process indeed lead to sustainable and broadly supported river management alternatives? Can the government influence the process to improve stakeholder support? How sensitive is the process for uncertain future developments such as climate change?

To address these questions, we present a coupled agent-based model—integrated river model that represents the policy process of the Grensmaas project. A conceptual model of this policy process can be found in Krywkow et al. [8]. This conceptual model includes processes of stakeholder-environment interaction, stakeholder-stakeholder interaction, and belief changes that may result from learning, cooperation, new insights, and calamities. In the current application, we have implemented a first, essential part of this model concept. We model stakeholder support and the outcome of the policy process (a preferred river management strategy) among a specific group of stakeholders with given goals and beliefs. Modeling the different interaction processes and the process of belief change is left for future research.

The literature reports a large number of agent-based applications, which are known under a variety of different but similar names (agent-based modeling, agent-based social simulation, multiagent simulation, etc.) [9]. In this article, we interpret the term *agent-based model* as any type of model containing distinct, identifiable entities (called agents) usefully characterized by some cognitive representation [10]. Current agent-based applications can be broadly organized along a continuum between (1) the ABMs with a simple cognitive representation ("simple agents") and a high level of interaction and (2) the ABMs with more detailed agent representations ("cognitive, deliberative agents"), with a smaller focus on interaction processes [9]. The ABM presented in this article falls clearly in the second group.

The article is organized as follows. In section 2, we present a short overview of the historic course of the Grensmaas project. In section 3, we describe our simulation model. In section 4, we analyze the Grensmaas project in retrospect. We (1) assess the perspectives of the stakeholder of the Grensmaas project in terms of their goals and beliefs, (2) analyze the observed course of the Grensmaas project using the ABM to assess stakeholder support along the way, and (3) reconstruct the observed course of the Grensmaas project to provide a first validation of the ABM. In section 5, we investigate the sensitivity of model results to changes in the agents' preference structures. In section 6, we assess how the policy process could change if all agents would acknowledge climate change as a fact. In the last section, we present our conclusions.

2. The Course of the Grensmaas Planning Process

In this section, we briefly describe the course of the Grensmaas planning process over the past 15 years. The description is used in section 4 for interpretation and validation of the model results.

A full description of the course of the Grensmaas planning process is presented in the appendix. For this article, it is particularly relevant to distinguish the three phases presented in Table 1. The first phase of the project (1990-1993) was characterized by a combination of ecological objectives and the economic objective of gravel extraction (a so-called win-win situation). The most influential parties involved were a nature-oriented planning bureau (basically representing the interests of nature organizations) and the government. The occurrence of floods in 1994 and 1995 brought in a second phase (1994-1998), with flood mitigation turning into a primary objective. The planning process became more integrative in character and included more stakeholders, particularly citizens and farmer associations. The third phase (1999-2003) was marked by the involvement of the gravel extractors and, consequently, much higher requirements for efficiency and profitability. The three phases are all represented by different policy outcomes in the form of well-documented river management strategies. These are the original Green for Gravel plan of 1991 [11], the Preferred Alternative of 1998 [7], and finally the Preferred Alternative of 2003 [12].

3. The Simulation Model

3.1 Model Overview

The simulation model is designed to represent the situation depicted in Table 1. Starting from a given set of

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[1] A safety level of 1/250 indicates that floods are expected to occur on average once every 250 years.

Table 1. A schematic overview of the evolution of the Grensmaas project from 1990 to 2003

Phase	Objectives	Stakeholders	Policy Outcome
Phase 1, 1990-1993	• Nature development • Gravel extraction	• Government • Nature organizations	Green for Gravel 1991 (GFG1991) • Main channel broadening • Floodplain excavation • Clay shield construction • Main channel elevation
Phase 2, 1994-1998	• Flood reduction • Nature development • Gravel extraction	• Government • Nature organizations • Citizens • Farmer associations	Preferred Alternative of 1998 (PA1998) • Main channel broadening • Floodplain excavation • Clay shield construction • Additional nature area
Phase 3, 1999-2003	• Flood reduction • Nature development • Gravel extraction	• Government • Nature organizations • Citizens • Farmer associations • Gravel extractors	Preferred Alternative of 2003 (PA2003) • Main channel broadening • Floodplain excavation • Clay shield construction with lowered surface level • Additional nature area

stakeholders, the model is used to calculate stakeholder support and the policy outcome in the form of a preferred river management strategy. To this end, the stakeholders of the Grensmaas project are represented with computer agents endowed with goals and beliefs. This agent architecture is inspired on existing theories for social behavior, such as the theory of cognitive and social action [13] and the theory of reasoned action [14]. In our application, the goals of the agents are related to the various impacts of river engineering. Typical impacts are flood reduction for the inhabitants, nature development for nature organizations, profit for the gravel-extracting companies, and so on. The agents are endowed with quantitative goal standards to evaluate their goals as described later on. The beliefs of the agents are related to their uncertainty perspectives for evaluating a river management strategy. These perspectives are represented as value settings for uncertain integrated river model (IRM) parameters (e.g., related to the costs and benefits calculation) and a climate change scenario. This interpretation of beliefs corresponds strongly to the notion of worldview (how the world works) of Rotmans and de Vries [15], Van Asselt and Rotmans [16], and Van Asselt [17].

The procedure for calculating agent support and the policy outcome is illustrated in Figure 1.

For a given river management strategy, the IRM is used to calculate impacts in relation to flooding, nature development, agriculture, and costs. The impact values generally differ among agents since they are endowed with different uncertainty perspectives. The impact values pertaining to each individual agent's goals are referred to as their goal values. These values form the input for the agents' support evaluations performed on the basis of their goal standards. Total support is then calculated as a function of the individual stakeholder supports. The policy outcome, finally, is calculated as the river management strategy with maximum total agent support.

3.2 The Integrated River Model

The agents in our model are informed by an IRM to assess the main impacts of river management options. The concept of the IRM is depicted in Figure 2. The main input variables are the different river engineering measures that together constitute a river management strategy. The main output variables are several long-term impacts (with a typical time horizon of ~50 years) with respect to flooding, nature, agriculture, and short-term costs and benefits (e.g., monetary costs, gravel extraction, and hindrance) associated with river engineering.

The model concept was implemented for a simple cross-section representation of the river Meuse. The modules are based on basic principles of hydrology, hydraulics, groundwater dynamics, and nature development and are partially based on existing expert modules (e.g., to assess flood and agricultural damage). The model was conceptually validated with experts from the Grensmaas project organization and partially numerically calibrated and validated with respect to their model results (see [18]).

Estimating the impacts of river engineering involves a number of fundamental uncertainties. Some examples are climate change for estimating peak flow probability in the discharge module, vegetation roughness for estimating water-level changes in the hydraulics module, and soil and price parameters for estimating the monetary costs and benefits within the costs module. To account for these uncertainties, a model user (in our case, "the agent") can easily adjust a predefined set of uncertain model parameters and choose different scenarios for climate change.

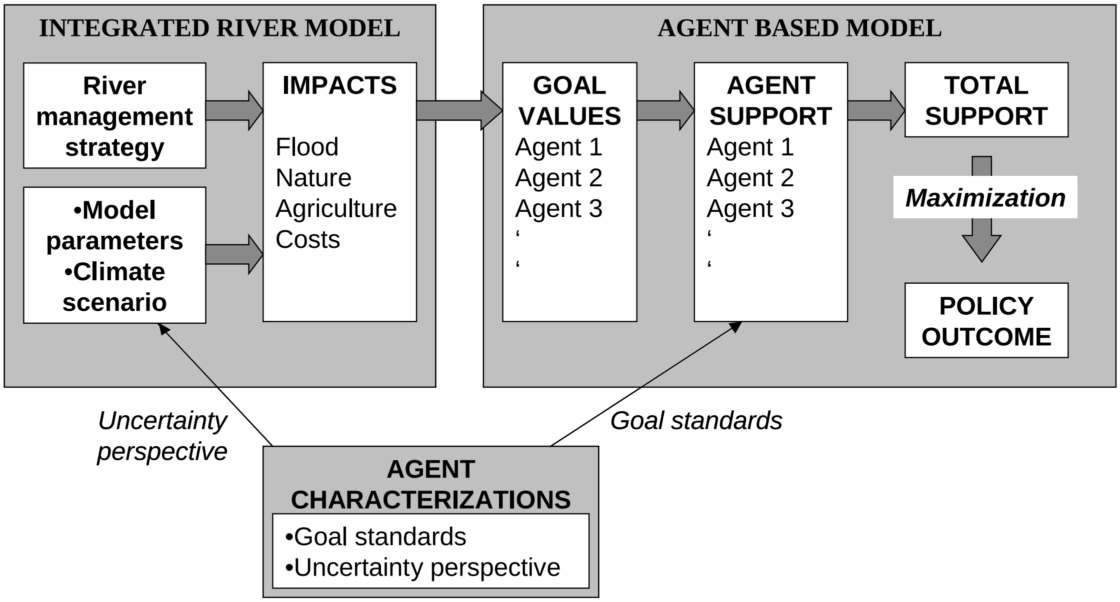

Figure 1. Overview of the simulation model

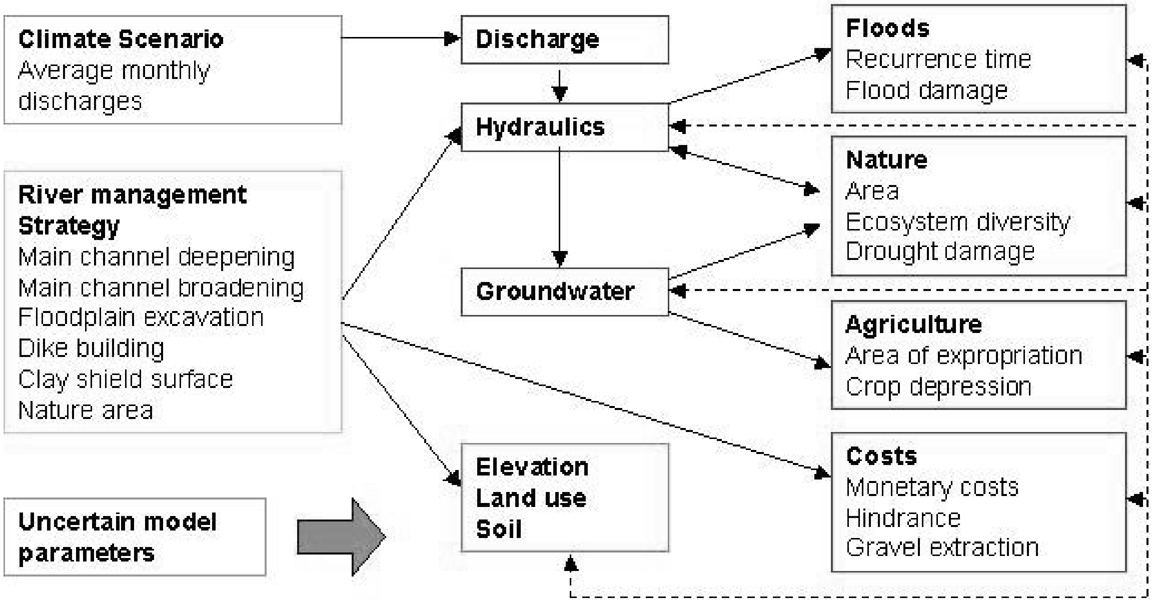

Figure 2. The concept of the integrated river model

3.3 *The Agent-Based Model*

In the following, we describe the sequential modeling steps in the ABM as concisely as possible. In our notation, we use ***bold italic*** print to denote sets of variables and *italic* print to denote single variables.

Step 1: Assessment of the River Management Strategy

We consider a set of agents $\boldsymbol{A}$, each one having a set of goals $\boldsymbol{G}_A$. The agents and their goals for our case study are displayed in Table 2. For a given river management strategy, each agent applies the IRM to calculate the impacts

Table 2. Agents and associated goals for the case study of the Grensmaas project

	Policymaker	Citizen	Nature Org.	Farmer	Gravel Extractor
1. Flood recurrence	*	*		*	
2. Nature area	*		*		
3. Gravel extraction	*				*
4. Ecosystem diversity	*		*		
5. Loss agricultural area	*			*	
6. Δ groundwater level	*		*	*	
7. Hindrance	*	*			
8. Profitability	*				*

of the strategy corresponding to its goals (e.g., the level of flood recurrence). These values are denoted "goal values" (i.e., the set $\boldsymbol{GV}_A$). For calculating the goal values, an agent passes two sets of arguments to the IRM: (1) the river management strategy $\boldsymbol{RMS}$: a set of river engineering parameters specifying main channel deepening, main channel broadening, floodplain excavation, surface elevation of the clay shield, and additional nature area and (2) its uncertainty perspective $\boldsymbol{UP}_A$: settings for the uncertain IRM model parameters and for a climate change scenario. In formula form, we could (cryptically) write for the set of goal values $\boldsymbol{GV}_A$:

$$\boldsymbol{GV_A} = \text{EVALUATE\_IRM}(\boldsymbol{RMS}, \boldsymbol{UP_A}). \tag{1}$$

Step 2: Individual Goal Evaluation

Each agent now determines its so-called goal satisfactions $\boldsymbol{GS}_A$ with the goal values calculated in the previous step. To this end, each of its goal values $GV_{A,i}$ is evaluated on the basis of a goal satisfaction curve:

$$GS_{A,i} = \text{GOAL\_SATISFACTION}(GV_{A,i}, \text{standards}_{A,i}). \tag{2}$$

Goal satisfaction is expressed on a continuous scale of –1 to 1, representing evaluations ranging from unacceptable (–1), to neutral (0), to full satisfaction (1). The shape of the goal satisfaction curve is determined by parameters, called goal standards. This is described and interpreted below.

Step 3: Agent Support

The support an agent attaches to a river management strategy $\boldsymbol{RMS}$ is now calculated as the unweighted average of its goal evaluations $\boldsymbol{GS}_A$. However, if one of its goal satisfactions indicates "unacceptable" (–1), the overall evaluation of the river management strategy is equally considered unacceptable, and support is set to –1. So,

$$\begin{aligned} S_A &= \text{AVERAGE}(\boldsymbol{GS}_A),\\ &\quad \textbf{if } (\exists GS_{A,i} = -1) \textbf{ then } (S_A = -1). \end{aligned} \tag{3}$$

Observe that a goal satisfaction of –1 cannot be compensated with a positive satisfaction for another goal. An "unacceptable" judgment is thus fundamentally different from a negative judgment arbitrarily close to –1, which can be compensated.

Step 4: Total Support

Total agent support S_{tot} is calculated as the unweighted average of the individual agents' supports. However, there is one requirement to this rule related to the power of stakeholder agents. Some stakeholders have a much larger influence over the decision-making process than the other parties and are considered "essential" for supporting a final decision. (In the practice of the Grensmaas case, these parties are the policy maker and the gravel extractor.) Those parties must support the river management strategy (i.e., $S_{A\rightarrow essential} > 0$) for the strategy to be approved. If not so, total support is set to –1. In other words,

$$\begin{aligned} S_{tot} &= \text{AVERAGE}(\boldsymbol{S}_A),\\ &\quad \textbf{if } (\exists S_{A\rightarrow \text{essential}} < 0) \textbf{ then } (S_{tot} = -1). \end{aligned} \tag{4}$$

Step 5: The Policy Outcome

Finally, the optimal strategy $\boldsymbol{RMS}_{opt}$ is obtained by varying the parameters $\boldsymbol{RMS}$ within predefined ranges to find the absolute maximum in S_{tot}:

$$\boldsymbol{RMS}_{opt} = \text{MAXIMUM}(S_{tot}(\boldsymbol{RMS})). \tag{5}$$

This optimal strategy is assumed to represent the outcome of the policy process.

3.4 The Goal Satisfaction Curves

The goal satisfaction curves of equation (2) are defined by applying different types of goal standards. We adopt three possible types of curves as represented in Figure 3. In the simplest possibility, an agent applies only a so-called conditional standard (CS). For such a conditional goal, the goal satisfaction curve is a step function flipping from –1 (unacceptable) to 1 (fully satisfied) at the conditional standard CS. As a second possibility, the agent only specifies

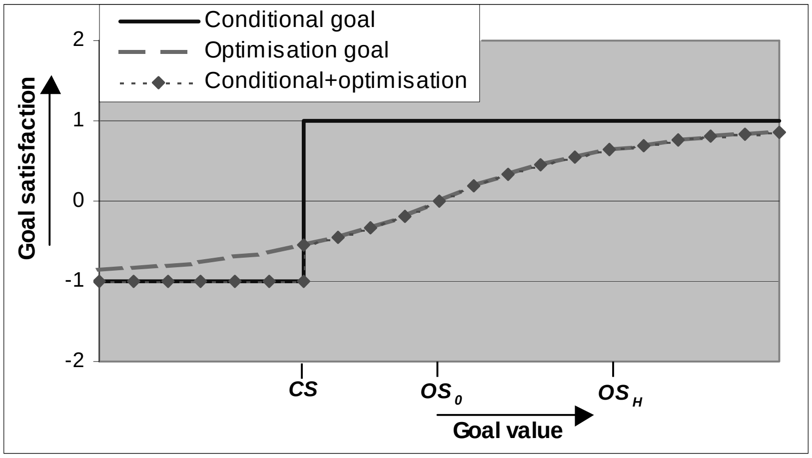

Figure 3. Three typical goal evaluation curves that specify goal satisfaction as a function of the expected goal value. A "conditional goal" is evaluated only on the basis of a conditional standard CS; an "optimization goal" is evaluated on the basis of the optimization standards OS_0 and OS_H. Agents may also specify both conditional and optimization standards.

two so-called optimization standards: an optimization zero point value OS_0 (the goal value for which the agent's goal satisfaction is "neutral") and an optimization high value OS_H (the goal value for which the agent's goal satisfaction is "high"). The goal satisfaction GS is then calculated as

$$\begin{aligned} GS &= 1 - \exp(-|X|) \text{ for } GV \geq OS_0, \text{ and} \\ GS &= -(1 - \exp(-|X|)) \text{ for } GV < OS_0, \end{aligned} \tag{6}$$

with $X \equiv (GV - OS_0)/(OS_H - OS_0)$. Finally, an agent can choose to apply both types of standards, which leads to a truncated preference curve as illustrated in Figure 3.

The adopted preference curves are interpreted as follows. We observe from the Grensmaas project that decisions are made first on the basis of a set of minimal requirements. This is expressed by means of the conditional standards. Any strategy that does not meet one of these standards is considered unacceptable. When the requirements are fulfilled, optimization occurs on the basis of other criteria. This is expressed with the optimization standards. By applying optimization standards, the goal satisfaction curve is a smoothly increasing function of the goal value *GV*. Note that, with optimization standards, goal satisfaction can become arbitrarily close to –1 without being unacceptable. A negative satisfaction for an optimization goal can thus be compensated by a positive satisfaction for another goal. The agent will thus seek the river management strategy for which the set of optimization goal values provides maximum satisfaction, within the constraints posed by the conditional standards.

It may seem natural to include goal weights in the function for individual agent support (equation (3)) and stakeholder weights in the function of total agent support (equation (4)). These weights are omitted, however, since actual calculations show that the model results do not strongly depend on the values of such weights. Rather, the results depend on the values of the constraints posed by the conditional standards described above.[2] Thus, including these weights may lead to only a slight improvement of model accuracy but goes strongly to the cost of transparency with respect to the mentioned primary effects.

4. The Grensmaas Project in Retrospect

In this section, we apply the simulation model to analyze the Grensmaas project in retrospect for the period from 1990 to 2001 outlined in Table 1. We first assess the perspectives of the stakeholders of the Grensmaas project in terms of their goals and uncertainty perspectives. On the basis of these perspectives, we calculate agent support for the observed policy outcomes of the Grensmaas project. Finally, we reconstruct the observed course of the Grensmaas project to provide a first validation of the ABM.

4.1 *Stakeholder Perspectives*

The description of stakeholder perspectives is based on a number of sources. First, interviews were carried out with the main stakeholders of the Grensmaas project to get a first qualitative overview of their perspectives [19]. This information was supplemented with quantitative data from the governmental environmental assessments of the proposed river management alternatives [7, 12] and on the official stakeholder reactions to those assessments [20, 21].

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[2] A similar argument applies in section 5.1, where model sensitivity with respect to the optimization standards is considered to be small.

4.1.1 Agents and Goals

We consider the following main stakeholders/stakeholder groups: (1) parties representing the national and provincial government, including the project organization Maaswerken; (2) citizen organizations representing the inhabitants of Borgharen; (3) the farmers organized in a regional farmer association; (4) the nature organizations involved; and (5) the gravel extraction industries. These are represented by the corresponding agents "policy maker," "citizen," "farmer," "nature organization," and "gravel extractor."

To these agents, we associate the goals shown in Table 2. The policy maker supports all the main objectives of the Grensmaas project, including flood reduction, nature development (i.e., nature area and ecosystem diversity), gravel extraction, and profitability. The negative side effects (loss of agricultural area, groundwater level decrease, and hindrance) are to be minimized [7]. The nongovernmental stakeholders hold various goals as presented in Table 2.

4.1.2 Goal Standards

The quantitative standards that the agents attach to their goals are displayed in Table 3. The conditional standards for the main project objectives (goals 1-3 of Table 2) are stated clearly by the government: a maximum flood recurrence of 1/250,[3] minimally 1000 ha of new nature, and minimally 35 million tons of extracted gravel. The citizen, nature organization, and farmer have adopted these standards for their respective goals of flood reduction and nature area [19]. Ecosystem diversity is measured by means of the Shannon diversity index [22]. The policy maker states that the distribution of nature "may not deviate strongly" from their ecological vision [7]. This is modeled by attaching a conditional standard of 0.7 to the Shannon diversity index for both the policy maker and nature organization. With respect to the goal of "profitability," we assume that both the gravel extractor and policy maker adopt a standard of 4%. This value corresponds to the discount rate of 4%/year considered to be profitable by the Dutch government for risk-free investments [23].

The optimization standards for goals 4, 6, and 7 were derived from the environmental impact assessment [7]. This document contains impact assessments of five different river engineering alternatives. Agents selectively adopt estimations of the goal variables for the different alternatives as goal standards. For example, we assume that the nature organization adopts its optimization high value OS_H for ecosystem diversity from the so-called environmental alternative, while its optimization zero point level for this goal variable is chosen in correspondence with the basis alternative. We furthermore assume that agents holding a self-interest (i.e., all agents except the policy maker) consider their optimization high value to be their conditional standard as well.

The loss of agricultural area forms a special case. It is both a goal of the policy maker and farmer, but the attached standards are quite different. The policy maker considers the goal to be inferior to the main project objectives and considers it merely an optimization goal, with an optimization zero point level of 1000 ha and an optimization reference of 2000 ha. The farmer, on the contrary, is unwilling to give up more land than absolutely necessary [19] and adopts a conditional standard of 1000 ha.

4.1.3 Perspectives on Uncertainty

Although the stakeholders of the Grensmaas project acknowledge a number of uncertainties, there are practically no conflicting views on the interpretations of those uncertainties [19]. Consequently, the stakeholder agents are generally endowed with "central" estimates for the uncertain model parameters and do not consider climate change. An exception to this rule occurs for the case of gravel extraction. The calculation of the amount of extracted gravel depends critically on the values of the soil density and on the relative fraction of gravel in the soil. The estimated uncertainty ranges of these parameters are 8% and 3%, respectively [12]. These ranges legitimate the real-life difference in opinion between the policy maker and the gravel extractor on the profitability issue. In the policy maker's view, the amount of extracted gravel is sufficient to reach its primary goals without additional expenditure. According to the gravel extractor, additional gravel extraction is required to reach an acceptable level of profitability. Therefore, the gravel extractor agent adopts a "conservative" estimate for the amount of extracted gravel, while the policy maker and other agents adopt the "central" estimate.

4.2 Analyzing Support for Observed Policy Outcomes

As a first application of the simulation model, we assess goal satisfactions and stakeholder support for the observed policy outcomes of Table 1. Recall that we distinguish three phases in the planning process with different objectives and stakeholders involved. The respective policy outcomes are the river management strategies Green for Gravel of 1991 (GFG1991), the Preferred Alternative of 1998 (PA1998), and the Preferred Alternative of 2003 (PA2003). These "observed" river management strategies are represented by the following river engineering parameters: main channel deepening, main channel broadening, floodplain excavation, surface elevation of the clay shield, and additional nature area, as derived in Valkering [18] and shown in Table 4. For calculating support for these strategies, we adopt the stakeholder perspectives presented in section 4.1. Note that for the assessment of the GFG1991, the policy maker, citizen, and farmer omit their goal of flood recurrence be-

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[3] The flood recurrence goal only applies for the second and third phases of the policy process (see Table 1). During the first phase, the issue of flood reduction was not important at that time.

Table 3. Conditional and optimization standards associated with different goals

Agent	Goal	Sign	Conditional Standard	Optimization Zero Point Value	Optimization High Value
Policy maker	Flood recurrence (years)	Min	250	—	—
	Nature area (ha)	Min	1000	—	—
	Ecosystem diversity (–)	Min	0.7	0.7	1
	Loss agricultural area (ha)	Max	—	1000	2000
	Δ groundwater level (m)	Min	—	0	–0.2
	Hindrance (person*years)	Max	—	20,000	30,000
	Gravel extraction (*10^6 tons)	Min	35	—	—
	Profitability (%)	Min	4	—	—
Citizen	Flood recurrence (years)	Min	250	—	—
	Hindrance (person*years)	Max	30,000	20,000	30,000
Nature organization	Nature area (ha)	Min	1000	—	—
	Ecosystem diversity (–)	Min	0.7	0.7	1
	Δ groundwater level (m)	Min	–0.2	0	–0.2
Farmer	Flood recurrence (years)	Min	250	—	—
	Loss agricultural area (ha)	Max	1000	0	1000
	Δ groundwater level (m)	Min	–0.2	0	–0.2
Gravel extractor	Gravel extractor (*10^6 tons)	Min	—	35	70
	Profitability (%)	Min	4	—	—

Note: The standards determine the evaluation curve that an agent uses to evaluate its goal (see Fig. 3). The “sign” indicates whether the standard refers to minimal or maximal requirements.

Table 4. Calculated river management strategies compared to the historically observed strategies Green for Gravel (GFG1991), the Preferred Alternative of 1998 (PA1998), and the Preferred Alternative of 2003 (PA2003)

	GFG1991		PA1998		PA2003	
	Observed	Calculated	Observed	Calculated	Observed	Calculated
Main channel deepening (m)	–1	–2	0	–2	0	0
Main channel broadening (m)	125	50	150	100	125	100
Floodplain excavation (m)	350	250	150	250	100	125
Clay shield surface (m)	0	0	0	0	2.4	4
Additional nature area (m)	0	250	200	125	300	250
Error		0.72		0.95		0.33

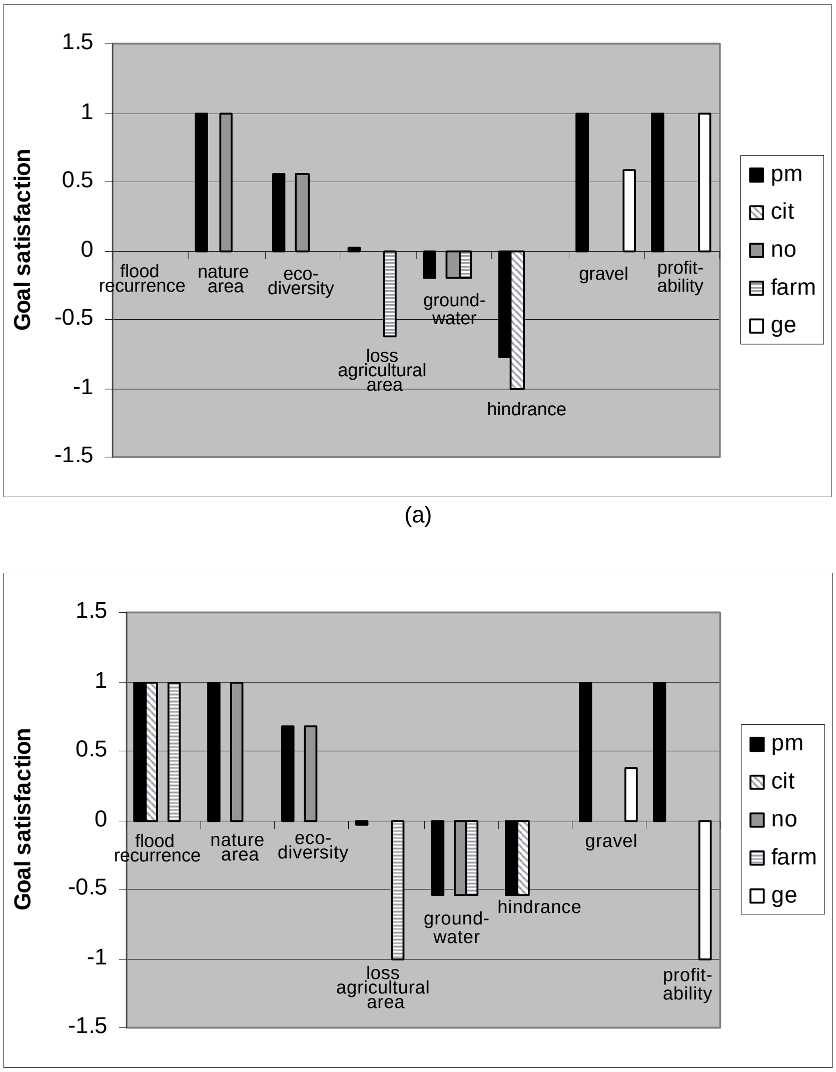
cause in this phase of the planning process, the issue of flood reduction was not important.

4.2.1 GFG1991

The calculated stakeholder goal satisfactions and stakeholder support for the strategy GFG1991 are shown in Figure 4a. The initiators of the plan, the policy maker and nature organization, are indeed supportive of the strategy since their goals of gravel extraction and nature development are sufficiently met. Also, the gravel extractor, who was not intensively involved in the planning process, would have agreed with the proposed plan. The magnitude of gravel extraction is such that both of its goals of “profitability” and “gravel” (extraction volume) are fulfilled. The citizen and farmer are unsupportive of the strategy. For the citizen, the strategy fails because the hindrance levels are considered to be too high. The farmer objects primarily to the loss of agricultural land, whereas the potential negative effect of groundwater level decrease has been sufficiently mitigated through the elevation of the river’s main channel.

4.2.2 PA1998

After the floods of 1993 and 1995, the aspect of flood reduction is added as a primary objective. The proposed strategy PA1998 meets this objective, which is reflected in a maximum goal satisfaction on the criterion “flood recurrence” for all owners of this goal (see Fig. 4b). As a whole, the strategy PA1998 is more “efficient” than the previous GFG1991. With somewhat more riverbed broadening and a smaller emphasis on floodplain excavation, and by omitting the measure of main channel elevation, the main project objectives are reached with less gravel extraction and correspondingly smaller hindrance levels and consequently higher citizen support. The changes go to the cost of nature and agriculture because of the anticipated decrease in groundwater level. Figure 4b also shows



(a)

(b)

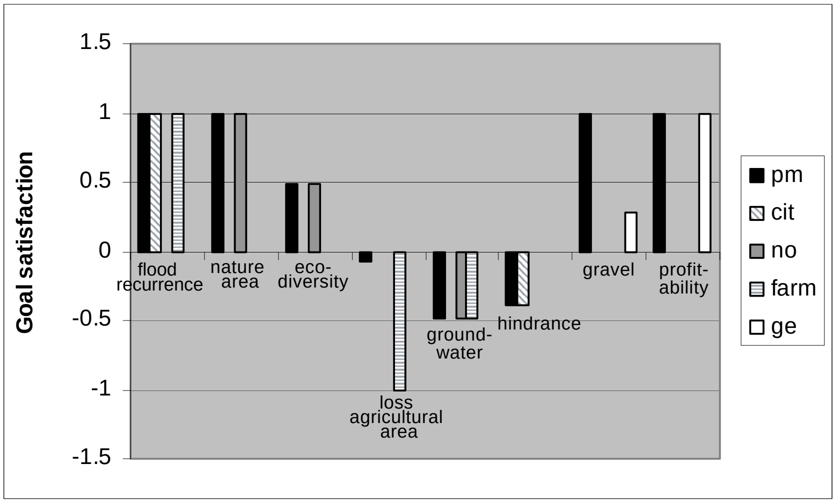
Figure 4. Assessment of stakeholder support for the three historic river management strategies Green for Gravel (1991), the Preferred Alternative (1998), and the Preferred Alternative (2003). Figures (a) through (c) show goal satisfaction of stakeholders for each goal considered. Figure (d) summarizes the results by displaying total stakeholder support for each river management strategy. pm = policy maker; cit = citizen; no = nature organization; farm = farmer; ge = gravel extractor. *(continued on next page)*

that the strategy lacks support of the gravel extractor because in his view, the standard for profitability is not met.

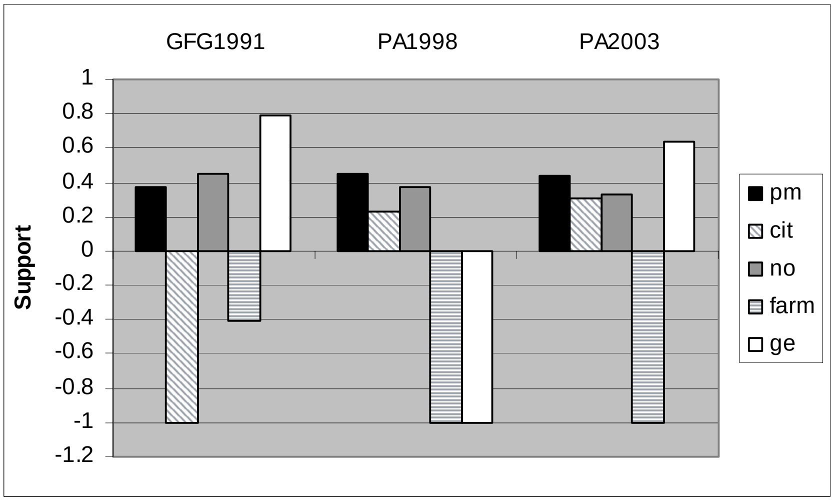
4.2.3 PA2003

When the gravel extractor was included in the planning process, the PA1998 was revised again to increase its profitability, leading to PA2003. The solution was found by allowing the surface level of the clay shield to be 2 to 3 meters below the original surface level. Hereby, more gravel could be extracted in a more profitable fashion with smaller amounts of the by-products clay and sand. The gravel extractor now observes a sufficiently high profit, which is displayed in Figure 4c. Due to lesser river-widening measures, the flood recurrence is smaller compared to PA1998, but the standard of 1/250 years is still met. The compromise with the gravel extractor does go to the cost of ecological objectives. Ecosystem diversity decreases but remains at an acceptable level. The farmer remains very unsatisfied, primarily due to an unacceptable loss of agricultural land.

In conclusion, we observe that the planning process can be characterized as a process of compromise. With an increasing number of stakeholders and objectives, new strategies are found that are acceptable to all. However, conces-



(c)



(d)

Figure 4. *(continued from previous page)*

sions are made, which are reflected primarily in the gradual decrease of support from the nature organization along the various stages of the planning process (see Fig. 4d).

4.3 Calculating Policy Outcomes

As a second application, we compare the policy outcomes calculated with the simulation model to the corresponding observed policy outcomes for each policy phase of Table 1. For calculating the policy outcomes, we consider only those goals and stakeholders involved in that phase of the planning process. Furthermore, we apply the condition that the policy maker and, for the last phase, the gravel extractor are "essential" stakeholders who must have at least positive support.

The main purpose of this exercise is to provide a first validation of the ABM. To this end, we calculate a formal model error E_{RMS} as the least squares difference between the five observed and calculated river management parameters displayed in Table 4. Denoting these parameters RO_i and RC_i, respectively, the error is written as

$$E_{RMS} = \sqrt{\frac{1}{5}\sum_{i=1}^{5}\left(\frac{RO_i - RC_i}{RR_i}\right)^2}. \qquad (7)$$

The reference values RR_i are taken as the mean of all nonzero absolute values of the observed river management parameters RO_i. For a model error of 1, the differences between the river management parameters roughly equal the reference values. Given the complexity of the policy process, this model error is considered an upper bound for an acceptable correspondence between the observed and calculated strategies. For a model error < 0.5, the correspondence is considered good.

The results show a good correspondence for PA2003 and acceptable correspondences for GFG1991 and PA1998. The error between the observed and calculated GFG1991 is related to the calculation of ecosystem diversity. Our model results show that the ecosystem diversity of the observed GFG1991 is significantly below its optimal value. So, either the calculation of ecosystem diversity in the river model is inaccurate or the optimization criterion of ecosystem diversity for GFG1991 is incorrect. The large simulation error for PA1998 is related to the calculated profitability. The calculated profitability is sufficiently high to allow main channel elevation (returning profitable gravel to the river for mitigating groundwater level decrease) as part of the calculated optimal strategy. In reality, however, the profitability was not considered sufficient for main channel elevation. Again, the model error may be related to inaccuracy in the IRM results or to the choice of goal standards.

Despite these difficulties, the general characteristics of the river engineering strategies are reproduced to a satisfactory degree. The calculated GFG1991 is a nature-friendly strategy with a large area of floodplain excavation and main channel elevation. The calculated PA1998 is an integrated strategy, with a mix of river engineering measures. The calculated PA2003 corresponds particularly well to the observed strategy and represents a compromise among the different interests within the boundary conditions of a high profitability. Especially, the lowered clay shield surface, necessary for reaching a sufficient profitability, is well reproduced.

To further illustrate the model results, we compare calculated stakeholder supports for the observed and calculated river management strategies in Figure 5. Observe first that in all cases, total support for the optimized strategies is higher than the support for the observed strategies,[4] which is a natural and correct consequence of the adopted optimization approach. The patterns of support between the observed and calculated strategies generally correspond well, which simply reflects the correspondence between the calculated and optimized river management strategies. The most striking observation is that in some cases, the individual agent supports differ strongly between the observed and calculated strategy due to an "unacceptable" support evaluation in either one of the cases. The farmer, for example, judges the observed PA2003 as unacceptable, while the calculated PA2003 receives approximately "neutral" support. According to our model results, this difference arises from a slight variation in the goal value "loss agricultural area," which falls just below the farmer's conditional standard in the calculated PA2003 and just above for the observed PA2003. The support calculations can thus be very sensitive to changes in river management strategy due to the model formulation in terms of conditional standards.

So, can we consider our model to be valid? On one hand, we showed that the general characteristics of the observed river management strategy are reproduced well. On the other hand, we observe significant model errors. These may be related, for example, to the validity of the IRM or inaccuracy in the values of the different goal standards. Moreover, the errors may be related to the ABM structure—for example, the assumption that the outcome of the policy process is the river management strategy with maximum stakeholder support. Our model must therefore not be considered a "truth machine" that predicts policy making for river management with considerable accuracy. Rather, the tool should be applied to explore different river management options and reflect on these as part of a participatory process with stakeholders. For such an application, we conclude that the model is a satisfying way to describe the policy process.

5. Sensitivity for Changing Goal Standards

In this section, we investigate the sensitivity of the model results to changes in the agent's goal standards. We focus on the conditional standards since the effects of changing the optimization standards are expected to be small.

5.1 Sensitivity of Support

That the effects of changing optimization standards are small can be seen on the basis of the following argument. We consider small changes in the optimization standards ΔOS_0 and ΔOS_H pertaining to a given goal of any agent A. The change in total support will then read as follows (see equations (3)-(5)):

$$\Delta S_{tot} = e^{-|X|} * \frac{1}{N_G} * \frac{1}{N_A} \left\{ (X+1) \frac{\Delta OS_0}{OS_H - OS_0} - X \frac{\Delta OS_H}{OS_H - OS_0} \right\}, \quad (8)$$

with N_G the number of goals of agent A and N_A the number of agents considered. Since the changes in optimization standards are scaled with the factor $(OS_H - OS_0)$, the corresponding change in support will generally be small. Even for large relative changes $\sim (OS_H - OS_0)$, the effective change in the total support is maximally of the order $1/(N_G * N_A)$. A small change in a conditional standard, however, may cause a sharp change in agent support of the order 1 and a corresponding change of total support $\Delta S_{tot} \sim 1/N_A$. Consequently, largest effects are expected from the change of conditional standards.

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[4] The (often negative) evaluations of the parties not involved in that phase of the planning process are not included for the assessment of total support.

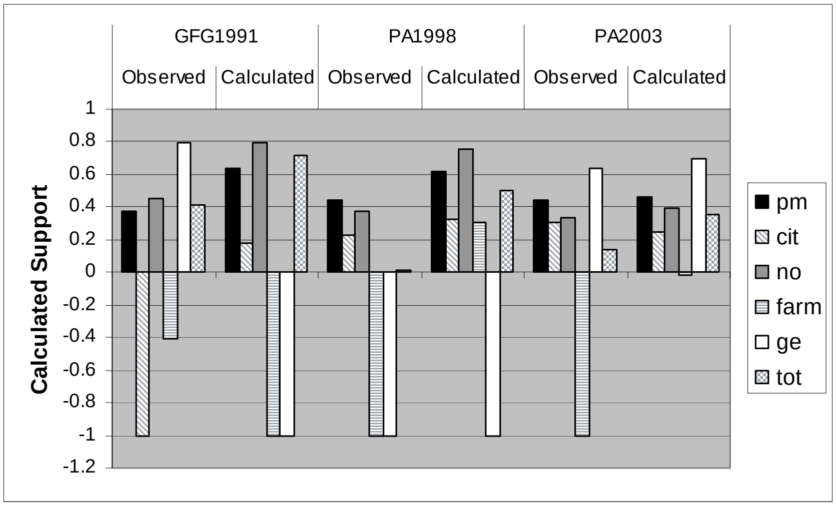


Figure 5. A comparison between the calculated stakeholder support for the "observed" and "calculated" river management strategies. pm = policy maker; cit = citizen; no = nature organization; farm = farmer; ge = gravel extractor.

Next, consider the effect of changing a conditional standard on the support of an agent A with an acceptable support evaluation ($S_A > -1$) for some river management strategy. It is a priori clear that for infinitesimal changes in one of its conditional standards, its support will remain constant. For larger changes, a sudden drop in support occurs when the conditional standard exceeds the goal value so that the adopted river management becomes unacceptable. The sensitivity of support to the conditional standards is thus best expressed as the relative difference D_{CS} between the goal value GV and the conditional standard CS:

$$D_{CS} \equiv \left| \frac{GV - CS}{GV} \right| . \qquad (9)$$

When the difference is small ($GV \sim CS$), the conditional standard is considered an important constraint in the policy process.

Using this parameter, we can analyze support for a given river management strategy on its stability for changing conditional goal standards. As an example, we consider the case of the calculated PA2003. In Table 5, it is shown that for this case, the expected value of flood recurrence (633 years) is much higher than the value required by various parties (250 years). This indicates that the criterion of flood recurrence is not the primary constraint for finding an acceptable river management strategy. A much larger constraint originates from the conditional standards "nature area" for the policy maker and nature organization (D_{CS} = 0.05) and "loss agricultural area" for the farmer (D_{CS} = 0.02). Also, hindrance for the citizen (D_{CS} = 0.11) and profitability for the gravel extractor (D_{CS} = 0.17) are shown to be significant constraints in the policy process. Change of support obviously may lead to change in the optimal strategy. This effect will be investigated in detail in the next section.

5.2 Sensitivity of the Policy Outcome

In this section, we study the sensitivity of the optimal river management strategy PA2003 for changes in various conditional goal standards. Hereby, the different conditional standards are varied for all agents in the same way, with the conditional standard "flood recurrence," for example, referring to the conditional standards of the policy maker, citizen, and farmer. The results of the sensitivity analysis are displayed in Figure 6. The figures show total stakeholder support S_{tot} and the model error E_{RMS} with respect to the observed PA2003 for the calculated optimal strategies as a function of the conditional goal standard.

In Figure 6, one recognizes some general features. Note that the points marked with open squares refer to our estimates of the actual conditional standards of stakeholders presented in Table 3. For all cases, these points lie at the (often unique) minimum of the error function. This indicates that the estimates of the actual conditional standards are realistic and supports the general validity of the ABM.

A second feature is that total support S_{tot} is always a monotonic function of the conditional standard CS, increasing or decreasing. This can be understood as follows. A conditional standard may change in two directions: (1) constraining the range of acceptable river management strategies or (2) enlarging the acceptable range. Constraining the acceptable range can only lead to decreasing or constant support, while enlarging the acceptable range can

Table 5. Sensitivity of support to changes in the conditional standards for the case of the calculated PA2003

Agent	Goal	CS	GV	D_{CS}
pm	Flood recurrence (years)	250	633	0.61
	Nature area (ha)	102	107	0.05
	Ecosystem diversity (–)	0.7	0.98	0.29
	Gravel extraction (*10^6 tons)	3.7	5.6	0.34
	Profitability (%)	4	13.7	0.71
cit	Flood recurrence (years)	250	633	0.61
	Hindrance (person*years)	30,000	27,022	0.11
no	Nature area (ha)	102	107	0.05
	Ecosystem diversity (–)	0.7	0.98	0.29
	Δ groundwater level (m)	–0.2	–0.11	0.82
farm	Flood recurrence (years)	250	633	0.61
	Loss agricultural area (ha)	102	100	0.02
	Δ groundwater level (m)	–0.2	–0.11	0.82
ge	profitability (%)	4	4.8	0.17

Note: Sensitivity is expressed as the relative difference D_{CS} between the goal value GV and the conditional standard CS.

only lead to increasing or constant support, as illustrated in Figure 6.

We now consider the effect of constraining the acceptable range on the policy outcome. The curves indicate ranges for which the policy outcome remains constant, as well as gradual (linear) changes and stepwise (nonlinear) shifts. A constant range is illustrated for the case of flood recurrence in Figure 6a. For a conditional standard ≤ 633 years, the optimal strategy is invariant and equal to the calculated PA2003, as indicated for point A. This model behavior is easily explained from the differences between the *GV* and *CS* for the goal of flood recurrence, displayed in Table 5. In a constant range, the original optimum in support is thus unaffected by the changing conditional standard. A gradual change occurs, for example, in the case of the nature area in Figure 6b. Here, an increase in *CS* from the original 1000 ha to 1500 ha leads to the new optimal strategy D, which slightly deviates from the calculated PA2003 by including more “additional nature area.” For these types of gradual changes, the original optimum *is* affected by the changing conditional standard, but the new optimum lies on the same local support maximum in river management space.

For a typical example of a stepwise shift, we return to the case of flood recurrence. When the conditional standard exceeds the critical point $CS = 633$ years, the optimal solution shows a stepwise shift. The new optimal river management strategy B strongly differs from the calculated PA2003, consisting primarily of broadening and main channel elevation. Our model results indicate that the citizen does not accept the strategy B because the hindrance levels associated with this strategy are too high. This explains why the new optimum is so different. Since citizen support is fixed at –1, it becomes effectively irrelevant for the optimization procedure. The new optimum thus represents a significantly different situation of optimization among the interests of the remaining stakeholders.

A further illustrative example is the case of profitability (Fig. 6h). Increasing the required profitability to 5% results in the new optimum strategy L, coincidentally identical to the strategy corresponding to point B, which the citizen could not accept. Increasing the required profitability further to 6% leads to a gradual change in river management strategy, with somewhat less main channel elevation, as indicated by point M. However, when the required profitability is increased further to 8%, a new step is observed toward river management strategy N, characterized by main channel deepening. Both the nature organization and farmer now object because of unacceptable impacts on the groundwater level. The citizen, on the contrary, has regained its support since the expected hindrance levels have dropped.

Finally, we briefly discuss the effects of enlarging the acceptable range. A reduced profitability standard of 2%, for example, leads to the new optimal strategy K. This strategy is significantly different from the calculated PA2003, with significantly higher stakeholder support. The reduction in the profitability standard could be obtained by providing an additional expenditure of some 10 million Euros (2% on a total budget of 500 million Euros). Also, a reduction of the conditional standard for the nature area to 750 could lead to a different policy outcome (point C in Fig. 6b) with much higher support. Enlarging the acceptable range may thus lead to new, strongly supported solutions. However, the current quantitative estimates must be interpreted with care.

We conclude that the calculated policy outcome may show large changes for changes in conditional goal standards. Constraining the range may lead to stepwise shifts in optimal strategies, often accompanied by unacceptable judgments of one or more agents. Enlarging the range, on the other hand, may reveal new optima with significantly higher agent support. These types of model results may provide new, possibly controversial, viewpoints on river

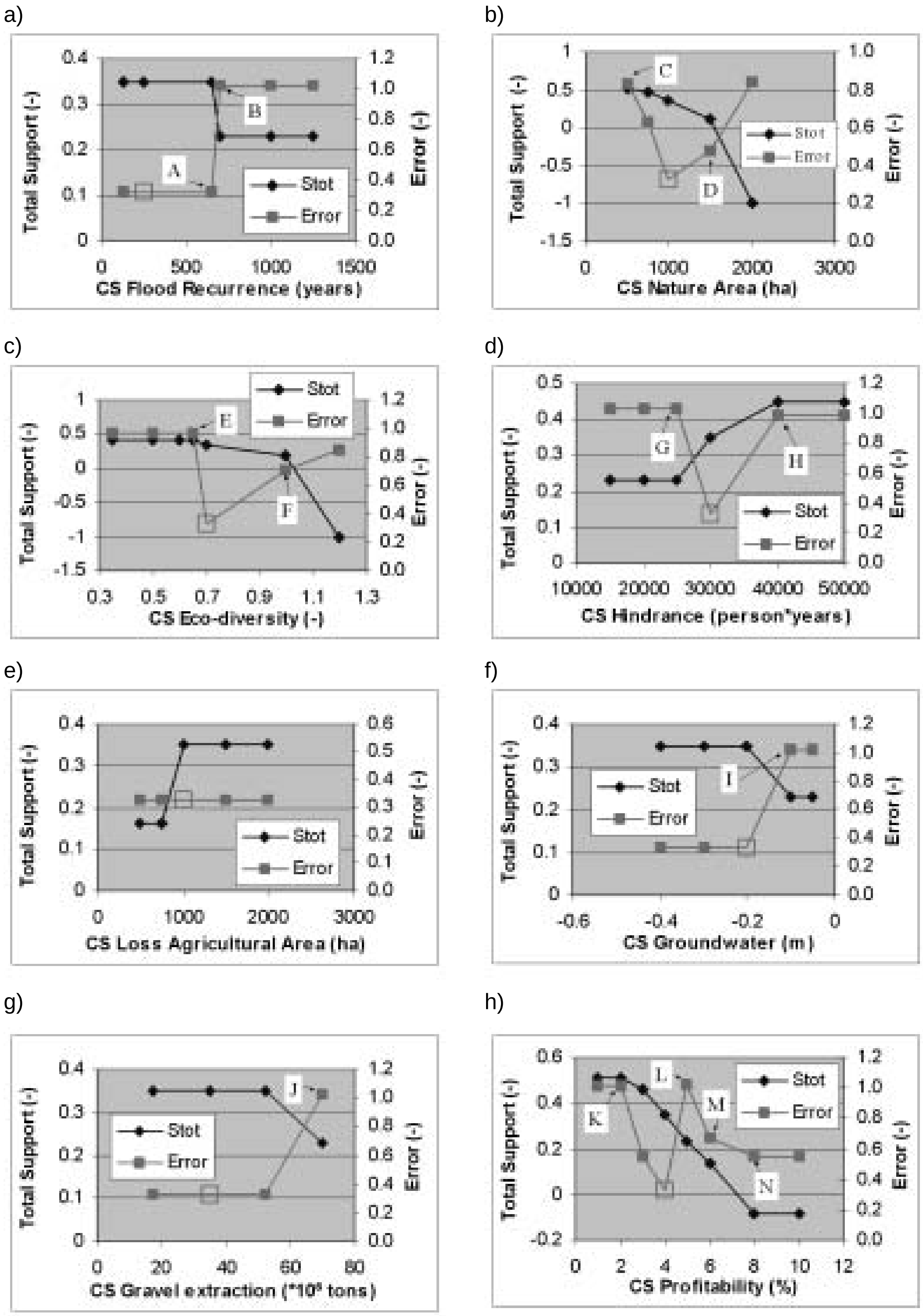


Figure 6. Sensitivity of the policy outcome to changes in conditional standards. The figures show total stakeholder support (S_{tot}) and the error (E_{RMS}) with respect to the observed PA2003 values of the calculated optimal strategies as a function of the conditional standards. Points marked with open squares refer to the estimated conditional standards for the Grensmaas stakeholders listed in Table 3. For points marked with capital letters, the corresponding river management strategies are displayed in Table 6.

management. As such, the model seems useful to explore different river management strategies and stimulate discussions among stakeholders.

6. Changing Uncertainty Perspectives: The Case of Climate Change

As a final model application, we assess how stakeholder support and the policy outcome change when all agents take climate change into account. Climate change is a highly uncertain development, which may cause an increase in discharge of 20% by the year 2050 [24]. Stakeholders are aware of this issue, and it is brought up multiple times, both in the stakeholder reactions [20] and in the stakeholder interviews [19]. In this final model experiment, increasing awareness of climate change among stakeholders is modeled by changing the climate change estimate as part of the agents' uncertainty perspectives. Instead of assuming "no climate change," all agents adopt a central estimate for climate change containing an increase in average winter discharge of 10% with respect to the current situation.

We first assessed stakeholder support for the calculated PA2003 under climate change conditions (see Fig. 7a). In comparison with Figure 4c (the case without climate change), one observes significant changes in support. On one hand, the support of the policy maker, citizen, and farmer would drop because safety standards are no longer met. On the other hand, the support of the nature organization would increase because climate change could lead to a more diverse ecosystem distribution. Second, we calculated the new optimal strategy among stakeholders for conditions of climate change. This strategy incidentally coincides with strategy *B* in Table 6. It contains large-scale riverbed broadening, in combination with raising the river main channel. This would allow society to maintain current safety standards without compromising on the criteria of nature development, groundwater, agricultural area, profitability, and gravel extraction (see Fig. 7b). The citizen, however, would not accept this river management strategy because the hindrance levels are too high.

The model results illustrate that current river management objectives may not be realizable in the case of climate change. A particular dilemma is reaching the required safety level while adhering to a maximum acceptable level of hindrance. The model thus seems useful for reflecting on one's goals in light of uncertain future developments. It may stimulate stakeholders to anticipate these developments by reconsidering adopted goals and standards.

7. Conclusion

In this article, we have presented a coupled agent-based model—integrated river model for describing a policy process among stakeholders of river management. The model must not be considered a "truth machine" that predicts policy making for river management. It is rather a heuristic tool that provides a framework for a "what-if" analysis. Given the goals and beliefs of stakeholders, the model calculates stakeholder support for a river management strategy. The outcome of the policy process is then derived as the strategy with maximum stakeholder support. A simple model validation was performed by reconstructing the preferred river management strategies that were documented in policy reports along three stages of the Grensmaas project. The validation showed acceptable correspondences between the observed and calculated strategies, giving sufficient credibility to the model results for proceeding with some model experiments.

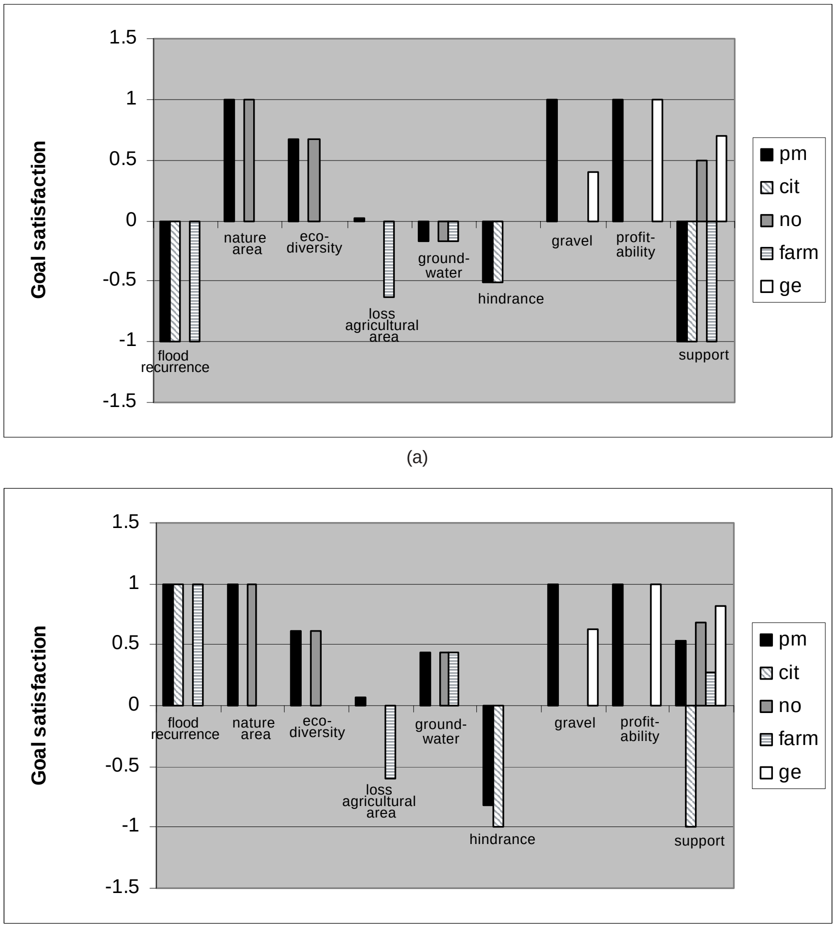
The model results indicate that stakeholder support and the policy outcome depend strongly on the minimal requirements that stakeholders attach to their goals (the so-called conditional goal standards). For example, increasing the requirements for flood recurrence and profitability could imply new river management strategies that will be unacceptable for one or more stakeholders. Improvements in societal support, on the other hand, may be obtained by reducing the requirements for profitability (e.g., through additional governmental expenditure) and nature area. The government may thus influence the policy process through shifting its conditional standards in an appropriate way, encouraging other stakeholders to do the same. In a further experiment, we assessed how the policy process would change if stakeholders took climate change into account. According to our results, climate change could imply main channel broadening in order to cope with increasingly high peak discharges. The citizen, however, would not accept this river management strategy because the hindrance levels would be too high.

In the climate change experiment, we assumed that the goals and standards derived for the current situation would remain the same. We know from the ABM literature that this assumption is not likely to hold. Cognition is likely to adapt in response to a changing environment and/or social interactions [13]. Adaptive cognition can be incorporated in the agent-based model by giving the agents autonomy for changing their goals in response to the stakeholder- environment and/or stakeholder-stakeholder interaction. The former may be modeled by defining a proper set of heuristics for changes in the conditional goal standards to represent learning in response to environmental change. The latter may be modeled as mutual goal adoption among agents to represent cooperation. Modeling adaptive cognition is left for future research.

The main potential of the current simulation model is its application within participatory stakeholder processes. It is outside the scope of this article to treat this application in detail. As with adaptive cognition, the application of this model approach in participatory settings is left for future research. In this article, we did show that the model is sufficiently well developed and valid for application in such a process to address relevant issues in a realistic way. For instance, it may be used in small working groups to explore different river management options

Table 6. River management strategies corresponding to the characteristic points in Figure 6

	Main Channel Deepening (m)	Main Channel Broadening (m)	Floodplain Excavation (m)	Clay Shield Surface (m)	Additional Nature Area (m)
□	0	100	125	4	250
A	0	100	125	4	250
B	–2	200	125	4	125
C	–1	100	125	0	0
D	0	100	125	4	500
E	–2	200	0	3	250
F	–1	100	250	4	125
G	–2	200	125	4	125
H	–2	200	125	3	125
I	–2	200	125	4	125
J	–2	200	125	4	125
K	–2	100	250	3	125
L	–2	200	125	4	125
M	–1	200	125	4	125
N	1	50	125	3	375



(a)

(b)

Figure 7. Assessment of stakeholder support given climate change conditions for (a) the originally simulated river management strategy, the Preferred Alternative (2003), and (b) the optimum strategy given conditions of the climate change strategy.

in relation to the different stakeholder interests and uncertain future developments such as climate change. This may serve to elicit stakeholder perspectives, improve communication, and stimulate the development of shared problem perceptions. A specific feature of the presented model is that goals and goal standards are made explicit. This, we expect, will encourage stakeholders to reflect on their goals in a social context and possibly reconsider adopted goal standards. This may lead to a better agreement about minimal needs and requirements for all stakeholders involved, which could be a small step toward better collaborative and sustainable river management.

8. Appendix: The Course of the Grensmaas Project

The Grensmaas project has its origins in the advisory study "Toekomst voor een grindrivier" (future of a gravel river) of 1991 [11]. In this study, the possibilities are investigated to combine gravel extraction with nature development in the river Grensmaas. ("Grensmaas" is translated as "Border Meuse," referring to the 40-kilometer stretch of the Meuse River north of the city of Maastricht that forms the border between the Netherlands and Belgium.) This combination was sought, on one hand, to comply with the national policy for ecological recovery in the Meuse valley and, on the other hand, to fulfill an obligation of the Province of Limburg to extract 35 million tons of gravel for national use. To this end, Helmer, Overmars, and Litjens [11] developed the innovative concept of "Green for Gravel": riverbed widening in combination with ecological rehabilitation as an ideal solution for reaching both the ecological and economic objectives. The concept contains the following elements: (1) riverbed widening through floodplain excavation and main channel broadening, (2) storage of extracted top layer of river clay in so-called clay shields in the floodplain area, and (3) elevation of the main channel bed through restoring a fraction of the extracted gravel in the main riverbed. The benefits of clay storage are threefold: first, it is a cheap solution for handling the large volume of strongly polluted river clay; second, it allows more and efficient gravel extraction; and finally, a clay shield restrains water drainage and thereby mitigates a potential drop in the groundwater table. Main channel elevation is equally performed to mitigate groundwater level decrease but is very cost-ineffective.

Only a few years later, the Province of Limburg was shocked by two floods that occurred in successive years. In December 1993, the Meuse flooded in the Limburg part of the river basin. An area of 18,000 ha was flooded, affecting about 13,000 people and causing 115 million Euros of damage [25]. In the beginning of 1995, the water levels in the Rhine and Meuse again rose to extreme levels. The total material damage mounted up to 75 million Euros [26] and was inflicted mainly in the Province of Limburg. After these flood events, the aspect of flood protection came strongly into play. The national government quickly responded by launching a river management plan: the so-called "Delta plan Main Rivers" [27]. The Delta plan contained two basic elements. First, it dictated an immediate construction of embankments to achieve a minimal safety level of roughly 1/50. These works were quickly performed and finished within the year at several locations alongside the Meuse. Second, it proposed additional measures of riverbed widening to achieve a safety level of 1/250 on the longer term. This strategy differed from the original concept of Helmer, Overmars, and Litjens [11] by including less main channel elevation to ensure the flood standard to be reached [25].

In 1997, the project organization "Maaswerken" was set up to manage all ongoing river training projects for the Meuse in Limburg, including the Grensmaas project. In 1998, they published a detailed river engineering plan: the Preferred Alternative of 1998 [7]. With this plan, the original Green for Gravel plan was further adapted on a few accounts. The area of floodplain excavation was significantly smaller, which was compensated by additional riverbed broadening. The original idea of main channel elevation was abandoned to ensure a low flood risk and a high profitability. The Preferred Alternative was subject to stakeholder participation in the summer of 1998. Some stakeholders expressed their worries—for example, citizen groups that feared serious noise as a result of the excavation works and farmers who objected to the loss of agricultural land. But overall, the Maaswerken organization concluded that "the majority of stakeholders agree with the underlying objectives and the approach of river widening" [20] so that the Preferred Alternative 1998 can be considered to be broadly supported by the stakeholders involved.

This successful phase of the planning process ended in 1999, when the Maaswerken started negotiations with the gravel-extracting companies for the execution of the proposed river engineering works. The gravel extraction companies hold a powerful position since they own the land and are therefore entitled to perform the works. With the argument that the proposed works were not sufficiently profitable, the gravel extractors demanded either a payment of 100 million Euros or permission for additional gravel extraction [28]. With an intermediate agreement for the extraction of 70 million tons of gravel (20 million tons more than proposed in the Preferred Alternative of 1998), it seemed that the gravel extractors would get what they required. However, because of the expected noise pollution and damage to the landscape and the natural environment as a result of the additional gravel extraction, this agreement led to such a strong opposition from nature organizations, inhabitants, farmers, and governmental parties that it was abandoned right away.

After a deadlock of several years, the Province of Limburg took the initiative to bring all parties together and design a broadly supported plan. In only a few months, a new river management strategy was designed in close collaboration with all parties involved [29]. The Preferred Alternative of 2003 [12] was a compromise in which both the objectives of the Preferred Alternative of 1998 and the objective of profitability were sufficiently met. This was achieved by increasing the volume of gravel extraction from clay shield construction, allowing the surface of the clay shield to be 2 to 3 meters below the original surface level, and decreasing the area of floodplain excavation. In this way, the same amount of gravel could be extracted in a more profitable fashion with lesser amounts of the by-products clay and sand.

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