A Computational Agent Model of Flood Management Strategies

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ABSTRACT

A geographically explicit flood simulation model was designed and implemented as a tool for policy making support, illustrated here with two simple flood management strategies pertaining to the Upper Tisza area in Hungary. The model integrates aspects of the geographical, hydrological, economical, land use, and social context. The perspectives of different stakeholders are represented as agents that make decisions on whether or not to buy flood insurance. We demonstrate that agent-based models can be important for policy issues in general, and for sustainable development policy issues in particular, by aiding stakeholder communication and learning, thereby increasing the chances of reaching robust decisions. The agent-based approach enables the highlighting and communication of distributional effects of policy changes at the micro-level, as illustrated by several graphical representations of outputs from the model.

INTRODUCTION

In the period 1988-1997, the cost for major natural disasters was approximately USD 700 billion, according to 1998 figures from Munich Re, with floods causing around 50 per cent of economic losses (Abramovitz, 2001). As a result, policy makers at the national level are facing increasing costs for compensation and mitigation of floods. Most countries have a disaster compensation policy based on solidarity, in which the government compensates for losses that individual property owners suffer. A higher degree of private responsibility is a distinguishing feature for compensation policies in only a few countries, such as the UK and Australia.

Our simulation model estimates the economical consequences of floods, with respect to different flood risk management strategies. Part of the Upper Tisza river in the relatively poor Szabolcs-Szatmár-Bereg region of Hungary was investigated, with a focus on financial mitigation measures and insurance. For such a complex model—solving the kind of problem that Weaver (1948) famously dubbed a *problem of organized complexity*—to be useful, it must integrate data from different systems. In our case, this translates to geographical, hydrological, economical, land use, and social systems.

We seek to provide evidence for the usefulness of spatially explicit agent-based models in the domain of disaster policy management. In our model, the government, insurer, and property owner stakeholders are represented. Property owner agents are spatially explicit agents in the model, in that their properties have specific locations, affecting agent actions. In each simulated year, for example, the agent makes a decision on whether to buy insurance or not, for a particular property. In a simulation, the model is run to cover a long period of time, normally 50 years. Floods of different magnitude occur stochastically and cause damages to properties in the area. A flood causes either a levee failure or seepage. Different flood management strategies are tested and compared, and a strategy can implement a policy, e.g., subsidy insurance premiums for all poor households and set the compensation level from government to 50 per cent of property loss. The financial consequences for all stakeholders are then estimated at the end of each simulation round.

In the following section, we frame our work inside the field of related research. The third section describes our model, the fourth presents two policy scenarios and their analysis, and the final section gives our conclusions.

BACKGROUND

While the agent area started off with artificial intelligence assistants, service robots, and many other forms of one-agent systems (Agre & Rosenschein, 1996), the potential for societal applications naturally reside with multi-agent systems (O'Sullivan & Haklay, 2000; Gimblett, 2002). In geography, physical components of a complex system—vegetation, fauna, soils, and climate/hydrology—are usually separated from socio-economic ones, like demography, culture, economy, and policy (Reenberg, 2001). An agricultural management strategy then advices and implements a policy by carefully considering those two sets of components separately. An agent-based model like our own, by contrast, lets the stakeholders be represented by agents taking actions in various states of information and in various geographical spaces, in situations where agents are informed of all components to very different extents. Heterogeneity in the agent population is thus an important feature (Wooldridge, 2002).

In microsimulation, the population is usually homogeneous. Early models (Orcutt 1957; Orcutt *et al.*, 1961; Hägerstrand 1975) purported to address the shortcomings of the macro models then reigning in economics, demography, and geography (Merz, 1991), a promise delivered on as computing power became available with which to execute models in scenario analysis fashion (Caldwell & Keister, 1996). The development in computer hardware and software has naturally also benefited agent-based simulations, making them a widely used complement to mathematical theorizing (Axtell, 2000). When to go for agent heterogeneity and when the simpler microsimulation models suffice is a question part of a methodological scientific development still in rapid progress (Boman & Holm, 2004), but agent-based social simulations have proved increasingly important to policy making (Polhill, Gotts & Law, 2001).

The computational model reported on here has in part been discussed in academic theses (Brouwers 2002; Brouwers 2005; Hansson 2007), with the decision-theoretic aspects of the model described in more detail elsewhere (Brouwers *et al.*, 2004; Hansson, Danielson & Ekenberg, 2008).

A SCENARIO SIMULATION MODEL

The model was developed in an iterative process. Initially, an executable prototype model was implemented, using synthetic data. This prototype was based on an existing cyclone model, developed by Ermolieva (1997) at the International Institute of Applied Systems Analysis (IIASA), the host institution for the project. Hydrological inundation and flow models of the area of study in the Upper Tisza river basin were delivered by consultants linked to the project, and these models were included in simulation models developed at IIASA (Ermolieva *et al.*, 2003), where stakeholder interview studies were also carried out. The model described in this chapter consists of five modules, each briefly described in its own subsection below.

The Monte Carlo Module

At the beginning of each simulation round, three stochastic variables are used to simulate flood events of two types: levee failure and seepage. The variables are assigned random numbers in the interval [0,1] from a uniform distribution. The term *flood* is used to describe that the water level in the river is higher than normal. In an unprotected river, all floods would overflow the embankments. However, the parts of the river investigated are protected by levees designed to hold back most floods. The hydrological model gives the probabilities for floods of different magnitudes to occur. The different magnitudes used in the simulations are 100-year floods (minor), 150-year (medium), and 1 000-year (extreme). A 100-year flood denotes a flood that in a long time perspective, the average time between floods of that magnitude or greater, is 100 years. The probability concerns a single year and says nothing of the accumulated risk. The probability distribution for floods is:

- no flood: 0.9823
- minor flood (100-year): 0.0100
- medium flood (150-year): 0.0667
- extreme flood (1 000-year): 0.0010

If the value of the variable *Magnitude* is less than or equal to the threshold for the three floods (0.0100, 0.0167, and 0.0177), the corresponding flood occurs. If a flood occurs, three things might happen:

- levee failure: a levee fails, either by being overtopped or getting burst
- seepage: water finds its way under a levee
- no flood event: the levee holds back the water

The first two events can be combined. The hydrological model gives the failure- and seepage risks for three specific locations along the river. If there is a flood, the values of the variables *Failure* and *Seepage* show whether or not the flood inundates the neighboring land. The variable *Failure* determines whether or not the flood will cause a levee failure, in one out of three possible locations (see Table 1). A careful estimate made by hydrologists in our project indicated that seepage occurs twice as often as levee failures, and so this approximation was used in our model. The probability for a levee failure at location 3 to occur from a 1 000-year flood is thus $0.001 \cdot 0.45$.

Location	Magnitude	Probability of Levee Failure	Probability of Seepage
1	100-year flood	12 %	24 %
2	100-year flood	20 %	40 %
3	100-year flood	28 %	56 %
1	150-year flood	18 %	36 %
2	150-year flood	22 %	44 %
3	150-year flood	40 %	80 %
1	1000-year flood	19 %	38 %
2	1000-year flood	33 %	66 %
3	1000-year flood	45 %	90 %

Table 1: Levee failure and seepage probabilities. Data from the 1999 World Bank report on Hungary's flood control development and rehabilitation project.

The Catastrophe Module

When a flood event has occurred, the effects of the failure and seepage events are calculated, considering, the elevation of the location, how long the inundation lasted and the magnitude of the flood. Only direct damages to private property are considered. The size of the losses further depends on soil type and building materials. The model uses 18 pre-compiled flood event damage scenarios: nine levee failure events and nine seepage events, with the corresponding losses for all properties. When a property is damaged both by a failing levee and by a seepage, only the largest loss is used.

The Spatial Module

The river basin studied is represented explicitly, in the form of a grid with $1\,551 \cdot 1\,551$ cells, each measuring 100m^2. For each cell, rich data is available, including elevation, current land use, asset value, soil type, and vegetation. Each cell belongs to one of eleven municipalities. Example values for the variables are: swamp (soil type), area for sport/recreation (land use), and broad-leaved forest (vegetation).

The Agents Module

The stakeholders in the flood-risk management problem are represented in our model as agents: insurers, property owners, and government. Other agents could have been included, but these were considered by far the most important to financial flood management policy.

The insurer agent is represented by wealth and insurance contracts. The insurer agent is not situated, but the insurance contracts pertain to specific locations. The initial wealth of the insurer agent is HUF one million (corresponding roughly to ten per cent of the expected damage for all properties in the basin caused by levee failures, just to give an indication). An insurance contract is specified by coverage, premium size, and a deductible. The terms of the contracts are decided in the policy strategy currently used in the model. The insurance agent does not offer insurance against seepage events, reflecting the real situation in Hungary, a country in which approximately two per cent of the total claims from private property insurance come from flood damages.

The property owner agents have the following attributes: location, wealth, income, expenditures, and insurance. The location is the cell where the (mid-point of the) property is situated. Each property agent is assigned an initial random wealth, using a uniform distribution in the range [0,10000] HUF. The 2 580 property owner agents in our model have a yearly net income, which is a random value in the range [0,100000] HUF, taken from a normal distribution with the mean 36 900. This mean value was the average net earning per month as of 1998, in the Szabolcs-Szatmár-Bereg county, pertaining to employed persons working in enterprises with more than 20 employees, or in the public sector (according to data from the Hungarian Statistics Central Office). The expenditures are assumed to be high, 90 per cent of the income. The area studied has a high degree of unemployment. In Hungary, 60 per cent of the property owners have property insurance with flood protection included. Property owner agents make annual insurance decisions, i.e., whether or not to buy insurance. Their decisions depend on their risk-willingness and their current wealth. A random value from a uniform distribution is compared with an *InsuranceRate* variable. When the property agents consider buying the more expensive top-insurance, with a risk-based premium, their financial situation determines if they can afford it or not.

Only the part of the governmental budget that concerns flood management is taken into consideration in the model, and only the financial load is considered; i.e., no incomes are included in the model. This is mainly because of the small size of the pilot basin and also due to lack of data. The government agent has a compensation level attribute, and a yearly maintenance cost attribute. The size of the compensation level is set in accordance with the current policy strategy. Maintenance costs for structural mitigation are also considered as a policy parameter, as the maintenance of levees is costly and the degree to which they are attended to vary with the financial climate.

The Consequence Module

At the end of each simulation round, the Consequence module calculates the changes in wealth, for all agents, whereafter their economy is updated. The wealth transformation functions for the different agents are described in detail elsewhere (see, e.g., Hansson, Danielson & Ekenberg, 2008), and are described only informally below.

The policy vector X contains possible policy strategies. An instance x of the vector describes a specific policy strategy. A policy strategy consists of a number of policy parameters, each of which can take on different values. Policy parameters include level of governmental compensation, premium size, and size of the deductible. An example policy strategy could then correspond to, e.g., governmental compensation set to 40 per cent, premium size one per cent of property value, and size of deductibles set to HUF 100 000. The uncertainty is treated explicitly in the model, i.e., the vector X contains all stochastic variables. The modeled system can be in different states, and a state can be thought of as a snapshot of the model with all the values of all variables displayed. The values of some of the variables are impossible to predict with certainty, and these stochastic variables include wind speed, precipitation, water level, and discharge. In the experiments reported on here, the vector X contains only the three variables described in the Monte Carlo module subsection above: *Magnitude*, *Failure*, and *Seepage*.

Let W^P be the wealth of the property agent P. The wealth is transformed over time as a function of the compensation received from the government, with the size depending on the severity of the flood, and the degree of compensation which is decided by the policy parameter x. Cost for flood damages on the property are deducted, and the income is added to the wealth, with expenditures deducted. The wealth W^P is finally updated according to the collected claims, and the paid premiums. Naturally, more than one insurance company may be involved. How much insurance compensation the property owner receives from each insurer depends on two things:

- the current policy strategy x, which decides the size of the deductible, and coverage, i.e., the proportion of the property insured, and
- the severity of the flood.

A 70 per cent coverage of a building worth HUF one million means that the building is only insured up to 700 000. Such a building might have an insurance contract with the following features: coverage 70 per cent, deductible 10 per cent (with the first ten per cent of the losses not covered by the insurance, this being an example of a policy parameter). If a flood occurs that destroys 50 per cent of the property, the property owner would receive HUF 315 000 from the insurance company (losses: 500 000, deductibles: 50 000). Compensation from the government is added to the wealth, according to the policy parameter x, with the size depending on the severity of the flood. The cost for insurance premiums is then deducted. The premium is considered a policy parameter, which is dependent on the size of the coverage and can vary among the insurer agents. For example, if the premium is set to five per cent of the property value, and coverage to 50 per cent, then a HUF one million building would cost HUF 25 000 (per year) in insurance premiums.

In a similar fashion, the wealth W^{Gov} of the government agent *Gov* can be calculated. It is reduced by flood compensation G paid to the property agents $P_1,...,P_n$, where x is the policy parameter, as explained above. The government agent also suffers direct costs for flood mitigation, as well as costs for maintenance of structural flood mitigation measures, represented together in the below equation as M for the flood ω:

$$W^{Gov}(x,\omega) = W - \sum_{P=1}^{n} G_P(x,\omega) - M(x)$$

The wealth of an insurance agent W^I increases with the premiums received from the property agents. Coverage is determined by the policy strategy x, and x also determines how much compensation must be deducted from the wealth of W^I, given the severity of the flood. Risk-based premiums are calculated per location. Each levee failure scenario has its damage costs multiplied by the probability of the failure, and the expected damages for all scenarios are calculated. A safety load accounting for margins of profit and administrative costs is then added to the premium by W^I.

TWO POLICY SCENARIOS

Policy strategies for coping with losses vary from country to country, and several grounds for choosing a policy can be identified. The capacity of the insurance industry in a country may affect the degree to which a local government becomes involved. In Hungary, an increased use of private catastrophe insurance is still a debated matter on the political agenda. The history and the tradition of how the government acts have had a significant influence on the prevailing flood management policies. At the outset of the research project, Vári (1999) carried out interviews with the stakeholders in the Upper Tisza region, and most respondents agreed to measures protecting the high-risk settlements, at all costs. Only a minority of respondents would support even partial relocation of the local population. Regarding strategies for sharing economical responsibility, most respondents thought that the government should compensate the victims. However, many would accept a policy combining government compensation with private or community self-insurance schemes. As many as 46 per cent of the respondents were of the opinion that taxes should be used as a means to compensate victims.

Linnerooth-Bayer (2001) subsequently designed three possible flood risk management policy scenarios for Hungary, based on interviews and surveys of the views of the stakeholders. A crucial problem was to find a balance between social solidarity, private responsibility and community responsibility. Two of the three scenarios were implemented and tested within our simulation experiments.

Scenario 1 represents the current flood management strategy in Hungary, which is why we refer to this scenario as *Business as usual*. The government continues to compensate the property owners from floods caused by levee failures, as this is considered the responsibility of the government. It also compensates for seepage, but the compensation is smaller than for levee failures. The government finances the costs for mitigation and compensation from its catastrophe budget, meaning that all taxpayers contribute. The insurance is a bundled property insurance, where the all-hazard insurance part accounts for two per cent of the total premiums (in accordance with assumptions recommended by insurance experts employed by the project). The size of the premium is based on property value alone, which implies a cross-subsidization of premiums from low-risk locations to high-risk locations.

In Scenario 2, which we named *Market Model*, part of the responsibility is shifted from the government to the individual property owner, which is why the compensation from the government is reduced. The seepage events are still compensated for, but only to a low extent. The property owner agents also receive less compensation than in Scenario 1 from their normal insurance, the intention behind this being to reduce the level of cross-subsidization. The gap in insurance coverage can be filled by buying a risk-based insurance, with its premiums based on the local flood-risks. The expected damage for a property is the base for calculating the size of the premium, and in our experiments, 545 properties were affected by levee failures. The expected damages are multiplied by a safety load, as was explained earlier. In Figure 1, the expected damages for the properties are presented.

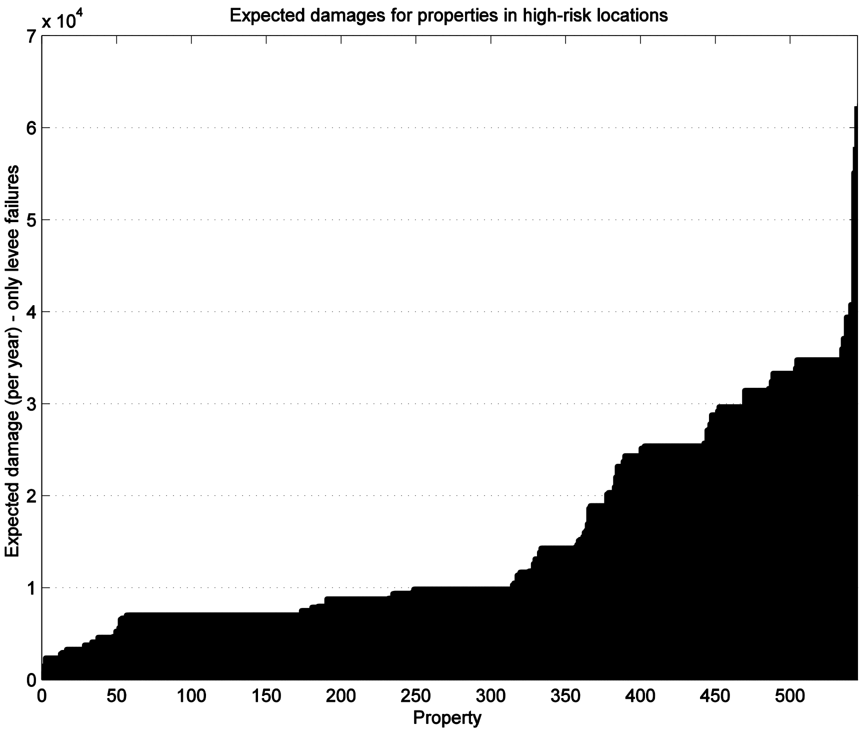

Figure 1. Expected damages for properties, given levee failures. The properties on the x axis are sorted according to the size of the expected damages.

Experiments

The following settings were used for simulation experiments for the Business as Usual scenario.

- Maintenance cost: HUF 100 000 per year (for the levees in the basin)
- Compensation from government (levee failure): 100% of damages
- Compensation from government (seepage): 50% of damages
- Deductible: the first 5% of the damages
- Coverage: 100%
- Insurance rate: 60% of the households have property insurance
- Insurance premium: cross-subsidization, 0.2% of property value per year

It might seem strange that property owners are compensated from the government even if they hold private insurance, but the rationale for this policy of double compensation as implemented in Hungary was to encourage house owners to buy insurance. If insurance holders were punished by not being compensated by the government, the incentive to buy private insurance would be reduced.

The following settings were used for the simulations of the scenario Market Model.

- Maintenance cost: HUF 100 000 per year (for the levees in the basin)
- Compensation from government (levee failure): 75% of damages
- Compensation from government (seepage): 30% of damages

- Deductible for cross-subsidization: the first 5% of the damages
- Coverage for cross-subsidization: 60%
- Insurance rate for cross-subsidization: 60%
- Premiums for cross-subsidization: 0.1% of property value/year
- Coverage for risk-based top-insurance: 100%
- Insurance premium for top-insurance: risk-based (as explained above)
- Insurance rate for top-insurance: approximately 10%; first decided by financial situation, then by risk-willingness
- Deductible for risk-based premium: 0%

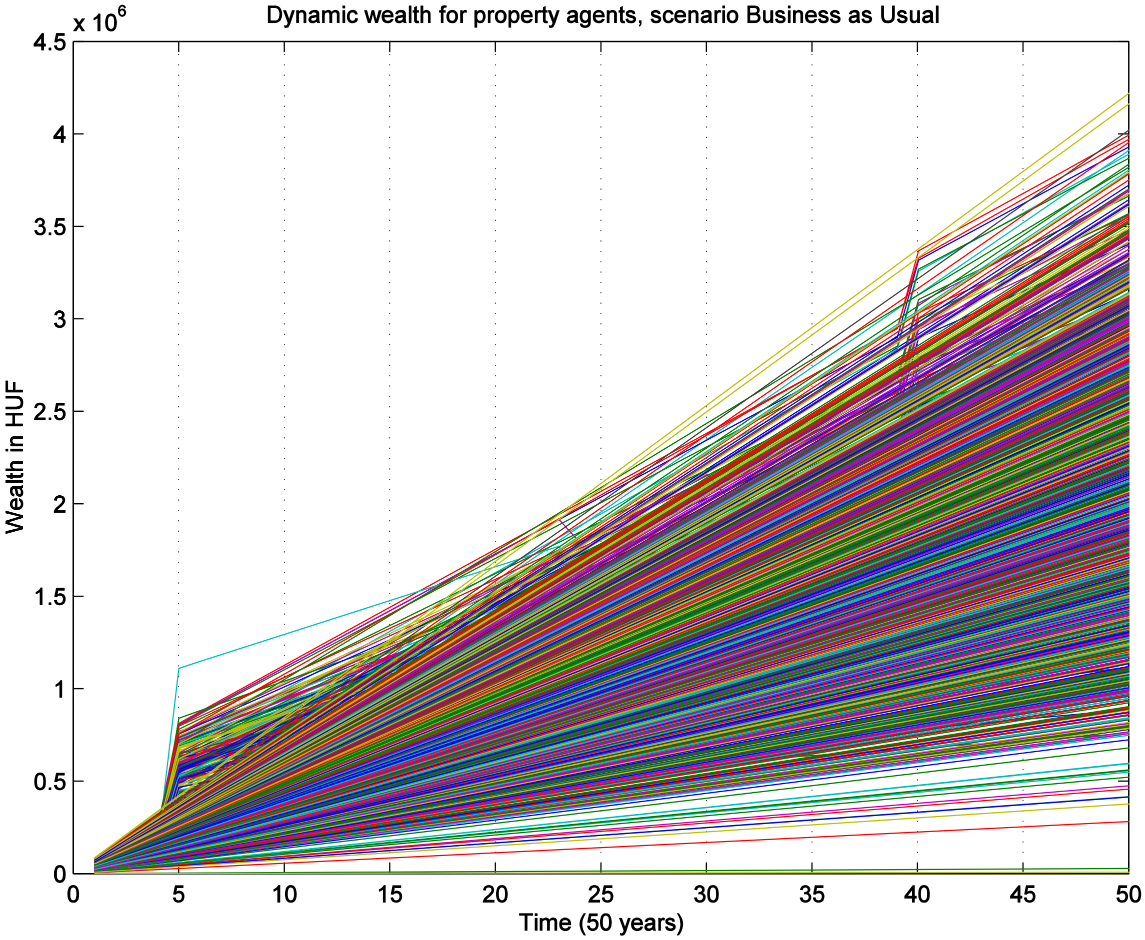

Figure 2. Dynamic wealth of property agents in the pilot run for the Business As Usual scenario.

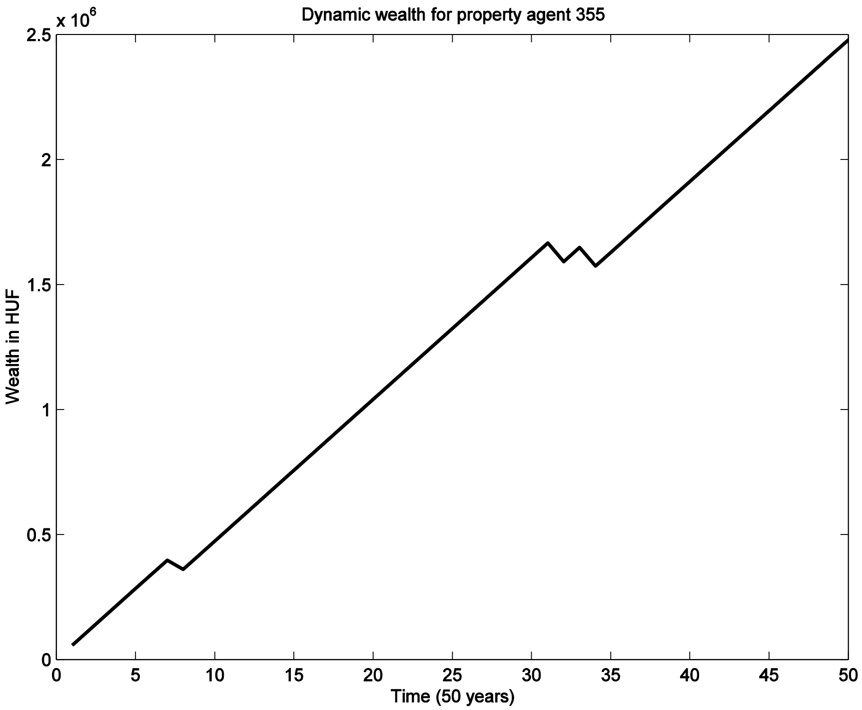

Figure 3. Dynamic wealth of a single property agent in the pilot run for the Business As Usual scenario.

The same distribution of flood events and baseline insurance were used for the two scenarios. Each scenario was first simulated only once, for a time-period of 50 years, as a pilot. The goal of the pilot was to investigate how the consequences for individual property owners may vary. The figures presented are merely included to show the variety in consequences among the agents. This serves here as an illustration of how our output can support policy considerations. The wealth of the property agents grows steadily during the simulated 50-year period, as the expenditures are smaller than the income. During this time-period in the pilot, four flood events occurred: two failures (in years 8 and 41) and two seepage events (in years 32 and 34). Looking carefully at the dynamic wealth trajectories (Figure 2), the effects of the double compensation are visible at the years in which the failures occurred. No property owners show a negative balance during the time period. When the seepage events occurred, the changes in wealth are too small to show, but by inspecting the wealth of a single property agent we can clearly see how its wealth is affected (Figure 3). This again serves to illustrate the usefulness of an agent-based model: any agent can be monitored more carefully, as needed, e.g., for the purpose of fairness studies. Model heterogeneity is also displayed here, in that not all property owners are affected by all flood events; this example property owner was not affected by the failure event that occurred in year 41.

A second set of simulations was run after the pilot experiment, in which the number of simulations was increased to 1 000. The time period was still 50 years and both scenarios used the same distributions of flood events and cross-subsidized insurance contracts. These experiments showed that the difference between the two policy scenarios mainly affected the property owners. The property owners who experienced seepage failures suffered severe losses, since the government only compensated 30 per cent. The property owners in high-risk areas, who had much insurance, gained economically from levee failures. The majority of the property owners who most needed the top-insurance could not afford one, reflecting the real situation in the area. The experiments further indicate that the reduction in governmental compensation (as in the Market Model scenario, see Figure 4) was too small to bring any significant changes to the governmental flood management budget. If the compensation is reduced further, a market approach is likely to be very efficient for the government, since the responsibility of the loss lies more with the individual. This strategy also forces both industry and individuals to reduce risk, e.g., through constructing measures of their own. Governments carry a large responsibility for the infrastructure in the corresponding countries and they may wish to reduce catastrophic losses by diversifying with insurance, or other risk transfer instruments. On the other hand, the pressure of people living in risk prone areas might be high since they may not afford insurance. To illustrate how the government stakeholder perspective can be presented, we can simply turn to the wealth trajectory of the government agent (Figure 5).

The deductible can be used as a policy tool for reducing the concentration of people and properties in high-risk areas. A high deductible, or an upper limit on the insurance contract, puts a larger financial responsibility on the individuals. The fairness of subsidization of insurance premiums is also debatable. It is not self-evident that insurance should be cross-subsidized, for instance. In Figure 6, we illustrate how the fairness issue can be made clear by noting a number of property agents gone bankrupt.

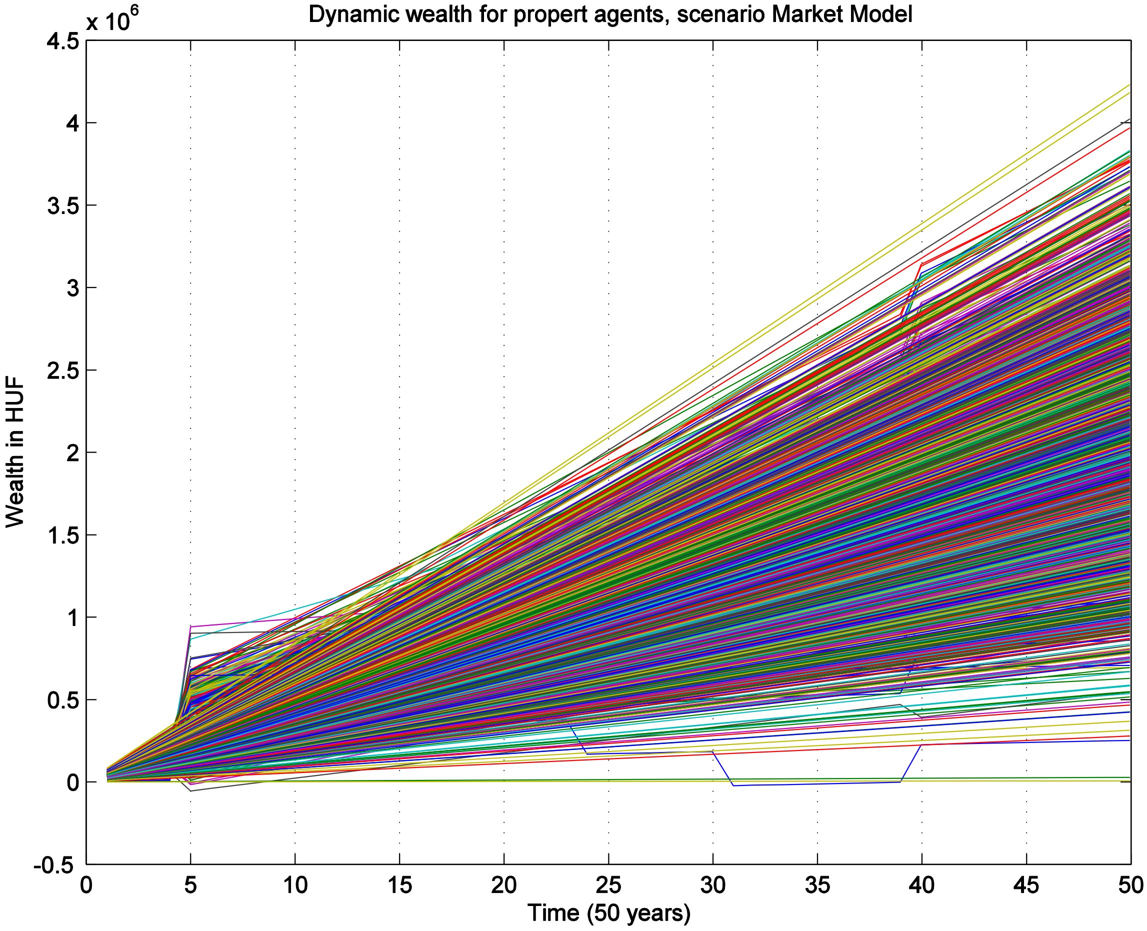

Figure 4. Dynamic wealth of property agents in the pilot run for the Market Model scenario.

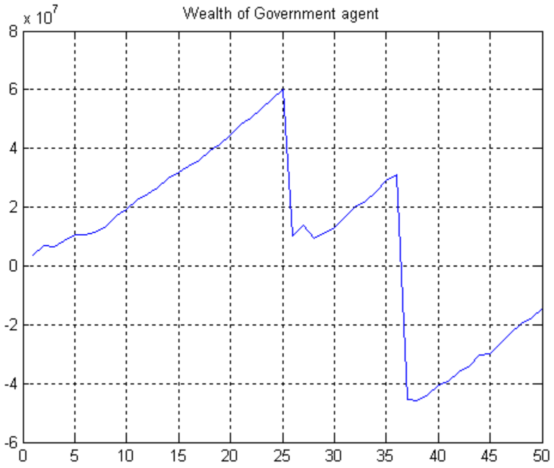

Figure 5. Dynamic wealth of the government agent in one particular run of the Business As Usual scenario, in which the government went bankrupt after 37 years. The y axis shows wealth in HUF, and the x axis shows years.

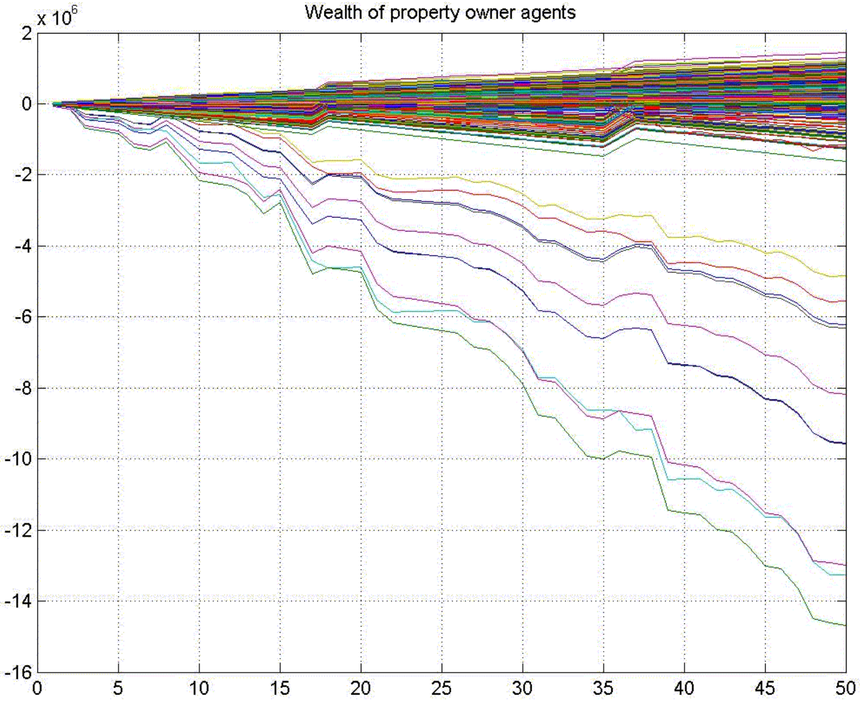

Figure 6. Dynamic wealth of property agent in a set of runs of the Market Model scenario, in which several agents went bankrupt almost immediately, later followed by numerous agents in a less spectacular fashion. The y axis shows wealth in HUF, and the x axis shows years.

CONCLUSIONS

A flood-risk management model like ours is potentially useful as a basis for discussions of alternative policy strategies, in settings where policy makers and stakeholders work together. As a case in point, one may show that a flood management strategy that seems fair at the aggregate level may hide large inequalities apparent only when considering the outcomes for specific agents. For a model like ours to be useful, it is important that the results are presented to the individuals also in more aggregate ways. The model can then contribute through visualization at stakeholder meetings on catastrophe management questions, on both mitigation strategies and issues of fairness.

Since the Tisza project was completed, we have pursued agent-based modeling as a way of supporting policy. Executable and spatially explicit models for several applications were made, chiefly within the area of epidemiology. Whatever the application area is, visualizing results down to the individual level has proven to be a powerful way of providing policy background material, and grounds for debate. With the advent of faster computers and improved methodologies for large-scale simulation, we expect even more interest for executable agent-based models in the future.

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