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# What are the merits of endogenising land-use change dynamics into model-based climate adaptation planning?

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## Abstract

Integrated assessment models often treat land-use change as an external driving force. In reality, land-use is influenced by environmental conditions. This paper explores the merits of endogenising land-use change, i.e. making land-use change an internal dynamic process in models used for supporting climate adaptation planning. For this purpose, we extend the Waas environmental impact assessment model, a hypothetical case study previously used for exploring new model-based climate adaptation approaches. We use a utility-based land-use change model for endogenising the land-use dynamics, evaluate its implications, and identify the conditions under which endogenising land-use change becomes important. We find that endogenising land-use dynamics changes the performance of the policies, allows for assessing policies that target land-use, and widens the outcomes of interest that can be considered. The relevance of endogenising land-use dynamics depends on (i) the expected degree of future climate change, (ii) the society's sensitivity to climate events, and (iii) the types of policies that decision makers want to evaluate. Ignoring the interaction between the environment and the society (in this case the land-use) can result in both under- and overestimation of the impacts of adaptation and might limit the adaptation options that are considered.

## Keywords

Land-use; adaptation planning; integrated assessment model

## Code Availability

The loosely-coupled Waas model was developed by coupling an environmental impact assessment model (EIAM) and a land-use change model (LUCM). The EIAM was developed using the high level programming language Python 2.7 and the open spatio-temporal model software PCRaster 4.0.2 (<http://pcraster.geo.uu.nl/>). The LUCM was developed using the Land Use Scanner model (<https://spinlab.vu.nl/research/spatial-analysis-modelling/land-use-scanner-model/>). The model can be made available upon contact with the authors. The data from the simulation results and the scripts used for the analysis can be accessed at [https://github.com/bramkaarga/waas\\_landuse\\_couple](https://github.com/bramkaarga/waas_landuse_couple).

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## 1. Introduction

Decision makers in climate adaptation planning face uncertainties about the future context within which adaptation measures need to be implemented (Dessai & van der Sluijs, 2007). Nevertheless, decisions still have to be made, or at least planned in advance, as failing to do so may result in adverse impacts (Füssel, 2007) and may limit options (Haasnoot et al., 2012). Embracing this challenge means changing the adaptation planning approach from developing static plans that assume a well-characterised future to designing dynamic plans that perform good enough under deep uncertainties (Maier et al., 2016; Walker et al., 2013). The central idea behind dynamic planning is that the plan should allow for flexible adjustment over time in response to new information that decision makers will obtain in the future. One way to develop dynamic plans is to evaluate alternative sequences of decisions (adaptation pathways) in order to identify short-term actions and long-term options for adaptation. This way of dynamic planning is exemplified by the Dynamic Adaptive Policy Pathways approach (Haasnoot et al., 2013). To support decision makers in developing dynamic plans, Haasnoot et al. (2014) suggest the use of fast integrated assessment models to design adaptation pathways.

Integrated assessment models (IAMs) combine the knowledge of a broad range of disciplines in order to provide added values for policy support and decision-making processes (Van Delden et al., 2011). The transdisciplinary nature of IAMs has increased their popularity as a decision support tool for climate adaptation planning (Chambwera et al., 2014; Patt et al., 2010). IAMs have been used for decision support at various scales, ranging from city scale (Chang et al., 2008; Hall et al., 2010), province scale (Carmona et al., 2013; Qureshi et al., 2013), national scale (Gao & Bryan, 2017; Oxley et al., 2013), regional scale (Cofala et al., 2010), and global scale (Rotmans et al., 1990; Schwanitz, 2013).

The shift to designing dynamic plans requires a modelling approach that considers a large ensemble of plausible futures (Lempert, 2003). This necessitates a model that has a limited simulation runtime. There is no one clear-cut time threshold to indicate whether a model is sufficiently fast. Rather, it depends on one's computational capacity and the time availability for the analysis. The model should be fast enough to run a large number of scenarios (in the order of thousands to hundreds of thousands of simulation runs).

Such models can be developed by simplifying detailed models while retaining the ability to sufficiently mimic the system. To realise this, Haasnoot et al. (2014) suggest the use of theory informed metamodeling, resulting in fast integrated assessment meta-models (IAMMs). The aim of IAMMs is to approximate the behaviour of a more detailed model within a reasonably shorter runtime. IAMMs can be constructed purely based on statistical inferences between the variables in the complex model (Barton, 1998), or based on the combination of the statistics and the representation of the processes within the system (Davis & Bigelow, 2003). Given the same set of inputs, the IAMM is expected to yield outputs that are similar to the complex model (Hamilton et al., 2015).

Uncertainties in climate adaptation planning may arise from natural, socioeconomic, and technological systems (Haasnoot et al., 2009; Moss et al., 2010; Refsgaard et al., 2007). Recent studies suggest that in the context of climate adaptation planning, the impacts of socioeconomic uncertainties may be more profound than climate change uncertainties (Harrison et al., 2016). For instance, Audsley et al. (2015) show that population growth and commodity import dynamics have a bigger impact on agriculture intensification and deforestation, compared to uncertainties about precipitation and temperature. Holman et al. (2016) demonstrate that a higher variability in the urban, coastal, land-use, water, and biodiversity impact indicators can be attributed to socioeconomic scenarios rather than to uncertain temperature dynamics. Fant et al. (2016) investigate the magnitude of population exposed to water stress while isolating climatic and socioeconomic uncertainties independently, and find that the socioeconomic drivers yield higher variance in outcomes. In fact, a part of climate change adaptation is the autonomous choices by the people to change their social and economic livelihood, such as by migrating to areas that are less exposed to climate impacts (Hauer, 2017). Such autonomous adaptation is not comprehensively addressed in climate adaptation studies, or is treated as an uncertainty that is exogenous to the analysis. This practice may undermine human adaptations to climate change and may result in a flawed analysis which overestimates negative impacts (Cass, 2018).

In spatially explicit IAMs, socioeconomic uncertainties are often manifested in the form of several alternative future land-use maps (Swetnam et al., 2011). The land-use maps, however, are often treated as a static exogenous input to the IAMs (Wada et al., 2017). They are created by other independent means and then used as input to the IAM (Brown et al., 2004; Taylor et al., 2012). In reality, land-use dynamics and climate change are part of an inseparable socio-environmental system. There are bidirectional interactions between them (Filatova et al., 2013). Land-use decisions are influenced by the behaviour of the natural system (Lambin & Meyfroidt, 2010; Wagner & Waske, 2016), while the performance of the natural system is affected by land-use decisions (Abd El-Kawy et al., 2011; Laliberté et al., 2010; Stonestrom et al., 2009). To this end, a recent study by Wagner et al. (2016) has demonstrated a new approach by dynamically adding new land-use maps to a hydrologic model at multiple points of time in the simulation. The standard static land-use maps approach has proven to underestimate the hydrological impacts if future land-use changes follow a non-linear path (Wagner et al., 2017). In spite of the innovativeness, the interaction between the dimensions in this work is still unidirectional: from the land-use to the environment.

This paper aims to identify the merits of making the land-use change dynamics an internal process in a spatially explicit integrated assessment model used for supporting climate adaptation planning. What are the implications of endogenising land-use change dynamics in simulation models used for supporting adaptation planning? Under what circumstances do these implications materialise? For answering these questions, we utilise a flood risk IAMM of the stylised Waas case study (Haasnoot et al., 2012). We make the land-use change endogenous by extending the environmental-based IAMM with an independent land-use change model. We apply pairwise comparisons between simulation runs where land-use dynamics are endogenised and are kept exogenous, and observe how the policy performance indicators are affected. We also explore the potential of having policies that target the land-use dimension in addition to the original physical-based policies. We extend the performance indicators being observed by having disaggregated, actor-based policy performance indicators (e.g., welfare/utility of actor groups, flood risk for each dike ring) in addition to the aggregated policy performance indicators (e.g., total welfare, total rice production, total flood risk) that are prominent in model-based climate adaptation studies.

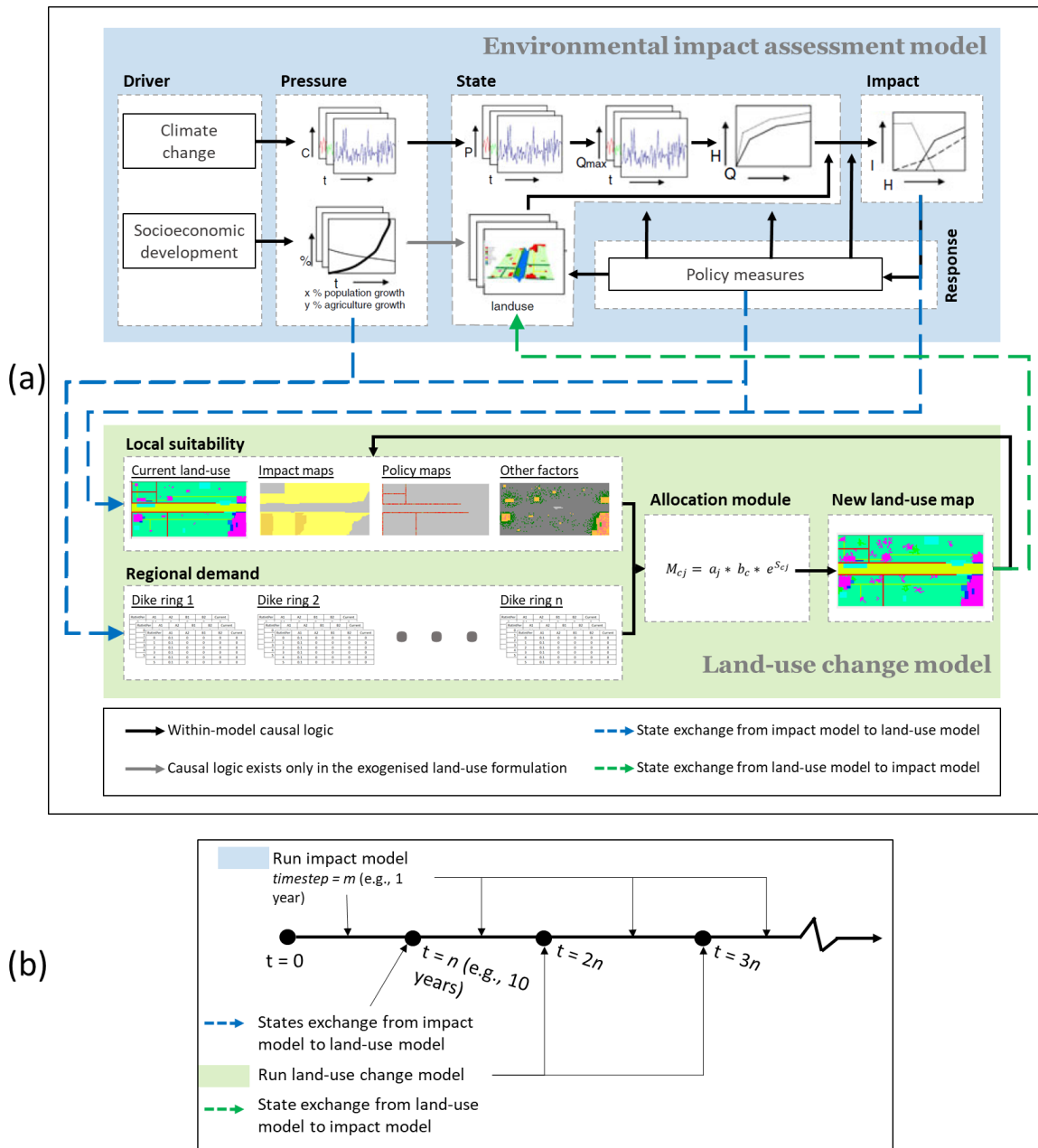
The remainder of the paper is structured as follows. In Section 2, we outline the building blocks of the model that comprise the environmental impact assessment model, the land-use change model, and the coupling mechanism between these two models. In Section 3, we introduce the case study and the experiments design. In Section 4, we report the results of the experiments, and in Section 5, we discuss the key findings from the experiments. Last but not least, the conclusions are presented in Section 6.

## 2. Loosely-coupled integrated assessment and land-use change model

### 2.1 The Environmental Impact Assessment Model

The natural system in this study is encapsulated in an environmental impact assessment model. The main aim of this model is to translate climatic pressures into socioeconomic impacts. The model is built upon the integrated assessment meta-model (IAMM) paradigm. The IAMM follows the theory-motivated metamodel approach (Davis & Bigelow, 2003). In this approach, the IAMM is constructed partly from statistical inferences from more complex models, and partly from the physical processes of the system. The Drivers-Pressures-State-Impacts-Responses (DPSIR) concept (Niemeijer & de Groot, 2008) underlies the cause-effect relations. The approach is applied in the context of flood risk management in the presence of climate change (Haasnoot et al., 2012).

As an example of the DPSIR framework, uncertainties about future climate change and socioeconomic development (drivers) are translated into maximum annual river discharge and future land-use claims (pressures), which in turn affect the probability of flood event occurrence and the land-use pattern (state). If flood events occur, the damage (impact) is incurred based on the physical properties and the land-use function of the flooded area. Decision makers then respond to these risks by implementing policies (responses) that may reduce the probability (affecting the state) or the consequences (affecting the impacts) of the flood risks. In this paper, an iterative process of the DPSIR concept is followed: responses are predetermined and implemented in advance so that their efficacy can be evaluated ex-ante. The implementation of the DPSIR concept into the IAMM is schematised in the blue box in Figure 1a.



**Figure 1:** Conceptualisation of the integrated assessment model; (a) cause-effect relationships within and between the Environmental Impact Assessment Model (blue box, adapted from Haasnoot et al. (2012)) and the land-use change model (green box); (b) the states and time integration scheme for models coupling, the colored boxes and arrows refer to modules and relationships in (a).

## 2.2 The land-use change model

Land-use modelling approaches can be classified into two categories: the inductive, data-driven approach, and the deductive, theory-induced approach (Overmars et al., 2007b). The two approaches differ in how local suitability, i.e. the attractiveness of a given parcel on a grid to each land-use class, is defined. Given a set of spatially explicit variables, the inductive approach employs statistical techniques to identify the variables that are significant in explaining land-use changes (see e.g. Lesschen et al., 2005; Serneels & Lambin, 2001). Conversely, the deductive approach starts from understanding the underlying decision-making processes for

each land-use class, then combines this information with the spatially explicit variables (see e.g. Diogo et al., 2015; Van Delden et al., 2010).

The inductive approach is more widely used in economics-based land-use modelling due to its better performance in reproducing historical land-use pattern (Overmars et al., 2007a). This approach, however, has a conceptual drawback. Due to the nature of statistical techniques, this approach fails to capture the importance of variables that have historically been constant. For instance, if the data shows no significant changes in precipitation patterns, then the importance of this variable would be underestimated by the inductive approach, while in reality this variable may play a significant role in the agriculture sector's decision making. This makes the inductive approach less suitable for model-based support for climate adaptation, in which the main objective is to explore the performance of policies under uncertain changing conditions (Dessai et al., 2009). Therefore, in this paper we adopt the deductive approach.

The local suitability of the land-use classes is defined based on a utility framework (Koomen et al., 2015). Here, the local suitability of a parcel for a certain land-use class is calculated based on the combined economic and social utility of that parcel. This approach establishes a behavioural logic to the model and facilitates a forthright interpretation of the decision-making processes.

Besides the local suitability module, the land-use change model in this study has two other modules: the regional demand module and the allocation module (Koomen et al., 2011). The regional demand module contains information on the projections of the total future demand for each land-use class, distributed over the specified regions. The projections and the current existing area of a land-use class become the future land claim of that land-use class, which in turn will be allocated to the individual parcels by the allocation module. The allocation module uses a doubly-constrained logit model that combines the land claims and the spatially explicit local suitability information (Hilferink & Rietveld, 1999). The relations among the local suitability, regional demand, and allocation modules are exhibited within the green box in Figure 1a.

### 2.3 Loose and bidirectional coupling of the model

We integrate the environmental impact assessment model and the land-use change model in a loosely-coupled and bidirectional manner (Antle et al., 2001). In this approach, the coupling is done between two or more standalone submodels that can still be run independently despite the presence of the other models. The state variables of one submodel become the input vector for the other submodels. The bidirectional nature implies that state exchange happens in two directions.

The loose and bidirectional coupling of the two models involves states and time integrations as schematised in Figure 1b. First, the environmental impact assessment model is run for  $m$  time step. Every  $n$  time step, where  $n \geq m$ , several states from the environmental impact assessment model are fed into the local suitability and the regional demand modules within the land-use change model (the blue dashed lines in Figure 1a). The allocation module is then executed and the resulting new land-use map is fed back to the environmental impact assessment model. The impact assessment model then continues running and the same states exchange procedure is carried out every  $n$  time steps.

Three types of state information are transferred between the models: the impact maps, the socioeconomic pressures, and the land-use maps. The impact maps become one of the determinants of the local suitability. The socioeconomic pressures are translated into future land area claims of each land-use class in the regional demand module, distributed across the regions in the system. This is the key difference between the endogenised and the exogenised land-use dynamics model formulation. In the exogenised one, new land-use maps are created top-down in advance without taking into account the climatic impacts. In the endogenised case, new land-use maps emerge from bottom-up decisions that consider experienced climatic impacts.

There are two additional types of policies that could be implemented when land-use change dynamics are endogenised: the region-level and the grid-level zoning policies. The former influences the regional demand module while the latter adds additional policy maps to the local suitability module (see the green box in Figure 1a). An example of the first type could be the restriction of further industry development in disaster prone regions. Applying this policy means subtracting the industrial land claim in certain regions to zero and adding it to the other regions in the regional demand module. An example of the second type could be the protection of

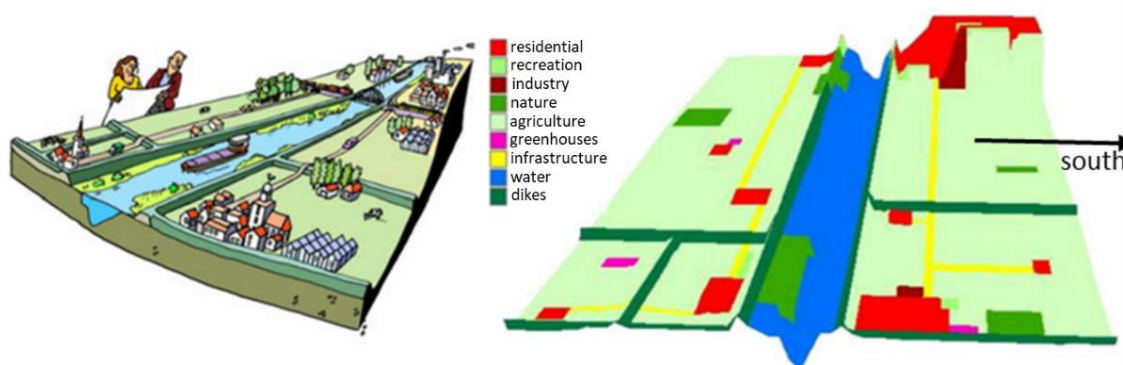
nature area from urban development. This policy could be applied by adding an additional policy map that represents the closeness of each parcel to the nature area. The closer a parcel to any existing nature area, the less suitable it is for future residential area.

### 3. Application: The extended Waas case

#### 3.1 Background

We use the hypothetical ‘Waas’ case, a climate adaptation flood risk case study that schematises the Waal, a river reach in the Netherlands part of the Rhine Delta (Haasnoot et al., 2012). The Waas case is an Environmental Impact Assessment Model that simplifies the land-use representation of the Waal river, for instance by having fewer dike rings. However, the modelled physical processes are highly representative. The flooding mechanisms are derived from other validated models previously used for studies on the Waal river. This theoretical case study has been frequently used as a lab experiment to test the consequences of new approaches for model-based adaptation planning (e.g., Buurman & Babovic, 2016; Kwakkel et al., 2015, 2016; Manocha & Babovic, 2018; McPhail et al., 2018).

Figure 2 shows the spatial representation of the model. There are five dike rings protected by embankments alongside the river. Agricultural is the dominant land-use function. A large city exists on the higher elevated ground in the southeast part of the delta. The model encompasses an area of approximately 300km<sup>2</sup>, divided into parcels 200m x 200m in size.



**Figure 2:** Spatial visualisation of the Waas Environmental Impact Assessment Model (Haasnoot et al., 2012).

The Environmental Impact Assessment Model comprises cause-effect relations, depicted in the blue box in Figure 1a. The climate realisations ( $C$ ) define the precipitation rate ( $P$ ), in turn translated into the maximum annual discharge of the river ( $Q_{max}$ ). The discharge is translated into maximum water levels ( $H$ ) using discharge rating curves. The water levels are compared with the dike heights. The difference between the water levels and the dike height determines the probability of dike failures due to overtopping, breaching, and/or piping. Dike failures cause inundation of the floodplain. The water depth on the floodplain is calculated based on the intersection of the water level of the river and the elevation of the area. As we only consider large-scale annual flood events, smaller pluvial flood events caused by rainfall and surface runoff are not accounted in the model. Damages from flood events ( $I$ ) are calculated based on the water depth and land-use damage relations functions. The model is developed by using the PCRaster library, a Python-based environment to simulate process-based spatiotemporal models (Karsenberg et al., 2010; Schmitz et al., 2013; Wesselung et al., 1996).

Focusing on flood risks, we evaluate the following outcomes that were used in the original Waas case study: the total flood damage (M euro), the area of residential sector flooded (km<sup>2</sup>), and the agricultural flood damage (M euro). Flood damage on each cell is calculated based on the water level, the elevation, and the dominant land-use class on that cell. The shape of the damage curves is derived from the Standard Dutch Damage and Casualty Model (Kok, 2005). The model is run with an annual time step for a planning horizon of 100 years. Therefore, the values of each indicator are aggregated over all dike rings and accumulated across this planning horizon in order to assess the performance of the policies.

The same set of physical flood risk policies that was applied in the original Waas case paper is employed here (Table 1). The policies focus either on flood risk reduction or on flood damage reduction. The former aims at reducing the possibility of the occurrence of flood events while the latter aims at reducing the damage incurred from inundation.

Both climate and socioeconomic uncertainties are considered. Three categories of climate scenarios, formulated by the Royal Dutch Meteorological Institute (KNMI), are incorporated: no climate change, G scenario (moderate climate change, temperature rise of 1°C in 2100), and Wp scenario (severe climate change, temperature rise of 2°C in 2100). These climate scenarios are grounded on the combination of downscaled General Climate Model and Regional Climate Model simulations used in IPCC reports, meteorological observations, and expert judgement (Van den Hurk et al., 2007). For each category, ten climate realisations are constructed by using the KNMI Rainfall Generator (Buishand & Brandsma, 1996) in combination with the delta change approach (Lenderink et al., 2007), resulting in a total of 30 climate realisations. Each climate realisation is a 100-year time series of precipitation. In general, a more severe climate change scenario leads to higher precipitation rates, and thus higher maximum river discharges.

**Table 1:** Overview of original physical flood risk policies applied.

No	Name	Description	Category
1	No policy	Do nothing	-
2	DH500	Dike height rise to cope with a 1:500 discharge, based on measurements	Flood risk reduction
3	DH1000	Dike height rise to cope with a 1:1000 discharge, based on measurements	Flood risk reduction
4	DH1.5	Dike rise: adapting to 1.5 times the second highest discharge ever measured	Flood risk reduction
5	RfR small	Room for the river - Small scale: with extra side channels, the river is given more space after a threshold discharge is exceeded	Flood risk reduction
6	RfR medium	Room for the river - Medium scale: with extra side channels, the river is given more space after a threshold discharge is exceeded	Flood risk reduction
7	RfR large	Room for the river - Large scale: with extra side channels, the river is given more space after a threshold discharge is exceeded	Flood risk reduction
8	CopU	Upstream cooperation: discharges are reduced to 14.000 m <sup>3</sup> /s	Flood risk reduction
9	FloaTH	Floating houses: resulting in damage functions with 10 times less damage for the residential land-use class	Flood damage reduction
10	FaC	Fort cities: extra embankments around the residential area	Flood damage reduction
11	Mound	All residential area are raised by 4 m, resulting in houses on an area of elevated ground	Flood damage reduction

The socioeconomic uncertainties take form of future land-use maps based on the work of Kwakkel et al. (2015). In this study, we use three socioeconomic scenarios: (i) no land-use claim change, (ii) deurbanisation, and (iii) urbanisation. In the deurbanisation scenario, future land-use maps are generated where the total number of residential area is reduced by 15% within the entire planning horizon. In the urbanisation scenario, the number of residential area is increased by more than 30% by the end of the simulation run. The increase and the decrease of the residential area are uniformly distributed throughout the simulation run.

### 3.2 Extension for the land-use change dynamics

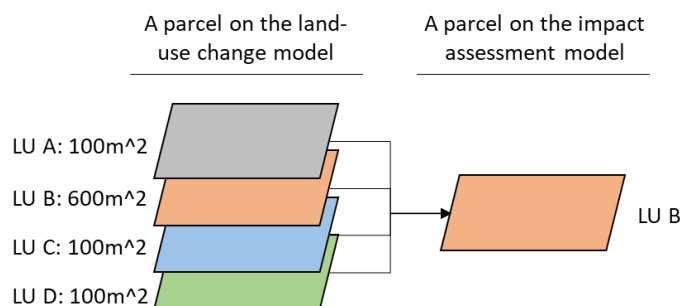
We use the LandUse Scanner software (Hilferink & Rietveld, 1999) for the utility-based land-use change model. Coupling the land-use change model entails five additional steps: 1) adjusting land-use map resolution between the land-use change model and the Environmental Impact Assessment Model, 2) differentiating between endogenous and the exogenous land-use classes, 3) defining the local suitability function for each land-use class, 4) formulating regional demand, and 5) exchanging the states between the two models in a timely manner.

The parcels in the Environmental Impact Assessment Model have a different resolution compared to the parcels in the land-use change model. In the impact assessment model, a parcel is represented by a single land-use class,



while in the land-use change model, a parcel consists of multiple layers of land-use classes. The land-use class with the largest area in a certain parcel becomes the dominant land-use class of that parcel. Taking the example in Figure 3, as land-use class B has the largest area, it represents that parcel in the impact assessment model.

The land-use change model makes a distinction between endogenous and exogenous land-use classes (Koomen et al., 2011). Exogenous land-use classes do not undergo the local suitability calculation, and their spatial distribution is exogenously defined. Permanent land-use functions such as dikes, infrastructure, and water body/river belong to this category. Endogenous land-use classes undergo the local suitability calculation, and thus the allocation procedure, as their presence is not permanent and the spatial distribution of their utility changes over time. Residential, industry, agriculture, recreation, and greenhouse land-use classes belong to this category.



**Figure 3:** Schematisation of a parcel's resolution transformation.

A similar formulation of utility-based local suitability is applied to all endogenous land-use classes. The utility of a land-use class is a function of: (i) the presence of that land-use class in the parcel, (ii) the distance decay factor to the nearest same land-use class (as suggested by Diogo et al. (2015)), and (iii) the severity of the flood events from the impact assessment model. The severity is defined as a function of the flood water depth and the 'flood sensitivity threshold' of the society. If the water depth on a given parcel exceeds this threshold, the land-use actors on that parcel will re-evaluate the local suitability of that parcel. Otherwise, they will maintain their current land-use decision. The base model formulation in this study assumes a flood sensitivity threshold of zero. This makes flooding events with any severity trigger the land-use actors to adjust their decisions. The logic of the utility calculation can be found in the Supplementary Material.

The exogenous land-use maps developed in Kwakkel et al. (2015) are used as a basis for determining the regional demand in the land-use change model. Within each dike ring, the number of parcels of each land-use class in the new exogenous land-use map is subtracted from the number of parcels in the current land-use map. The difference between the two becomes the future area claim for the land-use class, to be inputted in the regional demand module of the land-use change model.

The exchange of state information between the models takes place every ten years ( $n = 10$  in Figure 1b), which is similar to the time window of five to nine years as proposed by Wagner et al. (2017). The information of the occurrence of flood events in the impact assessment model within this time period is stored and is averaged by the end of the tenth year. The spatially explicit average flood water depth becomes one of the drivers that determines the local suitability (see the dashed blue line to the green box in Figure 1a). The land-use change model then creates a new land-use map. This new land-use map goes back into the impact assessment model and affects the impacts of the subsequent flood events.

### 3.3 Experiment design

Table 2 shows the five experiments carried out in order to answer different questions. The first four experiments are intended to compare the results of endogenising land-use dynamics with the exogenised land-use dynamics. The last one explores the potential of adding new land-use based policy performance indicators and a zoning policy in model-based support for climate adaptation.

In the first two experiments, the influence of the land-use claim (socioeconomic) scenarios and the climate change scenarios is independently assessed. A full factorial design is used to sample the parameters in these experiments. There is a total of 330 unique simulation runs in each experiment (3 climate change scenario categories x 10 precipitation realisations in each category x 11 original policies (see Table 1) in the first experiment, 1 climate change scenario category x 10 precipitation realisations x 3 land-use claim scenarios x 11 original policies in the second experiment).

The third experiment aims at investigating how the sensitivity of the society's land-use decisions to flood events affects the implications of endogenising land-use dynamics. To consider this factor, we introduce a new uncertain variable termed 'flood sensitivity threshold'. The value of this variable is set to zero in the other experiments, while the value will be an integer number between zero and twenty five in this experiment. The threshold value translates linearly to flood depth; a threshold value of one implies flood depth of 0.5 meter. Since flood events are climate-induced, only climate change uncertainties are considered. The full factorial design is used to sample the uncertainties.

**Table 2:** The five research questions and their corresponding experiment design.

No	Main questions	Uncertain variables	Policies	Endogenised land-use?	Number of simulation runs
1	How does future climate change development influence the impact of endogenising land-use dynamics?	Climate change	11 original policies	Both – yes and no	330
2	How does future socioeconomic development influence the impact of endogenising land-use dynamics?	Socioeconomic (land-use claim)	11 original policies	Both – yes and no	330
3	How does the society's sensitivity to flood events influence the impact of endogenising land-use dynamics?	Climate change + flood sensitivity threshold	No policies	Both – yes and no	780
4	How does endogenising land-use dynamics affect the policy performance of each policy?	Climate change + Socioeconomic	11 original policies	Both – yes and no	990
5	What are the implications of adding land-use based policies and indicators on top of the standard ones?	Climate change + Socioeconomic	11 original and zoning policies	Yes	1980

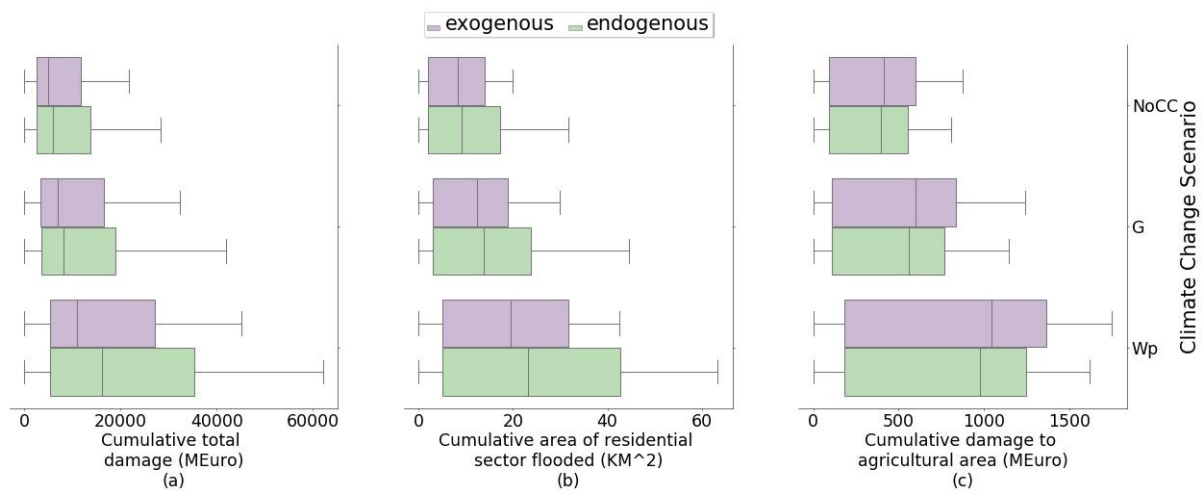
The fourth experiment aims at evaluating how the performance of each policy is affected by the endogenised land-use dynamics. This experiment applies a full factorial design, resulting in 90 unique parameters settings (3 climate change scenario categories x 10 precipitation realisations in each category x 3 land-use claim scenarios). The performance of all policies listed in Table 1 is evaluated for each of the 90 parameters settings, resulting in a total of 990 simulation runs (90 parameters settings x 11 policies).

In the fifth experiment, an additional zoning policy is tested. The zoning policy applied here is a simple region-level zoning policy that aims at preventing future residential area development in flood-prone dike rings. This policy entails the displacement of residential land-use claim in dike ring 4 and 5 (regions at the south of the river) to dike ring 1, 2, and 3 (regions at the north of the river) in the regional demand module. This policy is applied concurrently with the 11 original policies, resulting in a total of 22 policies combinations. Using a full factorial design approach, this experiment setting results in 1980 simulation runs. Furthermore, an additional land-use based indicator, the weighted mean suitability (Bubeck & Koomen, 2008), is introduced. This indicator averages the local suitability of each land-use class from all parcels on the grid.

## 4. Experiment results

### 4.1 Experiment 1 – Influences of climate change uncertainties on endogenising land-use dynamics

Figure 4 shows the results of the first experiment. The figure condenses the outcomes of all policies. A more severe climate scenario in general has a higher precipitation rate, thus higher flood events frequency. Consequently, the outcomes always become worse when the climate scenario is more severe. When land-use dynamics are endogenised, this effect exacerbates in the cumulative total damage and cumulative area of residential sector flooded indicators, as shown in Figure 4a and Figure 4b. Conversely, Figure 4c shows that endogenising land-use dynamics causes a slight reduction in the damage to the agriculture sector. These results indicate that in this particular case study, endogenising land-use dynamics may lead to emerging bottom-up land-use changes, which benefit the agriculture sector at the expense of the residential sector.



**Figure 4:** Implications of endogenising land-use dynamics under different climate change scenarios.

### 4.2 Experiment 2 – Influences of socioeconomic uncertainties on endogenising land-use dynamics

Figure 5 displays the results of the different socioeconomic scenarios. In the no land-use claim change and the deurbanisation scenarios, endogenising land-use dynamics increases the cumulative total damage and the area of residential sector flooded. Counterintuitively, the values of these indicators slightly decrease in the urbanisation scenario, although we would expect that there would be more residential areas in this scenario. This finding can be attributed to the difference between the exogenous runs' and the endogenous runs' spatial distribution of future residential area. In the exogenous runs, the future land-use is not allocated based on the internal dynamics of the system. Hence, the newer urban sprawl does not consider the spatial distribution of past flood events. The agriculture sector reacts oppositely. Here, by visually inspecting the graph we can see that the damage in the urbanisation scenario is reduced substantially when land-use dynamics are endogenised, while the deurbanisation scenario causes a slight increase to the damage.

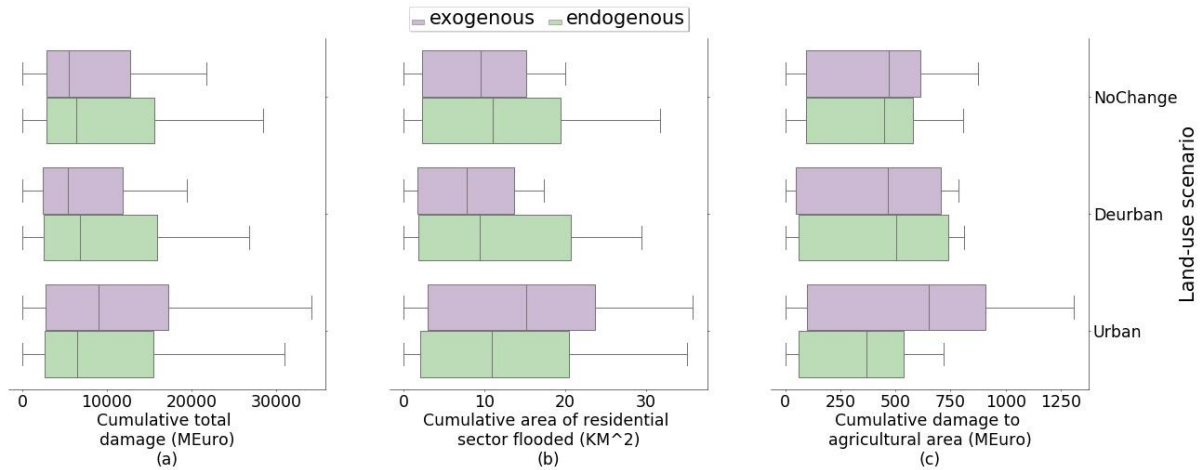


Figure 5: Implications of endogenising land-use dynamics under different socioeconomic (land-use) scenarios.

#### 4.2 Experiment 3 – Influences of the society’s sensitivity to flood events on endogenising land-use dynamics

Figure 6 shows the comparison of the cumulative total damage from the endogenous runs and the exogenous runs for different flood sensitivity thresholds. Therefore, a ratio higher than one in Figure 6 implies that the total cumulative damage from the endogenised land-use dynamics is higher compared to the exogenous land-use dynamics. The x-axis shows the flood sensitivity threshold. The lower the value of this threshold, the more sensitive land-use change decisions are to flood events. Figure 6 shows that the median of the damage ratio tends to be higher when the flood sensitivity threshold is low. This can be attributed to the higher occurrence of land-use changes that exacerbate the increase in total damage as described in experiment 1 and 2. After a certain point when the threshold gets higher, the damage ratio converges to one, and the range of the boxplots starts to diminish. This happens because the flood events do not trigger the society to change its land-use pattern if the severity of the events does not exceed the high flood threshold value.

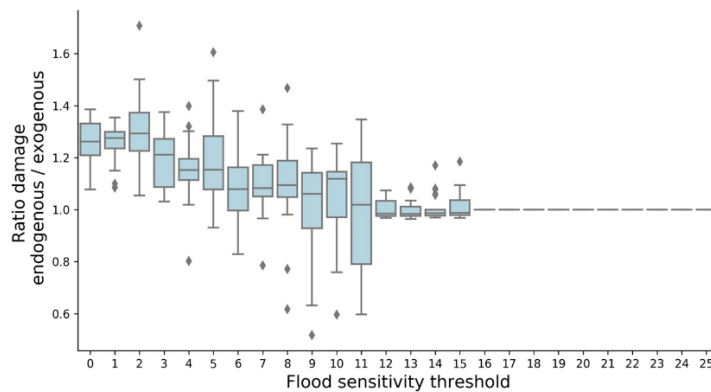


Figure 6: Ratio of cumulative damage between the endogenous runs and the exogenous runs for different flood sensitivity threshold values.

#### 4.4 Experiment 4 – Implications of endogenising land-use dynamics to each policy

Figure 7 compares the performance of the policies between the endogenous and the exogenous runs. There are some findings observed from this figure. First, the third indicator (the damage to agriculture sector) in most cases shows an opposite effect in comparison to the two other indicators. The only difference is for the fort cities (FaC) policy, where the values of all the indicators decrease when land-use change is endogenised. Second, the figure gives insights into which policies are sensitive to endogenised land-use dynamics. We observe that the dikes heightening (DH500, DH1000, DH1.5) and the room for the river (RfRSmall, RfRMed, RfRLarge) policies

are less sensitive. For flood damage reduction measures, such as floating houses (FloatH) and fort cities (FaC), the implication of endogenising land-use dynamics is more noticeable. Third, although the magnitude of the indicators changes, the ranking of the policies does not change if we rank them based on the median value of the indicators (the approach followed in the original work in Haasnoot et al. (2012)).

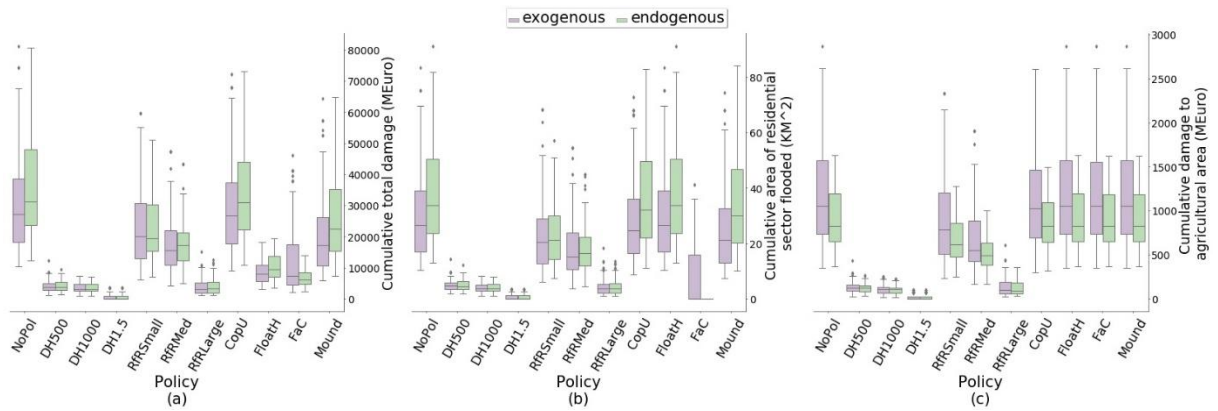


Figure 7: Implications of endogenising land-use dynamics to the performance of each policy.

#### 4.5 Experiment 5 – Analysis of the additional zoning policy and the land-use based indicator

Figure 8 compares the performance of the original Policies when the additional zoning policy is applied. The zoning policy on the one hand almost does not yield any impact on the total cumulative damage from the flood risk reduction policies (Figure 8a). On the other hand, it increases the total cumulative damage of the floating house and fort cities policies. The reason behind this is that moving the protected houses to another area that is safer from floods has a drawback of leaving behind the other land-use classes vulnerable in the flood prone area. In the long run, more flood events hit the other unprotected land-use classes in the flood prone area, in turn incurring higher total damage. Figure 8b shows that the zoning policy proves to be effective in reducing the cumulative area of residential sector flooded, which is a conceivable result as the houses are moved to regions that are safer from flood events. Unsurprisingly, Figure 8c shows that the zoning policy has almost no effect to the agriculture sector.

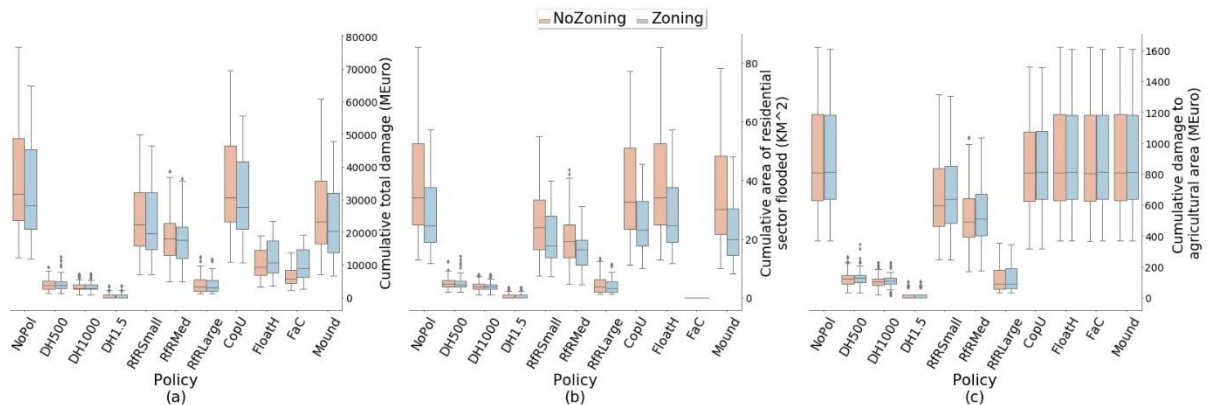
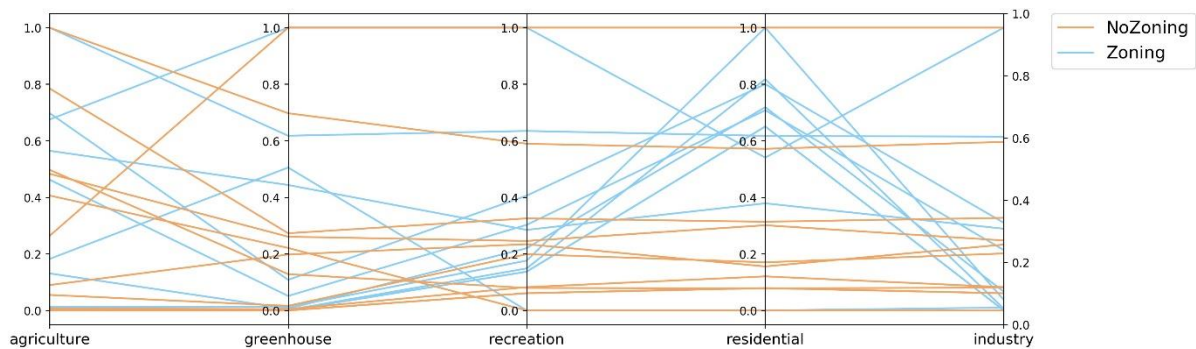


Figure 8: Implications of including a zoning policy in addition to the original policies.

Figure 9 contrasts the weighted mean suitability of each land-use class when the zoning policy is in place. The weighted mean suitability of each land-use class is an example of a disaggregated, actor-specific policy performance indicators that can be calculated in models used for adaptation planning. Each line in the figure represents the median of the weighted mean suitability values from a policy. We normalise the value in order to ease the comparison, as the concept of the local suitability itself has to be treated in a relative manner (Hilferink & Rietveld, 1999; Koomen et al., 2015). One clear pattern that we can observe here is that the zoning policy substantially increases the suitability of the residential area.



**Figure 9:** Parallel plot of the weighted mean suitability of the land-use classes. Each blue and orange line represents the median result of a single original policies (see Table 1).

## 5. Discussion

### 5.1 What are the implications of endogenising land-use dynamics in model-based support for climate adaptation?

We find three implications of endogenising land-use dynamics: it affects the performance of the policies, enables the evaluation of land-use based zoning policies, and broadens the types of outcomes that can be evaluated.

First, we can see the implications to the performance of the policies by observing (i) the changes in the ranking of preferred policies and (ii) the changes in the absolute values of the policy performance indicators. We observe that the ranking does not change if we rank them based on the median value of the indicators. It might change slightly if we also take into account the statistical dispersion of the indicators. For instance, from Figure 7b we see that endogenising land-use dynamics diminishes the variance of the fort cities policy (FaC), making this policy the most preferable one. With respect to the changes in the absolute values of the indicators, we observe that the numbers may change when land-use dynamics are endogenised. This finding supports previous studies that show that failures to capture this bottom-up response in climate adaptation studies may lead to implausible policy conclusions (Cass, 2018; Di Baldassarre et al., 2016; Wada et al., 2017). This becomes important when the aim of the climate adaptation study is not only to rank policies, but also to assess their cost-benefit ratio. In that case, failing to better characterise the policy's performance may lead to a different conclusion on the attractiveness of the investments.

Second, by endogenising land-use change we can consider land-use zoning policies. In contrast to physical flood risk policies, zoning policies incur lower costs. This makes the combination of zoning policies and physical policies interesting. Such combinations are rarely evaluated in model-based climate adaptation studies (Newman et al., 2017), while they are relevant in practice. In this paper, we introduce an additional zoning policy where we restrict further residential land-use development in the flood prone area.

The zoning policy is effective in improving the weighted mean suitability of the residential land-use actor and reducing the cumulative area of residential sector flooded. However, the impact of the zoning policy varies across the different physical policies. When the floating houses (FloatH) and fort cities (FaC) policies are applied, the zoning policy results in a higher total cumulative damage. These actor-specific physical policies substantially improve the resistance of the residential sector to flood events, thus counteracting the also actor-specific zoning policy. The increase in total cumulative damage can also be attributed to the damages experienced by the other land-use classes, especially the industry sector that has a relatively high damage factor. These land-use classes are left vulnerable in flood prone dike rings. This raises a flood risk transfer problem, which is a prominent ethical issue in flood risk management (Doorn, 2014a, 2014b). Endogenising land-use dynamics enables the exploration of this risks transfer problem transparently.

Third, by endogenising land use change we enable a broader perspective in the evaluation of alternative climate adaptation plans. Here, we use the weighted mean suitability to evaluate the utility of each land-use class. Incorporating this indicator provides two benefits. First, this indicator can approximate the distributional impacts of policies (i.e., disaggregated, actor-based policy performance indicators). This intra-generational distributional problem has been one of the key ethical challenges in climate adaptation planning (Donna, 2016; Kolstad et al., 2014). Based on this indicator, an aggregated system-level inclusivity indicator can be further developed in many ways, for instance by calculating the discrepancy between the better-off and the worse-off land-use actors. Second, we can explicitly explore the multi-actor trade-offs of policies. Analytical techniques derived from ongoing works on multi-stakeholder model-based robustness analysis can be adapted for this purpose (e.g. Herman et al., 2014; Trindade et al., 2017; Zeff et al., 2016).

The area of residential sector flooded and the cumulative damage to the agriculture sector can be categorised as actor-based indicators. However, acknowledging so could be misleading as we only see the utility from the environmental perspective. The concept underlying the utility-based land-use change model can help in better apprehending the utility of the land-use actors from environment, social, and economics perspectives. The same reasoning also applies to zoning policies. Practically speaking, we can set rules in the exogenous land-use scenarios in such a way that future new residential areas do not sprawl in the flood-prone area. However, we would have missed the emerging bottom-up responses of the land-use actors. This in turn might result in a misleading policy conclusion especially if the study is done for regions where land-use functions are highly dynamic.

## 5.2 When does endogenising land-use dynamics become (ir)relevant?

We evaluate four factors that have the potential to influence the relevance of endogenising land-use dynamics: severity of future climate change, future socioeconomic development characterised as (de)urbanisation scenarios, society's responsiveness to climate events, and the nature of the policies that decision makers want to appraise. We evaluate them with regard to the changes in magnitude of the policy performance indicators, when compared to simulation runs that exogenise the land-use dynamics. If the results do not differ much, endogenising land-use dynamics can be considered as irrelevant.

In more severe climate change scenarios, the G and the Wp scenarios, the impact of endogenising land-use dynamics is larger. In these scenarios, the frequency of flood events is generally higher. The more frequent flood events trigger the society to adjust their land-use pattern. In the land-use change model, it is assumed that different land-use classes responded to the flood events differently. A slightly higher flood sensitivity parameter value is given to land-use classes whose flood damage function was higher in the original Waas case (e.g., higher values for the residential and the industry sectors as their original flood damage function is larger). Consequently, when flood events occur, the residential and the industry land-use classes are more affected, in comparison to the agriculture and greenhouses land-use classes. This triggers an agglomeration for the residential and industry land-use classes. The agglomeration increases the number of dominant residential and industry land-use parcels while decreases the number of dominant agriculture parcels. In combination with the higher flood damage function to these land-use classes, the agglomeration results in higher total cumulative damage.

When urbanisation is expected in a particular area, surprisingly, endogenising land-use dynamics leads to a lower total cumulative damage in comparison to the exogenised case. This is explained by the spatial distribution of the new residential area in the exogenous land-use maps. The new residential area from the exogenous maps sprawls uniformly around the smaller cities in the delta, where the elevation is relatively low. Conversely, when the land-use dynamics are endogenised, the new residential area tends to sprawl near the large city in the southeast part of the delta (see Figure 2). This area in general has higher elevation, thus safer from flood. Therefore, the effect observed here cannot be generalised, as it is strongly influenced by the spatial pattern of the exogenous land-use maps. Nevertheless, the insight shows that by endogenising land-use dynamics we can observe the area where new residential land-use might potentially emerge. This information can be used to develop further zoning policies for reducing climate impacts. Such an approach is typical in the Dutch flood planning context (De Moel et al., 2011).

The responsiveness of a society to climate events, characterised by the flood sensitivity threshold parameter, strongly affects the implication of endogenising land-use dynamics. A higher threshold results in indifferent

outcomes for both the exogenised and the endogenised case. This suggests that endogenising land-use dynamics becomes more relevant in a society that is highly responsive to climate events (i.e. has low flood sensitivity threshold). As an example, endogenising land-use dynamics is relevant for climate adaptation planning in the Vietnam Mekong Delta, where extreme weather events have empirically been proven to be one of the key determinants in people's land-use decisions (Chapman & Tri, 2018; Kim & Le Minh, 2017). Failure in capturing such phenomenon in the integrated assessment model resembles the 'policy myopia' problem (Nair & Howlett, 2017), which in turn might result in misleading policy conclusions. Conversely, it is less relevant for climate adaptation planning in Alba town, Italy, where recurring flood events have not had significant influence to the land-use dynamics of the city (Luino et al., 2012).

The nature of the policies to be evaluated also plays a role in the relevance of endogenising land-use dynamics. If the benefit of a policy does not disproportionately affect certain land-use actors, endogenising land-use dynamics tends to give only marginal effect. We observe this in the performance of the dikes heightening measures and the room for the river, which benefits are experienced by all land-use actors. Consequently, as shown in Figure 7, the total cumulative damages resulting from the endogenised and the exogenised land-use dynamics do not differ much. If a policy targets specific land-use actors, such as in the case in fort cities and floating houses, the dynamics of the land-use actors affects the performance of the policy. Hence, the effect of endogenising land-use dynamics becomes more profound.

## 6. Conclusions

Although models used for supporting climate change are becoming even more integrated (Harrison et al., 2016), future land-use maps are still often treated as an exogenous factor. Strong interconnectedness between land-use change and climate change has long been acknowledged (Dale, 1997). Ignoring the interaction between the environment and the society (in this case embodied by the land-use) can result in miscalculation of the impacts of adaptation and might limit the adaptation options that are considered. Motivated by these facts, this paper explores the merits of using utility-based land-use change model for endogenising land-use dynamics in a spatially explicit integrated assessment model.

Three implications of endogenising land-use dynamics have been identified: (i) changes in the performance of policies, (ii) the possibility of including land-use based zoning policies, and (iii) the inclusion of disaggregated, actor-level policy performance indicators. With respect to the first point, the ranking of policies did not substantially change while the absolute scores of the policy performance indicators did change in some cases. With respect to the second point, this approach enabled the evaluation of zoning policies. The performance of such policies has only been descriptively evaluated in separate independent studies, often neglecting the infrastructural policies. By using the approach presented here, the performance could be evaluated in a quantitative and integrative manner. Moreover, the land-use maps generated by the model can be used as a starting point to identify potential land-use based policies. With respect to the third point, the weighted mean suitability was used to evaluate the actors' utility not only from the environmental perspective but also from the social and economic perspectives. These indicators can be a starting point to evaluate the distributional impacts of alternative policies.

We found three factors that might affect the implications of endogenising land-use dynamics in model-based decision support for climate adaptation described above. We evaluated the effect by observing how the policies performance indicators changed. The analysis suggests that the implications of endogenising land use are more profound if (i) more severe climate change is expected, (ii) society is reactive or sensitive to climate events, and (iii) some of the policies are targeting specific actor groups within the society. Special attention should be put to point (ii). In a society that is sensitive to climate events, changing land-use functions is one form of autonomous adaptation (see e.g. Ahmed, 2011; Smajgl et al., 2015; Thai et al., 2014). Failing to capture these dynamics may overlook the adaptive responses of the people, and thus may have a profound influence on the conclusions of the study.

Although endogenised land-use dynamics here are specifically investigated in the context of flood risk adaptation planning, the approach can be used for other climate adaptation contexts. The importance of dynamically adding land-use change in integrated assessment models has been put forward in studies on watershed planning (Wagner et al., 2017; Zhang et al., 2018), desertification (Xu et al., 2016), ecological



vulnerability (Zhang et al., 2017), agricultural systems (Li et al., 2018), and livestock production systems (Havlik et al., 2014). In order to endogenise land-use dynamics in other contexts, the key challenge is to identify the relevant states to be exchanged and the right time integration window between land-use and the environment systems. This study has shown merits of making land-use dynamics endogenous in a theoretical case study as a proof of concept. The challenge now is to apply this approach to a real world case study.

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