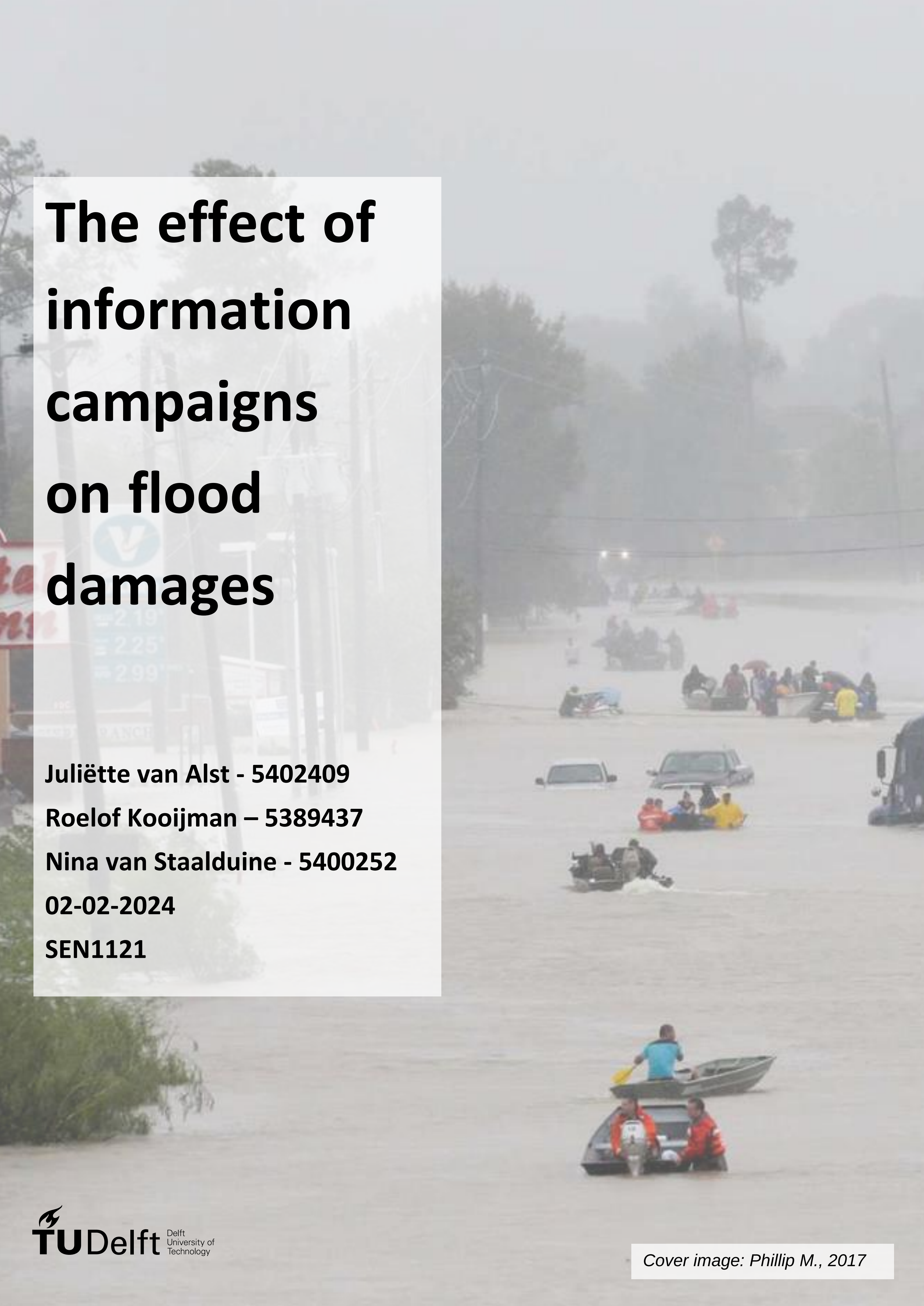
The effect of information campaigns on flood damages



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02-02-2024

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1. Introduction

Urban flooding is one of the biggest threats posed by natural disasters in the United States. Storms like Sandy in New York (2012) and Hurricane Harvey in Houston (2017) resulted in billions of dollars in property damage. This makes storms the worst natural disaster in terms of economic and social impact (National Academies of Sciences, Engineering, and Medicine, 2019). The national Government of the United States created the Spring 2019 Disaster Aid Package, releasing $19 billion to make America more flood-proof (NCSL, n.d.). Municipalities, like Houston, that experienced severe damage due to flooding, created flood mitigation plans focusing on various aspects of flood mitigation. One of these aspects is improving the flood resistance of households. An example is the FMA Grant Program from the Federal Emergency Management Agency (2024), where households can receive funds to raise their houses if they live in an endangered area.

Engaging homeowners to participate in programs like the FMA Grant Program is crucial. The Evaluation of the Performance evaluation task Force (2007) shows that during Storm Katrina (2005), residential damage alone was around 16 billion dollars. The total amount of damage was 20 billion dollars. The fact that such a significant portion of the damage is from residential buildings alone means that the greatest impact can be achieved by improving residential buildings.

Various studies have already examined the government's influence on households' flood preparedness. Burningham et al.'s (2008) study aimed to gain insight into people's recognition that their property is in an area at risk of flooding. The study concludes that awareness of flooding is not the main issue, but rather that people have a hard time assessing the impact of flooding based on past knowledge of flooding. Another study that concludes risk awareness is not a main driving force for mitigation measures is the literature review of Bubeck et al. (2012). Here they conclude that coping appraisal is strongly associated with mitigation behaviour and that risk awareness does not lead to mitigation behaviour without coping appraisal.

Haer et al. (2016) created an Agent-Based Model (ABM) to measure the effects of different government communication strategies on the mitigation behaviour of households. Four different strategies were tested, and two of these strategies emphasized coping appraisal. The first strategy was a top-down approach, and the second a person-centred approach. The results focused on the implementation rate of mitigation measures. However, no insights are given about the effect of the implementation rate of mitigation measures on damage avoidance during actual flooding events.

This research will investigate the effects of government communication on damage mitigation for homes. For this purpose, an ABM model will be created based on Houston, a city in Texas, United States. In the ABM model, the top-down and person-centred communication strategies of Haer et al. will first be modelled to influence households' risk awareness and coping appraisal. Then, the resulting changed mitigation behaviour will be

examined, along with how much less damage this changed behaviour leads to. This is encapsulated in the research question given below:
What is the effect of top-down and people-centred information campaigns on adaptation rate and damage avoidance under conditions of multiple flooding scenarios as measured by four indicators: average flood awareness, average self-efficacy, number of adapted households and total damage?

Accompanying the main research question are the following sub-questions that need to be answered to address the main question.

1. What is the effect of the top down information campaigns on the 4 indicators?
2. What is the effect of the people-centred information campaigns on the 4 indicators?
3. What is the effect of the combination of top-down and people-centred information campaigns on the 4 indicators?

This research will be conducted in six parts. First, the conceptualization will explain which concepts have been used in the research. In the formalisation section, it will be clarified how these concepts are implemented in the ABM model. In the verification and validation part, the reliability of the model will be examined. The experimentation part elaborates on the set up of the experiments that are run with the model. Finally, in the results and conclusion section, the outcomes of the model and their implications will be discussed.

2. Conceptualisation

The goal of the conceptualization is to explain the key concepts that are used to answer the research question. The key concepts can be divided into five parts being: System boundary, Protection motivation theory, government communication strategies, conceptual model and Model purpose and key performance indicators. These concepts will be the foundation of the formalisation and therefore the model itself.

2.1 System boundary

The research will be conducted for the city of Houston. The simulation of flooding will be based on flood maps. The red area in Figure 1 shows which part of Houston is covered by the flood map. Within this area, households will be randomly assigned a location. The location of the household will determine the estimated flood depth for their house. The estimated flood depth will depend on the flood map used. In this study, the 100-year, 500-year, and Harvey flood maps were utilized. The first two have a chance to occur once every 100 years or once every 500 years, respectively. The Harvey map is based on the real-life case of Storm Harvey from 2017.

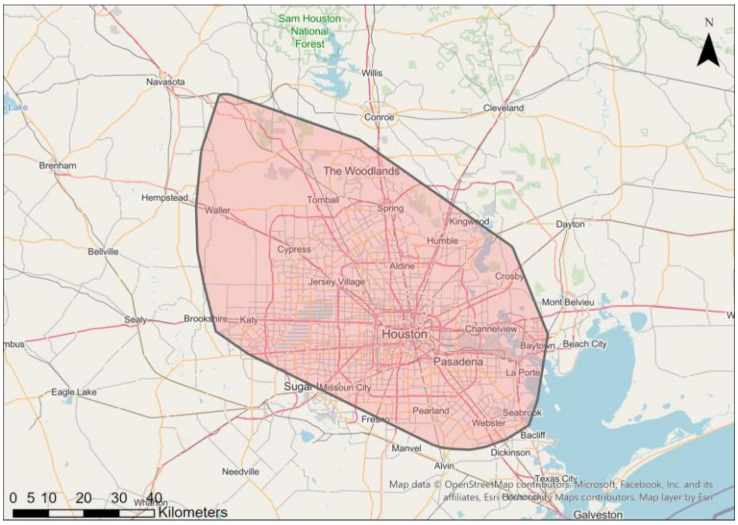

Figure 1: Houston coverage of flood map

The severity of the flood maps is shown in Figure 2. The colour of the pixels in the figure indicates the estimated depth in that place. When red, the flood is quite shallow. If blue or yellow, the flooding is significant. Notably, there is a significant difference between the 100-year, 500-year, and the Harvey flood map. The Harvey map has a larger area that is flooded and areas with higher flood depths.

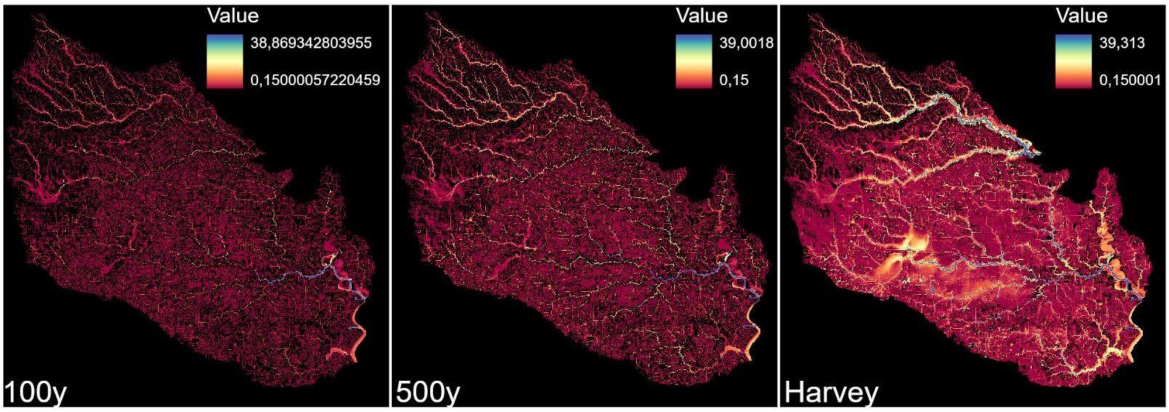

Figure 2: Severity of floods for 100y, 500y and Harvey

2.2 Protection motivation theory

Protection motivation theory (PMT) was first used to examine the relationship between fear and health-related issues and behaviour (Rogers, 1975). Since then the PMT has been used and further expanded. The meta-analysis of Floyd et all examined 65 different implementations and created an overview of which components of PMT recurred the most. From this meta-analysis can be concluded that the protection motivation is built up from two cognitive processes Threat Appraisal and Coping Appraisal.

Threat Appraisal indicates how an individual evaluates a certain threat and their desire to avoid it. Threat Appraisal consists of three components. The first factor is Maladaptive response rewards indicate the individual's appreciation when not acting on the potential danger. This can be divided into Intrinsic Rewards and Extrinsic Rewards. If these rewards become bigger the chance for a maladaptive behaviour increases. An increase of the two other factors threat severity and threat vulnerability will decrease the chance of maladaptive behaviour. Threat severity is the perceived seriousness of a threat. Threat vulnerability is the perceived probability of the threat.

Coping appraisal indicates how well an individual can act on the potential threat. It exists out of three factors. The first two are different cognitive processes. First, the response efficacy indicates if the individual trusts that the response to the threat will result in protection from the threat. The second is self-efficacy is the individual's perception of the executability of a certain response. A high response and self-efficacy will increase the chance that an individual perceives the response to the threat as executable and effective. The third factor is response cost for responding to the threat. Response costs can take the form of time, effort, social capital and monetary resources. High Response costs will worsen the individuals' perception of the executability of a response.

Due to the time scope of this study, a simplification of PMT will be used. For threat appraisal, the threat vulnerability and severity will combined into one variable that will be called flood awareness. For coping appraisal, only self-efficacy will be completely considered. An element of response costs will be included in the form that the households will need savings to purchase flood mitigation measures.

2.3 Government communication strategies

In the research of Haer et al. (2016) an ABM model was made that used two different government communication strategies to communicate information regarding PMT. The first communication strategy is top-down communication. The strategy of top-down communication is to reach as many people as possible. There is no distinction made as to which communities are vulnerable and therefore need to be informed the best. Examples of these top-down communication methods are brochures, websites and guidelines (Fekete, 2012). Haer et al. identify two criteria for communicating strategies, the probability that the receiver receives the information and the probability that the information changes the behaviour of the receiver. The Top-down approach has a high probability of receiving the information, but a low probability of behaviour modification.

The second communication strategy is a people centred approach. Here a distinction is made between people who have a high vulnerability and those who do not. The people centred approach will focus on the most vulnerable group and try to provide information based on the needs of this group. In this study the vulnerable group will be identified based on the estimated flood depth. Cooney (2012) acknowledges that this approach is essential if one wants to reduce the effects of threats. The receive probability of the people centred approach will be low because it does not try to reach all the individuals but only the ones that are the most vulnerable. The probability of changing behaviour will be high because the information provided will be aligned with the needs of the vulnerable groups. Both of the communication strategies will be implemented in this study to examine which one is the most effective.

2.4 Conceptual model

Figure 3 shows the conceptual model, which displays what is being modelled. In the model, there are two types of agents: Household agents and a Government agent. The household agents have characteristics, for example a location, insurance, savings and house value. In addition, they have attributes related to flooding. Some of these attributes, for instance, are the estimated flood depth and estimated flood damage of the house. Households can also be aware of the fact that floods occur, which is reflected in their threat vulnerability (and it is good to note that threat vulnerability and flood awareness, in this report, have the same meaning and will be used interchangeably). They can also be aware of the fact that they can protect themselves against these floods by taking certain measures, which is reflected in their self-efficacy (Haer et al., 2016). A total overview of the agents and their attributes and their description is in table 1 and 2.

The households can communicate with each other, and influence their friends. When a friend of an agent is aware of the occurrence and risk of floods, and talks about flooding, households may become more aware of the flooding problem, and realise that flooding is a real problem. By talking about the possible measures they can take to adapt, they can influence each other's self-efficacy and they may be inspired to take measurements to protect their household from flooding. In short, the interactions with friends will influence their attributes related to floods.

Besides households' friends, the government agent can also influence the household agents. The government agent tries to inform citizens about the floods and adaptation measures. It can use two kinds of communication strategies to try and reach the citizens: top-down and people centred, which will be elaborated further later in the report.

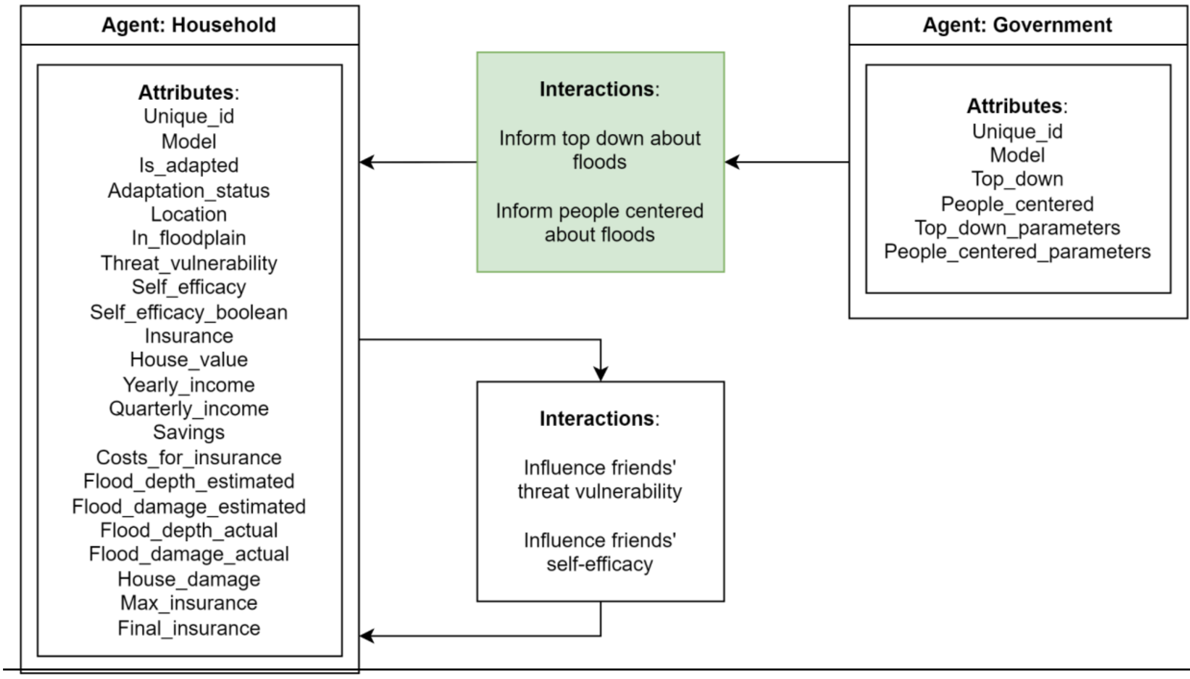

Figure 3: Conceptual model

2.5 Basic concepts of the model

This section describes what kind of main concepts are used throughout the model. The most important concepts for households are the measures they undertake to protect themselves against floods, the insurance they have and their savings.

Measures

In the model, agents can decide if they want to take measures. There are two types of measures, and they should be seen as stages of measures the agent is in. The types of measures, low effort and high effort, are based on Noll et al. (2021). In this model, it is assumed to not be possible to combine the measures, which creates the following three options:

1. No measures
2. Low effort measures
3. High effort measures

When an agent does not take measures, their house is most likely to get damaged when a flood arrives. An advantage of this stage is that it is free as long as there is no flood. The second option is buying low effort measures. These measures are temporary, and do cost some money, but are affordable for most people. Examples may be sandbags or investing in a sump pump. High effort measures are more expensive, but are also more effective. These can be seen as permanent strategies, for example raising your house a few metres, use flood-resistant materials at home, or encourage proper drainage by changing the garden landscape.

Insurance
Besides these three types of measures, agents can choose to insure themselves. There are two types of insurance: state insurance and private insurance. When agents live in areas where the estimated flood depth is really high, it is mandatory to take state insurance (FEMA, n.d.-b). This is relatively cheap, but covers damage up to a certain amount. Households pay an insurance premium each month, and in case of flooding, the damage is reimbursed up to a certain amount of dollars. The rest of the damage should still be paid by the household itself.

It is possible to upgrade the state insurance to private insurance. This type of insurance is more expensive, but, in this model, fully protects the agents. Thereby, in case of a flood, all the damage will be covered by the insurance and their savings stay the same.

The ideal situation is to have high effort measures and high insurance. This way, the least damage is done to the house and households don't have to use their savings to cover for the damage costs. This situation ensures the least unrest. The eventual damage will be completely covered by the insurance. It is possible for a household to have high insurance and have no measures taken. However, this may cause a higher repair time and may cause emotional damage due to the loss of products, which is why it is not recommended and not realistic.

Savings
To pay for the measures and insurance, the households have savings. Each step, their savings will change, and it is possible to buy measures. Savings increase when the households get income. In this model, households get income at every step, which is every quarter of the year. Each step, there is a chance that households spend savings on, for example, furniture or holidays, which means their savings will decrease.

2.6 Model purpose and key performance indicators

The purpose of the model is to check how effective the different communication strategies of the government are in preventing flood damage. First, a base case of the model is created to gain insights in the current situation, and to see if the parameters are plausible. Later, the different communication strategies of the government are added. To check how effective the measures of the government are, four key performance indicators are defined:

1. Average threat vulnerability (flood awareness)
2. Average self-efficacy
3. Number of adapted households
4. Total flood damage

The average threat vulnerability should change over time due to the interactions between agents. However, this will not always result in an adaptation of measures, since households might not have the budget for the measures. Self-efficacy should also be taken into account, as it indicates whether households know that they can protect their houses against floodings. Both the average threat vulnerability and the average self-efficacy give an indication of how well the households in Houston are educated about floods. The number of households who have actually adapted, and thus bought measures, can function as an indicator of how well the governmental communication strategies work. In addition, the total damage that the flood has done to Houston will be taken into account, since this can give a good estimate of the impact of the flood.

3. Formalisation

The purpose of this chapter is to show how the conceptualisation will be operationalized into an agent-based model. The initial model and processes of the model will be described. Furthermore, there is an overview of the variables.

3.1 Processes

There are various processes that can take place each step. At every step, households can consider buying measures and influence friends. The government could also provide information to the households and, of course, there may be a flood. Figure 4 below shows the main flow of the processes happening in the model for the two types of agents, and it shows the possible influence coming from the environment. These processes will be further elaborated in the following paragraphs.

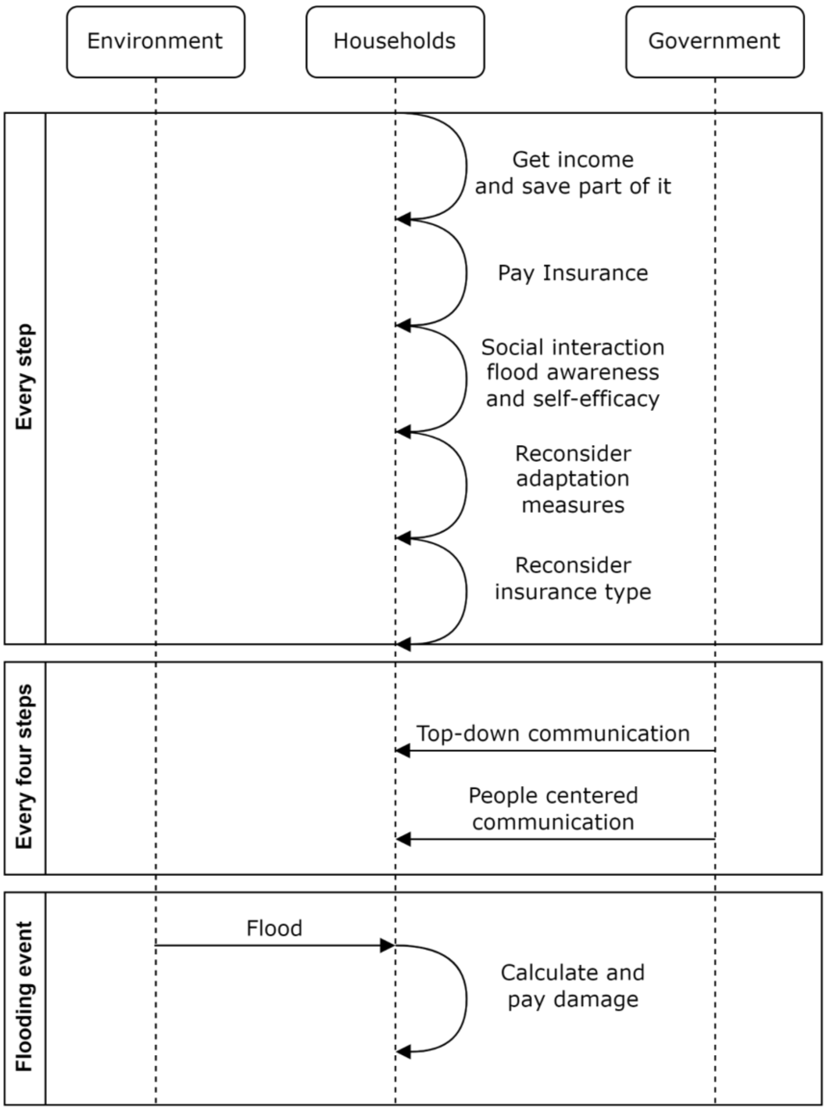

Figure 4: Sequence diagram indicating the main flow of the model, with main actions of the household and government agents, and actions form the environment

3.1.1 Flooding

Figure 5 visualises an overview of this process. When there is a flood, the first thing to look at is the adaptation status. What kind of measures did the household take? When low-effort measures are taken, the flood depth is slightly reduced by *low_effort_damage_reduction*. In case of high effort measures, the flood depth is reduced by *high_effort_damage_reduction*. When a household does not have measures, it is not protected, and the flood depth remains the original value.

Based on the depth of the flood, the actual damage of the flood is calculated. It is assumed that not the whole value of the house is damaged by a flood, there will be for example still a ground. Therefore, the actual damage to the house is the factor *house_ground_rate*, multiplied by the value of the house and the damage.

Furthermore, insurance coverage needs to be considered. When a household has no insurance, the total final damage needs to be paid out of the savings. If a household has state insurance, the first 250000 dollars will be reimbursed (FloodPrice, 2023). The amount to be paid out of their savings is then the house damage minus 250000 dollars. With private insurance, everything is covered.

Lastly, it is checked if the *house_damage* - *house_value* ratio is higher than the *awareness_shock_boundary*. If this is the case, the shock made quite an impact and the awareness of a household is increased by *awareness_increase_shock*.

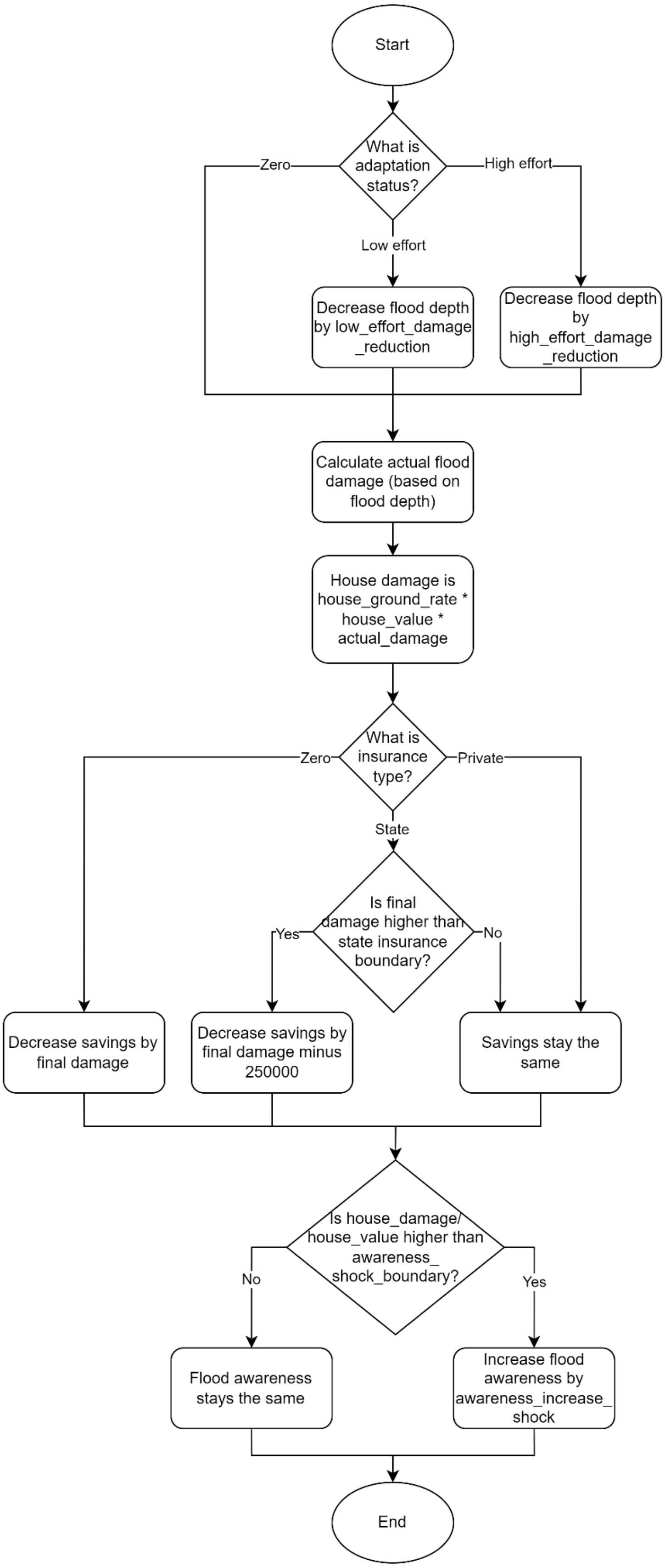

Figure 5: Flowchart indicating what households do if there is a flood

3.1.2 Adapting with measures

When the self-efficacy of an agent is "False", the agent is not aware that it can take measures, and they will not buy any measures. Otherwise, the first thing that is considered is their flood awareness. If the awareness of a household is high enough, higher than the adaptation boundary, and if the estimated flood depth is high enough, the household will invest in measures to protect the house.

If the estimated flood depth is between the low and high effort boundary, the household will consider low effort measures (as long as they do not have any measures already). The costs of the measures are based on a cost rate multiplied by the house value, as measures tend to get more expensive if the house is bigger. If a household has enough savings, it will buy the measure and is protected with low effort.

If the estimated flood depth is higher than the high effort depth boundary, the household agent realises it is in danger, and high-effort measures are considered (if the household does not have them already). If the household has enough savings, the agent will buy high effort measures and is protected with high effort. However, if the household does not have enough savings for high effort measures, it will still consider buying low effort measures. An overview of this process is displayed in figure 6 below.

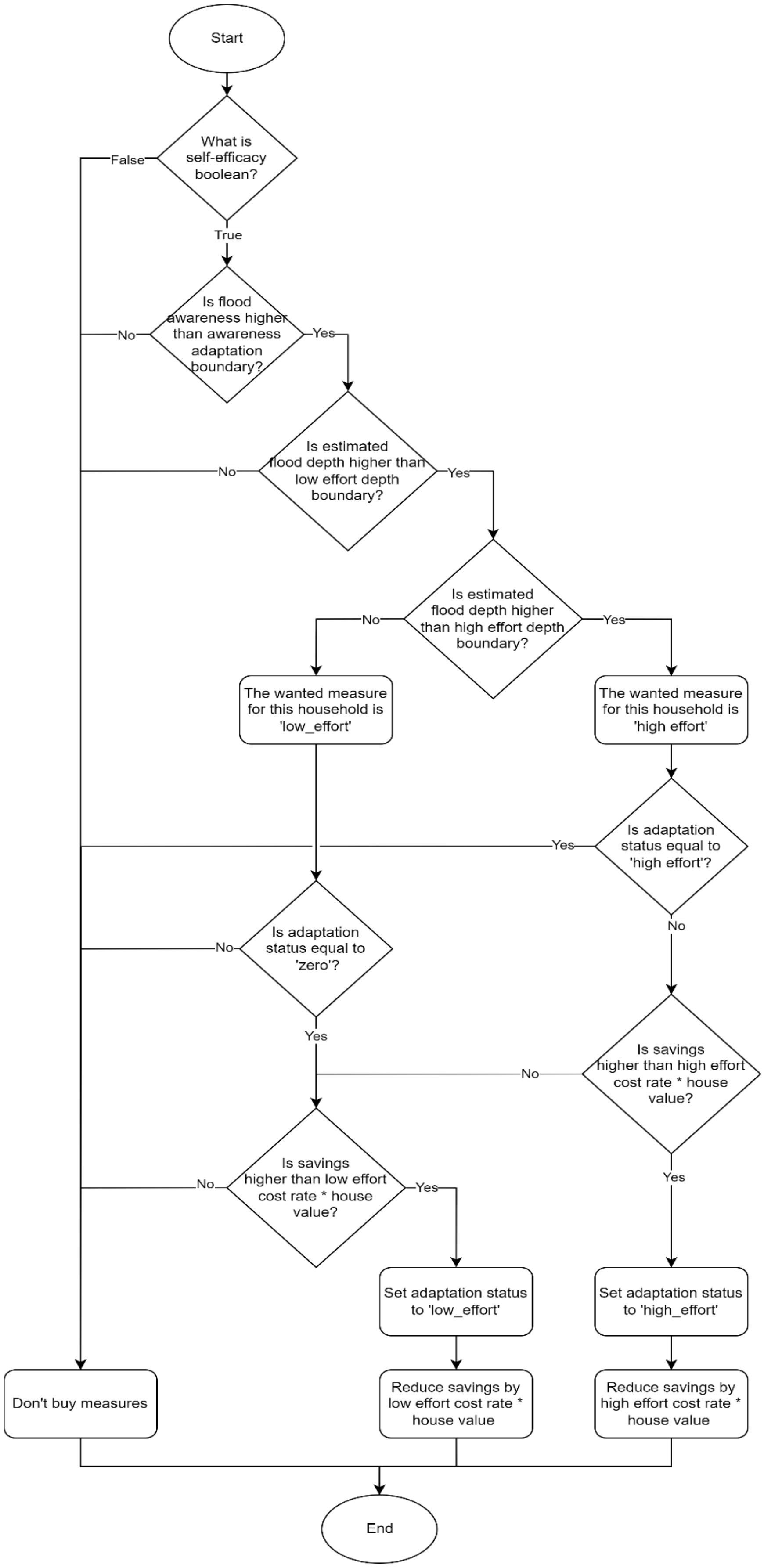

Figure 6: Flowchart indicating how households adapt with flood protection measures

3.1.3 Flood awareness through social interaction

Figure 7 shows the flowchart that indicates how social interaction of households can influence the flood awareness. Firstly, the flood awareness of a household is investigated. If households are not really aware of floods, they won't talk about it with friends. However, if the household is aware enough, there is a chance (based on the social interaction boundary) that it will talk to its friends about floods. The average flood awareness of the household's friends is then calculated, and compared to its own awareness. If the mean of the friends' awareness is lower than the household's awareness, the household's awareness will be negatively influenced and thus decreased. On the other hand, if the mean of the friends' awareness is higher than the household's awareness, the household's awareness will be positively influenced and thus increased.

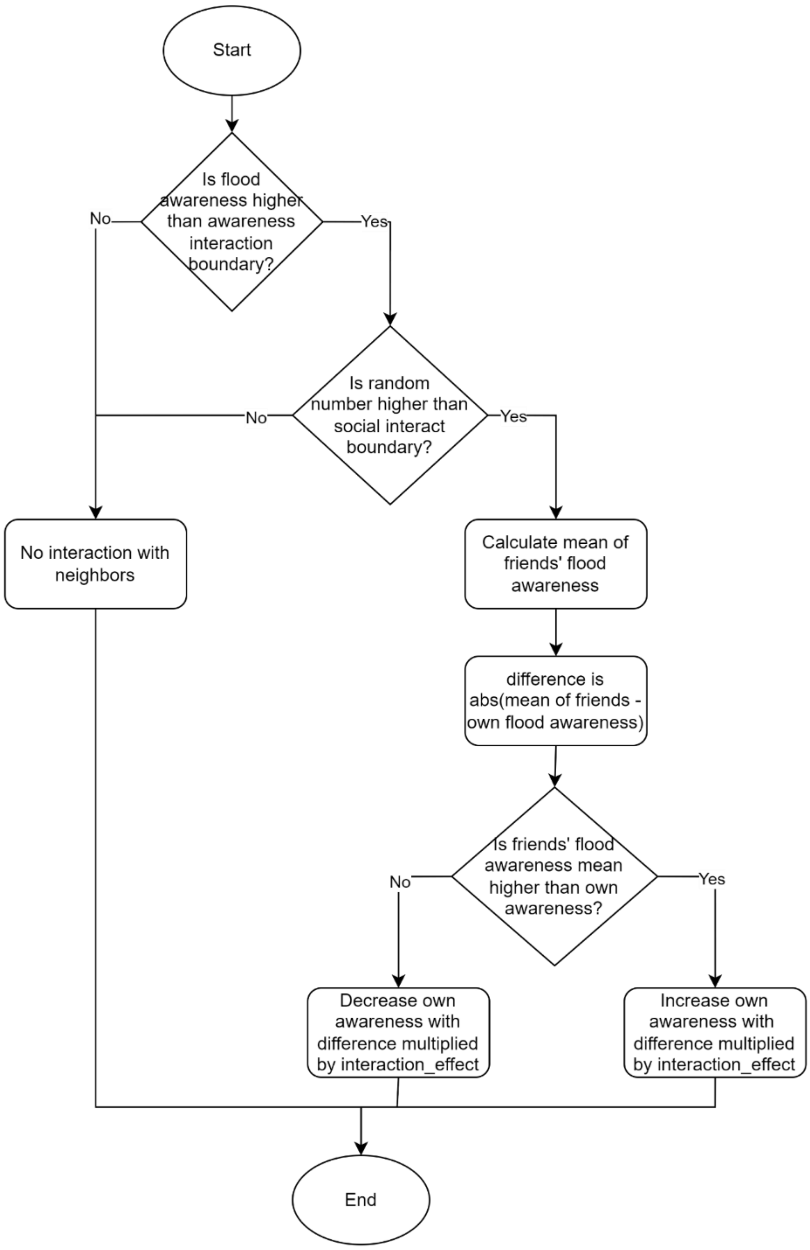

Figure 7: Flowchart indicating the change in flood awareness through social interaction

3.1.4 Self-efficacy through social interaction

It is important to keep in mind that there are two kinds of self-efficacy in this model: *self_efficacy* and *self_efficacy_boolean*. When the self-efficacy of a household is higher than 0.5, the self-efficacy boolean is True, and the household is aware that it can protect itself against floods (by buying measures). If the self-efficacy is lower than 0.5, the household is not aware of that and its self-efficacy boolean is False.

When the self-efficacy boolean is False, there will be a loop over all of the household's friends, and it is checked if its friends' self-efficacy boolean is true. A self-efficacious friend might change the self-efficacy of a household if the boundary is passed after generating a random number. In that case, the self-efficacy of a household is increased, and it is checked whether its self-efficacy boolean is now True (which is the case if self-efficacy is higher than 0.5). If all the friends have passed in the loop, the loop is broken.

When the self-efficacy boolean of a friend is false, the self-efficacy is left as it was, and the loop moves on to the next friend. This whole process is also shown in figure 8.

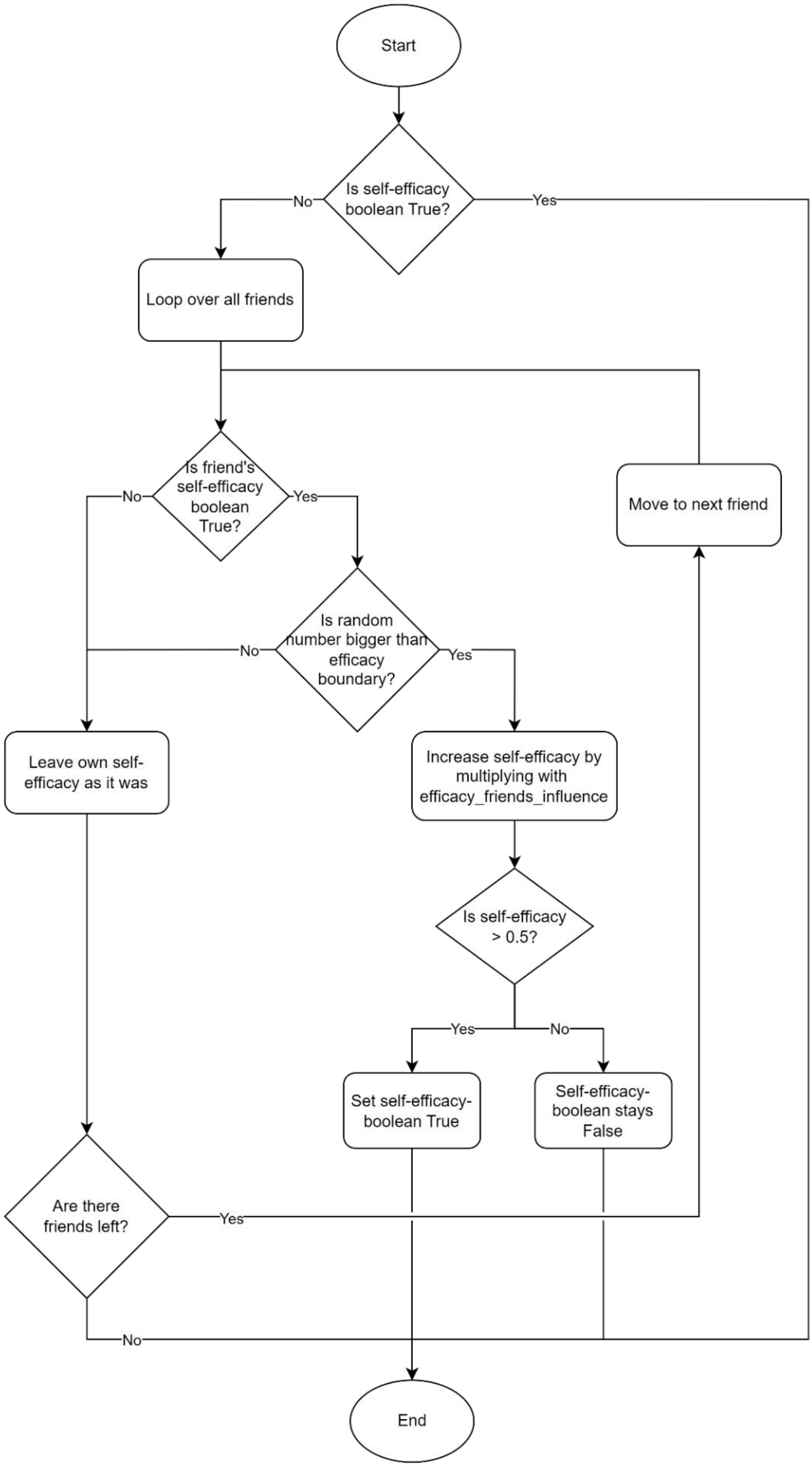

Figure 8: Flowchart indicating the change in self-efficacy through social interaction

3.1.5 Communication from government

The government agent can inform the household agents about floods. This could be done by choosing one of the following strategies that are inspired on the study of Haer et al. (2016):

1. People-centred communication: The government will organise information and Q&A sessions in neighbourhoods. Locals can get informed about flood protection in their neighbourhood and ask their questions. Since this method is more personalised, it will be more effective for every individual that is coming. Unfortunately, not everyone might come to the session, and as a result, the reach is smaller.
2. Top-down communication: The government communicates to all households, for instance by sending a letter. In this way, all households are targeted which makes the reach quite large. However, the effectiveness is not that high, because the message contains quite general information, and is not really 'personalised'.
3. No communication at all. The households are getting no information from the government. As a result, their flood awareness is only influenced by their friends.

The process of top-down and people-centred information communication is visualized in the flowchart depicted in figure 9. In the absence of communication (the "no communication" option), nothing happens, and therefore, no visualization is needed.

The communication process begins with the step "Selects agent from agent schedule," where a household is chosen from the agent schedule. If the strategy is people-centred, the estimated flood depth is checked against the threshold. If the depth is not higher than the threshold, the household will not be contacted. However, if the depth exceeds the threshold, the likelihood of communication reaching the household is assessed. This assessment is the same for both communication approaches.

A random number between 0 and 1 is generated, and if it is smaller than *receive_p*, the information reaches the household; otherwise, the communication is deemed unsuccessful. Subsequently, another random number between 0 and 1 is selected to determine whether the information actually influences the household. If the number is below *success_p*, the communication is considered successful. In the case of a higher number, the communication is unsuccessful.

Upon successful communication, flood awareness and self-efficacy are increased. Following this, the agent schedule is checked for households that have not been examined. If all households have been addressed, the process concludes; otherwise, it continues with the unexamined households. If the household is not contacted or the communication is unsuccessful, the agent schedule is also reviewed for unhandled households.

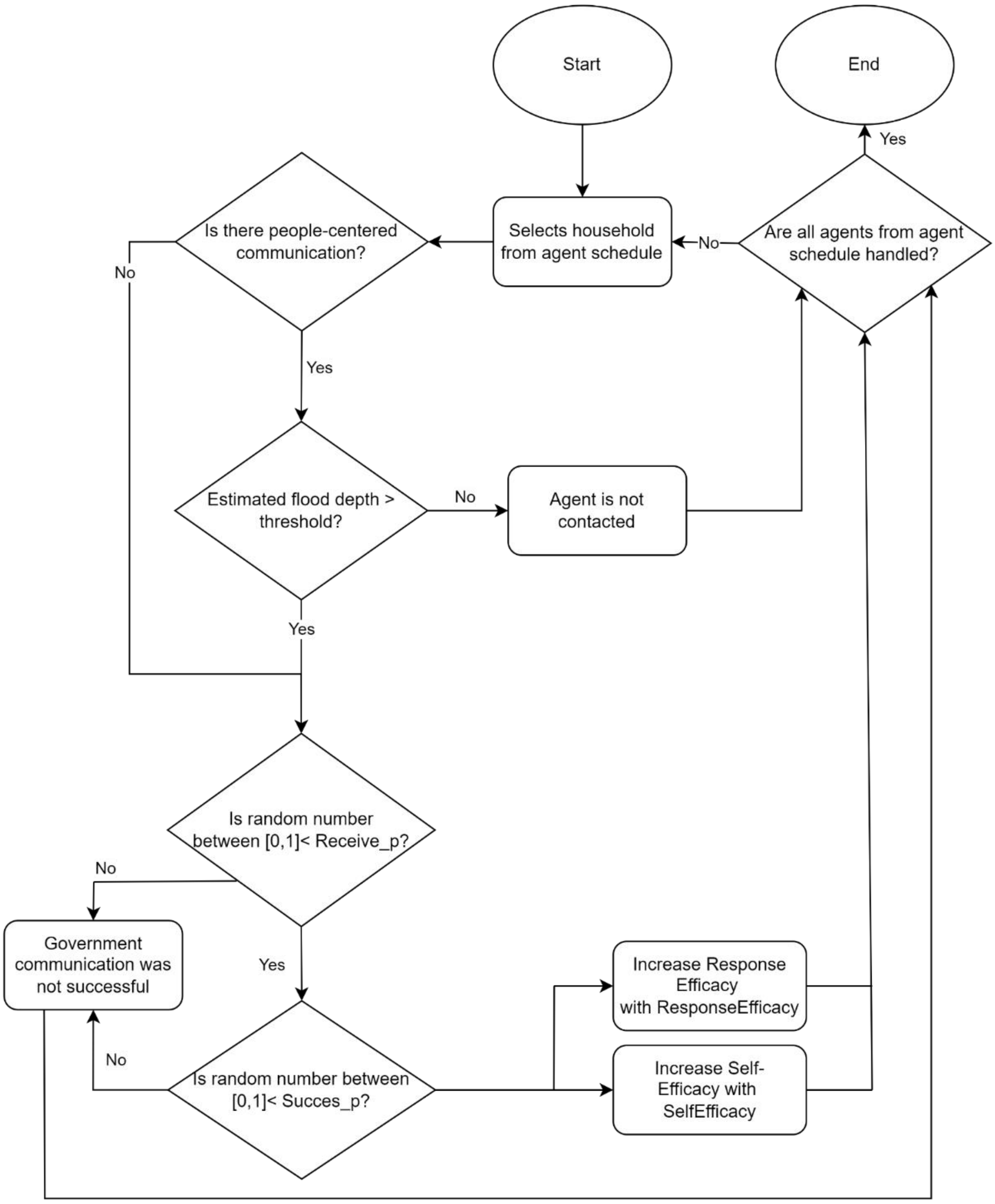

Figure 9: Flowchart indicating how the government informs households via the top-down and people-centred strategies

3.1.6 Choosing insurance type

At the initialisation of the model, households that are in the floodplain or have a high estimated flood depth, are obliged to have state insurance. However, it is possible to upgrade this insurance to private insurance, if the household wants extra 'protection'. First, it is checked if the household is aware that it can protect itself against floods (so if the self-efficacy boolean is True), and if its flood awareness is high enough. If the household is both aware of the danger and the protection possibilities, and its income is high enough to cover the extra costs, the household will also take private insurance. Otherwise, the insurance will stay the same. This process is shown in figure 10 below.

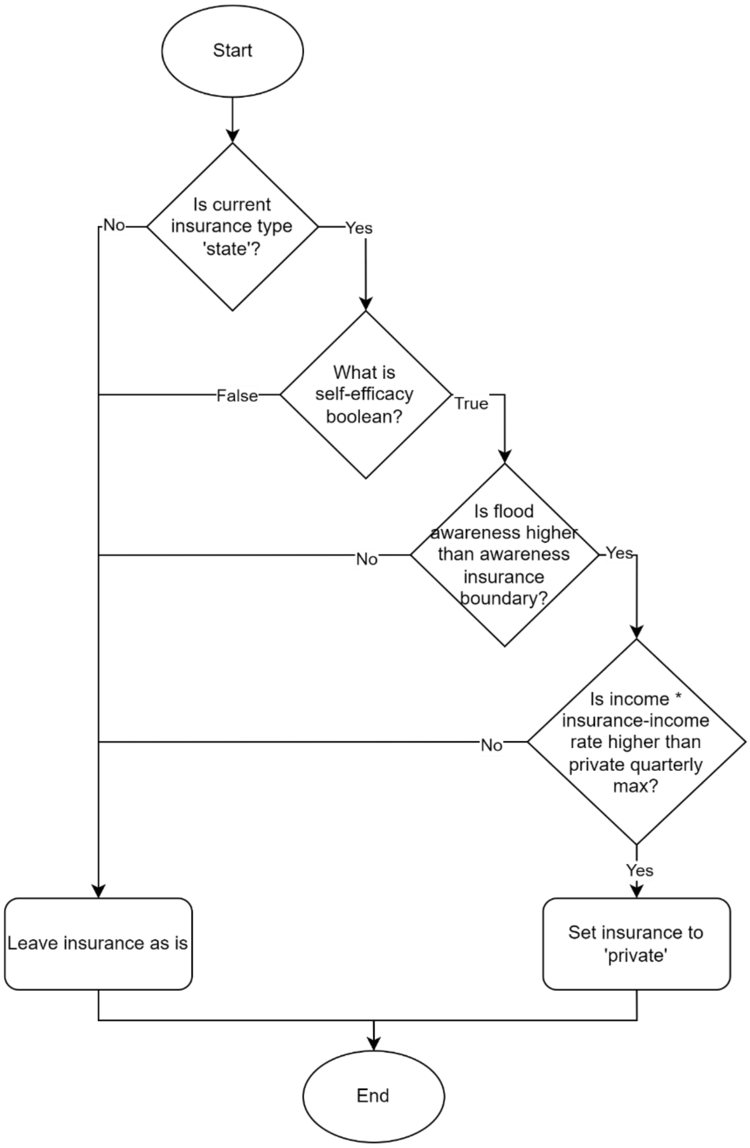

Figure 10: Flowchart indicating how households choose their insurance type

3.1.7 Pay insurance

When a household agent has insurance, it needs to pay its insurance premium at each step in the model. First, the current type of insurance is checked. In case of state insurance, the maximum insurance will be set to *state_quarterly_max*, while with private insurance the maximum insurance will be *private_quarterly_max*. There is a difference between the two insurance fees, since private insurance is more expensive (but it also covers all the damage in case of flooding).

Secondly, the adaptation status is taken into account. When an agent has no measures (and the adaptation status is equal to 'zero'), it needs to pay the maximum value for the insurance premium. However, when an agent does have measures, they get a small reduction on their insurance premium, based on the type of measures they have (FEMA, n.d.-a), as these measures will limit the damage in case of a flood. The final insurance premium will be distracted from the household's savings. The paying of insurance is also visualised in figure 11 below.

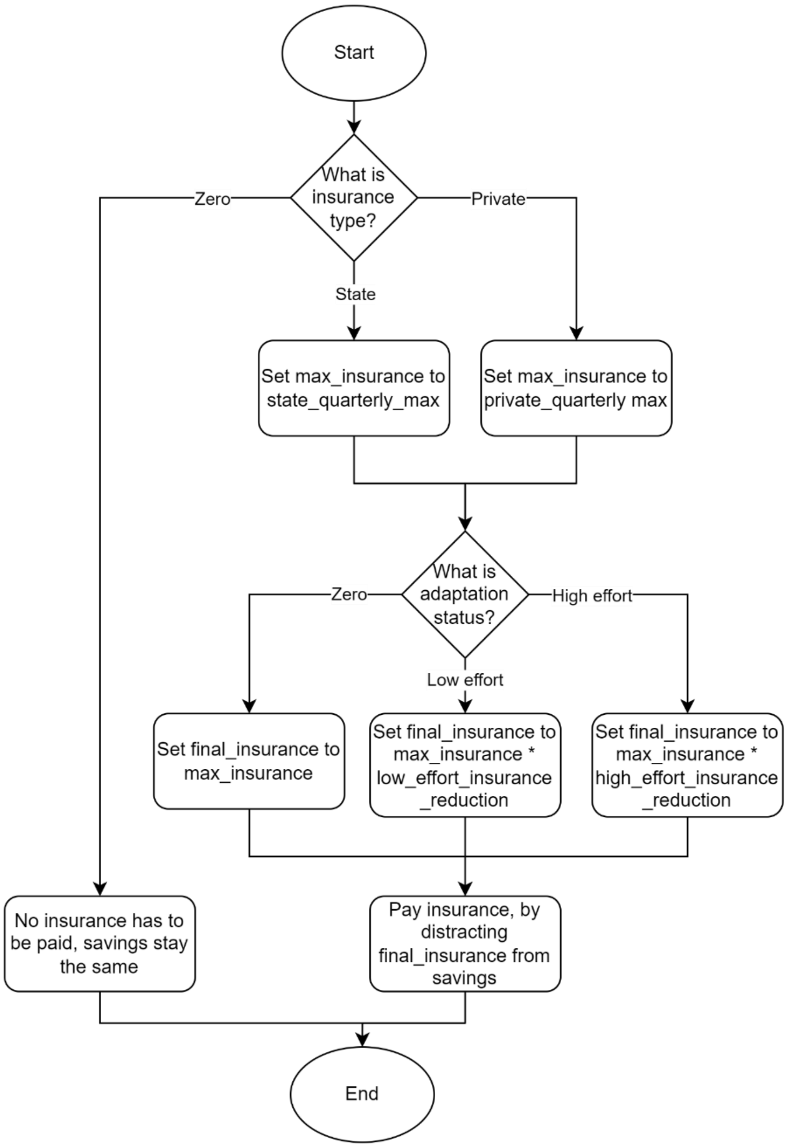

Figure 11: Flowchart showing a household's payment of insurance

3.2 Variables

To make it clear what kind of variables, or attributes, belong to which type of agent or the model, the three tables (table 1, 2 and 3) below provide an overview of respectively the household, government and model attributes. Many of the values for the attributes are based on assumptions, since it is very hard to find reliable sources for them. However, if the value is based on a source, the reference is put next to it.

Table 1: Household attributes

Households				
Variable	**Possible values**	**Initial values**	**Unit**	**Short description**
is_adapted	{True, False}	False	-	Boolean to describe whether households have adapted to floods. A household is adapted (is_adapted is True) when it has low or high effort measures.
adaptation_status	{‘zero’, ‘low_effort, ‘high_effort’}	‘zero’	-	Every household has an adaptation status. If they have not implemented any measures, it is ‘zero’. ‘Low effort’ measures include sandbags, and ‘high effort’ measures include raising the house
location	Point object	Point object	-	The household is given a location on the map. This is a Point object from the shapely library.
in_floodplain	{True, False}	False	-	The household can be in the floodplain or not, and thus have risk of a flood or not. If the household is in the floodplain, based on its location on the map, the in_floodplain variable is set to True.
threat_vulnerability	Real: [0, 1]	X ~ N (μ = 0.5, σ = 0.14) (Houston, 2017)	-	The threat vulnerability of a household describes to what extent a household is aware that floods can occur and damage their house. The higher the self-efficacy, the higher the awareness.
self_efficacy	Real: [0, 1]	X ~ N (μ = 0.71, σ = 0.706) (Houston, 2017)	-	The self-efficacy of a household describes to what extent a household is aware that it can undertake action to protect itself (against floods in this case). The higher the self-efficacy, the higher the awareness.
self_efficacy_ boolean	{True, False}	False	-	Self-efficacy indicates whether households are aware that they can protect themselves against floods by taking certain measures. If True, they know they can take measures, if False they don’t. This boolean is based on the numeric value of self-efficacy: SelfEfficacy.
insurance	{‘zero’, ‘state’, ‘private’}	{‘zero’, ‘state}	-	Type of insurance a household has. If the household is in floodplain or the estimated damage is high enough, the insurance type is state, otherwise zero.
house_value	Real: [0,∞]	X ~ N (	dollars	The monetary value of the house of a household

		μ = 300000, σ = 50000) (Realtor, 2023)		
yearly_income	Real: [0,∞]	X ~ N (μ = 53000, σ = 20000) /4 (US Census Bureau, 2023)	dollars	Income of a household per year
quarterly_income	Real: [0,∞]	Yearly_income / 4	dollars	Income of a household per quarter
savings	Real: [0,∞]	Yearly_income * 0.5	dollars	The savings of a household, each step, 20% of the households income goes to savings
costs_for_insurance	Real: [0,∞]	0	dollars	If a flood happens, the insurance can cover (part of) the damage. If a household has damage and has insurance, that amount will be stored in this variable.
flood_depth_ estimated	Real: [-∞,∞]	*Depends on flood map and location of household*	meters	The estimated depth of a flood in meters for a certain household (if negative, the house lies on elevated ground)
flood_damage_ estimated	Real: [0, 1]	*Depends on flood map and location of household*	-	The estimated damage done to a certain house after a flood, given in a number between 0 and 1, where 1 is completely damaged
flood_depth_actual	Real: [-∞,∞]	0	meters	The actual depth of a flood in meters for a certain household
flood_damage_ actual	Real: [0, 1]	0	-	The actual damage done to a certain house after a flood, given in a number between 0 and 1, where 1 is completely damaged
house_damage	Real: [0,∞]	0	dollars	The monetary value of the damage done to a house after flood
max_insurance	Real: [0,∞]	100 or 300, *depending on insurance type*	dollars	The maximal amount of insurance to be paid based on the type of insurance.
final_insurance	Real: [0,∞]	*Max_insurance - low_effort_insurance_ reduction* or *Max_insurance - high_effort_insurance _reduction*	dollars	The amount of insurance that has to be paid reduced based on adaptation measures (if there are any)

Table 2: Government attributes

Government				
Variable	**Possible values**	**Initial values**	**Unit**	**Short description**
top_down	{True, False}	False	-	Boolean to describe whether the government is using the top down communication strategy (True) or not (False)
people_centered	{True, False}	False	-	Boolean to describe whether the government is using the people centered communication strategy (True) or not (False)
Top_down_parameters (TD) & people_centered_ parameters (PC)*	Threat vulnerability Increase	TD:0,1 PC:0,2	-	This variable refers to an individual's perception of how dangers the flood is
	Self-efficacy Increase	TD:0,1 PC:0,2	-	Self-efficacy is the individual's belief in their ability to successfully perform a response.
	Receive Probability	TP:0,8 PC:0,5	-	The probability that the communication method reaches the individual
	Succes Probability	TP:0,2 PC:0,8	-	The probability that the communication succeeds in changing the perception of the environment.
	Agents of interest variables	TP: None PC: ["flood_depth_estimated",70le,"Bigger"]	-	The parameter that will be used to determine which agents are extra vulnerable to the threat and which are not. This Parameter should be given as a list in a list. For every list for the filtervariable should be formatted like:["filtervariable", threshold value, operator]. Filtervariable must be the attribute of the agent that will be used. The treshold value must be a number that indicates how high or low the filtervariable must be in order to be recognised as vulnerable. Lastly, operator must be a string called "Bigger" or "Smaller". When smaller the value must be lower than

	the threshold. When Bigger the value must be higher than the treshold.

* These variables exist out of multiple internal variables that are the same. Hence, they will be explained together.

Table 3: Model attributes

Model				
Variable	**Possible values**	**Initial values**	**Unit**	**Short description**
people_centered	{True, False}	False	-	Boolean to describe whether the government is using the people centred communication strategy (True) or not (False)
top_down	{True, False}	False	-	Boolean to describe whether the government is using the top down communication strategy (True) or not (False)
government	Government object	Government object	-	There is one government agent in this model
number_of_households	Natural: [0,∞]	250	-	The number of households that will be included in the model
flood_map_choice	{'harvey', '100yr', '500yr'}	'harvey'	-	There are three kinds of floods: Harvey, 100yr or 500yr. This variable defines which flood is coming in the model.
network	{'erdos_renyi', 'barabasi_albert', 'watts_strogatz', 'no_network}	'watts_strogatz'	-	There are different network topologies provided, which define the social network graphs.
probability_of_network_connection	Real: [0, 1]	0.4	-	The probability two neighbours have a connection.
number_of_edges	Real: [0,∞]	3	-	Number of connections each agent has with other neighbours. This defines the number of friends each agent has.
number_of_nearest_neighbors	Real: [0,∞]	5	-	The number of agents who are defined as neighbours for each agent. In this case, each neighbour has 5 nearest neighbours.
state_quarterly_max	Real: [0,∞]	100	dollars	The maximal amount that can be paid for state insurance (this has to be paid if households have no adaptation measures)
private_quarterly_max	Real: [0,∞]	300	dollars	The maximal amount that can be paid for private insurance (this has to be paid if households have no adaptation measures)
low_effort_insurance_reduction	Real: [0, 1]	0.8	-	The rate with which the insurance is reduced, if household has low effort measures
high_effort_insurance_reduction	Real: [0, 1]	0.5	-	The rate with which the insurance is reduced, if household has high effort measures

state_insurance_ boundary	Real: [0,∞]	250.000 (FloodPrice, 2023)	dollars	The state insurance covers damage costs up until a certain amount, which is this boundary.
insurance_income_rate	Real: [0, 1]	0.2	-	A certain percentage of the income of a household must be higher than the costs of private insurance, in order for a household to upgrade to private insurance. This variable indicates the percentage.
social_interact_ boundary	Real: [0, 1]	0.5	-	This variable acts as a boundary for households to socially interact or not. If a random number is higher than boundary, a household will interact with friends, otherwise not.
awareness_interaction_ boundary	Real: [0, 1]	0.25	-	If the flood awareness of a household is higher than this awareness boundary, it considers interacting about floods with friends
interaction_effect	Real: [0,∞]	0.5	-	When the awareness of a household changes, the change is determined by the differences with their friends multiplied by the interaction_effect
efficacy_boundary	Real: [0, 1]	0.8	-	When a random number between 0 and 1 is larger than the efficiacy_boundary, the agent will be influenced by their friends efficacy
efficacy_friends_ influence	Real: [0,∞]	1.01	-	Each step, the self efficacy of a household is multiplied by this number, if their friends have a true self-efficacy binary, and the households own efficacy binary is false.
flood_step	Real: [0, ∞]	50	-	The step at which a flood happens in the model
low_effort_damage_ reduction	Real: [0,∞]	0.1	meters	If there is a flood, and a household has low effort measures, the flood depth will be reduced by this number
high_effort_damage_ reduction	Real: [0,∞]	0.25	meters	If there is a flood, and a household has high effort measures, the flood depth will be reduced by this number
house_ground_rate	Real: [0, 1]	0.8	-	If there is a flood, not the entire 'market value' of the house is assumed to be damaged, since the ground itself is also worth something. This rate is used to calculate the actual house value without the ground

awareness_increase_ shock	Real: [0, 1]	0.25	-	The awareness of a household will increase with this factor when their house is damaged drastically (based on awareness_shock_boundary)
awareness_shock_ boundary	Real: [0, 1]	0.1	-	When house damage divided by house value is higher than this boundary after a flood, the awareness of the household will increase
flood_happening	{True, False}	False	-	Boolean that indicates if flood happens at a certain step in model
low_effort _depth_boundary	Real: [0, 1]	0.1	-	Households will consider adapting their house with low effort measures if the estimated flood depth is higher than this boundary (if this depth is higher than the low_effort _depth_boundary and lower than the high_effort _depth_boundary, it will consider low effort measures)
high_effort_depth_ boundary	Real: [0, 1]	0.25	-	Households will consider adapting their house with high effort measures if the estimated flood depth is higher than this boundary
low_effort_cost_rate	Real: [0, 1]	0.005	-	The costs of a low effort adaptation measure are a percentage of the house value, this rate (percentage) is indicated by this variable
high_effort_cost_rate	Real: [0, 1]	0.04	-	The costs of a high effort adaptation measure are a percentage of the house value, this rate (percentage) is indicated by this variable
awareness_adaptation_ boundary	Real: [0, 1]	0.3	-	If the flood awareness of a household is higher than this awareness adaptation boundary, it considers adapting its house to floods with measures
awareness_insurance_ boundary	Real: [0, 1]	0.3	-	Households will consider upgrading their insurance type from ‘state’ to ‘private’ if their flood awareness is higher than this boundary
step_awareness_ reduction	Real: [0, 1]	0.98	-	When no flood happens, the awareness of households decreases over time. Each step, the awareness is lowered by this variable
step_efficacy_reduction	Real: [0, 1]	0.995	-	When no flood happens, the self-efficacy of households

				decreases over time. Each step, the self-efficacy is lowered by this variable
spending_chance	Real: [0, 1]	0.5	-	This is the chance the household does a large spending each timestep
large_spending	Real: [0, 1]	0.85	-	The percentage of savings the household keeps when they do a large spending
flood_aware_increase_td	Real: [0, 1]	0.1	-	When the government communicates successfully top-down, the flood awareness of the households increases by this factor.
self_efficacy_increase_td	Real: [0, 1]	0.1	-	When the government communicates successfully Top Down, the self-efficacy of the households increases by this factor.
high_risk_hh_threshold	Real: [0,∞]	50	percent	This variable indicates how many percent of the households with the highest estimated flood depth get contacted via people-centred communication
flood_aware_increase_pc	Real: [0, 1]	0.2	-	When the government communicates successfully Person Centred, the flood awareness of the households increases by this factor.
self_efficacy_increase_pc	Real: [0, 1]	0.2	-	When the government communicates successfully Person Centred, the self-efficacy of the households increases by this factor.

3.3 Assumptions and model reductions

While creating the model, assumptions were made about the behaviour of the agents. These are listed below:

Regarding damages of the flood:
- Not the entire market value of the house will be able to be damaged, and the ground is also worth something. It has been decided to keep that part (in this case 20%) out of the calculation of the damage, and the house value will be multiplied by 0.8.

Regarding the interactions between governments and households:
- People with very high flood awareness want to go to the information session. If flood awareness is not that high, but the estimated flood depth is quite high, households will still try to go to the session.
- Not everybody who wants to go to the session will actually be able to go to the information session.
- Only 80% of the people who get an informational letter actually read the letter.
- If households are very unaware of the flooding, they will not talk about it at all with their friends.

Assumptions regarding measures:
- Low effort measures cost 0.5% of the house price.
- We assume that high effort measures cost 4% of the house price.

Assumptions about savings:
- Savings of the households are 50% of the yearly income
- Each step, 20% of the income goes to savings
- Each step, there is a 10% chance that households spend 50% of their savings on for example furniture/holidays.

4. Verification and validation

In this chapter, a sensitivity analysis is conducted to check the sensitivity of the input variables. Furthermore, the model is verified and validated.

4.1 Sensitivity analysis

During the setup of the model, various assumptions have been made about the values of the parameters, which are explained in chapter 3. To check the sensitivity of the input variables on the KPI's, a univariate sensitivity analysis has been conducted. It was not possible to take all the variables into account. Since we are focussing on the government's communication, it was therefore decided to focus on those variables: *flood_aware_increase_pc, flood_aware_increase_td, high_risk_hh_treshold, self_efficacy_increase_pc, self_efficacy_increase_td..*

The analysis is done by changing the input variables +20% and -20%, running the model for 80 timesteps, and running 100 iterations. Appendix B1 shows the input variables. The results of the changes in these input variables are measured by the KPI's: flood awareness, self efficacy, adaptation of measures and house damage. In figure 12, an overview of the results is shown, including the quantiles. An overview of the concrete values and percentages are shown in Appendix A.

The variables are run for the two different communication measures: top down and people centred. For the first two variables: *flood_aware_increase_td* and *self_efficacy_increase_td*, the top down measures are set True. As a result, the average for all KPI is different for the first two variables and the last three.

When looking at the first KPI: Flood awareness of the agents, there is no striking difference for the variables related to self-efficacy, and the distribution for Floodawarenessincrease is also logical. However, an increase in *high_risk_hh_treshold* of 20% leads to a significant decrease in the Floodawareness, this decreases by 25.87%. This makes this variable sensitivity by this KPI, since the original decrease (20%) is lower than the decrease in outcome (25.87%). This is logical: when the threshold increases, less houses are qualified for the people centred communication. Therefore, less households are influenced by the government, and the flood awareness is lower. This also declares why the boxplot for -20% for this variable is small: many people are influenced by the government, and the average flood awareness is almost maximal. The distribution of household's flood awareness is smaller, since many people are influenced by the government.

When looking at self-efficacy, the same phenomena becomes clear: the self-efficacy is much lower when the *high_risk_hh_treshold* increases by 20%. In addition, the distribution of this variable is larger: self-efficacy changes less than flood awareness due to this variable.

The house damage of agents does not extremely differ during the sensitivity analysis, and this makes the variables not sensitive for this KPI. The only small difference is by *high_risk_hh_treshold*, which is mentioned before. The adaptation does also have this fluctuation for *high_risk_hh_treshold,* and does have some differences for *self_efficacy_increase_td*. When the communication is more effective, and self-efficacy increases faster, more households are aware of the fact they can buy measures. As a result, the number of adapted households increases. This is still a small difference of a few percent, and does not make this variable sensitive.

All in all, out of all variables in this analysis, only *high_risk_hh_treshold* is sensitive. This variable is mostly sensitive to flood awareness and self-efficacy. By these KPI's, the increase and decrease of 20% leads to an effect of 25% difference in the KPI.

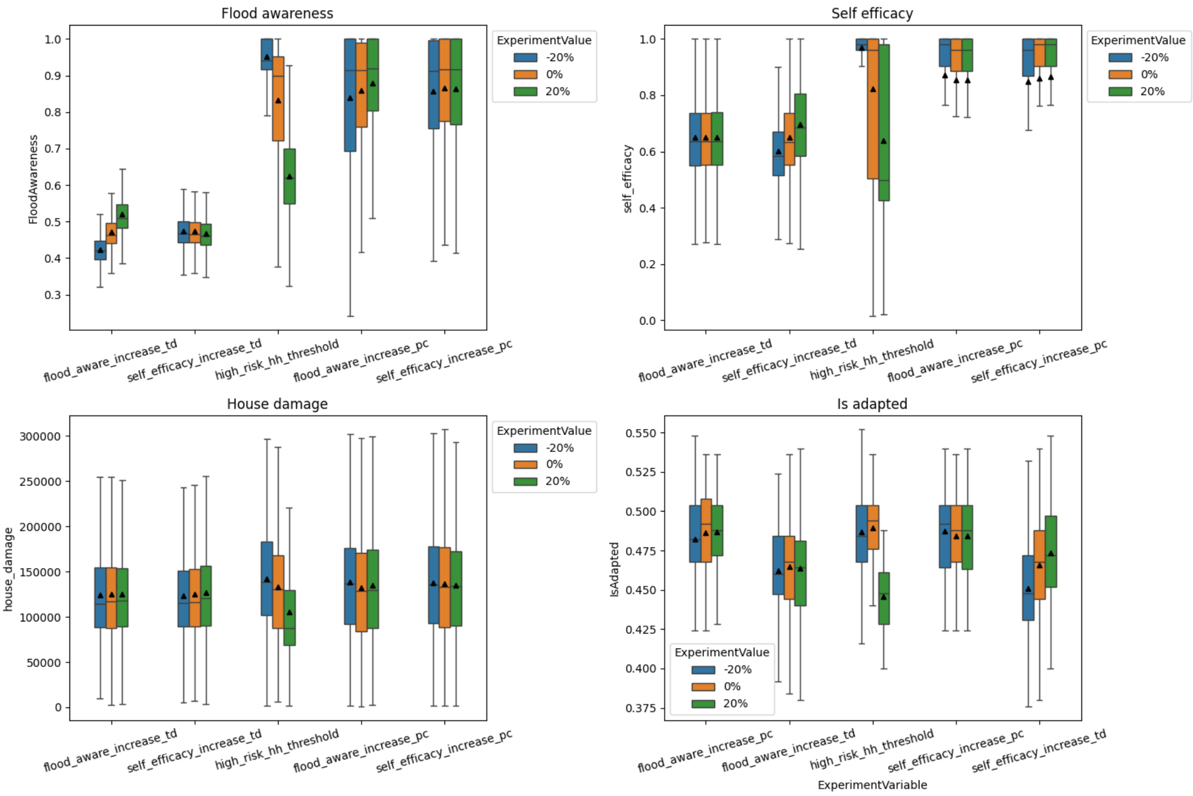

Figure 12: Sensitivity analysis for 5 input variables and the effect on the 4 KPI's

4.2 Verification

While verifying the model, it is checked if the processes that were defined in the conceptualisation and formalisation are implemented correctly and if the model behaves according to expectations. All the main processes of the model were verified and the results are put in table 4 below. The table shows what kind of behaviour was expected for a certain process and whether this behaviour was observed in the output of the model. The behaviour was checked by using certain print statements. For each concept/progress, proof of the behaviour is shown in Appendix B.

Table 4: Verification of the main concepts/processes of the model with the expected behaviour and whether this behaviour was observed.

Concept/Process	Expected behaviour	Behaviour observed?
Initialisation	250 household agents should be created, each with their own unique set of attributes	Yes
Paying insurance	Households that are insured should pay the insurance fee at every step	Yes
	This fee should be distracted from their savings	Yes
Shock: flooding	The flood should cause households to have an actual flood depth, based on their adaptation status.	Yes
	The flood depth creates damage to the house.	Yes
	Based on the household's insurance type, it either has to pay or not for the damage done to the house.	Yes
	The flood awareness should also increase for some households	Yes
Social interaction about flood awareness	Households' flood awareness can be positively changed through social interaction.	Yes
	Households' flood awareness can be negatively changed through social interaction.	Yes
	Households' flood awareness can be stay the same	Yes
Social interaction about self-efficacy	Households can either be self-efficacious or not.	Yes
	If not self-efficacious, households can interact with friends and change their own self-efficacy	Yes
Choosing insurance	Households have zero, state or private insurance.	Yes
	Households can upgrade their insurance	Yes
Adapting with measures	Households can buy low and high effort measures.	Yes
	If high effort measures are to expensive, households can buy low effort measures.	Yes
	Households can opt to buy no measures at all.	Yes
Government communication	Top-down communication increases self-efficacy of part of the households.	Yes
	Top-down communication increases flood awareness of part of the households.	Yes
	People-centred communication increases self-efficacy of part of the households.	Yes
	People-centred communication increases flood awareness of part of the households.	Yes

4.3 Validation

In this section, it will be examined if the model behaviour roughly corresponds with the real-live behaviour. This will be done by comparing the model's Output variables to their corresponding values in real life. The storm Harvey will be used for the validation. A report of the Housing and Community Development Department reports (n.d.) that there was total damage to residential buildings during Storm Harvey of 16 billion dollars. The same report says that during the storm, 209.000 houses were affected by flooding. This results in an average of 76.555 dollars worth of damage per household. The model outcomes for Storm Harvey without top-down and personal-centred communication resulted in an average damage of 63.340 dollars per household. Since the model is a simplification of the real world this is deemed close enough.

The total number of households in Houston is 771.000. Divide this by the total number of households impacted then 27% of all households were impacted by the storm. In the model, 45% were impacted. Here, the difference is quite big. A possible explanation, based on assumptions, could be that in reality households do not all live on the base floor but instead on higher floors in apartment buildings. The model assumes that everybody lives on the ground floor. One could state that households that live higher than the ground floor will not be directly impacted and therefore are not included in the 209.000 directly impacted.

Lastly, the average payout of state insurance is examined. Based on the report from the Housing and Community Development, an average payout of $98,000 per household that makes a claim on their insurance is reported. The model average payout for an insurance claim in the model is 86.303 dollars. This is also deemed close enough.

No other values were compared to the real-life scenario because the model had no other output values that were accurately measured in real life. However, the three comparisons indicate that the model can replicate properties of the real world well enough to be usable to study household behaviour and the effects of government communication.

5. Experimentation

This section describes the choices for the setup of the experiments. At first, the policy measures will be examined and afterwards the scenarios. Lastly, hypotheses will be defined.

5.1 Experimental setup

Each run, the model will run for 80 steps, each step representing three months. When the model has run, twenty years have passed. There are 250 household agents, and 1 government agent, which represent Harris County in Houston.

First, the base case will run without communication from the government. Thereby, it is possible to see how agents interact with each other without interacting with the government. This can also be seen as the baseline measurement.

Second, the model will be run with the different communication types of the government: people centred communication or top down communication. When running the model with these policies, it will show the effectiveness of government communication tools, in comparison to the base case.

This leads to four experiments, which are shown in table 5. It has been decided to run these experiments on flood map "Harvey", since this is the worst flood, and the communication should be sufficient for this type of flood. One single run in an agent-based model should never be relied upon, therefore, the model has run 100 times, and the average outcome of each run is taken.

Table 5: Experimental setup

Experiment number	Person centred communication	Top down communication	Flood map
1	False	False	Harvey
2	False	True	Harvey
3	True	False	Harvey
4	True	True	Harvey

5.2 Scenarios

There are three possible scenarios while running the model: 100 year, 500 year and Harvey. These represent the intensity of the flood:

- 100 year: Each year, there is a 1 percent chance that a flood will happen with the flood depth of the "100year" scenario (Harris County engineering department, n.d.)
- 500 year: The "500year" scenario has a flood depth that has 0.2 percent chance that will happen each year.
- Harvey: This is called after hurricane "Harvey" in 2017, which caused the most damages, and is the worst scenario out of three.

Each scenario will be run without the communication strategies of the government, to see the pure effect of the different flood maps on the model. An overview of these runs are shown in table 6. The scenarios are run with 250 agents and 100 iterations.

Table 6: Scenarios

Experiment number	Person centred communication	Top down communication	Flood map
1	False	False	100yr
2	False	True	500yr
3	True	False	Harvey

5.3 Hypothesis

The main research question is: *What is the effect of top-down and people-centred information campaigns on adaptation rate and damage avoidance under conditions of multiple flooding scenarios as measured by four indicators: average flood awareness, average self-efficacy, number of adapted households and total damage?*

Accompanying the main research question are the following sub-questions that need to be answered to address the main question.

1. What is the effect of the top down information campaigns on the 4 indicators?
2. What is the effect of the people-centred information campaigns on the 4 indicators?
3. What is the effect of the combination of top-down and people-centred information campaigns on the 4 indicators?

It is expected that both top-down and people-centred information campaigns are effective to reduce the damage for the average household and let households adapt, since both campaign types will increase the average self-efficacy and flood awareness compared to the base case (without any policy). With increased self-efficacy and flood awareness, households will sooner buy measures and thus protect themselves better and decrease damage in case of a flood. The combination of the two campaigns will have the most positive effect on the four indicators, since the two positive effects of the two campaigns will be combined.

6. Results

In this section, the results of the model will be discussed. Firstly, the scenarios will be analysed and secondly the policy results will be analysed.

6.1 Scenario analysis

The model has run for the three scenarios, the 100yr, 500yr and Harvey flood map. In this subsection, we will examine how the intensity of the flood (the scenarios) change the KPIs without any communication tools.

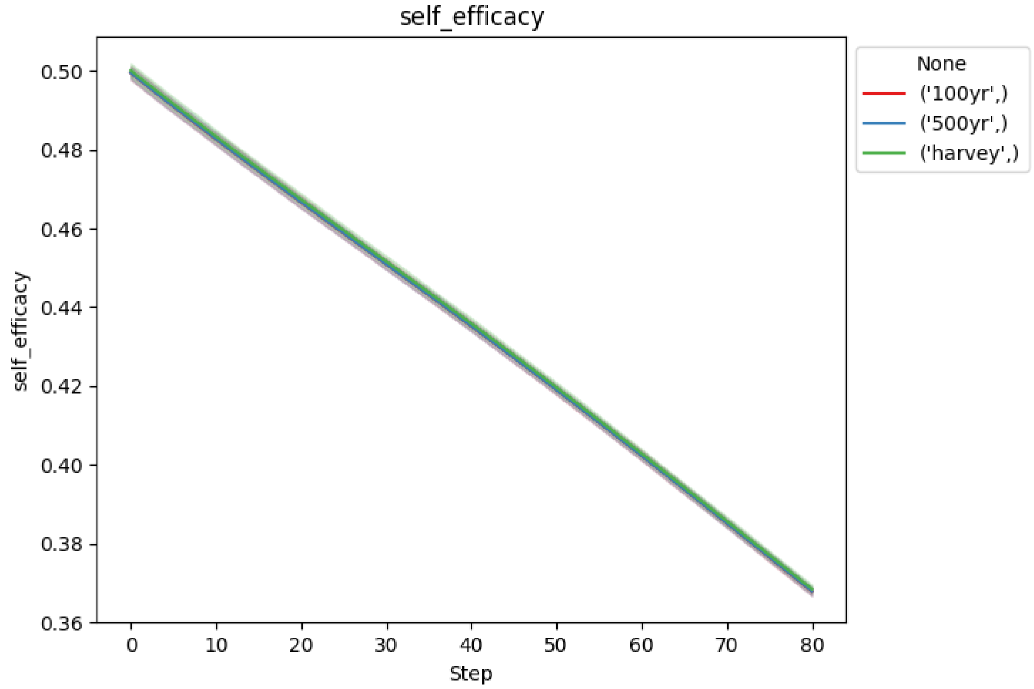

Figure 13: Average self-efficacy per scenario

First, self-efficacy of households: figure 13 shows that it remains the same in each scenario and is not influenced by the severity of the flood. This is logical since households do not suddenly become aware of their ability to act when the estimated flood is severe, this can only be influenced by their friends and the government. However, they do become more aware of the floods if a flood happens and damages their house.

This is illustrated in figure 14 around step 50: When flood Harvey happens, the households become more aware of the flood than during the 500yr flood or 100yr flood, and the sudden increase is higher. This can be explained by the fact that the damage due to flood Harvey is much higher, and households awareness only increases when the damage is high enough.

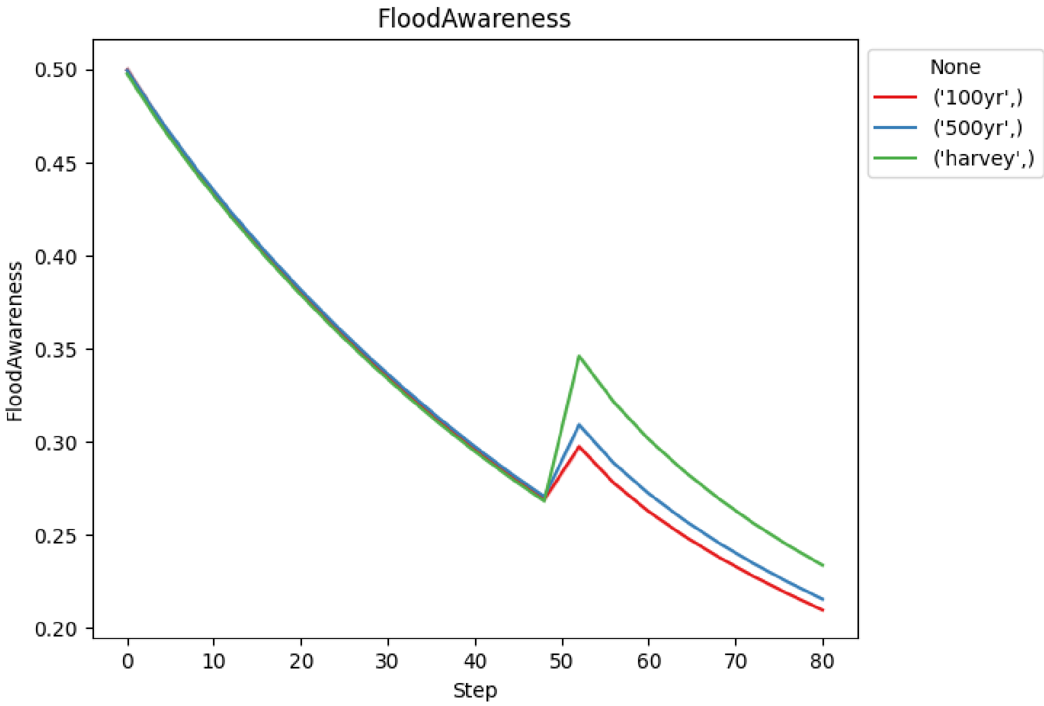

Figure 14: Average flood awareness per scenario

Figure 15 visualises the house damages during the different flood types. Flood Harvey causes the highest damage, the average damage is almost 65.000 dollars during this type of flood. The 500yr flood is much lighter, and the damage is almost half of the Harvey damage. The 100yr damage is even below 25.000 dollars. This was expected, since this was the mildest flood. It is important to note that this graph starts at step 50 instead of step 0, since the flood did not happen before, and there was no damage.

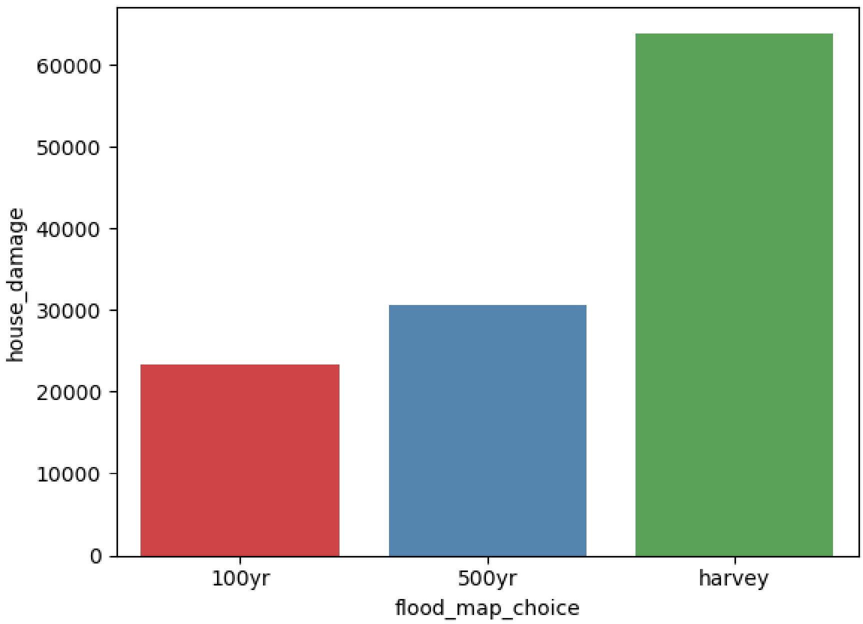

Figure 15: Average house damage per scenario

Lastly, figure 16 illustrates the adoption of measures over time. Measures are primarily purchased when there is a high flood awareness and high self-efficacy. When the estimated flood depth is higher, households will also be more aware of the flood. This is evident in the figure: almost 100 households adapted measures during the Harvey scenario, but during the 500yr scenario only 60 households.

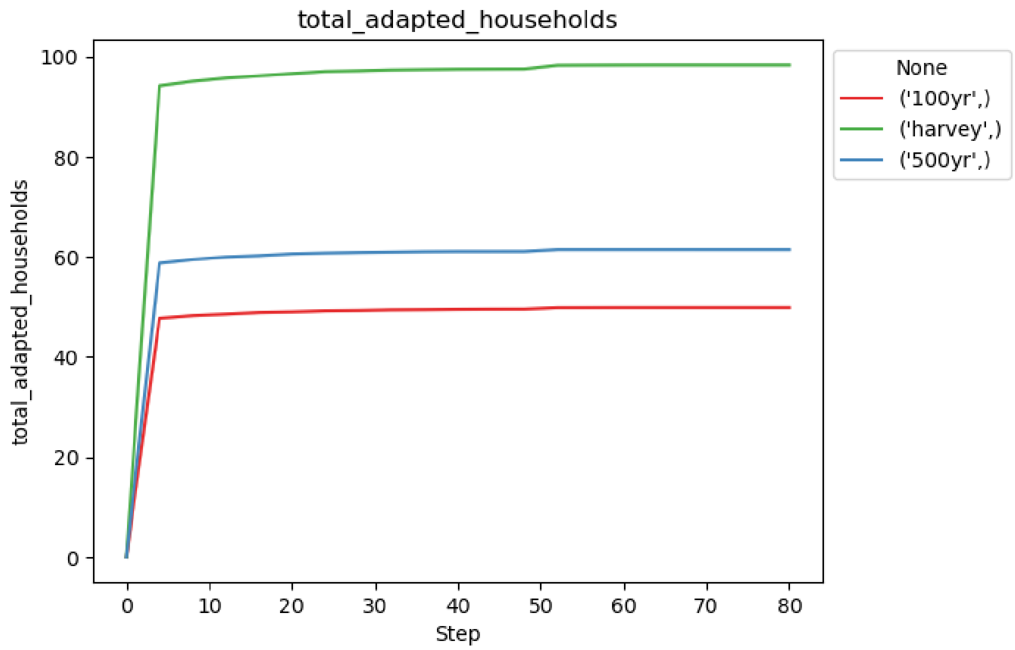

Figure 16: Total adapted households per scenario

6.2 Policy results

In this subchapter, the results of the different policies are visualised and explained. The effects of the different policy strategies on the 4 KPI's will be shown.

6.2.1 Self-efficacy

As figure 17 shows, without communication, self-efficacy decreases. With each step away from a flood and without reminders, households' knowledge about flood protection fades. The only thing that influences them at this point are their friends, but their friends' efficacy is also decreasing.

Everyone is, in theory, reached via *top-down communication*. Some households might not read the letter and immediately throw it away, not increasing their self-efficacy. However, most of the households will read the letter every four steps and hereby increase their self-efficacy. The letter keeps coming every year, increasing self-efficacy and that is why the line for this communication strategy in the graph is quite linear.

For *people-centred communication*, the influence on households is higher (+0.2 instead of +0.1 for top down communication), since it is more personalised information, but fewer people are reached. Therefore, the increase in self-efficacy is quite steep at the beginning. However, only a select group of households with the highest estimated flood depths are targeted via the people-centred communication. The rest of the households can only be influenced by friends, and, as can be concluded from the base case (without policy), this influence is small and the self-efficacy fades out over time. The result of this is that the people-centred strategy kind of stagnates over time.

For the *combination* of the two policies, the line in the graph clearly shows that the effect of this is also the combined effect of the two policies. The self-efficacy immediately increases steeply at the beginning (steeper than just people-centred) and does not stagnate over time, but keeps growing, because of the top-down strategy.

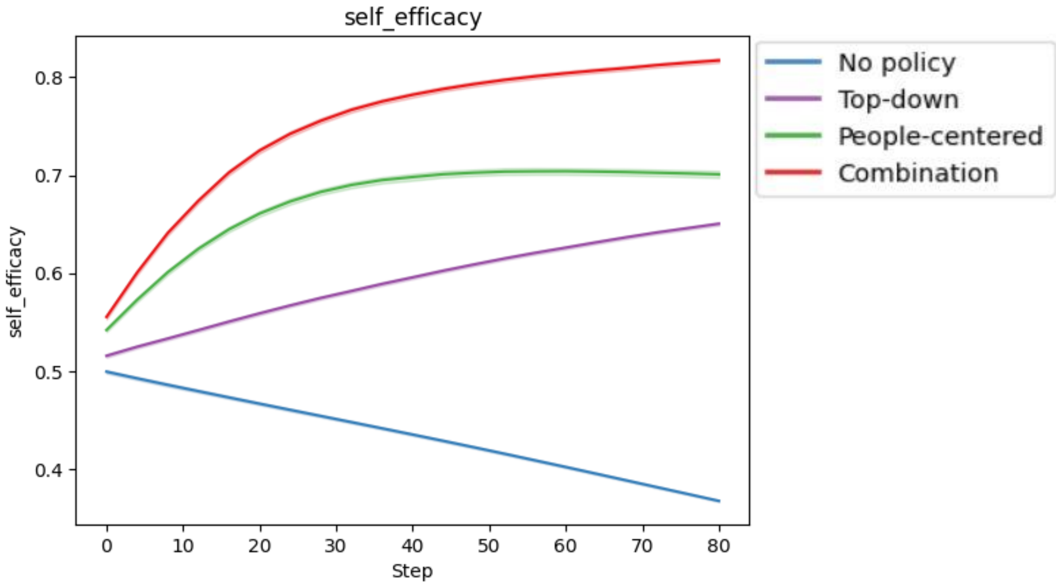

Figure 17: Average self-efficacy of households over the steps

6.2.2 Flood awareness

The distribution of the four lines in figure 18 is quite intuitive: the more effective communication, the more people are aware of floods. However, when there is *no communication*, the same happens as with self-efficacy: households become less aware of the floods, since they are not informed about them, and their friends are not informed either. Thus the flood awareness fades over time. The trend follows a slightly curved shape, due to the flood awareness decrease of 1% per step. Therefore, this is not a linear process, and there is a higher decrease in the beginning.

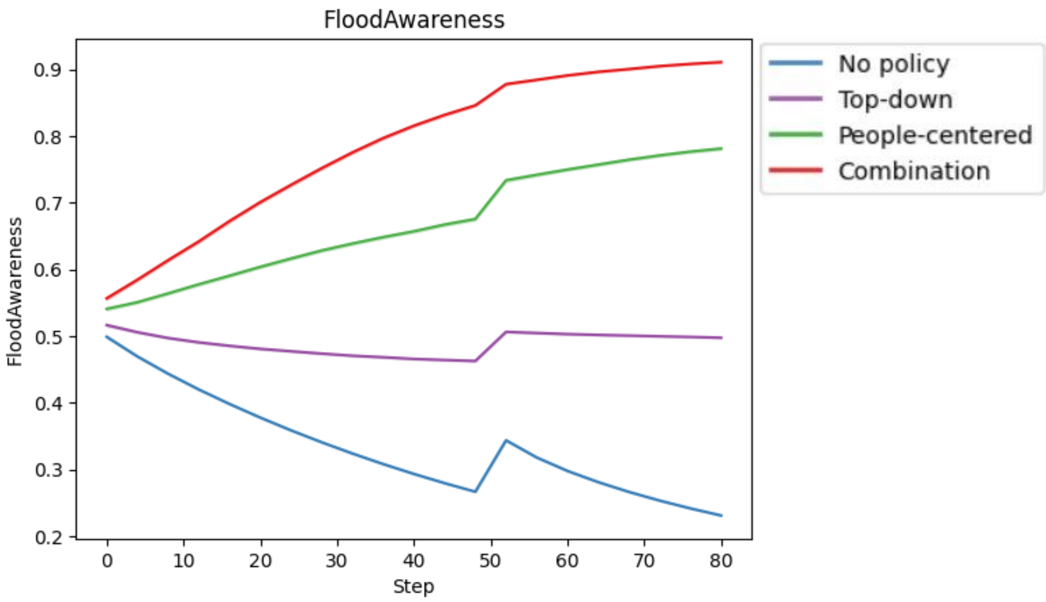

Figure 18: Average flood awareness of households over the steps

With all policy options, there is a flood at step 50. In every situation, households become more aware if they have a high enough damage. The increase during this step is the highest when there is no communication. This makes sense, since less households have been informed about floods, which means that fewer households have taken measures, resulting in a higher damage, and thus more households get an increase in flood awareness. After the flood, the flood awareness decreases again without any policy, the same as before the flood. This is because nothing has changed in the situation, and flood awareness decreases at the same rate as before the flood.

With *people-centred communication*, it is the same story as for self-efficacy: a select group of people, with the highest estimated flood depths, are effectively reached. The people-centred strategy might reach fewer households, but it is more effective than the top-down strategy, since the flood awareness increases, and keeps increasing. The selected households are effectively reached and can also influence their friends.

The *top-down* strategy is less effective than the *people-centred* strategy, as can be seen in the graph. This makes sense as the reach of households might be bigger, but the effect on flood awareness is a lot smaller.

When *both communication* policies are applied, most of the people in risk areas are informed, but people in other areas are also informed. As a result, a larger group is reached in comparison to the other policies, and the average flood awareness is the highest. Due to this, the effect of the flood on the flood awareness is the lowest.

When comparing the decline in flood awareness (figure 18) and self-efficacy (figure 17) when there is no communication tool, it can be seen that flood awareness decreases faster than self-efficacy. This can be explained by the fact that self-efficacy decreases by 0.5% per step, while flood awareness decreases by 1%. This is because someone's flood awareness decreases faster than their ability to know how to handle it. However, when there is no flood in several years, households may not remember exactly what the measures were, and this leads to a decrease of self-efficacy too.

6.2.3 Adaptation with measures

As can be seen in figure 19, in the first few steps, many households start to adapt with buying measures. This can be declared by the fact that zero households have any measures at the initialisation of the model, while some households already might have a high flood awareness and high self-efficacy. These households will quickly buy measures and they can influence their friends, increasing their friends' flood awareness and self-efficacy.

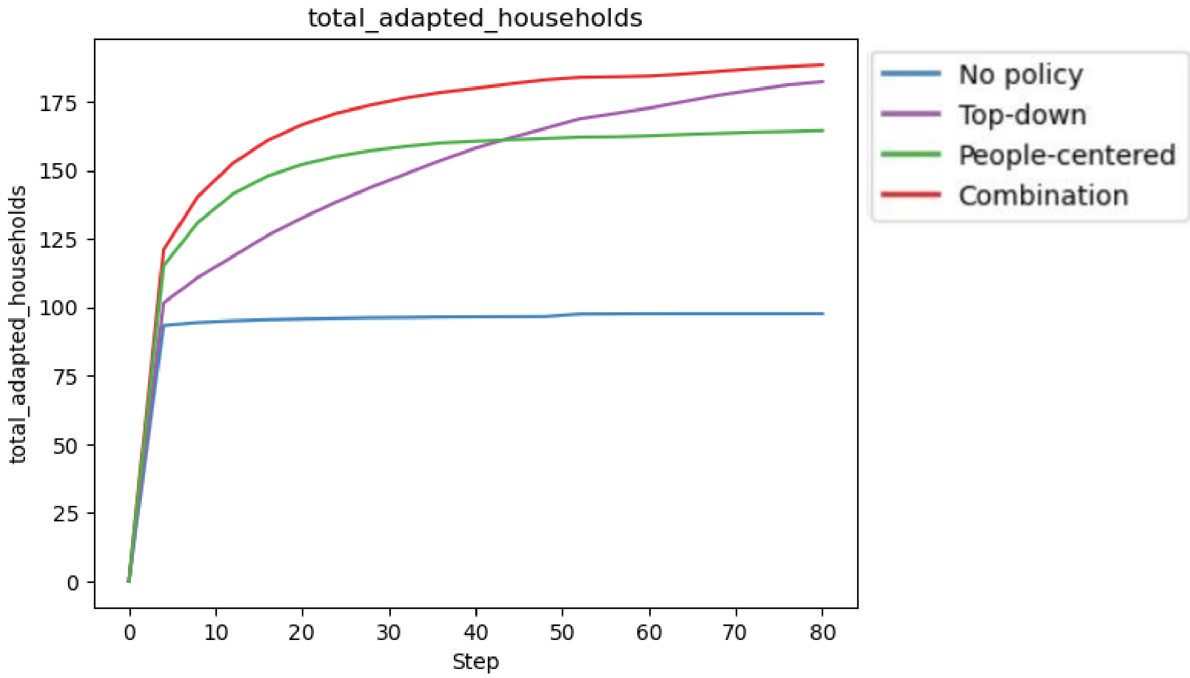

Figure 19: Total number of adapted households over the steps per policy

Figure 19 shows that the total number of people that adapted, without any policy, practically stabilises after a few steps of the model, except for the very slight increase after the flood at step 50. This is probably the case, because the average flood awareness and self-efficacy do not increase without policies, as can be seen in figure 17 and 18**.** Households that are quite flood aware and self-efficacious will buy measures quickly. However, people who are not flood aware or self-efficacious at the beginning, will probably not become much more flood aware or self-efficacious, and thus won't buy measures. The flood at step 50 will have influenced a few households in such a way that the flood awareness is high enough after the flood to buy measures, hence the slight increase in the graph.

The lines of the three *top-down, people-centred* and *combination* each have a similar course as their respective lines in the graph of self-efficacy, shown in figure 17. From this, it is possible to conclude that the number of adapted households is mainly based on the self-efficacy of the households. The reasoning for the course of the lines of the number of adapted households is mainly the same as for self-efficacy. However, the flood awareness also has an influence, since it is possible to see that the lines have a slightly off bump at step 50 after the floods, which is also the case in the graph of flood awareness. It is probably also because of the higher flood awareness with *people-centred* communication, that more people will adapt at the first part of the model, where the green line (people-centred) is higher than the purple one (top-down). As the top-down slowly but steadily influences the households, the purple line will eventually get higher than the green one.

6.2.4 House damage

Figure 20 visualises the average house damage for every communication strategy. This figure clearly shows the effects of the policies: if there is no government communication, the average damage is the highest: more than 60.000 dollars.

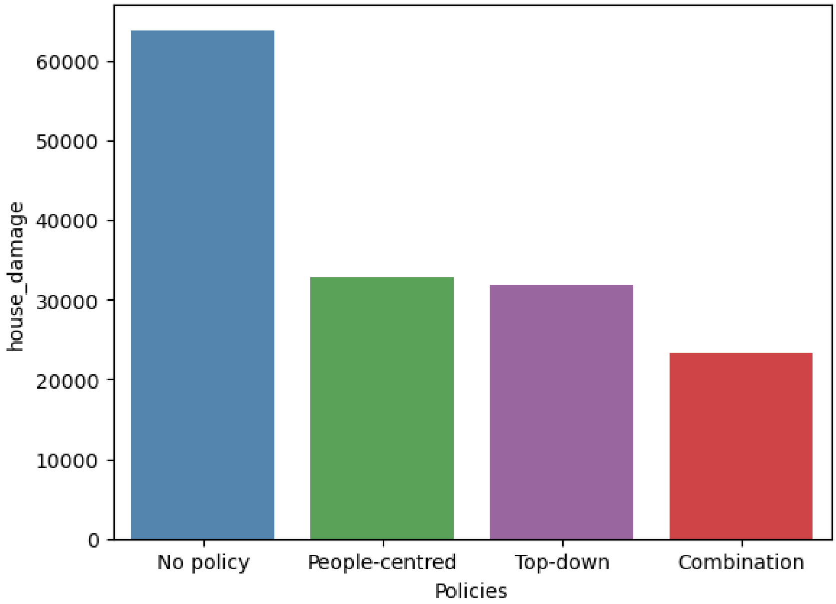

Figure 20: Average house damage per policy

When looking at *top-down communication* and *people-centred communication*, there is no clear difference. People-centred has a slightly higher damage. With the people-centred strategy, people in areas with a high flood depth are better prepared than with top-down communication. However, people in less risky areas still suffer from damage, since they did not get the information during this policy. As a result, the damage is approximately equal to the top-down situation.

When *both of the policies* are implemented, the damage is the lowest. This is the case since almost every agent is reached, and as a result more agents have taken measures to protect their house.

7. Conclusion, Recommendations and Limitations

This chapter discusses what can be concluded from the model results and what limitations the model has. Furthermore, recommendations for future work will be done.

7.1. Conclusion

The main research question is: *What is the effect of top-down and people-centred information campaigns on adaptation rate and damage avoidance under conditions of multiple flooding scenarios as measured by 4 indicators: average flood awareness, average self-efficacy, number of adapted households and total damage.* From the research it can be concluded that, top-down and people-centred information campaigns have a positive effect on the four key performance indicators: self-efficacy, flood awareness, number of adapted households and flood damage. Both the approaches lead to a somewhat similar reduction in house damage. Using both the approaches in combination will lead to an even bigger positive effect on the four indicators. When trying to avoid as much damage as possible a combination of both approaches should be implemented. Refraining from implementing information campaigns is unwise, due to the fact that this could lead to similar situations experienced during storm Harvey, with a lot of damage with high monetary value.

7.2. Limitations

The purpose of the model is to represent the behaviour of flood mitigation in real life. Making a model that can represent the real world 100% accurately is impossible and unwanted. Hence, simplification and assumptions were made. This will always lead to certain limitations of the model, making it less representative of the real world. These limitations find their roots in how the behaviour was modelled and on which data and literature the model is based. First, the assumptions will be explained that were introduced during the modelling itself. These are:

- Households get placed within a random location on the flood map. These flood maps contain a high number of river branches. These can result in households having an extremely high estimated flood depth. If this happens the household will always have the highest house damage even with the best flood mitigations.
- Randomly being placed on the flood map is not realistic. The centre of the city has a higher household density while other areas, like parks and industrial districts, have a lower housing density. This is not taken into account in the model.
- The model runs 80 steps which translates to 20 years. Within these 20 years, only one storm is modelled. In reality, there were 12 major storms in Houston in the past 43 years (Understanding Houston, n.d.). In the model, households get an increase in flood awareness when flooding affects their households. So flood awareness would be higher if more storms were modelled like in real life.
- The model is based on the protection motivation theory (Floyd, 2000). This theory includes more relevant attributes than flood awareness and self-efficacy that influence the choice to implement mitigation measures. Take, for example, threat

severity and response cost. These attributes were not taken into account due to time constraints. However, this can have skewed the results because the model is not based on how the protection motivation theory fully shows that behaviour changes.
- During the initialization of the model households will be assigned a social network. After this, the social network will remain the same. In reality, people will break social relations and make new ones. This does not happen in the model
- The model assumes that nobody moves in or out of Houston. This way, no new households that never experienced flooding are introduced resulting in the household's awareness slowly maxing out.
- The households buy measures with their savings. How the savings are increased and on what other things, besides flood mitigation measures they spend money is very simplified. This is probably not representable for saving use for real households
- The measures that households can implement are reduced to two types: low and high afford mitigations. For both is assumed that, when implemented, they reduce the actual flood depth by 1m for low afford and 2m for high effort. In reality there are a high variety of measures that can be taken that all have different effects. For example, floodproofing building utilities will not prevent water from getting into the house, while elevating your home does prevent water from coming into your house.
- Households living in apartments based on floors higher than the ground floor will have less damage than households living on the ground. This is not taken into account in the model.
- The model assumes that everybody that has insurance also makes a claim while having damage and that the insurance company will always check the damage of the households and pays the payouts. In reality this is not always the case.

7.3. Further research

This study examined the influence of government communication on the implementation of flood mitigation measures by households and the resulting prevention in damage to their households. This research can be used for two things. First, further research can be conducted using this model as foundation and try to solve the limitations that this study encountered. It could, for example, fully implement the relevant attributes of protection motivation theory. In addition, different communication tools could be examined and more detailed flood mitigation measures could be introduced.

Secondly, this study can be used to compare the effectiveness of flood mitigation measures on household scale and the effectiveness of bigger flood mitigation measures by governmental bodies that have the resources to implement on a bigger scale. Examples of this are building dykes or creating backup floodplains. This way it can be examined whether investing in projects on household scale or bigger scale is the most effective.

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Appendix A: Sensitivity Analysis

In this appendix, the tables with the output for the sensitivity analyses are provided. Table 8, 9, 10 and 11 are colour-coded. The more blue a cell is, the higher the positive value and the more red a cell is, the lower the negative value is.

Table 7: Input variables sensitivity analysis:

Variable	Low (-20%)	Original value	High (+20%)
FloodawereIncreaseTP	0,08	0,1	0,12
SelfEfficacyIncreaseTP	0,08	0,1	0,12
HighRiskHouseholdThreschold	40	50	60
FloodawereIncreasePC	0,16	0,2	0,24
SelfEfficacyIncreasePC	0,16	0,2	0,24

Table 8: Outcomes sensitivity analysis for KPI: house damage

	Changes in outcomes in percentage		
House damage	Low (-20%)	Original outcome	High (+20%)
FloodawareIncreaseTP	-0,07%	0,00%	1,65%
SelfEfficacyIncreaseTP	-0,96%	0,00%	-0,21%
HighRiskHouseholdThreshold	26,70%	0,00%	-3,92%
FloodawareIncreasePC	-0,35%	0,00%	0,13%
SelfEfficacyIncreasePC	4,38%	0,00%	11,66%

Table 9: Outcomes sensitivity analysis for KPI: house damage

	Changes in outcomes in percentage		
Flood awareness	Low (-20%)	Original outcome	High (+20%)
FloodawareIncreaseTP	-9,71%	0,00%	11,76%
SelfEfficacyIncreaseTP	1,43%	0,00%	0,89%
HighRiskHouseholdThreshold	10,75%	0,00%	-25,87%
FloodawareIncreasePC	-6,98%	0,00%	0,93%
SelfEfficacyIncreasePC	1,36%	0,00%	0,95%

Table 10: Outcomes sensitivity analysis for KPI: Adaptation high effort measures

	Changes in outcomes in percentage		
Is adapted	Low (-20%)	Original outcome	High (+20%)
FloodawareIncreaseTP	-0,14%	0,00%	0,00%
SelfEfficacyIncreaseTP	-3,26%	0,00%	1,66%
HighRiskHouseholdThreshold	-0,52%	0,00%	-8,88%
FloodawareIncreasePC	-0,86%	0,00%	0,14%
SelfEfficacyIncreasePC	0,64%	0,00%	0,00%

Table 11: Outcomes sensitivity analysis for KPI: Self efficacy

	Changes in outcomes in percentage		
Self efficacy	Low (-20%)	Original outcome	High (+20%)
FloodawareIncreaseTP	-0,09%	0,00%	0,00%
SelfEfficacyIncreaseTP	-7,62%	0,00%	6,97%
HighRiskHouseholdThreshold	12,84%	0,00%	-25,50%
FloodawareIncreasePC	-1,78%	0,00%	-1,71%
SelfEfficacyIncreasePC	2,21%	0,00%	2,26%

Appendix B: Verification

This appendix provides proof for the verifications that were done for this model, by providing the output that shows print statements that were placed in functions of the model to show their behaviour.

Initialisation

At the initialisation of the model, 250 agents should be created. Each of these agents should have a location on the map. Based on this location, the household is determined to be in the floodplain or not and its estimated flood depth is determined. If the household is in the floodplain or its estimated flood depth is higher than 0.5, then the household will have state insurance. Otherwise, it will have no insurance (or 'zero' insurance). The household should also have a flood awareness between 0 and 1 and it is either self-efficacious or not. Lastly, the household should have a house value and an income. Figure 21 and 22 show that the model actually creates 250 household agents, each with its own set of values for the attributes.

```
Household 0
        Location: POINT (232031.72883329206 3332802.090815305)
        In floodplain: False
        Insurance: zero
        Flood awareness: 0.5919601462573609
        Self-efficacy: False
        Flood depth estimated: 0.2021026611328125
        House value: 276583.981749581
        Income: 15899.456474276834
Household 1
        Location: POINT (286450.82992854516 3270242.007860793)
        In floodplain: False
        Insurance: zero
        Flood awareness: 0.27237851527498613
        Self-efficacy: False
        Flood depth estimated: 0.21857643127441406
        House value: 357793.91613398516
        Income: 11287.480579698407
Household 2
        Location: POINT (237730.93180514214 3313660.183816453)
        In floodplain: False
        Insurance: state
        Flood awareness: 0.4384840818997944
        Self-efficacy: True
        Flood depth estimated: 5.0283355712890625
        House value: 357999.243487536
        Income: 14868.756050605869
```

Figure 21: Start of output with print statements about initialising the household agents

```
Household 248
        Location: POINT (224233.30361356348 3320165.339024706)
        In floodplain: False
        Insurance: zero
        Flood awareness: 0.46815687256539884
        Self-efficacy: False
        Flood depth estimated: 0
        House value: 338234.8126160726
        Income: 17456.343366815752
Household 249
        Location: POINT (251895.89758205865 3304909.9186109337)
        In floodplain: True
        Insurance: state
        Flood awareness: 0.43705583975216783
        Self-efficacy: False
        Flood depth estimated: 0.3927726745605469
        House value: 182026.4978438851
        Income: 20458.00167188012
```

Figure 22: End of output with print statements about initialising the household agents

Paying insurance

Every household that has a state or private insurance, has to pay insurance every at every step in the model. The amount of dollars to pay for insurance is based on the type of insurance, and the way the house is adapted to floods. Figure 23 below shows that the households have different rates for their insurance, based on the insurance type and adaptation status, and that their savings decrease because insurance is paid.

```
Household 163 has insurance type: private, and adaptation status: high_effort
    And pays 150.0 dollars as insurance
    Old savings: 2493.62 dollars
    New savings: 2343.62 dollars
Household 0 has insurance type: state, and adaptation status: zero
    And pays 100 dollars as insurance
    Old savings: 41074.01 dollars
    New savings: 40974.01 dollars
Household 207 has insurance type: private, and adaptation status: low_effort
    And pays 240.0 dollars as insurance
    Old savings: 9450.22 dollars
    New savings: 9210.22 dollars
Household 80 has insurance type: private, and adaptation status: low_effort
    And pays 240.0 dollars as insurance
    Old savings: 8600.37 dollars
    New savings: 8360.37 dollars
```

Figure 23: Part of output with print statements about households paying insurance

Shock: Flooding

At a certain step in the model, a shock happens in the form of a flood. A flood causes households to have an actual flood depth. If the households have adapted with low effort or high effort measures, the actual flood depth should be reduced. If the actual flood depth is higher than zero, there should be damage done to the house, which can be measured in dollars. Depending on the insurance type, the household has to (a part of) this damage or everything could be covered by insurance. If the damage done to the house is big enough, the households should increase their flood awareness. As figure 24 below shows, the model's output is according to these expectations.

```
Household 68 has insurance type: state, and adaptation_status: zero
        Actual flood depth without measures: 1.709103165610682
        House damage: 179586.42130152014 dollars
        Damage to pay for: 0.0 dollars
        Old flood awareness: 0.4604259792041555
        New flood awareness: 0.7104259792041555
Household 55 has insurance type: zero, and adaptation_status: low_effort
        Actual flood depth without measures: 0.16698253618508524
        Actual flood depth with measures: 0.06698253618508523
        House damage: 97266.45737809021 dollars
        Damage to pay for: 97266.45737809021 dollars
        Old flood awareness: 0.3942204569990936
        New flood awareness: 0.6442204569990936
Household 182 has insurance type: private, and adaptation_status: high_effort
        Actual flood depth without measures: 1.171684370388595
        Actual flood depth with measures: 0.9216843703885951
        House damage: 124546.03300073757 dollars
        Damage to pay for: 0.0 dollars
        Old flood awareness: 0.43373416983685503
        New flood awareness: 0.6837341698368551
```

Figure 24: Part of output with print statements about the status of every household right after a shock

Social interaction about flood awareness

Households should interact with their friends, and their flood awareness can be influenced by their friends in a positive or negative way. However, some households do not interact about flood awareness, which means their flood awareness should not change through interaction. Figure 25 below shows that some households do not interact about flood awareness and their awareness stays the same. Others do interact, changing their flood awareness in a positive or negative way.

```
Household 52 does not interact about flood awareness
    Old flood awareness: 0.12892424769443628
    New flood awareness: 0.12892424769443628
Household 111 does not interact about flood awareness
    Old flood awareness: 0.26158994222597276
    New flood awareness: 0.26158994222597276
Household 67 interacts, flood awareness is changed by -0.0696680805271872
    Old flood awareness: 0.4780397647260266
    New flood awareness: 0.443205724462433
Household 158 does not interact about flood awareness
    Old flood awareness: 0.2980062551278841
    New flood awareness: 0.2980062551278841
Household 22 interacts, flood awareness is changed by +0.06666964491671568
    Old flood awareness: 0.6026534846989722
    New flood awareness: 0.63598830715733
```

Figure 25: Part of output with print statements about the social interaction of households affecting flood awareness

Social interaction about self-efficacy

If households are not yet self-efficacious, their self-efficacy could be influenced by friends. It should loop over all the household's friends, and there should be a chance that the household's self-efficacy is changed by a self-efficacious friend. If households are already self-efficacious, they should stay self-efficacious. Figure 26 below shows that nothing happens to households that are already self-efficacious. Households that are not yet self-efficacious can in fact interact with friends, and possibly change their self-efficacy to True (if the numeric self-efficacy is higher than 0.5). The figure also shows that if a households is influenced by its friend and its self-efficacy is changed to True, the household does not look at any other friends anymore. This is logical output, since households that are already self-efficacious should also stay self-efficacious.

```
Household 69 is already self-efficacious (self-efficacy = True)
Household 146 is not self-efficacious (self-efficacy = False)
    Number of friends = 5
    Household interacts with friend about self-efficacy
        New self-efficacy value = 0.5507393106864855
        Self-efficacy is changed to True
Household 233 is already self-efficacious (self-efficacy = True)
Household 65 is not self-efficacious (self-efficacy = False)
    Number of friends = 4
    Household interacts with friend about self-efficacy
        New self-efficacy value = 0.4408014646828777
        Self-efficacy is still False
    No interaction with self-efficacious friend
    No interaction with self-efficacious friend
    No interaction with self-efficacious friend
```

Figure 26: Part of output with print statements about the social interaction of households affecting self-efficacy

Choosing insurance

At every step, the households can reconsider upgrading their insurance. There should be households with insurance type zero, state and private. Furthermore, households should be able to change their insurance type. As Figure 27 shows, the model behaves according to the expectations.

```
Household 68 has insurance: zero
Household 147 had insurance: state, but changed to private
Household 193 has insurance: zero
Household 245 had insurance: state, but changed to private
Household 162 has insurance: zero
Household 157 has insurance: private
Household 88 has insurance: private
Household 175 has insurance: state
```

Figure 27: Part of output with print statements about households choosing insurance types

Adapting with measures

Households should be able to buy measures to be able to adapt to floods. They should be able to buy low-effort and high-effort measures. If high-effort measures are too expensive, households should be able to opt for low-effort measures. Figure 28 below shows that households can buy both types of measures, and they can opt to buy low-effort measures if high-effort measures are too expensive.

```
Household 164 does not buy measures
Household 68 does not buy measures
Household 90 does not buy measures
Household 248 wants to buy high effort measures
    Household buys low effort measures, because it cannot afford high effort measures
Household 124 does not buy measures
Household 241 wants to buy high effort measures
    Household buys high effort measures
Household 64 wants to buy low effort measures
    Household buys low effort measures
```

Figure 28: Part of output with print statements about households buying or not buying measures

Governmental communication

Once per year, so per four steps, the government spreads information about the risk of flood and mitigation strategies. These information campaigns are meant to increase self-efficacy and flood awareness. To verify that the function in the model used to spread the information leads to an increase in the variables for self-efficacy and flood awareness outputs before and after the information spread campaign are examined. This is done separately for the top-down and people-centred communication strategies.

Figure 29 shows the output for top-down communication of four households. The values for flood awareness and self-efficacy both increase with 0,2. This increase corresponds with the parameters of the top-down communication strategy so that is correct. The other agent's values do not increase. This is also logical because top-down only influences a small portion of the Households.

```
Household 0
        Flood depth estimated: 0
        Old flood awareness: 0.6479255499386647
        Old self-efficacy: 0.24820652747939642
        New flood awareness: 0.8479255499386646
        New self-efficacy: 0.44820652747939643
Household 1
        Flood depth estimated: 0
        Old flood awareness: 0.5372575491021657
        Old self-efficacy: 0.6243509649438546
        New flood awareness: 0.5372575491021657
        New self-efficacy: 0.6243509649438546
Household 2
        Flood depth estimated: 0.16298294067382812
        Old flood awareness: 0.5480338375616852
        Old self-efficacy: 0.508753135870492
        New flood awareness: 0.5480338375616852
        New self-efficacy: 0.508753135870492
Household 3
        Flood depth estimated: 0
        Old flood awareness: 0.6075112011875846
        Old self-efficacy: 0.6696315370079657
        New flood awareness: 0.6075112011875846
        New self-efficacy: 0.6696315370079657
```

Figure 29: Part of output with print statements about the top-down government communication for flood awareness and self-efficacy

The values for the personal-centred communication strategy are given in Figure 30. Here Households should only be affected by the communication campaign if their estimated flood depth is higher than the Threshold. The first line in Figure 30 shows that the Threshold is 0,37. Household 0 has a flood depth higher than 0,37, but the flood awareness nor the self-efficacy increases. This is logical because it is not guaranteed that the household is successfully convinced by the communication. However, household 3 has a high enough flood depth and has an increase in its value, which implies that the code can increase the values. Household 1 has a flood depth of 0, hence it values should not the case. From figure 2 it can be seen that this is not the case.

```
Depth Threshold is: 0.3682742118835449
Household 0
        Flood depth: 0.8025169372558594
        Old flood awareness: 0.44485150174273275
        Old SelfEfficacy: 0.5774701888220521
        New flood awareness: 0.44485150174273275
        New SelfEfficacy: 0.5774701888220521
Household 1
        Flood depth: 0
        Old flood awareness: 0.626884098806664
        Old SelfEfficacy: 0.6859526739526107
        New flood awareness: 0.626884098806664
        New SelfEfficacy: 0.6859526739526107
Household 2
        Flood depth: 1.0748157501220703
        Old flood awareness: 0.2560800259190441
        Old SelfEfficacy: 0.5388079930956579
        New flood awareness: 0.4560800259190441
        New SelfEfficacy: 0.7388079930956579
```

Figure 30: Part of output with print statements about the people-centred government communication for flood awareness and self-efficacy