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The effectiveness of flood risk communication strategies and the influence of social networks—Insights from an agent-based model

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ABSTRACT

Flood risk management is becoming increasingly important, because more people are settling in flood-prone areas, and flood risk is increasing in many regions due to extreme weather events associated with climate change. It has been proposed that appropriately designed flood risk communication campaigns can stimulate floodplain inhabitants to prepare for flooding, and encourage adaptation to climate change. However, such campaigns do not always result in the desired action, and the effectiveness of communication in raising flood risk awareness and improving flood preparedness has hardly been studied. We evaluate different flood risk communication strategies, using an agent-based modelling approach, which is especially suitable for examining the effect of communication on each individual, and how flood risk communication can propagate through an individual's social network. Our modelling results show that tailored, people-centred, flood risk communication can be significantly more effective than the common approach of top-down government communication, even when tailored communication reaches fewer individuals. Furthermore, communication on how to protect against floods, in addition to providing information about flood risk, is much more effective than the traditional strategy of communicating only about flood risk. Another main finding is that a person's social network can have a significant effect on whether or not individuals take protective action. This leads to the recommendation that flood risk communication should aim at exploiting this natural amplifying effect of social networks, for instance, through the use of social media.

1. Introduction

The severity and frequency of floods is expected to increase in many regions around the world as a result of climate change (IPCC, 2012) and economic and population growth in flood-prone regions (Jongman et al., 2012). It is becoming increasingly important to communicate the risks of flooding to communities living near rivers and coasts (IPCC, 2012), and to motivate those at risk to better prepare for flooding (Botzen and Van den Bergh, 2009; Kunreuther and Michel-Kerjan, 2011; Poussin et al., 2014). Although the importance of flood risk communication is widely acknowledged, little is known about the effectiveness of flood risk communication, as is apparent from a literature review on flood risk perceptions by Kellens et al. (2013). It is only recently that several studies have attempted to fill this gap, by applying questionnaires to analyse the effect of different risk communication strategies on risk perceptions and intentions to prepare for flooding (Botzen et al., 2013; De Boer et al., 2014a,b). These studies show that information tailored to the specific needs of an individual has an important influence on risk perceptions. Moreover, they find that risk communication can stimulate individuals to take measures that reduce flood risk, such as structural flood risk mitigation measures, flood-adapted building use, deployment of flood barriers, and/or purchase of flood insurance (Botzen et al., 2013; De Boer et al., 2014a,b).

Risk communication is commonly done by governments and organisations who disseminate information about floods in a top-down manner through guidelines, information brochures, media campaigns, and internet websites, which individuals may or may not read or receive (Fekete, 2012). Examples are the flood zone maps that delineate flood-prone areas and their flood probabilities provided by the Federal Emergency Management Agency in the United States (www.fema.gov) and the flood maps produced for the European Union Floods Directive. To a lesser extent, information on coping responses is provided, such as the effectiveness of the measures that people can take to protect themselves against floods. A recent study on communication strategies in England, the Netherlands, and Flanders showed that top-down government campaigns have not been very successful in motivating people to

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take protective measures against flooding (INTERREG, 2013). These campaigns were partly ineffective because they did not address the different attitudes that people have towards flooding because of their cultural differences and local circumstances (Burningham et al., 2008; Martens et al., 2009).

The need for people-centred risk communication, which focuses on the specific needs of different people, as opposed to a one-size-fits-all government campaign, was acknowledged by the IPCC (2012) to be a key factor in disaster risk reduction. In particular, local risk perceptions and local framing of risk should be included in communication processes. According to the IPCC (2012), risk communication should achieve the aims of both informing people about their particular risk and engaging the stakeholders in the identification of possible solutions. While the traditional top-down approach offers little opportunities for this, individual or community-based approaches can address the heterogeneous needs of individuals, and offer a means to provide tailored information on risk perception and coping measures (Bier, 2001; Martens et al., 2009; Terpstra et al., 2009). By providing tailored information, people are then enabled to assess their own risk situation, and are provided with the means to make informed decisions on the appropriate actions to take (Kellens et al., 2013).

Furthermore, there is a growing recognition in the scientific literature of the role of an individual's social network and social context in decisions about protecting against risk (Bubeck et al., 2013; Figueiredo et al., 2009; Kunreuther et al., 2013; Lara et al., 2010; Lo, 2013; Van der Linden, 2015). For example, both Lo (2013) and Bubeck et al. (2013) found that, in addition to risk perception, the expectations and adoption of flood risk reduction measures in the social networks of individuals are important determinants of individual flood preparedness. Kunreuther et al. (2013) found similar results in a laboratory experiment, where the major driver of an individual to invest in disaster risk reduction was the average investment level of his/her neighbours. Moreover, Van der Linden (2015) found that an individual's actions towards extreme weather risks amplify throughout his/her social network. Lara et al. (2010) found clear evidence for the relation between social involvement and the willingness to take action against floods. These studies show that social networks not only serve as a stimulus for taking action, but also convey information.

An improved understanding of the effectiveness of flood risk communication, as well as of the influence of a person's social network on this effectiveness, can provide valuable insights for flood risk management policies. This study examines both of these themes by applying an agent-based model, as advocated by Martens et al. (2009). This method is especially suitable for modelling the interaction between social networks on a micro-scale (household) level, and for analysing the emerging flood risk reduction and diffusion of information on a meso- or macro-scale (An, 2012). Although these models are only an approximation of the full complexity of human behaviour, agent-based models are especially useful for disentangling specific behavioural processes, as is of interest here. While agent-based models have previously been applied to investigate the diffusion of information (e.g. Macy and Willer, 2002; Rahmandad and Sterman, 2008), and flood risk management (i.e. Dawson et al., 2011; Filatova, 2013), we present here the first application specifically for flood risk communication purposes. The theoretical basis for individual flood-preparedness decisions is provided by Protection Motivation Theory (Rogers, 1983).

Protection Motivation Theory, shown schematically in Fig. 1, has become an important socio-psychological model of individual flood risk-preparedness decisions (Bubeck et al., 2012; Grothmann and Reusswig, 2006; Koerth et al., 2013; Poussin et al., 2014). For the study presented here, it offers a useful framework to analyse how flood risk communication, as a form of verbal persuasion, can influence a person's threat or coping appraisal, and how flood preparedness is affected. Communicating for instance the probability of a flood, as is done by the FEMA flood maps in the United States, aims to change people's threat appraisal. Communicating about the costs and the effectiveness of certain protection measures aims to change people's coping appraisal. We estimate the effectiveness of communication strategies by the implementation rates of different disaster risk-reducing measures. Moreover, the influence of the social network is estimated by including and excluding social networks of agents. By investigating different general types of flood risk communication strategies, the results can be used for making recommendations for the overall design of flood risk communication campaigns.

2. Methods

We developed an agent-based model to capture the effectiveness of flood risk communication and the influence of social networks. The applied modelling software is NetLogo V 5.2.0 (Wilensky, 1999). The model simulates how and when households take protective action and it evaluates the effectiveness of different flood risk communication strategies. Each simulation runs for 7 years with time-steps of 1 year and each stochastic simulation run is repeated 100 times. The 7-year period represents a realistic period for flood risk communication campaigns in the Netherlands, such as the 'The Netherlands lives with water' campaign (INTERREG, 2013). The model is applied to households in the outer-dike areas in the Rotterdam-Rijnmond region, shown in Fig. 2. The case-study area serves as an example from which we derive specific results for the region, and more general lessons that are transferable to flood-prone regions around the world. Different social, cultural and political conditions in other regions may imply that flood risk communication campaigns produce different results. To facilitate the reproducibility of the model, a technical description is given in supplement A following the ODD (Overview, Design concepts, Details) protocol by Grimm et al. (2010, 2006).

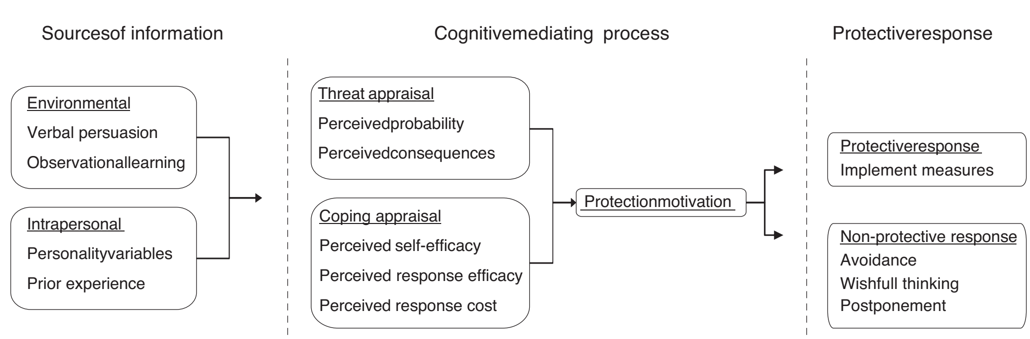

Fig. 1. A schematic overview of Protection Motivation Theory, adapted from Rogers (1983) and Bubeck et al. (2012).

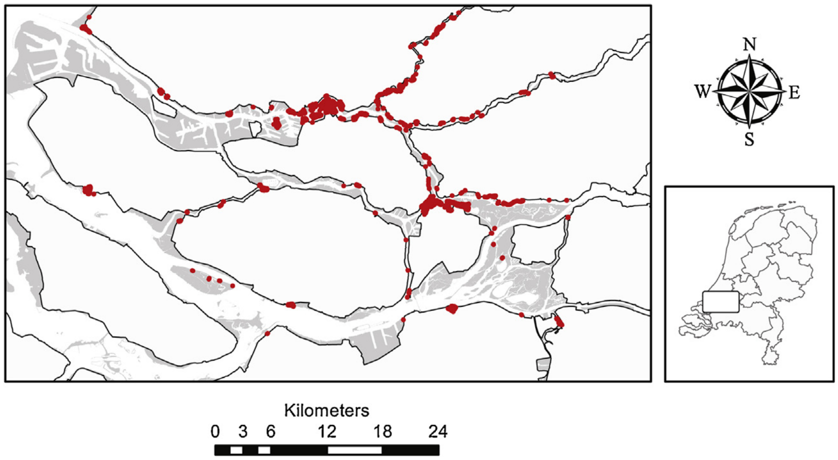

Fig. 2. The Rotterdam-Rijnmond area (left), and its position in the Netherlands (right). Areas that are not embanked are shown in dark gray. Houses outside the embankments included in this case-study are shown in red.

Table 1
Household attributes and attitudes that are part of Protection Motivation Theory (Adapted from Bubeck et al. (2013)).

Household attribute (i)	Description	Attitude levels (a)
Social network[a]	Individuals in a household's social network have implemented flood mitigation measures	1-none of them; 2-few of them; 3-some of them; 4-most of them
Response efficacy	Household's estimate of the effectiveness of a specific flood mitigation measure	1-ineffective; 2-rather ineffective; 3-rather effective; 4-effective
Self-efficacy	Household's estimate of its own ability to actually implement a specific flood mitigation measure	1-unable; 2-rather unable; 3-rather able; 4-able
Perceived probability	Perceived probability of a flood event occurring at the household's residence	1-unlikely; 2-rather unlikely; 3-rather likely; 4-likely
Perceived consequence	Perceived consequence of a flood event	1-not bad; 2-rather not bad; 3-rather bad; 4-bad
Avoidance	Household hopes not to be affected by a flood event in the future	1-does not apply to me; 2-rather does not apply to me; 3-rather applies to me; 4-applies to me
Wishful thinking	Household's belief in sufficient protection through technical flood defences	1-does not apply to me; 2-rather does not apply to me; 3-rather applies to me; 4-applies to me
Postponement	Flood mitigation is generally considered as wise, but implementation is postponed to the future	1-does not apply to me; 2-rather does not apply to me; 3-rather applies to me; 4-applies to me
Protected area	Household lives in an area that is protected by technical flood defences	1-yes; 0-no
Income	Income categories	1-above €4500; 0-below €4500
Age	Age categories	1 = 1-16; 2 = 25-34; 3 = 35-44; 4 = 45-54; 5 = 55-64; 6 = 65 and above
Flood experience	Household flood experience	1-yes; 0-no

[a] The variable social network is originally defined as 'social environment' by Bubeck et al. (2013).

2.1. Case study: Rotterdam-Rijnmond, the Netherlands

Although most households in the Netherlands are generally well protected against floods by dike-rings, the outer-dike areas are not protected, and are thus susceptible to flooding. Risk communication to increase preparedness is therefore of particular importance in the outer-dike areas, especially since risk perceptions are generally low in the Netherlands (Botzen et al., 2009). Two major risk communication campaigns took place in the Netherlands to raise flood risk awareness and stimulate individuals to better prepare for floods: namely, 'the Netherlands lives with water' launched in February 2003, and 'think forward' launched in 2006. A recent study showed that, although both campaigns raised awareness about flood risk, they were not successful in causing behavioural change, resulting in a lack of flood preparedness (INTERREG, 2013). One of the main limitations of both campaigns was that they were mostly government-controlled top-down programmes, which failed to address the heterogeneous need for information from the public (INTERREG, 2013). This makes Rotterdam-Rijnmond an interesting case-study region for evaluating the performance of different flood risk communication strategies.

2.2. Household flood-preparedness decisions

Each year (one time-step), households decide in a random order whether they implement structural flood mitigation measures[1], flood-adapted building use[1], deployment of flood barriers, and/or purchase flood insurance. Structural measures and flood barriers are permanent home improvements. The flood insurances and adaptive building use remain valid until a household moves. Households are assumed to move after 7 years, which is the average in the Netherlands according to the Society of Dutch Real-Estate Agents (Nederlandse Vereniging van Makelaars, 2004). At model initialisation, the period that a household has already lived at that location is set to a period of 1–7 years, following a uniform random distribution. As migration issues are not the focus of this study, it is assumed that a household moves out of the case study area. In the model, a household h has a yearly probability $p_{h,implementation}$ to implement one or more of the protective

[1] Examples of structural flood mitigation measures are elevating entrances, and installing tile floors. An examples of flood-adapted building use is moving vulnerable equipment, like dishwashers, upstairs.

measures. Equation 1 determines the odds of implementation and equation 2 transforms the odds into probability $p_{h,implementation}$. Households have a different $p_{h,implementation}$ for each measure.

$$Odds_{h,implementation} = C \times \prod_{i=1}^{I} OR_i^{a_{i,h}} \quad (1)$$

$$p_{h,implementation} = \frac{Odds_{h,implementation}}{1 + Odds_{h,implementation}} + p_{noise} \quad (2)$$

here, $OR_i^{a_{i,h}}$, is a value for the change in odds (odds ratio, OR) of implementing a measure, for each attribute i, for each attitude a related to attribute i, and for each household h. C is a base constant, which together with the calibration values for the odds ratios are provided in the supplement A (the ODD protocol). The variable p_{noise} introduces a small element of random behaviour with a probability which we assume to range from −5% to 5%. The attributes i and possible attitudes a for each household are provided in Table 1. This Table of attributes and possible attitudes is derived from a study by Bubeck et al. (2013), which presents unique empirical data from a survey of 752 households in floodplains. As the study specifically investigated how the Protection Motivation Theory attributes (Fig. 1) influence the implementation of flood-preparedness measures, it provides a solid empirical basis for our study. For more details on how the survey was conducted, which questions were asked, and how they lead to the odds ratios, we refer to the study by Bubeck et al. (2013) itself. Furthermore, previous studies have shown that there is a threshold of perceived threat that needs to be overcome before households take protective measures (Bubeck et al., 2012; Grothmann and Patt, 2005; Kunreuther and Pauly, 2006). To represent this, $p_{h,implementation}$ is reduced to p_{noise} if the attitude level for ‘perceived probability’ is ‘unlikely’ or ‘rather unlikely’, or if the attitude for ‘perceived consequence’ is ‘not bad’ or ‘rather not bad’.

To reflect heterogeneity, households have different attitude levels a for each attribute i, leading to a different probability of implementing measures for each household (see equation 1). Households are assigned attitude levels a from a uniform random distribution for ‘response efficacy’, ‘self-efficacy’, ‘response costs’, ‘avoidance’, ‘wishful thinking’, and ‘postponement’. Since research shows that the perceived flood risk in the Netherlands is low (Botzen et al., 2009; Terpstra and Gutteling, 2008), initial attitude levels a for ‘perceived probability’ and ‘perceived consequence’ are set, respectively, to ‘unlikely’ and ‘not bad’ for all households. All case-study households are outer-dike households, so the ‘protected area’ attitude equals 0. Since no major flood has occurred recently in the Rotterdam-Rijnmond outer-dike area, households have no ‘flood experience’, meaning that the attitude level a equals 0. The income and the location of the households are determined from spatial BAG data (http://www.kadaster.nl/BAG) and data from Statistics Netherlands (Centraal Bureau voor de Statistiek, 2012). The income variable of households is assigned a value of 0 when their gross income is below €4500 per month, and a value of 1 when their income is above €4500 per month. The benchmarks for the ‘social network’ are related to the percentage of outer-dike individuals in the social network who adopt flood protection measures. This variable is set at 0%, 0–25%, 26–50%, and >50% for, respectively, ‘none of them’, ‘few of them’, ‘some of them’, and ‘most of them’.

2.3. Social networks

Real-world social networks (i.e. not virtual) in the Netherlands are in general quite locally-orientated, with, on average, 53% of a person’s social ties, excluding neighbours, living within 15 min travel distance (Volker and Flap, 2007). Family and friends often live close-by (Dekker, 2007), and neighbours are well represented in a person’s social network (Bras and van Tilburg, 2007; Mollenhorst, 2015). All ~35,000 households in the outer-dike region are represented as individual agents in the model. To provide a realistic representation of social networks in the case-study area, we built upon the results of a number of studies on social networks in the Netherlands (Bras and van Tilburg, 2007; Dekker, 2007; Mollenhorst, 2015; Van den Berg et al., 2014; Volker and Flap, 2007). For each household h, the social network size s_h and the percentage of neighbours pn_h (i.e. households in the same neighbourhood, as defined by Statistics Netherland, CBS) in the social network are drawn from a random-normal distribution. The mean and standard deviation of this normal-distribution correspond to those of the different social network sizes and percentage of neighbours reported by the aforementioned studies. Each simulation run is set up such that each household h is linked to other households, in a way that the social network size for that household is s_h and the percentage of neighbours is pn_h. Details on the calibration, and the pseudo-code for setting up the social networks, can be found in the ODD protocol provided in Supplement A.

2.4. Flood risk communication

We evaluate four flood risk communication strategies compared with a baseline scenario, shown in Table 2. These strategies

Table 2
Flood risk communication strategies.

Scenario	Description	Probabilities	Effect
NC	No flood risk communication	–	None
TD-R	Top-down strategy focussed on risk	*p-reach*: N (0.8, 0.05) *p-success*: N (0.2, 0.05)	Raises attitude *a* for perceived probability and perceived consequence without priority
TD-RC	Top-down strategy focussed on risk and coping options	*p-reach*: N (0.8, 0.05) *p-success*: N (0.2, 0.05)	Raises attitude *a* for perceived probability, perceived consequence, perceived self-efficacy and perceived response efficacy without priority
PC-R	People-centred strategy focussed on risk	*p-reach*: N (0.2, 0.05) *p-success*: N (0.8, 0.05)	Raises attitude *a* for perceived probability and perceived consequence on the basis of priority of information need
PC-RC	People-centred strategy focussed on risk and coping options	*p-reach*: *N* (0.2, 0.05) *p-success*: N (0.8, 0.05)	Raises attitude *a* for perceived probability, perceived consequence, perceived self-efficacy and perceived response efficacy on the basis of priority of information need

are based on common practice (focus on risk) and advocated best practice (focus on risk and coping options), and based on the two principle ways of delivering information: namely, top-down and people-centred. Households only change their attitude levels *a* if (1) communication reaches them, for which the probability is given by *p-reach* and (2) communication is successful in changing attitude, for which the probability is given by *p-success*. To reflect a communicatively intensive people-centred approach versus a less communicatively intensive top-down approach, it is assumed that resource constraints limit the probability that households can be reached, *p-reach*, and that this number is inversely related to the probability, *p-success*, of successfully changing attitude levels *a* (i.e. if *p-reach* = *0.8*, then *p-success* = *1-0.8* = *0.2*). During each simulation for the TD-R and TD-RC strategies, *p-reach* and *p-success* are drawn from the random-normal distribution: *p-reach* ~ *N*(M = 0.8,SD = 0.05) and *p-success* ~ *N*(M = 0.2,SD = 0.05). The random-normal distribution causes *p-reach* and *p-success* to vary slightly for each of the 100 repetitions for each scenario, representing the uncertainty of our assumption. This is vice versa for people-centred strategies (PC-R and PC-RC), representing a more communicatively intense approach: *p-reach* ~ *N*(M = 0.2,SD = 0.05) and *p-success* ~ *N*(M = 0.8, SD = 0.05). Because empirical data to support these perhaps important assumptions is largely absent, we performed a sensitivity analysis that tests the full range of settings for *p-reach* and *p-success* (Supplement B)

If communication reaches a household, and it is successful in causing attitude change, then households change their attitude levels *a* for different attributes *i*. To overcome the lack of empirical data on flood risk communication, and to make the inter-comparison between communication strategies possible, we therefore assume that the magnitude of attitude change is similar for all communication strategies, and only the way in which attitude is changed differs. The communication strategies only focussing on risk, (TD-R and PC-R) raises the attitude *a* for the perceived consequence and perceived probability attributes of households *h*, which are threat appraisal attributes as shown in Fig. 1. The communication strategies that focuses on both threat and coping appraisal (TD-RC and PC-RC) also raise the attitude *a* for perceived self-efficacy and perceived response efficacy, which are coping appraisal attributes. As the top-down strategy targets a broad audience, it is assumed that the ability to determine the heterogeneous information need is limited, and therefore communication strategies targets the different attributes without prioritizing. For the personal communication strategies, it is assumed that the information need is determined upfront and therefore communication is prioritized to change the attitude *a* for needed attributes *i* (see Bier, 2001). Details and pseudo-code for the communication strategies are provided in Supplement A.

3. Results

3.1. Effectiveness of the communication strategy

Fig. 3 presents box-whisker-plot results on the implementation rates of the four flood-preparedness measures under each flood risk communication strategy. The baseline scenario in which no communication strategy is applied leads to a mean implementation rate of 4.0%, 1.7%, 0% and 1.8% for, respectively, structural risk mitigation measures, flood barriers, flood insurance, and adaptive building use. The top-down communication strategy that only

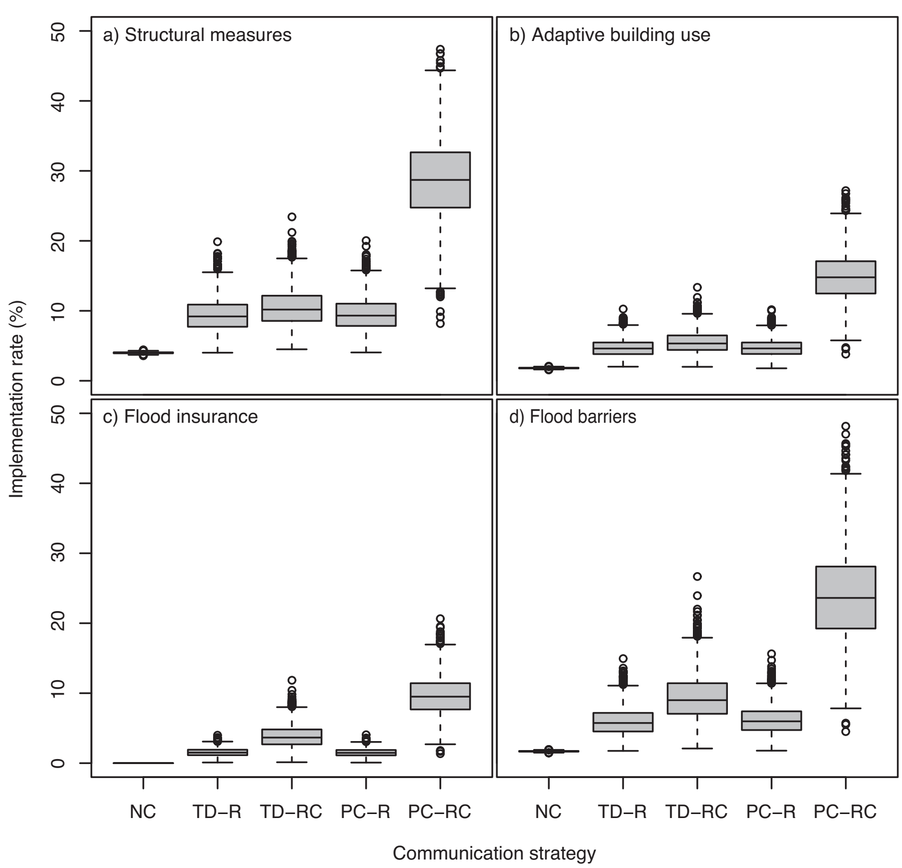

Fig. 3. Percentage of households that implement disaster risk reduction measures after 7 years under different communication strategies. NC: No communication. TD-R: top-down strategy focussed on communicating risk. TP-RC: top-down strategy focussed on communicating both risk and coping options. PC-R: People-centred strategy focussed on communicating risk. PC-RC: People-centred strategy focussed on communicating both risk and coping options.

focuses on risk, only results in slightly higher mean implementation rates, i.e. 9.4%, 5.9%, 1.5%, and 4.7% respectively. These results are qualitatively in line with the findings by Terpstra and Gutteling (2008), who reported a low level of engagement by Dutch citizens in flood protection activities, measured on five-point likert scales.

Of special interest is the inter-comparison of the mean implementation rates of flood-preparedness measures as a result of the different communication strategies. The mean results for each communication strategy are statistically significantly different ($p < 0.001$) for each measure, except when comparing the TD-R and PC-R strategies. These strategies show only significantly different results for flood barriers ($p < 0.001$). Furthermore, considering the great dispersion for the PC-RC strategy, we calculated the Coefficient of Variance (*CV*) to analyse if the relative dispersion around the means differs for each strategy (except for the 'No communication' strategy, as the mean is equal or near zero). We found that the *CV*, across measures, is 25–37% (TD-R), 26–43% (TD-RC), 25–37% (PC-R), and 20–29% (PC-RC). This shows that the dispersion is comparable for the communication strategies. The simulation results in Fig. 3 show higher mean implementation rates when communication also addresses coping appraisal: that is, information on the effectiveness and the costs of a particular measure. Top-down communication strategies that target both coping appraisal and risk awareness (TP-RC) lead to slightly (0.1–2.5 times) higher mean implementation rates than those which only focusing on risk awareness (TP-R). Comparing the two people-centred strategies (PC-RC, PC-R) shows a 3.0–6.5 times higher mean implementation rate. The effect is larger for flood barriers and flood insurance than for structural measures and adaptive building use. As the model was calibrated with empirical data and the assumptions are straightforward, it builds a strong case for communication strategies that focus on both raising risk awareness and coping appraisal. The model results presented here support the conclusions by previous survey studies (Bubeck et al., 2012; Grothmann and Reusswig, 2006; Poussin et al., 2014) that coping appraisal is strongly related to protective behaviour, and therefore it is fruitful to integrate and emphasise information on protective action in flood risk communication.

Another important distinction in the communication strategies is between government-controlled top-down communication versus people-centred communication. The agent-based model allowed us to analyse the effect of changing the specific attitudes of households. Our mean simulation results (Fig. 3) show that, considering our assumptions on communication resource constraints, a tailored people-centred approach focussing on both threat and coping appraisal aspects could be 2.5 times more effective as the one-size-fits-all top-down strategy. These results indicate that the identification of different attitudes and subsequent appropriate risk communication strategies can have a significant advantage over top-down communication. Our results support the arguments by Bier (2001),Martens et al. (2009), and the IPCC (2012) about the importance of identifying the information needs of the public in designing tailored risk communication campaigns.

Because uncertainty remains considering the chosen variables *p-reach* and *p-success*, we provide a sensitivity analysis in Supplement B. The analysis shows that in a direct comparison over the full range of *p-reach* and *p-success*, the people-centred approach always outperforms the top-down approach, and focussing on coping and threat appraisals outperforms only focusing on threat appraisal. This is also true when comparing the inverse *p-reach* and *p-success* for people-centred and top-down

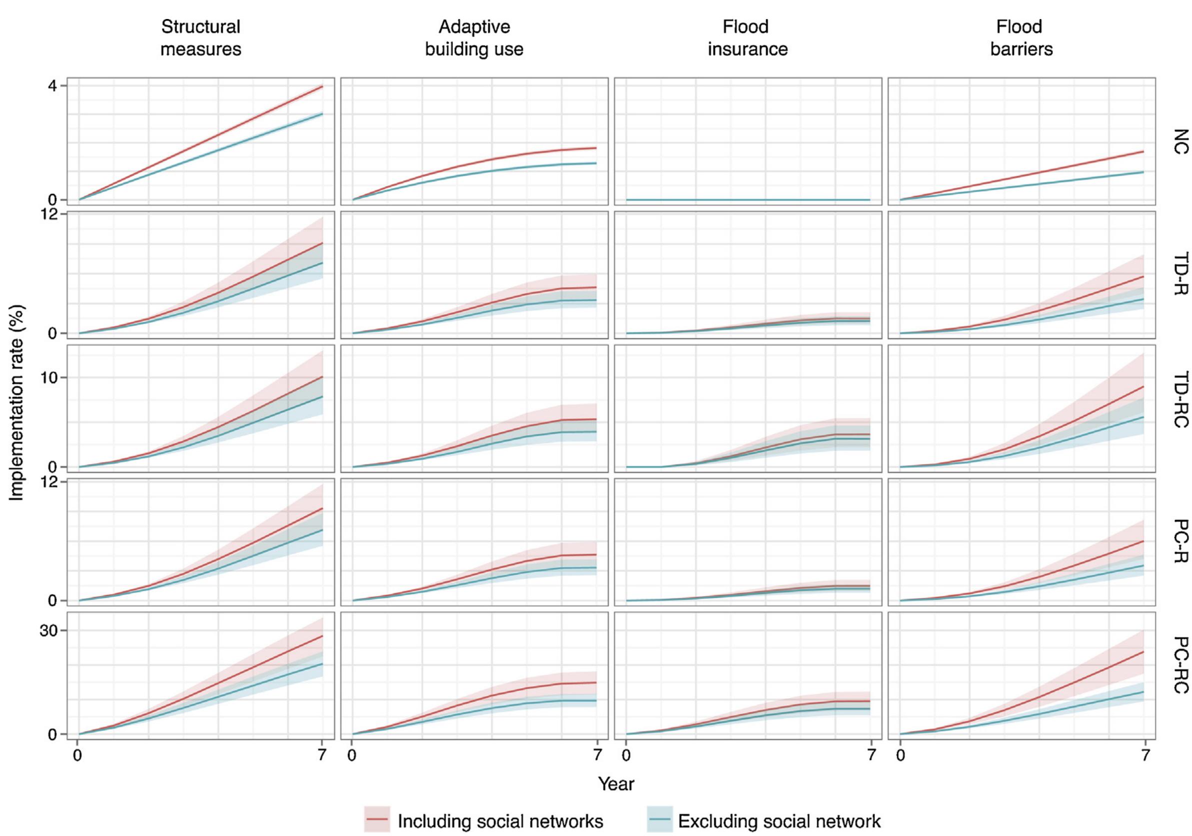

Fig. 4. Comparison of the implementation rates of disaster risk reduction options over time, under different communication strategies (100 repetitions; line = mean; shading = standard deviation). The results are shown for simulations including and excluding the social networks. NC: No communication. TD-R: top-down strategy focussed on communicating risk. TP-RC: top-down strategy focussed on communicating both risk and coping options. PC-R: People-centred strategy focussed on communicating risk. PC-RC: People-centred strategy focussed on communicating both risk and coping options.

strategies. As an illustration, the PC-RC strategy with *p-reach* = 0.2 and p-success = 0.8 is still more effective than the TD-RC strategy with *p-reach* = 0.9 and *p-success* = 0.3. While the absolute values presented in Fig. 3 should be considered with caution, the sensitivity analysis provides confidence in the robustness of the inter-comparison of results.

3.2. Influence of the social network on the effectiveness of communication

In addition to the effect of flood risk communication, actions taken by the households themselves influence the actions in a social network dynamically over time. People's tendency to implement protective measures increases when they see their neighbours, friends, and relatives implementing measures, either when observing the actions of others, or by verbal persuasion (Bubeck et al., 2013; Kunreuther et al., 2013; Lo, 2013; Van der Linden, 2015). To examine the effect of social interaction, we ran the simulations without the 'social network' attribute. This simulation reflects a situation where the decision about protective measures is not influenced by either verbal persuasion or observational learning of actions taken in the households' social network. As such, the use of the agent-based model allowed for the analysis of the propagation of the effect of flood risk communication through a social network. Fig. 4 presents a comparison of the results for including and excluding the 'social network' attribute.

A comparison of means furthermore shows that when the 'social network' is excluded, at the end of the simulation, adaptive measures are implemented 0.5–5.0% percentage points less, flood insurance 0–2% percentage points less[2], flood barriers 0.7–11.6% percentage points less, and structural measures 1.0–8.3% percentage points less. The people-centred communication strategy focussing on both threat and coping appraisal is at the high end of these results. Overall, Fig. 4 shows that up to ~12% of the mean implementation rates can be attributed to the influence of one's social network. A sensitivity analysis provided in supplement B shows that these results hold for different benchmarks of the 'social network' attribute. The results indicate that the social network effect results in higher implementation rates of protective measures. The order of effect found here supports the case made by Lo (2013) and Figueiredo et al. (2009) that the perceived social norms and context, related to a person's social network, significantly influence whether or not a person will take protective measures. With these results, we were able to show how the amplification of risk perceptions as described by Kasperson et al. (1988) could strengthen flood risk communication strategies. Our findings support the notion of Kasperson et al. (1988), that the transfer of information through the 'interpersonal network' via verbal persuasion or observational learning can lead to a behavioural response, which in this case is the implementation of protective measures. Importantly, our model results are in line with the findings by Van der Linden (2015) that the more people there are in a person's social network who recognise and act upon a risk, the more the individual's perception is amplified and intensified, which in turn leads to a higher potential for action.

4. Discussion and policy implications

Designing effective flood risk communication policies can have a large societal value in many areas around the world. This is illustrated by estimates of global flood risk of about 46 trillion USD, which may rise to 158 trillion in 2050 on account of socio-economic change alone (Jongman et al., 2012). Appropriately designed flood risk communication policies could play an important role in stimulating the flood-preparedness of individuals and, thereby, limit flood damage. Nevertheless, few empirical studies have examined the effectiveness of flood risk communication (Kellens et al., 2013). Furthermore, most existing studies on this topic lack a sound theoretical underpinning (Kellens et al., 2013). This study has unravelled some key dynamics of flood risk communication by applying an innovative agent-based model, as advocated by Martens et al. (2009), which is firmly based on Protection Motivation Theory.

The applied methodology offers a new approach for evaluating flood risk communication strategies before implementation. Since agents are constructed to represent real-life heterogeneity (An, 2012) of attitudes toward risk and coping measures, the approach allows for a comparison to be made between a traditional top-down communication strategy and people-centred strategies that make use of this heterogeneity. Moreover, the capability of modelling interaction and feedback amongst this heterogeneous population (An, 2012) makes it possible to analyse the influence of social networks. While empirical data on flood risk communication is lacking (Kellens et al., 2013), the availability of empirical data on individual behaviour has made it possible to analyse a specific case study in detail, and, if calibration data is available for other regions, the overall methodological approach can be transferable to other floodplains.

While it is the strength of the agent-based model that we can compare different communication strategies in-silico, the approach is still limited by the lack of empirical data on flood risk communication. Therefore, the absolute values presented in this study of the effectiveness of a communication strategy are associated with uncertainty. To make the analysis robust, we made sure that the communication strategies are comparable based on reasonable assumptions, and we tested a large range of communication variable settings with a sensitivity analysis. Three main policy recommendations follow from this inter-comparison of the results, which could inform the efforts of, for instance, the EU Flood Directive and FEMA to reduce the risk associated with climate change and natural hazards. First, flood risk communication campaigns should not only focus on communicating the risk, but also on communicating the coping capabilities of individuals. Our results supports previous recommendation, that, providing details on, for instance, the types of measures that are available to limit flood risk, or how they can be implemented, facilitates protective behaviour (Bubeck et al., 2013; Poussin et al., 2014). This study shows that such an approach can be up to 0.1–6.5 times more effective than focussing on risk alone. Nevertheless, communicating the risk (probability and consequence) of a flood is needed to raise threat appraisal above a certain threshold level of concern (Bubeck et al., 2012; Grothmann and Patt, 2005; Kunreuther and Pauly, 2006).

Second, preference should be given to people-centred communication over top-down communication. The results presented in this study show that a people-centred campaign focussing on both threat and coping appraisal aspects leads to 2.5 times more implemented risk reduction measures compared with a top-down campaign. Even though the reach can be higher in top-down communication, the overall effectiveness is expected to be lower. This can be explained by the inability of the top-down strategy to address the specific risk perceptions and concerns of individuals and communities (Bier, 2001) while, in contrast, a people-centred approach can be designed to address the information needs of the public (IPCC, 2012).

Third, consistent with other literature on information diffusion (Macy and Willer, 2002; Rahmandad and Sterman, 2008), the results show that the effect of flood risk communication can

[2] For the 'no communication' scenario, flood insurance implementation rates are 0% in both model runs.

propagate through a social network. This implies that the design of flood risk communication strategies should incorporate or facilitate the propagation of information and behaviour through a social network. While one can think of different ways to achieve this, such as actively motivating people to communicate about their (intended) actions to their network, an important part could be played by social media. The potential benefits of using social media in disaster response, such as reach and fast dissemination of information, has already been shown (Sutton et al., 2008; Vieweg et al., 2010). Since social media allow for a wide-scale interaction between individuals, organisations, and the government, it serves as an extended social network through which information can propagate. Keim and Noji (2015) recently argued that because of the benefits of social media, they need to be fused into existing institutional programme's for crisis informatics and disaster risk management. While Keim and Noji (2015) mainly discuss disaster response, the same arguments apply for pre-disaster risk reduction, because social media offer an entrance into social networks through which accurate information can steer protective efforts.

Even though these aforementioned general lessons can be broadly applicable, risk communication strategies should be tailor-made to reflect the local context. Risk communication can serve a range of purposes, such as building trust in the communicator, raising awareness, educating, reaching agreement, and motivating action (Rowan, 1991). This means that different strategies might be appropriate for different goals (Bier, 2001), and it means that the actual design of the *message* needs to be tailored to each specific case. For instance in the Netherlands, a survey by Terpstra and Gutteling (2008) showed that even though Dutch citizens are receptive to disaster-preparedness communication, they consider protection against flood as a major responsibility for the government. This suggests that, for the Netherlands, communication should be designed to stress that Dutch citizens themselves are also responsible for protecting their belongings. While this example is specific for the Netherlands, such regional-specific effects must be taken into account for each area for which flood risk communication campaigns are designed.

5. Conclusion

This study presents an innovative agent-based model capable of unravelling some of the key aspects that determine the effectiveness of flood risk communication. The general approach is applicable to regions around the world, although empirical input data is needed for modelling specific regions. Three main recommendations for flood risk communication strategies follow from our findings. First, people-centred flood risk communication is expected to be more effective than top-down communication, even when it reaches fewer people. Second, communicating about both the risk of floods and how to cope with floods is expected to be more effective than communicating about risk alone. Third, propagation of the effect of communication through a social network should be stimulated by, for instance, the use of social media. We recommend that future research should focus on obtaining empirical data for calibrating the model to other regions of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2016.03.006.

References

An, L., 2012. Modeling human decisions in coupled human and natural systems: review of agent-based models. Ecol. Modell. 229, 25–36. doi:http://dx.doi.org/10.1016/j.ecolmodel.2011.07.010.
Bier, V.M., 2001. On the state of the art: risk communication to the public. Reliab. Eng. Syst. Saf. 71, 139–150.
Botzen, W.J.W., Van den Bergh, J.C.J.M., 2009. Managing natural disaster risks in a changing climate. Environ. Hazards 8, 209–225. doi:http://dx.doi.org/10.3763/ehaz.2009.0023.
Botzen, W.J.W., Aerts, J.C.J.H., Van den Bergh, J.C.J.M., 2009. Dependence of flood risk perceptions on socioeconomic and objective risk factors. Water Resour. Res. 45 doi:http://dx.doi.org/10.1029/2009WR007743.
Botzen, W.J.W., De Boer, J., Terpstra, T., 2013. Framing of risk and preferences for annual and multi-year flood insurance. J. Econ. Psychol. 39, 357–375. doi:http://dx.doi.org/10.1016/j.joep.2013.05.007.
Bras, H., van Tilburg, T., 2007. Kinship and social networks: a regional analysis of sibling relations in twentieth-Century Netherlands. J. Fam. Hist. 32, 296–322. doi:http://dx.doi.org/10.1177/0363199007300244.
Bubeck, P., Botzen, W.J.W., Aerts, J.C.J.H., 2012. A review of risk perceptions and other factors that influence flood mitigation behavior. Risk Anal. 32, 1481–1495. doi:http://dx.doi.org/10.1111/j.1539-6924.2011.01783.x.
Bubeck, P., Botzen, W.J.W., Kreibich, H., Aerts, J.C.J.H., 2013. Detailed insights into the influence of flood-coping appraisals on mitigation behaviour. Glob. Environ. Chang. 23, 1327–1338. doi:http://dx.doi.org/10.1016/j.gloenvcha.2013.05.009.
Burningham, K., Lecturer, S., Fielding, J., 2008. Itll never happen to me: understanding public awareness of local flood risk. Disasters 32, 216–238. doi:http://dx.doi.org/10.1111/j.0361-3666.2007.01036.x.
Centraal Bureau voor de Statistiek, 2012. Kerncijfers Postcodegebieden 2008–2010. Den Haag/Heerlen.
Dawson, R.J., Peppe, R., Wang, M., 2011. An agent-based model for risk-based flood incident management. Nat. Hazards 59, 167–189. doi:http://dx.doi.org/10.1007/s11069-011-9745-4.
De Boer, J., Botzen, W.J.W., Terpstra, T., 2014a. Improving flood risk communication by focusing on prevention-Focused motivation. Risk Anal. 34, 309–322. doi:http://dx.doi.org/10.1111/risa.12091.
De Boer, J., Botzen, W.J.W., Terpstra, T., 2014b. More than fear induction: toward an understanding of people's motivation to be well-prepared for emergencies in flood prone areas. Risk Anal. 322, 768. doi:http://dx.doi.org/10.1111/risa.12289.
Dekker, K., 2007. Social capital, neighbourhood attachment and participation in distressed urban areas. a case study in the Hague and utrecht, the Netherlands. Hous. Stud. 22, 355–379. doi:http://dx.doi.org/10.1080/02673030701254103.
Fekete, A., 2012. Safety and security target levels: opportunities and challenges for risk management and risk communication. Int. J. Disaster Risk Reduct. 2, 67–76. doi:http://dx.doi.org/10.1016/j.ijdrr.2012.09.001.
Figueiredo, E., Valente, S., Coelho, C., Pinho, L., 2009. Coping with risk: analysis on the importance of integrating social perceptions on flood risk into management mechanisms–the case of the municipality of Águeda. Portugal. J. Risk Res. 12, 581–602. doi:http://dx.doi.org/10.1080/13669870802511155.
Filatova, T., 2013. Market-based instruments for flood risk management: a review of theory, practice and perspectives for climate adaptation policy. Environ. Sci. Policy 1–16. doi:http://dx.doi.org/10.1016/j.envsci.2013.09.005.
Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., Huth, A., Jepsen, J.U., Jørgensen, C., Mooij, W.M., Müller, B., Pe'er, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rüger, N., Strand, E., Souissi, S., Stillman a, R., Vabø, R., Visser, U., DeAngelis, D.L., 2006. A standard protocol for describing individual-based and agent-based models. Ecol. Modell. 198, 115–126. doi:http://dx.doi.org/10.1016/j.ecolmodel.2006.04.023.
Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol: a review and first update. Ecol. Modell. 221, 2760–2768. doi:http://dx.doi.org/10.1016/j.ecolmodel.2010.08.019.
Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Glob. Environ. Change 15, 199–213. doi:http://dx.doi.org/10.1016/j.gloenvcha.2005.01.002.
Grothmann, T., Reusswig, F., 2006. People at risk of flooding: why some residents take precautionary action while others do not. Nat. Hazards 38, 101–120. doi:http://dx.doi.org/10.1007/s11069-005-8604-6.
INTERREG, 2013. Raising Flood Awareness and Self Efficacy—Framework to Develop and Implement a Successful Social Marketing Programme.
IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge, UK, and New York, NY, USA doi:http://dx.doi.org/10.1017/CBO9781139177245.
Jongman, B., Ward, P.J., Aerts, J.C.J.H., 2012. Global exposure to river and coastal flooding: long term trends and changes. Glob. Environ. Change 22, 823–835. doi:http://dx.doi.org/10.1016/j.gloenvcha.2012.07.004.

Kasperson, R.E., Renn, O., Slovic, P., Brown, H.S., Emel, J., Goble, R., Kasperson, J.X., Ratick, S., 1988. The social amplification of risk: a conceptual framework. Risk Anal. 8, 177–187. doi:http://dx.doi.org/10.1111/j.1539-6924.1988.tb01168.x.

Keim, M.E., Noji, E.M.D., 2015. Emergent use of social media: a new age of opportunity for disaster resilience. J. Appl. Commun. Res. 43, 44–65. doi:http://dx.doi.org/10.5055/ajdm.2010.0000.

Kellens, W., Terpstra, T., De Maeyer, P., 2013. Perception and communication of flood risks: a systematic review of empirical research. Risk Anal. 33, 24–49. doi: http://dx.doi.org/10.1111/j.1539-6924.2012.01844.x.

Koerth, J., Vafeidis, A.T., Hinkel, J., Sterr, H., 2013. What motivates coastal households to adapt pro-actively to sea-level rise and increasing flood risk? Reg. Environ. Change 13, 897–909. doi:http://dx.doi.org/10.1007/s10113-012-0399-x.

Kunreuther, H.C., Michel-Kerjan, E.O., 2011. People get ready—disaster preparedness. Issues Sci. Technol. 28.

Kunreuther, H.C., Pauly, M., 2006. Rules rather than discretion: lessons from hurricane katrina. J. Risk Uncertain. 33, 101–116. doi:http://dx.doi.org/10.1007/s11166-006-0173-x.

Kunreuther, H.C., Meyer, R., Michel-Kerjan, E.O., 2013. Overcoming decision biases to reduce losses from natural catastrophes. In: Shafir, E. (Ed.), The Behavioral Foundations of Public Policy. Princeton University Press, Princeton, pp. 536.

Lara, A., Saurí, D., Ribas, A., Pavón, D., 2010. Social perceptions of floods and flood management in a Mediterranean area (Costa Brava, Spain). Nat. Hazards Earth Syst. Sci. 10, 2081–2091. doi:http://dx.doi.org/10.5194/nhess-10-2081-2010.

Lo, A.Y., 2013. The role of social norms in climate adaptation: mediating risk perception and flood insurance purchase. Glob. Environ. Change 23, 1249–1257. doi:http://dx.doi.org/10.1016/j.gloenvcha.2013.07.019.

Macy, M.W., Willer, R., 2002. From factors to factors: computational sociology and agent-Based modeling. Annu. Rev. Sociol. 28, 143–166. doi:http://dx.doi.org/10.1146/annurev.soc.28.110601.141117.

Martens, T., Garrelts, H., Grunenberg, H., Lange, H., 2009. Taking the heterogeneity of citizens into account: flood risk communication in coastal cities–a case study of Bremen. Nat. Hazards Earth Syst. Sci. 9, 1931–1940. doi:http://dx.doi.org/10.5194/nhess-9-1931-2009.

Mollenhorst, G., 2015. Window on the Netherlands neighbour relations in the Netherlands : new developments. Tijdschr. voor Econ. en Soc. Geogr. 106, 110–119. doi:http://dx.doi.org/10.1111/tesg.12138.

Nederlandse Vereniging van Makelaars, 2004. NVM-visie Strategisch Bouwen.

Poussin, J.K., Botzen, W.J.W., Aerts, J.C.J.H., 2014. Factors of influence on flood damage mitigation behaviour by households. Environ. Sci. Policy 1–9. doi: http://dx.doi.org/10.1016/j.envsci.2014.01.013.

Rahmandad, H., Sterman, J., 2008. Heterogeneity and network structure in the dynamics of diffusion: comparing agent-based and differential equation models. Manage. Sci. 54, 998–1014.

Rogers, R.W., 1983. Cognitive and physiological processes in fear appeals and attitude change: a revised theory of protection motivation.. In: Cacioppo, B.L., Petty, R.E. (Eds.), Social Psychophysiology: A Sourcebook. The Guilford Press, London, pp. 153–176.

Rowan, K.E., 1991. Goals, obstacles, and strategies in risk communication: a Problem-solving approach to improving communication about risks. J. Appl. Commun. Res. 19, 300–329.

Sutton J., Palen L., Shklovski, I., 2008. Backchannels on the front lines: Emergent uses of social media in the 2007 southern California wildfires, Fiedrich, F., Van de Walle, B. (Eds.), Proceedings of the 5th International ISCRAM Conference. Washington, DC, USA ., pp. 1–9.

Terpstra, T., Gutteling, J.M., 2008. Households' perceived responsibilities in flood risk management in The Netherlands. Int. J. Water Resour. Dev. 24, 555–565. doi:http://dx.doi.org/10.1080/07900620801923385.

Terpstra, T., Lindell, M.K., Gutteling, J.M., 2009. Does communicating (flood) risk affect (flood) risk perceptions? results of a quasi-experimental study. Risk Anal. 29, 1141–1155. doi:http://dx.doi.org/10.1111/j.1539-6924.2009.01252.x.

Van den Berg, P., Arentze, T., Timmermans, H., 2014. A multilevel analysis of factors influencing social interaction with neighbors. 93rd Annual Meeting of the Transportation Research Board 1–18.

Van der Linden, S., 2015. The social-psychological determinants of climate change risk perceptions: towards a comprehensive model. J. Environ. Psychol. 41, 112–124. doi:http://dx.doi.org/10.1016/j.jenvp.2014.11.012.

Vieweg, S., Hughes, A.L., Starbird, K., Palen, L., 2010. Microblogging During Two Natural Hazards Events: What Twitter May Contribute to Situational Awareness. CHI 2010 Cris. Informatics, Atlanta, GA, USA, pp. 1079–1088. doi: http://dx.doi.org/10.1145/1753326.1753486 April 10–15.

Volker, B., Flap, H., 2007. Sixteen million neighbors: a multilevel study of the role of neighbors in the personal networks of the dutch. Urban Aff. Rev. 43, 256–284. doi:http://dx.doi.org/10.1177/1078087407302001.

Wilensky, U., 1999. NetLogo. .