Perspective

Integrating Human Behavior Dynamics into Flood Disaster Risk Assessment

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The behavior of individuals, businesses, and government entities before, during, and immediately after a disaster can dramatically affect the impact and recovery time. However, existing risk- assessment methods rarely include this critical factor. In this Perspective, we show why this is a concern, and demonstrate that although initial efforts have inevitably represented human behavior in limited terms, innovations in flood-risk assessment that integrate societal behavior and behavioral adaptation dynamics into such quantifications may lead to more accurate characterization of risks and improved assessment of the effectiveness of risk-management strategies and investments. Such multidisciplinary approaches can inform flood-risk management policy development.

Introduction

Floods have caused the largest portion of insured losses among all natural catastrophes during recent decades, causing losses worth ~USD60bn in 2016 alone around the world.[1] Climate change, extreme rainfall events, and sea-level rise may further increase the frequency and severity of flood hazards. Moreover, global exposure to floods is expected to grow by a factor of three by 2050 due to the continuous increases in population and economic assets in flood-prone areas, which are often viewed as economically attractive regions for development.[2] Despite the trillions of dollars of assets allocated to riverine and coastal flood-prone areas,[3] governmental investments in flood protection are often inadequate. Moreover, spatial-planning policies that purport to reduce the exposure and vulnerability of people and assets (e.g., zoning and building codes) are unable to reverse the trends of rising risk and the increasing number of people who choose to live in low-lying, flood-prone areas.[4]

To cope with these trends, measures in climate-change adaptation and disaster risk reduction (DRR) must be implemented and prioritized based on reliable risk information. The utilization of evidence-based risk-assessment information lies at the forefront of discussions on contemporary global climate and disaster risk-reduction. At the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP) 22, members conducted the first review of the Warsaw International Mechanism for Loss and Damage (L&D),[5] which highlights the importance of limiting the impacts of current and future climate-related hazards.[6] Additionally, the recent Global Platform for DRR held in Cancun, Mexico reaffirmed the need for monitoring the implementation of the Sendai Framework for Disaster Risk Reduction (SFDRR), coordinated by the United Nations Office for Disaster Risk Reduction (UNISDR).[7]

Qualitative approaches to DRR can inform the prioritization of actions; however, they do not provide sufficient evidence regarding the appropriate amount to invest in risk reduction or the scale of actions that may be required.[8] They need to be supplemented by quantitative risk assessments that systematically estimate the magnitude and frequency of natural hazards, the exposed assets and people, and how vulnerable those assets and people are given certain hazard conditions (Fig. 1).[9] Such assessments can prioritize adaptation policies and assess whether investments in such policies are sufficiently robust to be appropriate given uncertain future conditions.[10,11,12]

One of the key challenges in quantitative risk assessment is how to address the role of individual perceptions of risk and how these perceptions influence risk-reducing behavior.[13] For example, which factors drive risk perception (e.g., previous flooding experience, income, and education), and how do these factors influence individuals' choice to take precautionary measures against flood risk? The importance of behavioral and social determinants of vulnerability in natural-hazard risk management has been addressed throughout decades of work by disaster sociologists, political ecologists, hazards geographers, psychologists, and decision scientists.[14,15,16,17] However, the disaster-risk and climate-change adaptation community only recently addressed the role of physical exposure and social vulnerability as key determinants of disaster risk and its impacts.[18] One reason for this is that human behavior and risk perception are inherently difficult to quantify; they form a complex subject for quantitative-risk scientists to understand and integrate into their methodologies. An example of such a complex subject is the behavior of households towards flood adaptation. Survey research demonstrates that many households insufficiently invest in protecting their property from flood disasters, even when such measures are economically efficient.[19] The reasons for this include a variety of determinants that influence risk perception, including lack of risk awareness, underestimation of the risk in the absence of recent experience of the hazard, and the use of short-term planning horizons by stakeholders in risk management.[20,21] Individuals often use simplified decision rules and heuristics, thereby neglecting or underestimating the hazard risk or ignoring it and failing to take preventive actions.[22,23] In this regard, Nobel Laureate Daniel Kahneman[24] summarized decades of cognitive-science research showing that individuals base complex decisions on intuitive (System 1) and deliberative (System 2) thinking processes. Intuitive thinking may outweigh deliberative thinking and result in behavioral biases with respect to adopting protective measures against flooding, such that these steps are taken only after a disaster occurs.

In this Perspective, we demonstrate why it is important to include human behavior and risk perception in quantitative risk-assessment models. In the first section, we explain the main components of risk-assessment models and how they relate to DRR, and address how risk perception and other factors influence human behavior and DRR. Next, we address recent research areas that capture behavioral aspects of risk management, provide examples on how risk perception influences vulnerability, and demonstrate how these factors interact over time. Finally, we address key challenges for future research and risk policy.

Main components in flood-risk assessment research

Fig. 1 (Box A) shows the main components of current quantitative *risk-assessment* models that aim to quantify risk to specific hazards. In these models, risk, expressed as the expected annual damage (EAD), is a function of three key elements: hazard, exposure, and vulnerability. Risk-assessment models were originally developed by catastrophe-modeling firms to aid the insurance industry and financial institutions in assessing the risk of their portfolios.[25] They are currently widely used to evaluate investment decisions in flood-risk management. In such approaches, the cost of investing in DRR to lower flood risk is compared to the benefits, expressed as the degree of risk reduction over time for these investments.[11] The main outputs of risk-assessment studies are risk estimations based on 'exceedance probability curves', which characterize the relationship between hazard and the amount of damage that the hazard inflicts on assets or peoples' lives.[26] *Vulnerability* in these models is represented using damage functions (also called 'vulnerability curves'), which show the relationship between potential losses (people and assets) and flood hazard (e.g., flood depth).[27] Such curves are often based on empirical loss estimates from historical data or expert judgement.[28] In reviewing the different components of risk assessment, it becomes clear that much progress has been made in simulating (trends in) *flood hazards* (e.g., flood probability, flood extent, and duration and depth). The methods applied are statistical methods that use historical data to provide estimates of the flood hazard (e.g., peak discharges and flood duration), or hydrological and hydrodynamic models that simulate the hydrological processes during a flood.[29] Data on the *exposure* of people and assets to those hazards are also rapidly improving through the availability of global-census data, earth-observation techniques, and land-use modeling.[30]

Fig 1: Extended risk assessment framework including behavioral factors and disaster risk reduction

In Fig 1., Box A shows the main components used in current risk assessments (Hazard, Exposure and Vulnerability). Vulnerability and Risk can be reduced through the implementation of DRR measures (Box B). Risk information and flood events, however, also influence factors that influence behavior and risk perception (e.g. flood experience, risk communication, Box C). Those factors influence stakeholders' decisions on whether to implement DRR measures. (*Note*: The factors listed in Box C are based on selected research, but many different factors and methods exist to classify social vulnerability; some DRR measures in Box B are developed by different stakeholders).

Although people and assets are exposed, stakeholders in flood-risk management (individuals, business, and government) lower their vulnerability, exposure, and probability of flooding via DRR measures (Box B, Fig. 1). Such risk-reducing measures include early warning systems to evacuate people to safer areas (reduce exposure), constructing levees to protect critical infrastructure or large urban centers (reduce hazard probability), and reducing vulnerability by flood-proofing buildings as enforced by building codes (e.g., by elevating the ground floor above the level of expected flood waters).[11] Other measures, such as establishing flood-insurance schemes to finance losses in the aftermath of an event, increase the financial resilience to residual risk.[31] However, certain actions or non-actions may exacerbate the risk, such as choosing to remain in an area that is about to suffer a flood despite warnings, or failing to move a car to higher ground.

However, the use of a single average-vulnerability curve representing only the relation between flood depth and damage does not address the entire range of human behavioral responses. Vulnerability and risk are determined by many factors that influence the behavior of stakeholders to lower their vulnerability or exposure through DRR. For example, it is well known that some of the factors listed in Box C (e.g., flood experience and communication by media) lead to a high perception of flood risks, and that people with high risk perceptions implement DRR activities at a relatively higher rate than those with lower risk perceptions.[19,20] More DRR activities (buying flood insurance, strengthening levees, etc.) lead to a reduction in risk (Box A). Finally, risk information and extreme events (Box A) influence certain behavioral factors in Box B (flood experience and risk communication), thereby completing the circle.

Current vulnerability-curve approaches, however, largely neglect the efforts made in *social vulnerability* research[2,33,34,35,36,37] which widely describes the factors that influence DRR behavior (Box B) and risk/vulnerability (Box C). This research has a firm foundation in fields such as sociology, geography, and ethnographic studies, and has provided greater insight into the social determinants of vulnerability (socioeconomic status, age, gender, housing tenure, and access to communication systems),[38] as well as how implementing DRR measures reduces vulnerability.[39] Social vulnerability research also reveals that determinants of vulnerability at a larger national scale rarely explain the variance in the vulnerability of local communities.[39] Research has shown, for example, that while there is no direct relation between GDP and flood vulnerability at a national scale, flood events at local scales have impacted low-income households more than wealthier households. This shows that certain population groups have more resources than others by which to prevent, mitigate, or recover from extreme flood events, which is not reflected in aggregated national-scale indicators such as GDP.[41,42] Furthermore, social vulnerability to flooding at local levels may stem from limited access to resources during a flood,[43] gender-related issues,[44] political ideology,[45] and beliefs in and experience with extreme events,[46] for instance. Other factors explain trends in exposure and show that socio-economic motives largely drive trends in global urbanization, including the expansion of low-lying vulnerable urban centers.[40]

Some research into social vulnerability uses more quantitative approaches. For example, index-based vulnerability research assesses and classifies the main factors underlying vulnerability and subsequently aggregates these factors into a composite index.[35] However, the majority of these indices are static assessments, providing an estimate of vulnerability for a discrete moment in time and space. The same holds for vulnerability curves applied in risk models, which can be integrated with scenario methods to address the temporal aspects of adaptation, vulnerability, and uncertainty in long-term trends.[47,48]

The challenge is to integrate the dynamic interplay between processes captured in the three boxes in Fig. 1 (risk assessment, factors influencing DRR behavior, and DRR) into one comprehensive risk-assessment approach. However, research into the interactions between the physical water system and societal processes, as well as how DRR and vulnerability change over time is in its infancy.[49,50,51] Most risk assessments assume that vulnerability remains constant across time and space, as though individuals and other stakeholders do not adapt, learn from experience, or prepare for an event based on risk information or early warning.[52] In reality, adaptation dynamics are largely determined by the behavior and perception of the aforementioned stakeholders, influencing both the risk and each other's decisions, sometimes in unpredictable ways.[53] For example, cognitive biases have played a pivotal role in past flood disasters and have catalyzed adaptation.[54] In most situations in which significant steps were taken to reduce flood risk, these steps were triggered by experiences from previous disasters.[55] Examples include the impacts of Hurricanes Katrina and Sandy, which led to investments of over USD10bn in risk-reduction measures, as well as the 1953 floods in the Netherlands and southern England, which initiated the Dutch Delta Plan and a reformulation of London's flood protection.[8]

Advances in risk assessment and behavioral research

Including the dynamics of risk perception, behavioral dynamics, and DRR in risk assessment requires a multi-disciplinary approach that integrates methods from the natural sciences with the social sciences. As risk assessment aims to quantify risk trends over time, there is a need not only to understand the behavioral patterns and factors underlying flood-risk management decisions. Additionally, there is a need to translate these factors into quantitative approximations regarding how a person, property owner, or community makes an investment choice in DRR and adaptation, as well as how this affects flood risk.[56] In what follows, we discuss recent advances in the main research domains related to flood risk (behavioral sciences, economics, social vulnerability, hydrology, and complex systems) that make such efforts.

Recent surveys and longitudinal studies provide empirical data on human decision processes that enable the integration of theory from the *behavioral sciences* with quantitative approaches to flood-risk assessment. For example, recent progress in behavior modeling is based on theories from psychology, such as the protection motivation theory (PMT). This theory has been implemented in various flood-risk studies, and shows how individuals process threats and select responses to cope with those threats.[57] Research into flood-risk management using PMT shows that individuals implement adaptation measures to protect themselves from floods if they believe that the threat of the hazard they face ('threat appraisal') is high, and if they perceive that the available protective measures are effective (high 'response efficacy'), easy (high 'self-efficacy'), and affordable to implement (low 'response costs')[5.8]

Furthermore, empirical research in the area of *behavioral economics* and flood-risk management shows that behavior towards risk and adaptation does not comply with the standard economic theory of expected utility.[59] Rather, it reflects bounded rational behavior when facing extreme risk as defined by behavioral economics. Prospect theory characterizes this behavior[60] and has been used to estimate an individual's willingness to implement adaptation measures,[61] as well as the interactions of household flood-preparedness decisions with incentives from other stakeholders, such as insurers.[62] Individual risk perceptions in terms of the subjective likelihood and consequences of flooding are important determinants of flood-preparedness behavior.[63] These risk perceptions are based on individuals' prior expectations, but can also be influenced by information provided about risk (e.g., by governments or insurance companies), as well as their personal vulnerability. In addition, hazard experience could lead individuals to learn and update their prior expectations of risk and subsequent behavior.[55,56,64]

The perspective of integrating behavioral dynamics with quantitative risk-assessment methods has recently sparked novel *social vulnerability research*.[65] In the DRR context, for example, Burton and Cutter[66] developed vulnerability-assessment models of hypothetical levee breaks and simulated the socio-spatial impacts for empirically defined and multi-dimensional social-vulnerability metrics. The use of statistical and spatial models of social vulnerability[67] offers policy makers improved quantification of social impacts and benefits in flood-mitigation planning, which heretofore was wildly underestimated. Improved spatial modelling of specific socially vulnerable groups[68,69] quantifies the role of language and culture in flood-risk assessment and protection-action behavior. Similarly, the use of mental models to understand the perception of flood risk and protective-action behavior advances the ability to include such data in formal flood-risk assessments through the risk-communication process.[70] Finally, a spatially explicit forensic analysis of the evolution of urban flood risk illustrates the differential power of antecedent decisions in altering the natural and social landscapes of places, which in turn heighten the risk and its social impact.[71]

Another recent line of inquiry stems from *hydrology research*, in which simplified dynamic system models are used to study the interactions between hydrological systems and human responses. Di Baldassarre et al.[72] and subsequent studies[73] model flood risk as a dynamic function of flood events, collective memory, and societal decisions on resettlement or investment in flood protection. These efforts were extended to a theoretical model of flood occurrence and economic growth.[74] Dadson et al.[75] demonstrate the potential for communities that are exposed to chronic environmental shocks, such as flooding, to become trapped in poverty and be unable to invest in beneficial protection. Each of these methods emphasizes the role of feedback (e.g., between flood losses and the capacity to take further adaptation actions). However, these simplified models lack the theoretical underpinning from the social sciences, and represent the different behavioral components in a lumped manner. Their simplicity, on the other hand, clarifies the role and effects of feedback, and allows for the exploration of many possible future scenarios.[76]

Novel *complex systems* studies in flood-risk assessment that use agent-based models (ABM) are gaining traction and show that it is possible to better integrate scientific theories on human behavior and perception into risk assessment by relating behavior to adaptation actions.[51,77,78,79,80] An ABM simulates individual behavior,[79] whereby agents represent different models of choice while acting in their own interests, such as maximizing their welfare or minimizing adaptation costs, often using simple decision rules. Agents can learn, move, and influence (and are influenced by) the risk they face, resulting in differing adaptation actions. Patterns of risk over time are achieved by aggregating the results of many individual actions. More broadly, the results of recent ABM studies show that societal water-climate systems all have the characteristics of complex systems, marked by time periods of both stability and large dynamics;[81,82] historical data regarding investments in flood protection show little change in the behavior of governments and households after floods that had a small impact, and large investment dynamics in adaptation following large disasters.[83] For instance, recent research into flood-risk trends in the Netherlands shows that, without considering behavioral aspects, future risk is overestimated by a factor of 2.[77] This is confirmed by

Wind et al.,[84] who observed a 35% decrease in losses for a large flood on the River Meuse in 1995 compared to a similar flood in 1993, which was primarily caused by the adaptive behavior of households.

Fig. 2 highlights in a simplified yet illustrative manner how a risk-assessment model that includes human behavior can simulate the interaction between flood risk and societal behavior in a select number of theoretical examples. The panels in Fig. 2 show future flood risk with climate change and socioeconomic growth, while allowing for interactions between DRR behavior, flood events, and risk, for theoretical situations with (panels B, C, and D) and without (panel A) extreme flooding events. In panel A, risk increases as a result of climate change and socioeconomic trends (e.g., urbanization in flood zones), with no new DRR measures being taken ('No DRR measures'); rational behavior (purple curve) leads to proactive, cost-efficient DRR investments that are informed by cost-benefit analysis. The purple curve is lower as risk is continuously reduced through DRR. Panel B shows a situation with one flood disaster inflicting large losses, assuming that agents (e.g., governments) behave as boundedly rational. Agents are expected to underestimate risk before the flood event and invest in DRR reactively after the flood, thereby lowering future risk. After some time, risk increases again due to the aforementioned trends. Panel C depicts a situation with two flood disasters that lie 20 years apart and assumes boundedly rational agents who also respond reactively to flood events. Despite investments after the first flood event, risk increases and the learning experience from the first flood (i.e., the collective memory of the agents) has disappeared. The second flood causes higher losses due to increased exposure, even though the flood volumes are similar to the first flood. The final graph, panel D, shows a sequence of large floods that cause multiple investments that reduce risk due to availability bias, whereby the likelihood of a future disaster is estimated by the salience of the event. The time between the first two floods is subsequently shortened to two years, and agents continue to have a high-risk perception. Therefore, they undertake precautionary measures that minimize the damage from the second event. If the time between the two most recent events is excessively long, perception between the events decreases, resulting in low preparedness and high risk levels; this is identical to the process described in panel C.

Fig. 2: Trends in flood risk influenced by events and human behavior

Panels A, B, C, and D show the development of flood risk over time under climate change plus socioeconomic growth (grey) and assumes only socioeconomic trends (purple). The blue bars represent extreme flood events, while the brown line represents trends in risk, assuming interactions between adaptive behavior, risk, and flood events. Panel A shows the development of risk without flood events. Panel B shows a situation with one flood disaster, assuming that agents (e.g., governments) behave boundedly rational, underestimating risk before the flood event and invest in disaster risk reduction measures reactively after the event. Panels C and D show multiple flood events and similar behavior. When the time between two floods is shortened (Panel D), agents continue to have a high-risk perception, and undertake more precautionary measures that minimize the damage from the second event.

Moving forward with disaster risk-assessment science

Recent scientific advances in flood-risk assessment and behavioral dynamics reveal several issues that need to be addressed in future research. One of those challenges relates to the issue of scale, and to better representing local scale (individual) behavioral dynamics of stakeholders at the larger regional to national scales. In view of this, it is important to continue social vulnerability research into which factors drive vulnerability at the local scales, as well as to improve our understanding of how these factors vary between developed and developing countries.[43,44,85]

Another key challenge in integrating behavioral factors into quantitative risk-assessment methods is that of deriving solid and replicable empirical data on human behavior. In recent decades, multiple surveys in developed and developing countries have provided new information regarding the behavior of households facing risk.[43,86,87] However, policy makers need to facilitate the public accessibility of empirical data from surveys, social media, and empirical loss data.[80,88] This point is particularly relevant for risk-assessment efforts in developing countries, where information regarding vulnerability and exposure is often limited, and significant resources and efforts are required to generate and apply this information.[89] Such empirical data of behavioral responses to past flood events can be used to calibrate modeling applications to flood risk. These surveys detail, for example, how households evaluate the costs and benefits of risk mitigation (e.g., flood-proofing homes) before and after extreme events,[43,58] how individuals make decisions about purchasing insurance, and how they respond to financial incentives for risk reduction, such as premium reduction.[90,91] Key findings also show that individual perceptions of the likelihood and consequences of flooding are indeed largely shaped by intuitive thinking processes, such as past flood experience, worry, trust, and threshold models, and are not solely based on the probability of a future flood.[91]

Improved risk assessments, including behavioral dynamics, can benefit flood-risk managers in governments by supporting their investment decisions, as in flood protection, building codes, or flood zoning[92]. Risk-assessment methods including behavioral dynamics can also be applied to adequately determine risk-based premiums for disaster-insurance programs. The role of insurance in flood-risk assessment is particularly relevant for households seeking to effectively implement DRR measures to reduce risk to their property.[94] For example, research shows that households in high-risk areas are often unaware of flood hazards and have low flood-risk perceptions, and therefore, by treating their risks below their threshold level of concern, do not take protective measures.[20,95] Given these trends and policies, insurers increasingly face challenges in providing viable insurance products that can finance extreme losses at an affordable price.[94]

The spatially explicit modeling of flood-risk perceptions and DRR actions can facilitate risk communication and disaster-reduction policies by targeting the areas or groups that are most exposed, most vulnerable, and with the least knowledge and inclination to undertake any type of mitigation. Learning about the behavior of individuals towards adaptation and risk, and how people perceive risk can also contribute to improved risk communication between the government and those living and working in hazard-prone areas. Behavioral risk modeling can compare the effects of such communication strategies[80] and leverage the enormous collective potential of individuals, which can significantly contribute to risk reduction.

Standard risk assessments are likely to overestimate future risk by assuming constant vulnerability in a changing climate (Fig. 2, grey curve). The assumption, however, that investments in DRR are linked to fully rational behavior results in an underestimation of risk (Fig. 1, purple curve). The reality is likely situated between these two extremes and is context-specific, which is where future research efforts should be concentrated.[96] Given the challenges, an appropriate way forward is to adopt a multi-disciplinary approach that integrates all components of risks, including vulnerability and behavioral assessments.[56,97] This promises to enhance flood-risk assessment as addressed in the Sendai Framework for DRR, and to drive more effective adaptation and DRR policies to cope with future challenges, such as climate change.

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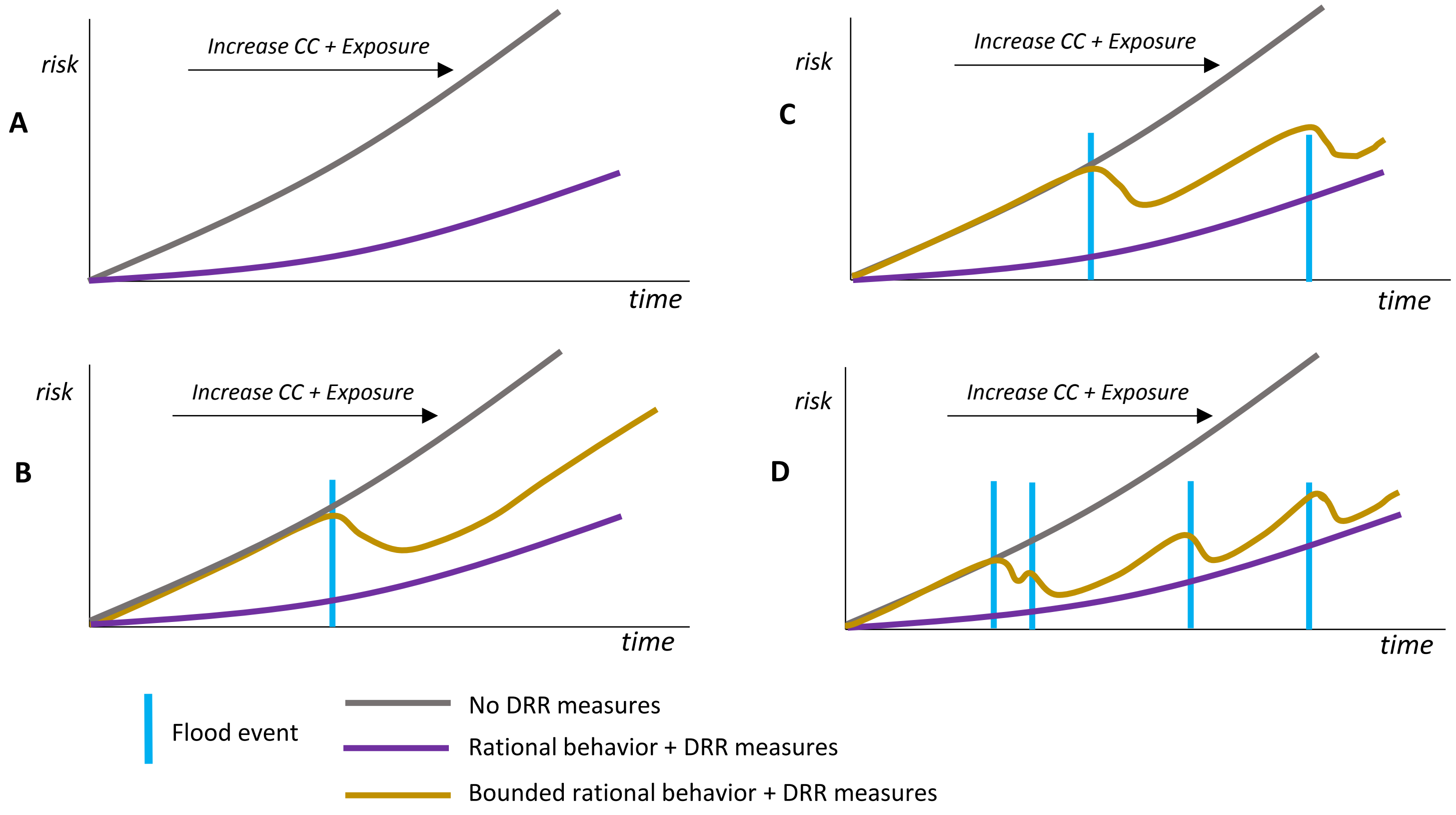
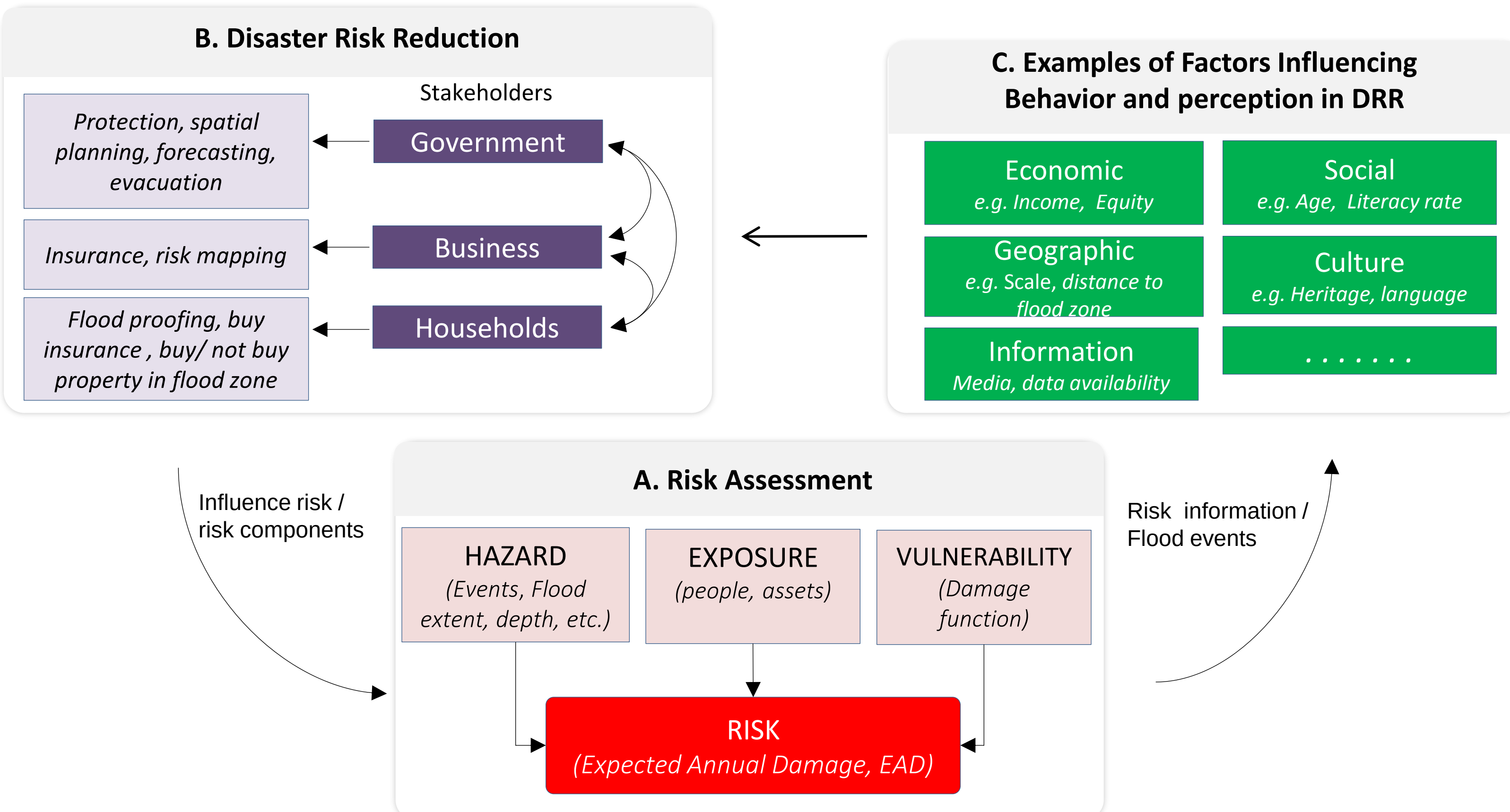


A
B
C
D
risk
time
Increase CC + Exposure
Flood event
No DRR measures
Rational behavior + DRR measures
Bounded rational behavior + DRR measures


B. Disaster Risk Reduction
Stakeholders
Protection, spatial planning, forecasting, evacuation
Government
Insurance, risk mapping
Business
Flood proofing, buy insurance , buy/ not buy property in flood zone
Households
C. Examples of Factors Influencing Behavior and perception in DRR
Economic
e.g. Income, Equity
Social
e.g. Age, Literacy rate
Geographic
e.g. Scale, distance to flood zone
Culture
e.g. Heritage, language
Information
Media, data availability
. . . .
Influence risk / risk components
A. Risk Assessment
HAZARD
(Events, Flood extent, depth, etc.)
EXPOSURE
(people, assets)
VULNERABILITY
(Damage function)
RISK
(Expected Annual Damage, EAD)
Risk information / Flood events