Bending the trend

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2019

Inaugural Speech: Prof. dr. Philip J. Ward (8 November 2019)

Bending the trend: Towards sustainable flood and drought risk solutions through understanding global disaster risk

'Rector, ladies and gentlemen'

An enduring story in classical Greek mythology is the battle between the Greek hero Hercules and the river god Achelous. Hercules defeats Achelous, who has taken the form of a bull, by wrenching off one of his horns. The horn becomes the Cornucopia, or Horn of Plenty, a symbol of abundance depicted as a large horn overflowing with produce. One interpretation of this myth suggests that Hercules' victory represents engineering operations, including channels, embankments, and dams, by which rivers were tamed to create a fertile tract of land for cultivation (Bengal, 1847). Therefore, the story can be interpreted as an early example of humans' efforts to master nature, hydrology, and the planet.

However, classic folklore and mythology also abound with examples of nature punishing humans for their treatment of the planet. Indeed, the great Roman author, philosopher, and geographer Pliny the Elder was painfully aware of the role that humankind can play in causing natural disasters. In his classic *Naturalis Historia* from ~79 AD, he writes:

> "*We trace out all the veins of the earth, and yet, living upon it, undermined as it is beneath our feet, are astonished that it should occasionally cleave asunder or tremble: as though, forsooth, these signs could be any other than expressions of the indignation felt by our sacred parent!*"
> Pliny the Elder (cited in Bostock & Riley, 1857)

It is this interplay between physical and human processes that causes disasters, including water-related disasters such as floods and droughts. Formally, we investigate this using the so-called risk framework. In this framework, risk is expressed as the combination of three components: the hazard, the exposure, and the vulnerability (Kron, 2002; UNISDR, 2011). The hazard refers to the physical event that may cause damage or losses. For example, in Figure 1 we see a flood with a given probability of occurrence. Its potential impacts depend on its physical characteristics, such as flood depth, velocity of the floodwaters, the rate at which the floodwater rises, and so forth. The exposure refers to the elements that are potentially in harm's way if a hazard were to occur, such as buildings, humans, assets, and so forth. In Figure 1, we see Manhattan – the densely packed urban environment means that the exposure is high. The vulnerability refers to the resistance, or lack of resistance, of the exposed elements to the hazard. For example, in Figure 1 we see a house on stilts. In the photo we can see that there is a flood hazard, as we see floodwaters under the house. There is also exposure, namely the house and its contents. Yet, because the house is raised on stilts its vulnerability is reduced. In this framework, all three of the risk elements must be present in order for risk to occur.

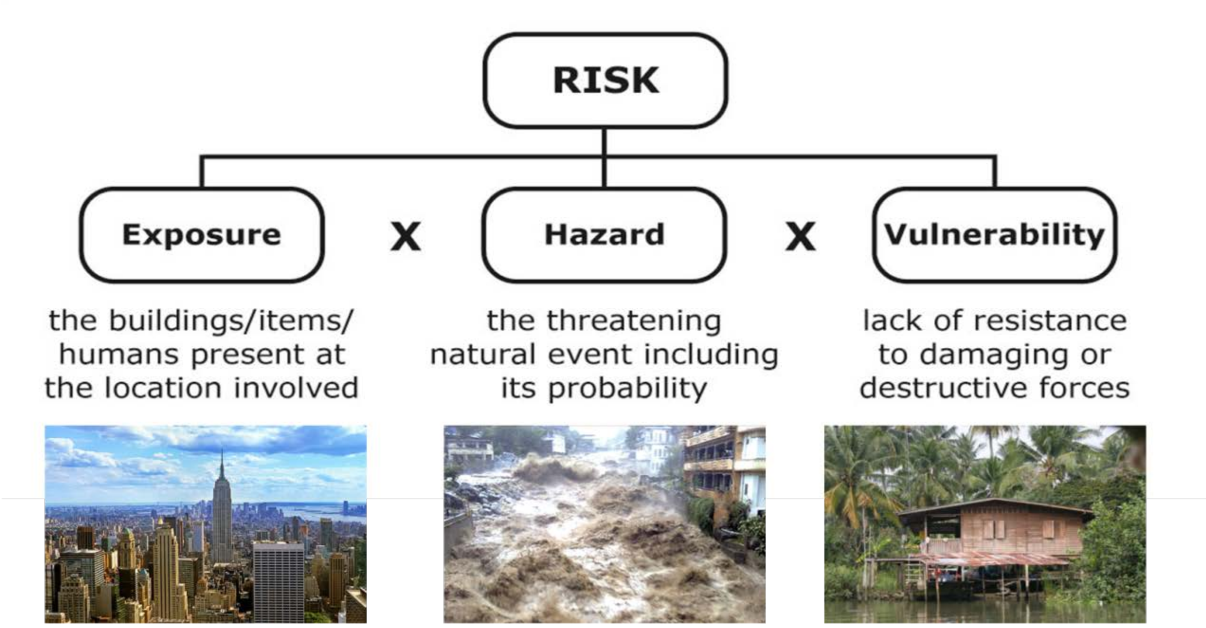

Figure 1: Risk is a function of hazard, exposure, and vulnerability

To begin this inaugural speech, I first want to take a step back in time about 30-35 years, to explain my own fascination with the subject of water risk. So here I am, somewhere in the Yorkshire Dales (Figure 2). This is a typical weekend for me growing up, going hiking with my family and friends in Northern England. It being the uplands of Northern England, it would invariably rain. This is an area where there are also a lot of hills and mountains, and a lot of fast-responding rivers. It is also an area in which a lot of people live downstream, where there is a lot of economic activity. The interplay between these physical and socioeconomic processes means that this is an area that also sees quite some flooding. Figure 2 shows the Boxing Day flood of 2015 in Hebden Bridge, where my brother and his family live. In fact, my wife and I drove down this road about 15 minutes before the river burst its banks and caused this flood, which would have been rather embarrassing for a flood risk Professor. These kinds of floods are relatively commonplace in this region, and so growing up in this region raised my interest in how interactions between physical and human geographical processes can cause risk.

Figure 2: Hiking in the Yorkshire Dales (left) and flooding in Hebden Bridge (Yorkshire) on Boxing Day 2015 (right)

Of course, we are all aware of the huge tragedies that floods and droughts can cause. In March this year, Cyclone Idai swept through Mozambique, Malawi, and Zimbabwe, causing at least 1000 deaths and destroying over 200,000 houses (Devi, 2019). In 2017, Hurricane Harvey inflicted >€100 billion in damage in and around Houston, Texas (Rözer et al., 2019). Ongoing droughts in the Horn of Africa mean that millions of people are in need of humanitarian and livelihood assistance (FAO, 2019). But these kinds of floods and drought disasters also occur much closer to home. The North Sea floods of 1953 led to over 2,300 deaths in the Netherlands, United Kingdom, and Belgium (Jonkman and Kelman, 2005), and led to a transformation in flood management practices in those countries. In terms of droughts, the summer of 2018 was a wake-up call for Europe. The long, hot, dry spring and summer led to reductions of yields of the main crops by up to 50% in parts of central and northern Europe (Toreti et al., 2019).

Global challenges and the role of science

Clearly, then, flood and drought risk are global challenges. And they call for a global response. As an international community, the world recognises the need to address the challenge of rising disaster risk. In 2015, United Nations (UN) Member States adopted the Sendai Framework for Disaster Risk Reduction, which calls for "*The substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries*" (UNISDR, 2015). To make this more concrete, the framework sets out seven global targets, including reducing disaster mortality and the number of affected people by 2030. The pressing need to address disaster risk is also at the heart of the Sustainable Development Goals.

These are all lofty goals, but how do we go about achieving them? The Sendai Framework sets out four specific priorities for doing just that. The first of these is *Understanding Disaster Risk*. It goes on to state that this is required at all spatial scales, from individuals right up to the global scale. In my Chair in Global Water Risk Dynamics, my research will aim to advance our scientific understanding of flood and drought risk right up to the global scale, and ensure that this research can assist in designing sustainable solutions for achieving the targets of international agreements such as the Sendai Framework and the Sustainable Development Goals. To do this, many challenges must be addressed. In the next half hour, I will discuss four main challenges that I will address in the coming years.

- First, I will discuss global projections of flood and drought risk in the 21st century;
- Second, I will discuss the importance of spatiotemporal variability in the assessment of risk;
- Third, I will discuss the importance of compound and consecutive hazards;
- Finally, I will discuss the imperative of science working in unison with practice if we are to develop solutions to the disaster risk challenges faced by society.

Global projections of flood and drought risk in the 21st century

Earlier this year, I gave a lecture at the General Assembly of the European Geosciences Union. In that lecture, I started by asking the ~300 scientists present for a show of hands on whether they expect flood and drought risk in 2050 to be higher or lower than today. Overwhelmingly, the audience said higher. Yet, as an international community we have agreed to reduce risk in the future. So what is going on?

Over the last 5-10 years, a growing number of scientific studies have tried to use global models to project the change in flood and drought risk between today and 2100. In Figure 3, the basic working of these models is shown with an example for flooding. Hazard is represented by maps showing flood extent and depth. Exposure is represented by maps of socioeconomic variables, such as population, GDP, or land use. In Figure 3, we see a map of assets for the same area as the flood hazard map. Vulnerability is often represented using so-called 'depth-damage functions'. They show how much damage would be caused for floods of different depths, for different exposed elements. For example, a flood of 2m would cause more damage than a flood of 2cm. By combining these three aspects, we are able to estimate the potential damage. We can also do this for the future. Hazard maps can be developed that show the potential extent and depth of floods in the future with different scenarios of climate change, and exposure maps can be developed showing, for example, the change in land use in the future under different scenarios of socioeconomic development.

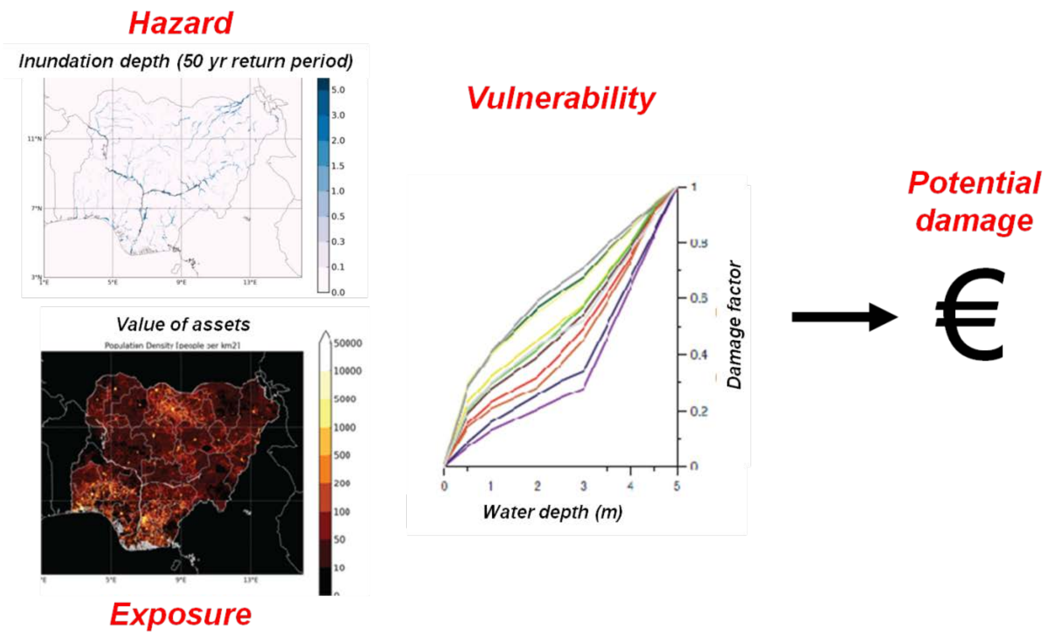

Figure 3: Schematic representation of the generic working of a flood risk assessment model

By doing this, several studies have shown that globally, river flood risk will increase in the future. For example, together with colleague Hessel Winsemius (Winsemius et al., 2016), we simulated the change in expected annual damage from river floods between today and 2080. If no measures are taken to increase protection against flooding, we found that the absolute expected annual damage could increase between 500% and 2,600%, depending on the scenario used. In Figure 4, the percentage increase in risk is shown per state, and we can see a large increase in almost all regions of the world.

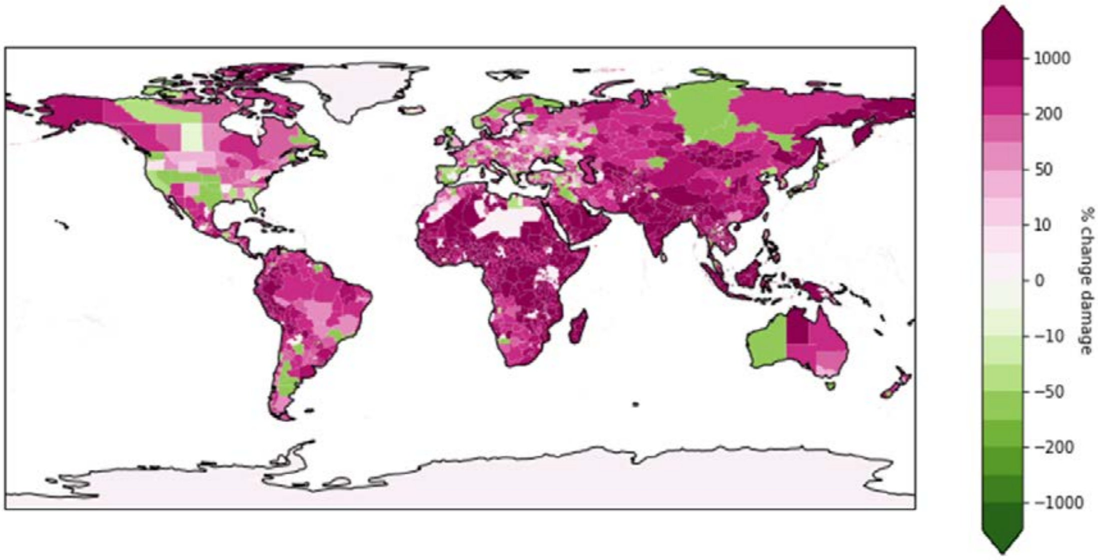

Figure 4: Change in expected annual damage (EAD) from river floods between 2010 and 2080 (based on data from Winsemius et al., 2016)

Similar numbers are found for coastal flooding. Colleagues in the UK and Germany, including Robert Nicholls, Jochen Hinkel, and Nassos Vafeidis have published several studies using the DIVA model. Here at the VU, together with Timothy Tiggeloven and former colleague Andres Diaz, I am currently investigating the potential increase in global coastal flood risk due to sea level rise, population growth, urban expansion, and land subsidence. In Figure 5, we see modelled coastal flood risk today and in 2050 for 20 regions of the world. In the left-hand part of each ball, the grey part, which you don't see very well because it is so small, is the current risk. The right-hand part is the future risk – so we see this explosion in future risk in almost all of the regions shown. An interesting aspect of this study is that we can start to attribute those changes in risk to different risk drivers, namely sea level rise, socioeconomic development, and land subsidence.

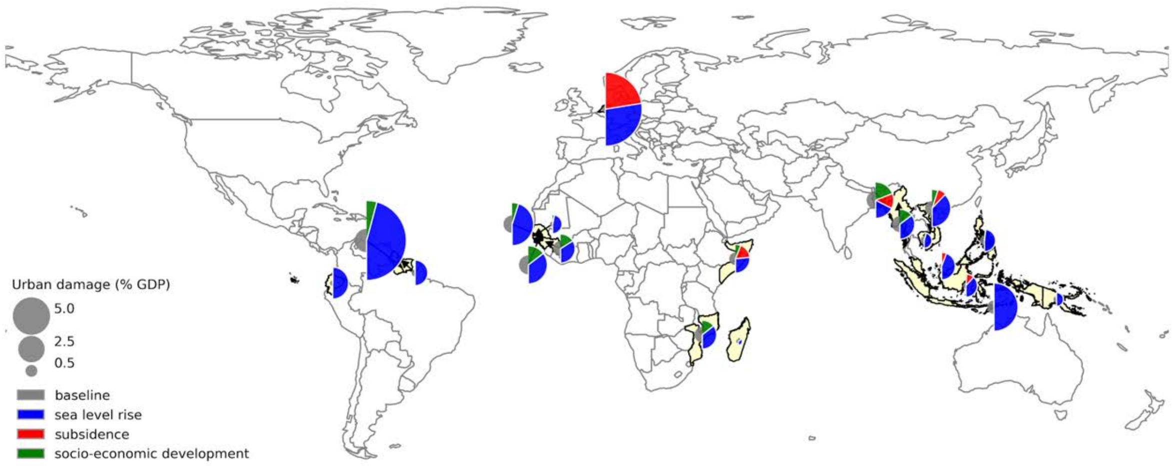

Figure 5: Change in expected annual damage from coastal floods (as a percentage of GDP) between 2010 and 2080 (based on data from Tiggeloven et al., 2019)

Increase in future global risks are also found when investigating droughts. Together with colleague Ted Veldkamp, we made projections of the number of people per year who will suffer from water scarcity between 1990 and 2080 (Veldkamp et al., 2016). Just as with flooding, Figure 6 shows increases through the 21st century compared to the 20th century.

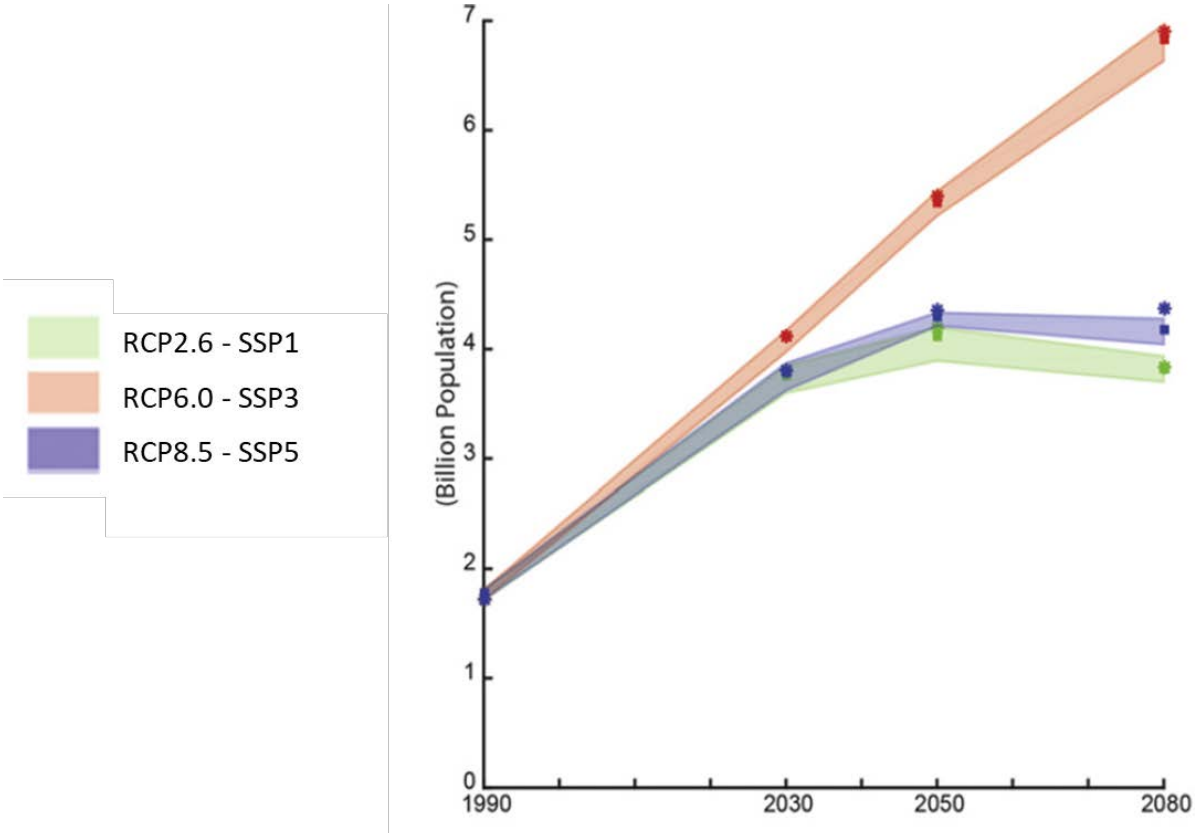

Figure 6: Expected annual population exposed to water scarcity (i.e. <1700 m^3 water per person per year) (Veldkamp et al., 2016)

These analyses paint a rather sombre picture of the future. But, none of the studies discussed so far actually looked at changes in vulnerability. They simply assume that vulnerability is constant and unchanging through time. This is understandable – my former PhD student Yus Budiyono showed how difficult it is to even correctly represent current vulnerability in risk models in his study in Jakarta (Budiyono et al., 2015). But whilst it is understandable, is it realistic? The answer is no. We know that humans and societies take actions to reduce vulnerability. This has been demonstrated in a study together with colleague Heidi Kreibich at the German Research Centre for Geosciences (Kreibich et al., 2017). In this study, we looked at case studies of river basins that have experienced 2 floods in succession. For these river basins, we found that the economic damage and number of fatalities were lower following the second flood than following the first flood. We then examined why this was the case. An interesting finding is that in all cases, major efforts were taken after the first flood to decrease the vulnerability, for example by increasing awareness and preparedness and improving the organisation of emergency management.

This study therefore showed that societies take actions to reduce vulnerability after a flood, but is this only limited to places that have seen a previous disaster? We studied this question in a paper by my former PhD student Brenden Jongman (Jongman et al., 2015). In this study, we looked at changes in vulnerability over the period 1990-2010. Here, vulnerability was expressed in a very simplified way: the ratio of people killed in floods to the number of people affected by floods. We refer to this as the vulnerability ratio. In Figure 7 (left), we show this vulnerability ratio for each country, averaged over the period 1980-2010. The figure shows that the vulnerability ratio decreases as GDP per capita increases. In other words, vulnerability decreases with increasing wealth. We then assessed the change in these vulnerability ratios over time, by classing each country into one of four income groups (ranging from low income to high income). In Figure 7 (right), we see that the vulnerability ratio decreases over time for all income groups.

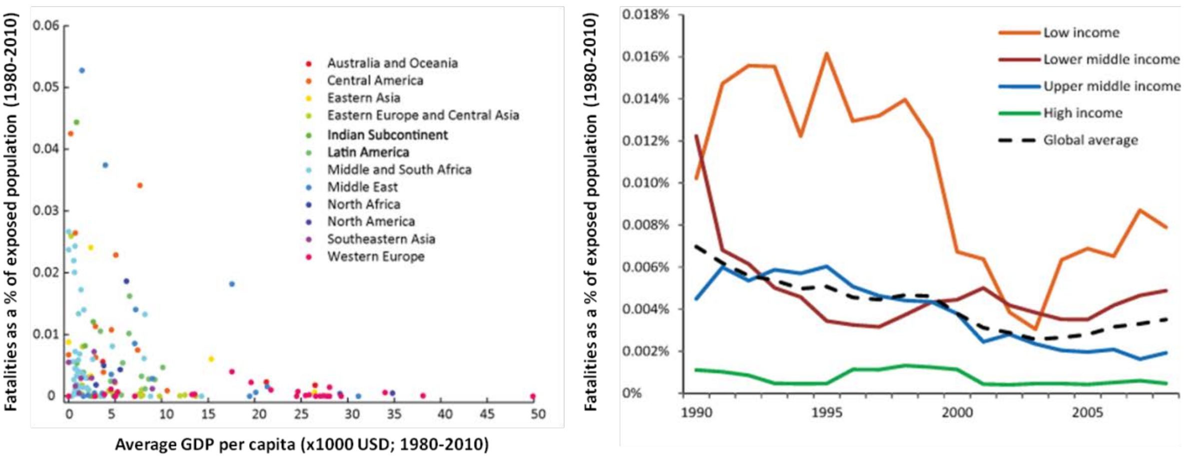

Figure 7: On the left, average GDP per capita per country (1980-2010) plotted against fatalities from floods expressed as a percentage of the population exposed to floods. On the right, the change in fatalities from floods expressed as a percentage of the population exposed to floods over the period 1990-2008. Adapted from Jongman et al. (2015)

We then used this knowledge to project the change in fatalities between 2010 and 2080. First, we simulated the fatalities assuming static vulnerability, i.e. we used the vulnerability ratios from 2010. Doing this, we find that fatalities will increase between about 10 and 220% by 2080, depending on the scenario used (Figure 8). We then used a dynamic vulnerability scenario, where we assumed that by 2080 all countries have the same vulnerability ratio currently found in high income regions, in other words, if people take action to reduce their vulnerability. The results are rather different: instead of an increase in risk, we now see a decrease in the number of fatalities compared to 2000, by between about 5 and 60%

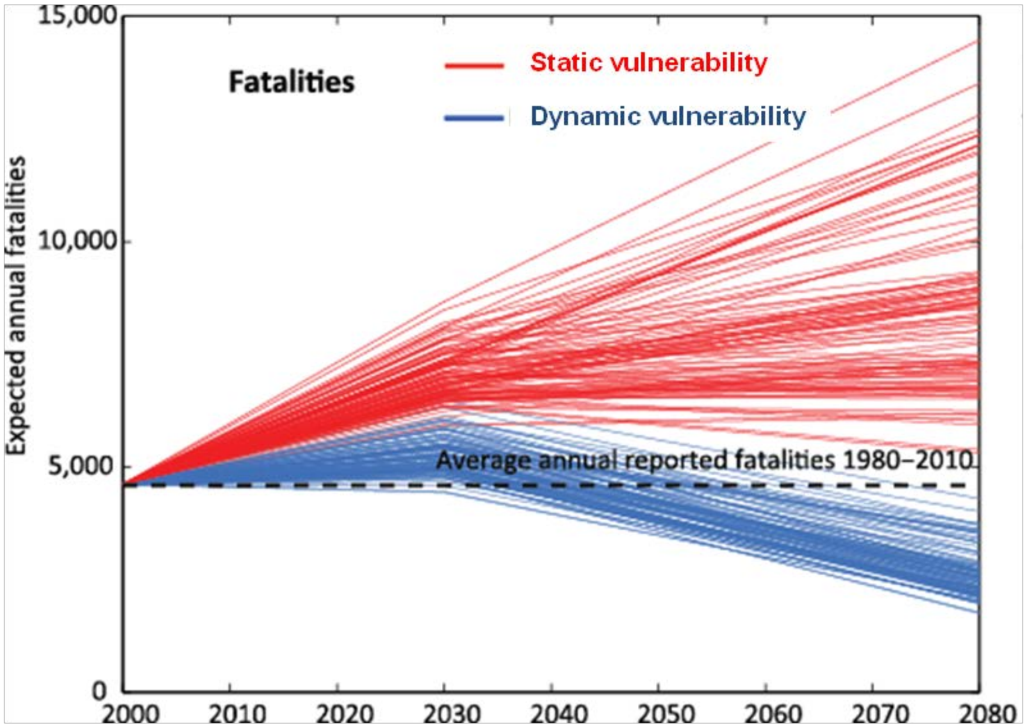

Figure 8: Projections of expected annual fatalities from river floods between 2010 and 2080 assuming static and dynamic vulnerability scenarios. Adapted from Jongman et al. (2015)

This illustrates an important point. It is people who determine risk, through their interaction with natural processes (Figure 9). Or, as the geographer Gilbert F. White put it "*Floods are an act of God; flood damages result from the acts of men*".

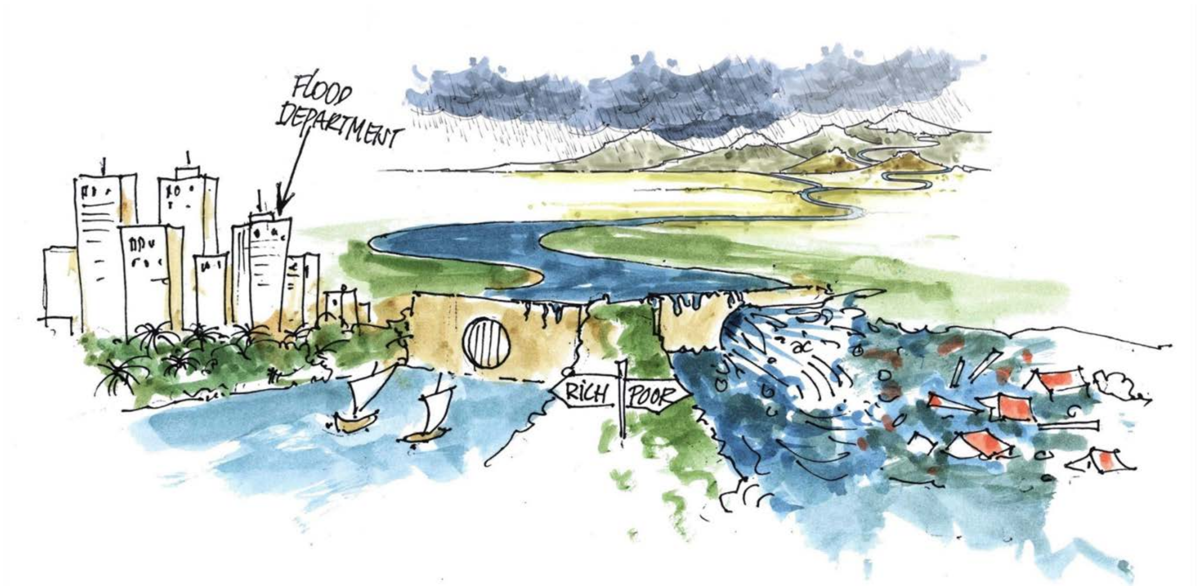

Figure 9: Illustration of how humans determine risk through their interaction with natural processes. Artwork: © Henk de Boer (www.henkdeboer.nl)

For global scale models to be able to properly inform on future risk, it is essential that they include these actions of people, and this will be a major focus of this new Chair. But how can we do this? An example can be taken from a study that I led with colleagues at IVM (Ward et al., 2017). In this study, we developed a new module for our global flood risk model, GLOFRIS, to be able to assess the benefits and costs of adapting to flood risk using dikes and levees. In this study, we explored how much we would need to increase dike heights around the world, in order to keep risk relative to GDP constant in 2080 compared to today. We then assessed what the costs would be of doing this, and carried out a cost-benefit analysis. In Figure 10, we can see the benefit:cost ratios according to one future scenario. In simple terms, the green regions show locations where the benefits exceed the costs, whilst the red regions show locations where costs outweigh the benefits.

The message to be taken from this figure is not that we should build dikes in all of the green regions, and that risk increase is inevitable in the red regions. There are other options that may be preferable, both from an economic viewpoint and well as from other viewpoints, in all of the regions shown. The message to be taken is that it is essential that we develop our models in such a way that they can be used to assess the effectiveness of potential risk reduction solutions, so that we can help decision-makers to the bend trend of increasing disaster risk.

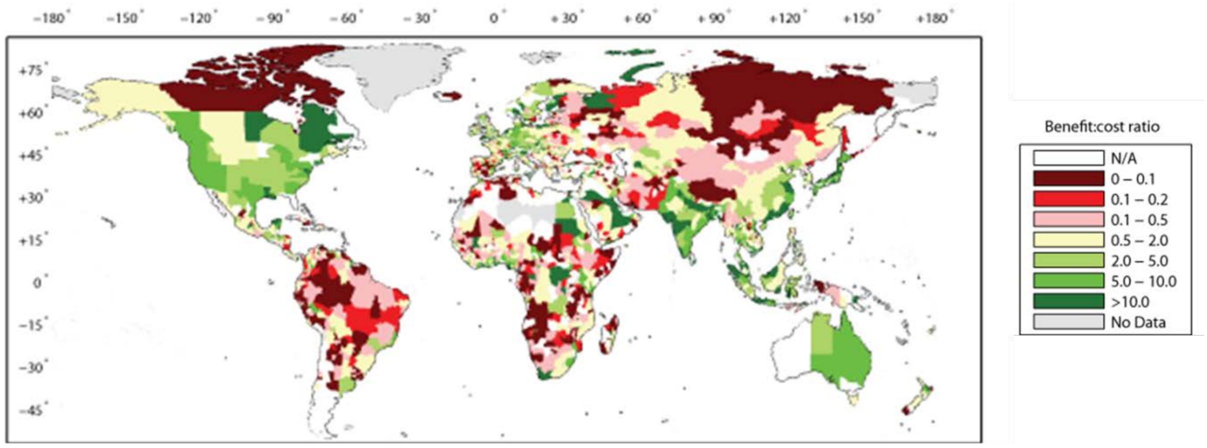

Figure 10: Benefit:Cost ratios (B:C ratios) per state of adaptation to river flood risk by 2100 by means of dikes and levees. Adapted from Ward et al. (2017)

Bending the trend will be a major focus of the new “Future Water Challenges 2” project, led by PBL Netherlands Environmental Assessment Agency over the next 3 years. In this project we will be working to assess the benefits and costs of a multitude of measures for reducing both river and coastal risk, including spatial planning and nature-based solutions. In another project, I am working with PhD student Juliana Castaño Isaza, who is assessing the use of green measures, like beach nourishment and mangroves, to protect the economies and societies of Caribbean nations.

Another key element that needs to be considered when assessing the impacts of risk reduction is the role of human perceptions and behaviour, which can lead to unexpected feedbacks. A classic example of this is the levee effect, first described by Gilbert F. White in 1945 (White, 1945) and recently studied extensively by sociohydrologists such as colleague Giuliano di Baldassare in Uppsala University, Sweden, or colleagues Toon Haer and Jeroen Aerts at the IVM. The theory suggests that building higher levees can lead to the perception that risk has been eliminated, leading to more development behind the dike, and therefore increased exposure. Other examples of human behaviour influencing the effectiveness of risk reduction measures abound. For example, offering drought insurance to farmers can lead to farmers not taking actions to protect crops, as they are compensated for losses anyway. This is an example of so-called moral hazard. An important question is how can we include these kinds of perception and behavioural aspects in global risk models? One way to do this is to use so-called agent-based models, which try to mimic human decision-making behaviour. My group is currently part of a European consortium - led by Silvia Torresan and Jaroslav Mysiak of CMCC in Venice - that recently submitted a major grant proposal to examine exactly these aspects at the European scale, using new methods like virtual and augmented reality to monitor how humans behave in the face of disasters.

Spatiotemporal variability in global water risk assessment

So far, I have discussed long term projections of risk, which are essential for developing long-term plans to reduce risk. But risk is also dynamic on shorter timescales. An example is the temporal fluctuations in risk caused by El Niño South Oscillation, or ENSO. ENSO is a natural climate cycle of fluctuating ocean temperatures and sea surface air pressure over the tropical Pacific Ocean. The two extreme phases of ENSO are the well-known El Niño and La Niña. El Niño and La Niña can cause changes in weather patterns, including rainfall and temperature, in regions all around the world (Dettinger and Diaz 2000). In my VENI project, generously funded by the Netherlands Organisation for Scientific Research (NWO), I hypothesised that relationships also exists between ENSO and the risk of flood and drought risk. In Figure 11, from a paper with Ted Veldkamp, we show that water scarcity is indeed strongly correlated with ENSO, with statistically significant relationships (shown in red or blue) for river basins inhabited by about 31% of the global population (Veldkamp et al., 2015). I found similar results for flood risk; flood risk is significantly higher or lower than normal during El Niño years in river basins covering 29% of the Earth's land surface. For La Niña, the figure is 23% (Ward et al., 2014).

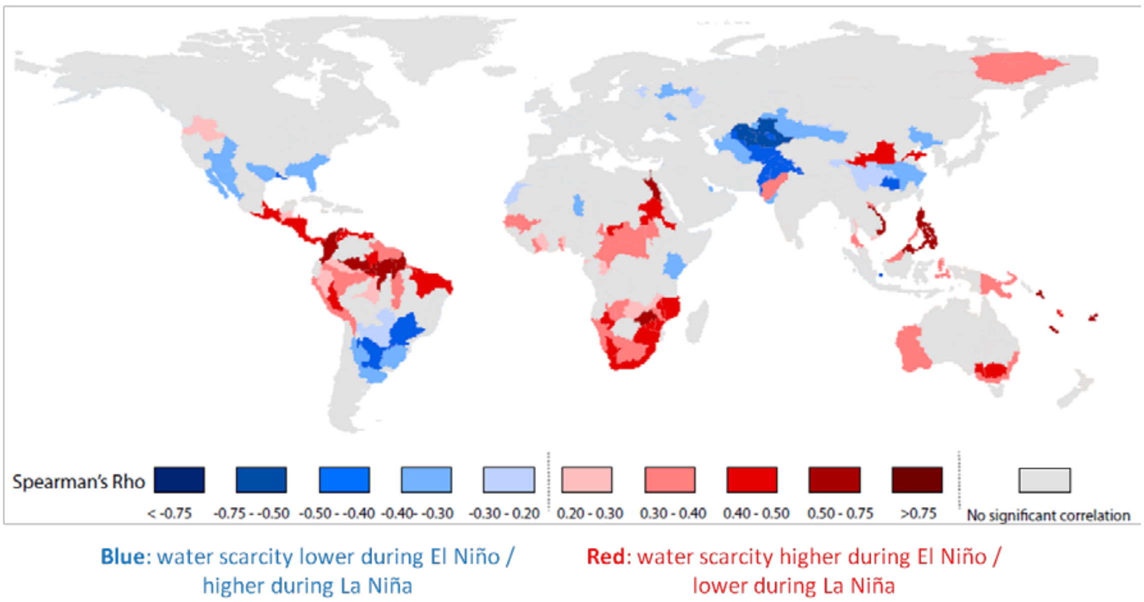

Figure 11: Correlation between water scarcity and ENSO at the global scale. Adapted from Veldkamp et al (2015)

An important question that arises is how can this information be used to reduce risk? Some examples can be found in the literature. For example, in 2008 the International Federation of Red Cross and Red

Crescent Societies' regional office in West Africa was able to pre-position disaster management supplies prior to flooding, based on seasonal ENSO forecasts. This means that they were able to start preparing supplies up to 40 days in advance of the floods (Braman et al., 2013). But such examples are not yet commonplace. More research is needed to be able to look at the effectiveness of taking risk reduction actions based on such forecasts. This kind of research is being carried out within my group, for example by Gabriela Nobre as part of her PhD thesis. She used so-called machine learning methods to assess the cost effectiveness of compensating famers in Kenya for lost maize yields prior to a disaster, using forecasts of crop yields based on forecasts of El Niño (Guimarães Nobre et al., 2019). She showed that in some regions, it is more cost effective to compensate farmers for potential lost maize yield several months in advance of the harvesting season based on ENSO forecasts, rather than compensating farmers for actual lost yields after a drought season. Whilst this is a theoretical study, we are now testing the potential of implementing such a scheme in several pilot regions in Africa, in a project funded by the World Bank Global Facility for Disaster Reduction and Recovery.

Another important aspect is spatial variability. Due to computational expenses and the low resolution of many global datasets, the spatial resolution of most global risk models is still fairly low. This can pose challenges in correctly representing both physical and human processes. Let's take an example from the modelling of global coastal flood risk. In the EU RISES-AM project, my group and I worked together with Deltares to develop the Global Tide and Surge Reanalysis database (GTSR (Muis et al., 2016). The work was carried out by colleague Sanne Muis, as part of her PhD. Using the model, we simulated extreme sea levels along the entire global coastline as a result of tide and storm surge. The model performs very well in extratropical regions, but tends to underestimate extreme sea levels in areas affected by tropical cyclones. One of the reasons for this lies in the resolution of the model's input. The model uses wind fields and atmospheric pressure from the ERA-interim climate reanalysis dataset. This dataset has a resolution of about 80km, but tropical cyclones have strong gradients in pressure and wind fields that are not captured at this low resolution. To address this problem, Job Dullaart in his PhD is using the higher resolution ERA-5 data to run the model. These data have a much higher resolution of about 30km. Figure 12 shows the maximum surge height during Hurricane Irma using the model forced with both ERA-5 (on the left) and ERA-Interim (in the middle), with the difference between the two simulations shown on the right. Using the higher resolution ERA-5 data, the model simulates surge from tropical cyclones much better (Dullaart et al., 2019).

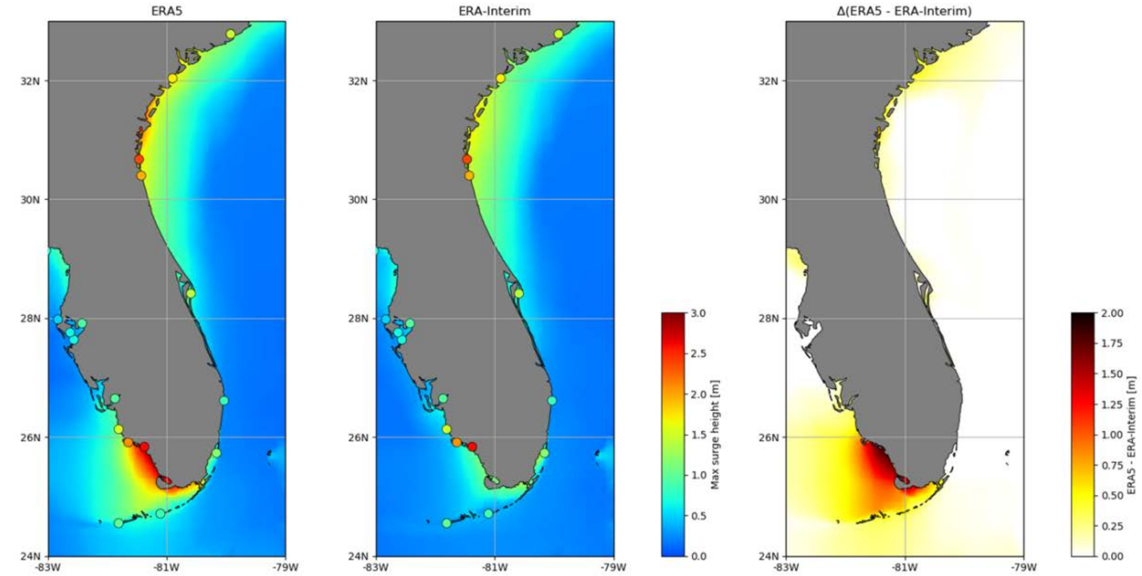

Figure 12: Maximum storm surge height of Hurricane Irma simulated in GTSR using ERA-5 (left) and ERA-Interim (middle) forcing data. The difference between ERA-5 minus ERA-Interim is shown on the right (Dullaart et al., 2019)

Moreover, tropical cyclones are very localised and occur infrequently at a given location. Therefore, if we only look at the tropical cyclones that have actually occurred over the last 40 years or so (i.e. the period of time for which observations are required), we will not capture all of the tropical cyclones that could potentially occur. To address this, models are needed to develop thousands of years of tropical cyclone tracks. In her PhD, Nadia Bloemendaal has developed such a model, which is capable of simulating tens of thousands of synthetic storm tracks, as shown in Figure 13, thereby better representing both the spatial and temporal dynamics of tropical cyclone risk (Bloemendaal et al., 2019). These kinds of model calculations are computationally expensive, and therefore in the coming 3 years Sanne Muis and I will work together with computer engineers from the Netherlands eScience centre in the MOSAIC project, to improve the computational efficiency of large scale coastal flood risk simulations.

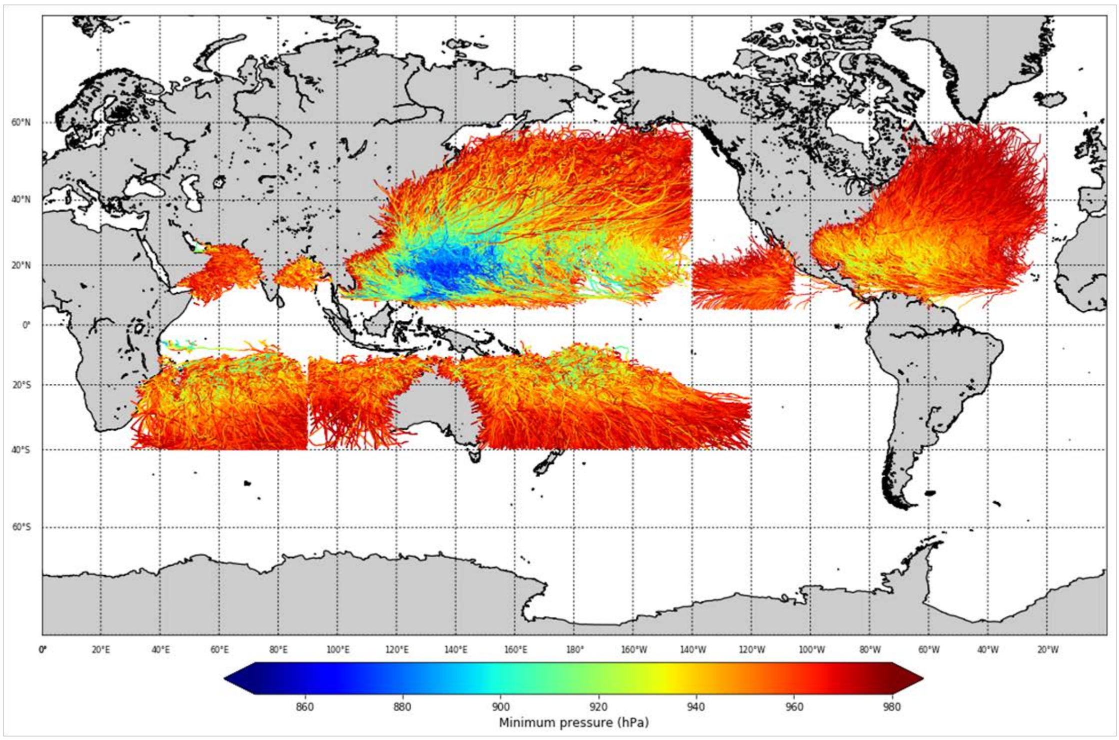

Figure 13: Synthetic storm tracks simulated using the STORM model (Bloemendaal et al., 2019)

But if we are really going to improve global scale assessments of flood risk, we also need to improve the representation of exposure and vulnerability. In Figure 14, we see a city that is being flooded. We see that all the houses in this city are exactly the same – that is to say, the exposure and vulnerability of those buildings is the same across the entire area.

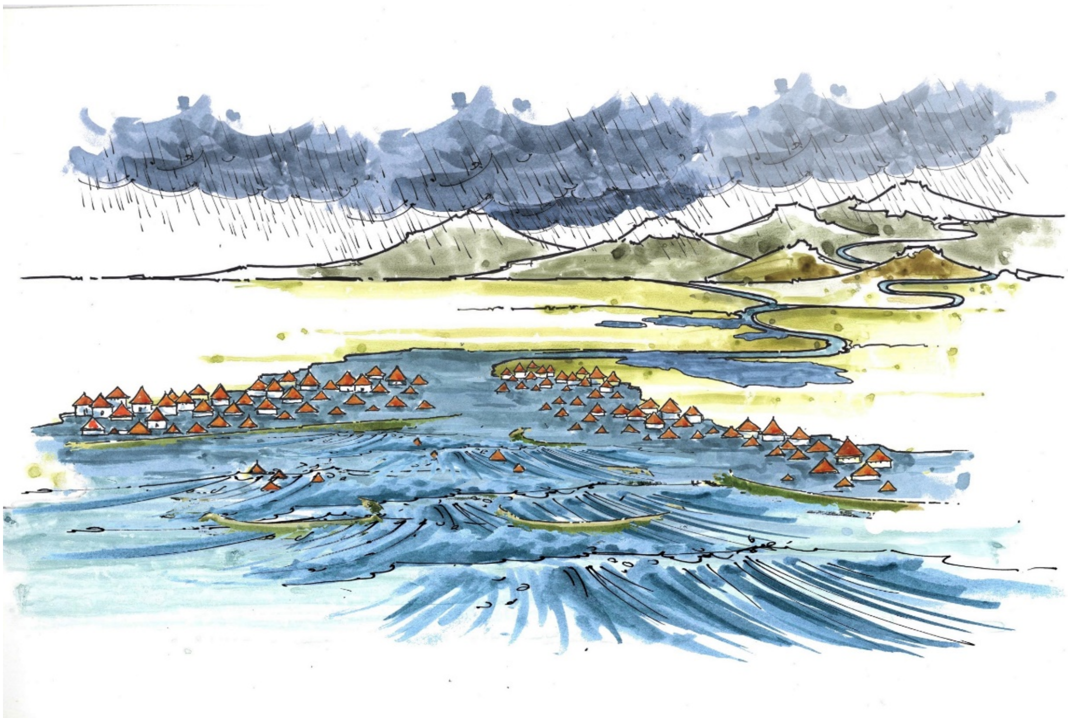

Figure 14: Illustration of a delta city with uniform exposure and vulnerability being flooded. Artwork: © Henk de Boer (www.henkdeboer.nl)

But we know that in reality, land use shows a rich tapestry, even within a single city. For example, Figure 15 we see an area with high-rise buildings, and we see buildings in the floodplain that have been built on stilts, elevated above the floodwater. The exposure and vulnerability of these buildings is very different to that of the buildings on the right.

Figure 15: Illustration of a delta city with spatially homogeneous exposure and vulnerability being flooded. Artwork: © Henk de Boer (www.henkdeboer.nl)

In global flood risk models, we represent exposure using broad land use maps, often with a resolution of about 1km, where each land use category is assigned a maximum damage and a depth-damage function. Let's take a look at what this looks like for the area where we are now. In Figure 16, on the left we see a land use map of the area around Amsterdam taken from a global land use model. We see that Amsterdam is classed as 'urban', shown by the red colour. Whilst this is of course correct, it ignores the richness in different types of land uses and buildings within the area. Datasets are now available that allow us to get information on individual buildings. For example, data for the area around the Zuidas, where we are now, are shown on the right, in a map from OpenStreetMaps. Together with colleague Elco Koks, we are working to improve global risk models by integrating them with this kind of data on individual buildings.

Figure 16: Land use in Amsterdam as represented in a global land use model (left), and individual buildings in the Zuidas from OpenStreetMaps (right). Figure courtesy of Timothy Tiggeloven and Elco Koks.

Another approach is being taken by my PhD student Johanna Englhardt, following the concept of the fairy tale of the three little pigs. The wolf threatens to blow down the first pig's house. This is made of straw, and with no effort, he blows it down. The second little pig's house is made of wood. It takes a bit more effort, but still the wolf manages to blow it down. The third little pig's house is made of bricks. Try as he might, the wolf cannot blow the house down. This is a perfect example of vulnerability. We can use this concept in our global flood risk modelling. Flood vulnerability is also highly dependent on building materials, and so Johanna is using information on building materials and building types to develop exposure maps showing different building-material types (e.g. mud, wood, brick) throughout Africa (Figure 17) (Englhardt et al., 2019). In the coming years, I also plan to explore other new avenues to improve the global mapping of exposure and vulnerability, for example working with NASA and the German Aerospace Center to use data from satellites and Google Streetview to automatically detect building characteristics type, use, and height. This is part of a Marie Curie European Training Network grant proposal that I am current leading to examine the use of novel data to improve disaster risk management.

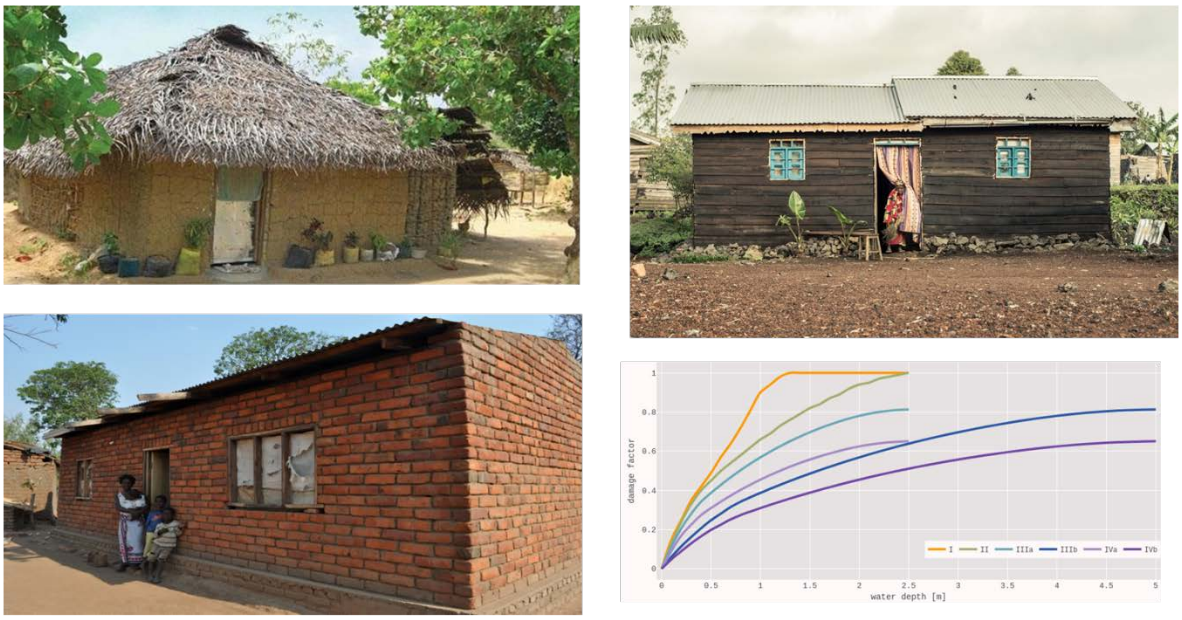

Figure 17: Exposure and vulnerability mapping and assessment based on building material types, as applied in Englhardt et al. (2019)

Compound and consecutive hazards

So far, I have talked about risk from single hazards, and this is very much the state of the art in global risk modelling. Here is a simple schematic of a delta city (Figure 18). It can potentially face floods either from the coast, or due to rainfall on land causing localised floods or causing rivers to burst their banks. Scientists have developed models to investigate these processes separately.

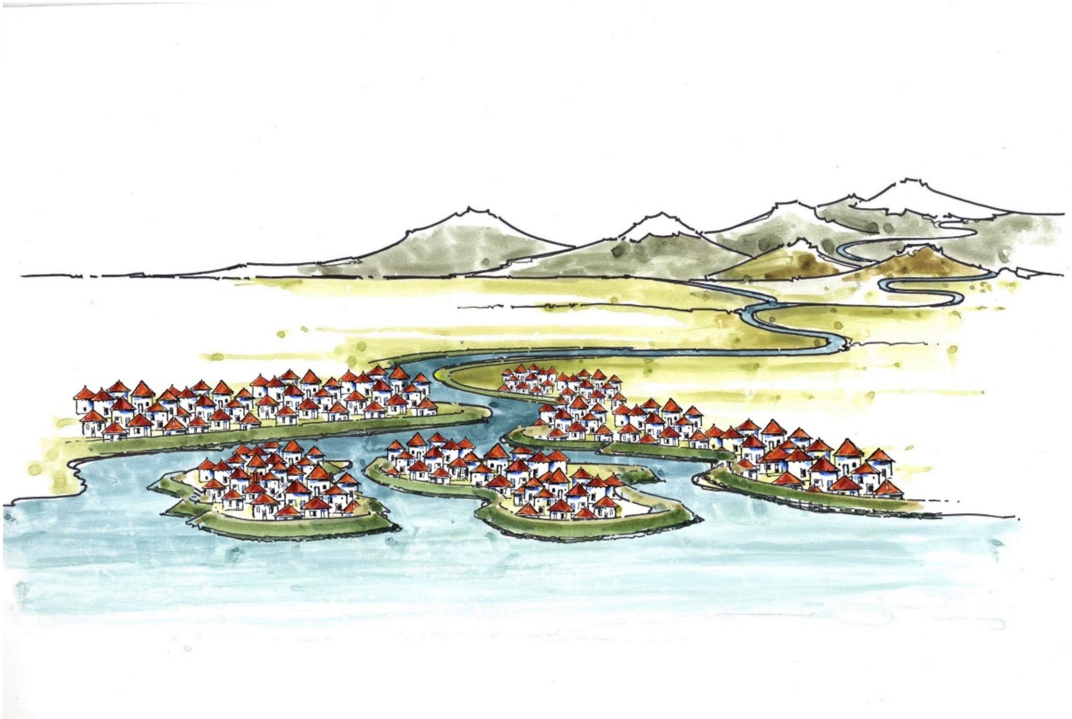

Figure 18: Illustration of a delta city. Artwork: © Henk de Boer (www.henkdeboer.nl)

But, we know that many of the large flood disasters occur when different kinds of hazards occur together, for example when coastal and river flooding occur at the same time as shown in Figure 19. These are examples of so-called compound events (Zscheischler et al., 2018).

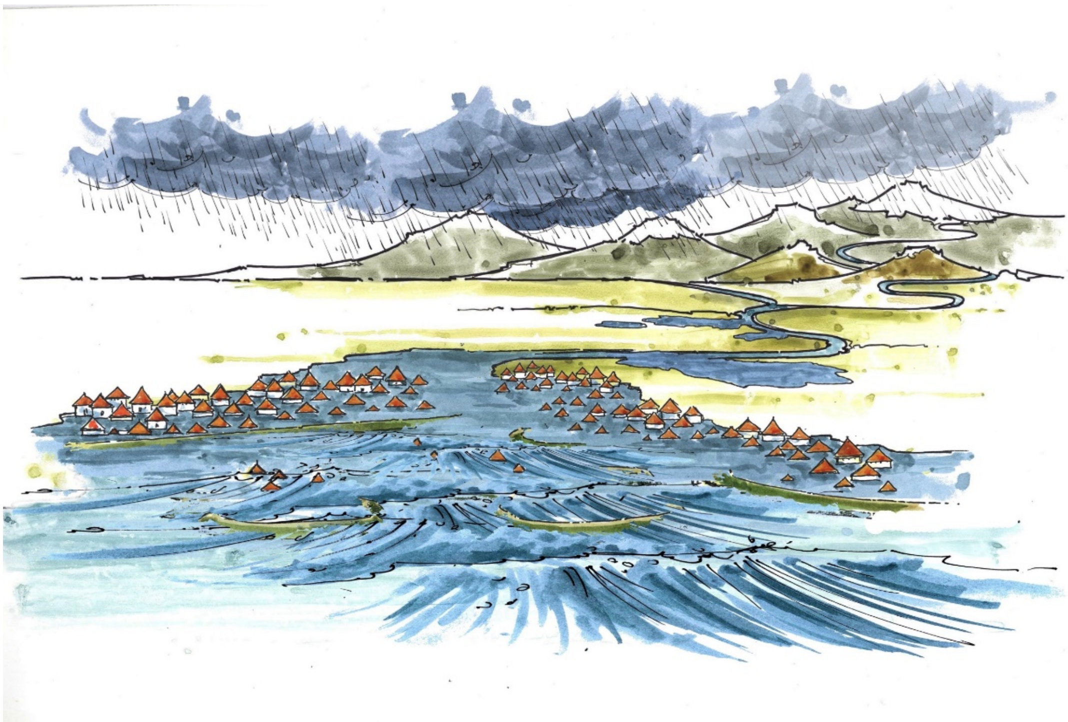

Figure 19: Illustration of a delta city being affected by a compound river and coastal flood. Artwork: © Henk de Boer (www.henkdeboer.nl)

In global models, this interaction has so far been completely ignored. For the sake of convenience, it has been assumed that river floods and coastal floods are not related to each other. This is convenient for a few reasons. Firstly, it means that we can assume no statistical dependence between them – we can therefore use univariate statistical methods instead of having to use more complicated multivariate approaches. Secondly, it means that we can use either a river or coastal flood model, without having to address the complex issue of coupling the two. But whilst this is convenient, the important question is whether it makes sense in reality? In Figure 20, we see satellite images of several major storms. These are the kind of storms that can lead to coastal flooding. But we also see that they are associated with huge areas of potential rainfall, which can lead to river flooding. So it would seem fair to hypothesise that there may be a relationship between the two.

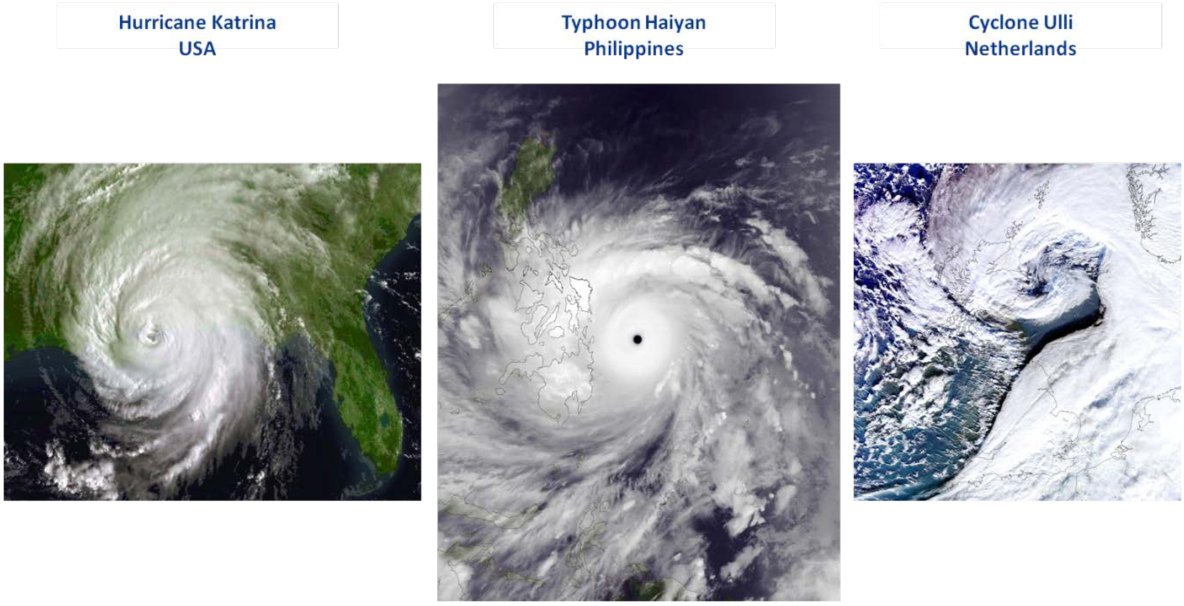

Figure 20: Satellite images of three storm systems

In my VIDI project, I am investigating these questions with PhD students Anaïs Couasnon and Dirk Eilander. We have shown that there is in fact a statistically significant relationship between coastal flooding and river flooding along about a quarter of the global coastline (Ward et al., 2018; Couasnon et al., 2019; Eilander et al., 2019).

But what about the impacts of compound floods? Together with Dai Yamazaki and Hiroaki Ikeuchi of the University of Tokyo, we examined this question for the case of Cyclone Sidr (Ikeuchi et al., 2017), which hit Bangladesh in 2007, and led to over 3,000 fatalities and billions of Euros of economic damage (Paul and Dutt, 2010). In this paper, we used a global hydrodynamic model to simulate river flooding during Cyclone Sidr, with and without interactions with the coast. In Figure 21, on the left we can see the area that would be flooded if we ignore interactions with the coast. However, we know that in reality, sea levels were elevated during Cyclone Sidr due to storm surge. So, on the right, we show the area that would be flooded if we include these interactions. The area flooded is much larger, and this does not even include flooding coming directly from the coast. Clearly, then, if we want to understand global flood risk in deltas and estuaries, we need to improve our ability to look at river and coastal processes together. One way to do this is by “nesting” local hydrodynamic models within global models, which provides a more flexible approach than modelling the entire world at once. It also allows the flexibility to use the best exposure and vulnerability data available in the area being studied, instead of being reliant on coarse global dataset. This is an avenue that I am exploring with Dirk Eilander and colleagues at Deltares, and also within the European COST Action project DAMOCLES, where we are trying to improve our understanding of compound climate events.

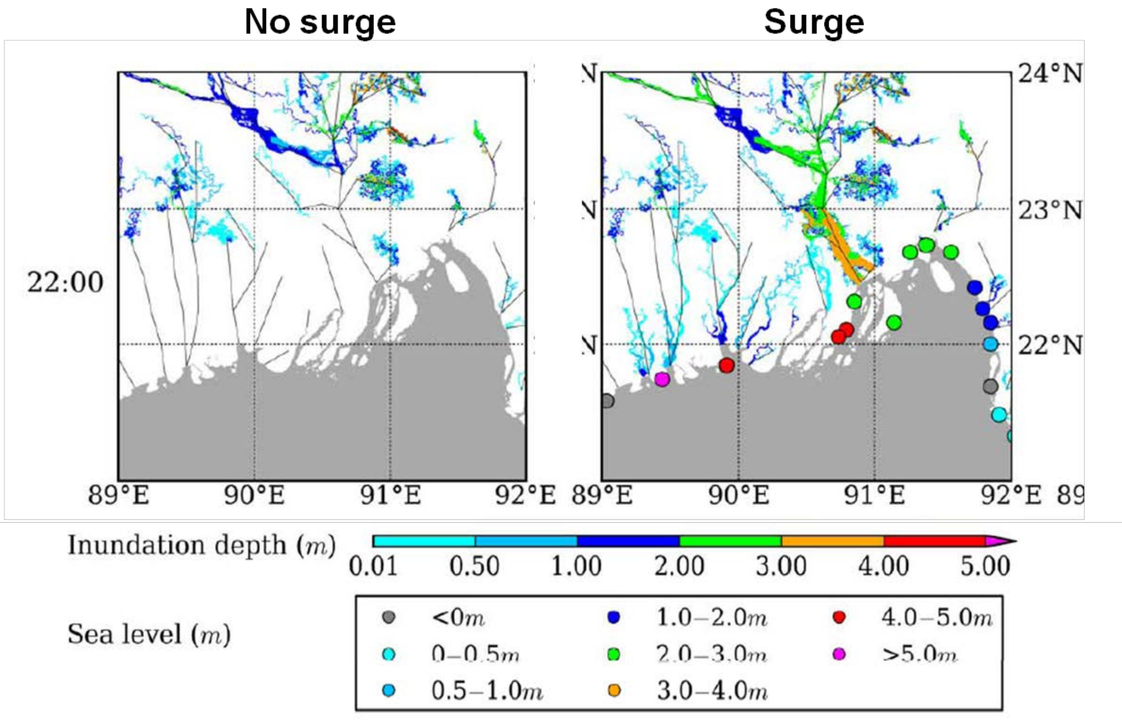

Figure 21: River inundation during Cyclone Sidr simulated using the Cama-Flood model. On the left, inundation when storm surge at the coast is ignored, and on the right inundation when storm surge is taken into account. Adapted from Ikeuchi et al. (2017)

The need to examine risk across different types of hazards does not stop at flooding. In order to better prepare and respond to natural disasters, first responders and disaster planning agencies need to have an improved understanding of the risk faced by different sectors from a whole range of hazards. In this conceptual figure (Figure 22) by PhD student Marleen de Ruiter, we examine the potential influence of consecutive hazards occurring in the same region (De Ruiter et al., 2019). On the vertical axis, we see 'quality of the built environment'. On the horizontal axis, we see various natural hazard events that could take place in time. For example at point t_1, an earthquake occurs, leading to a decrease in the quality of the built environment. After that, a period of recovery and rebuilding begins, in which the quality of the built environment increases. However, at point t_2, a tropical cyclone hits the same region, leading to a further drop in the quality of the built environment. The earthquake and tropical cyclone are independent hazards, i.e. there is no statistical relationship between them. However, the occurrence of the two hazards in sequence may affect the overall risk. On the one hand, one could hypothesise that the economic damage from the tropical cyclone may be lower than if the earthquake had not occurred previously: many houses have already been destroyed and so they cannot be destroyed again. On the other hand, one could hypothesise that the preceding earthquake leads to an increase in vulnerability of people living in the affected area. Many people have already lost their homes and livelihoods, and are therefore more vulnerable to the tropical cyclone. Resources for emergency response and relief may already have been used in the earthquake, again raising vulnerability. To understand this systemic risk, we therefore need to take a multi-hazard approach. This is the focus of the MYRIAD-EU proposal, a consortium of partners from across Europe that I am currently leading, in which we hope to secure EU funding to improve multi-hazard risk assessment in Europe. This emphasises the importance of strong collaboration across the European Union for addressing the key challenges of our time.

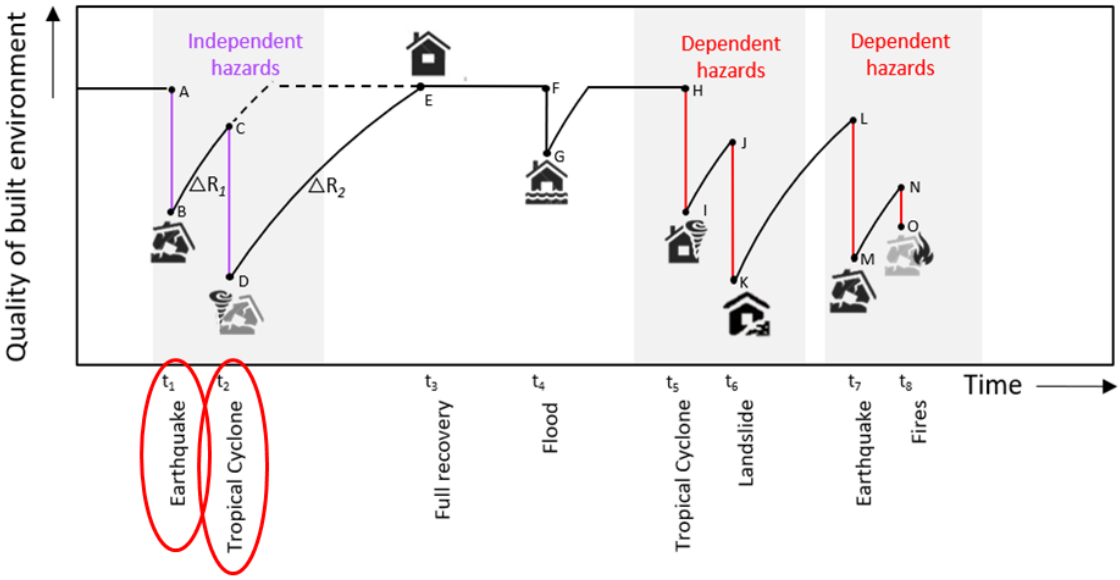

Figure 22: Conceptual illustration of the potential influence of consecutive hazards occurring in the same region. Adapted from De Ruiter et al. (2019)

Science working in unison with practice to develop solutions to the disaster risk challenges faced by society

I have discussed several scientific challenges that I plan to address in the coming years. If we want to provide solutions to the large societal issues caused by natural hazards, there is a clear need for science to work in an ever-closer unison with practice. This means that our scientific research should be codesigned and carried out together with stakeholders involved in the field of disaster risk reduction. It also means that our education programme should be designed in a way that our students are able to effectively address these challenges, whether they enter the field of academia, consultancy, policy-and decision making, or business.

In terms of research co-design and collaboration between science and decision-making, a successful example is the Aqueduct Global Flood Analyzer (Figure 23). This is a web-tool develop by my team, Deltares, PBL, Utrecht University, and the World Resources Institute, which allows anybody to go online and very simply carry out a flood risk analysis for any location. In Figure 23, we even see His Royal Highness King Willem-Alexander of the Netherlands engaging with the Analyzer.

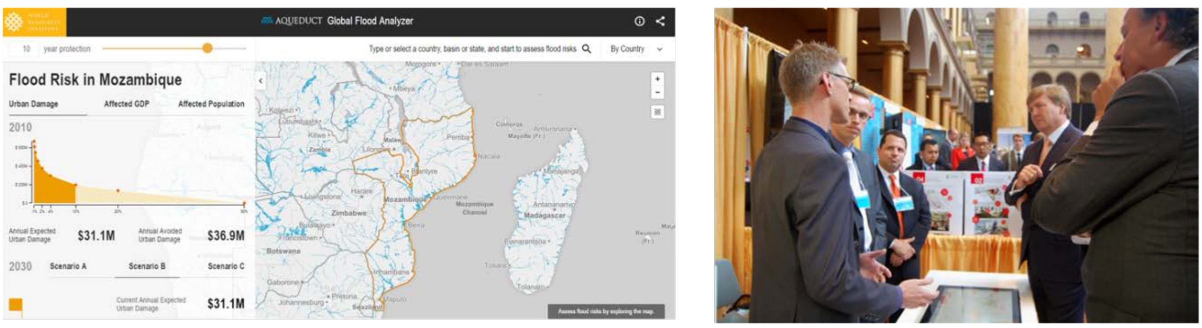

Figure 23: Screenshot of the Aqueduct Global Flood Analyzer (www.wri.org/floods) and presentation of the Analyzer to His Royal Highness King Willem-Alexander of the Netherlands

Promoting this kind of exchange between science, decision-makers, NGOs, businesses, and others involved in disaster risk reduction is at the heart of the UN Office for Disaster Risk Reduction (UNDRR) Global Risk Assessment Framework (GRAF). GRAF is an international framework for developing and sharing risk information and promoting a pro-active culture of risk-informed decision making. I have the pleasure to be a member of the inaugural Expert Group charged with designing this framework, and in doing so will ensure that the work of my team at the VU will be aligned with international efforts towards achieving the goals of the Sendai Framework and Sustainable Development Goals.

The Vrije Universiteit Amsterdam can, and is, playing an important role in this process. Through its Science for Sustainability theme, and the establishment of the Amsterdam Sustainability Institute (ASI), sustainability and the Sustainable Development Goals are at the heart of our research and education. Through my new chair in Global Water Risk Dynamics, I will contribute to this process by ensuring intrinsic linkages between research and education on disaster risk and other activities on sustainability at the VU. This is essential, since a recent report by UNDRR clearly states that '*Nothing undermines development like disasters*' (UNDRR, 2019).

Summary and research agenda

Dear rector, colleagues, friends, and family,

At the start of this inaugural speech, I described the devastating impacts of several recent disasters caused by floods and droughts. I also described how disaster risk will continue to increase in the future, if society does not act to develop solutions.

However, I also showed evidence that we can bend that trend. There is hope. And as Pliny the Elder stated, '*Hope is the pillar that holds up the world*'. I believe that science must take a leading role in improving our understanding of disaster risk and solutions, so that this hope can be turned into reality. Therefore, with this new Chair in Global Water Risk Dynamics, my mission is to increase society's ability to assess and reduce global flood and drought risk, by developing new scientific approaches and tools, and a generation of researchers and professionals, for co-designing sustainable flood and drought risk solutions.

To achieve this, I have set out a research agenda that I will address together with my research team, colleagues at the Vrije Universiteit Amsterdam, and colleagues both nationally and internationally. The most important of these are:

- Developing scientific methods to allow us to better project changes in future flood risk, and the role of adaption and human behaviour;
- Increasing our understanding of the spatial and temporal dynamics of risk, and in the spatiotemporal dynamics of hazard, exposure, and vulnerability;
- Working on a shift in thinking about natural hazards from a single-hazard perspective, to assessing systemic risks across multiple hazards; and
- The imperative of an approach to co-designing research and solutions between science and practice.

Achieving the overall mission explicitly requires a new generation of researchers and professionals capable of developing the understanding, methods, and approaches described. This can only be achieved by ensuring that our educational activities are fully embedded in the above described research agenda. I look forward to working together with our enormously talented students and teaching teams in the coming years to ensure that this occurs.

Acknowledgements

At the end of this inaugural speech, I would like to extend my thanks to a number of people who have had an important role in my scientific adventure.

Firstly, I thank the Executive Board of the Vrije Universiteit Amsterdam and the Faculty Board of the Faculty of Science for the confidence placed in me by appointing me Chair of Global Water Risk Dynamics.

One of the biggest influences on my academic career has undoubtedly been Jeroen Aerts. Many thanks for the trust you have shown in me, allowing me the freedom and continued support to allow me to develop my own research field and group within the Institute for Environment Studies (IVM). I also thank the Management Team of the IVM for their support, as well as all of my IVM colleagues, past and present, who have made working at the IVM so rewarding, stimulating, and enjoyable. Special mention goes to the PhD students and postdocs who have I have had the privilege to mentor over the last 14 years: Brenden, Jennifer, Ted, Yus, Sanne, Anouk, Johanna, Marleen, Gabriela, Anaïs, Dirk, Nadia, Timothy, Juliana, Job, Sadhana, Paolo, and Andres. Also, special thanks to Ralph, Hans, Hans, Dim, Bart, Toon, Elco, Mark, Marjolijn, Laurens, and Corry, who have played such an important role in the life of the Water and Climate Risk Department over the years.

I'd like to thank several people who have been important in forming my academic interests. First, my Geography teacher from secondary school, Paul Garvey, who accelerated my interest in geographical and environmental issues, and was the first person to alert me to the problem of climate change, some 28 years ago. And later, my PhD mentor Jef Vandenberghe, and co-supervisors Hans Renssen, Jeroen Aerts, and Ronald van Balen, for their guidance during my period as PhD student. I hope to be able to impart so much knowledge on my own students, here at the VU. I thank all the students who I have had the privilege to teach, for their drive and enthusiasm, which is a constant source of inspiration to my own work.

In a large organisation such as the VU, it is impossible for us researchers to carry out our work without the support of many people behind the scenes. I would therefore like to give special thanks to the support staff of the IVM, Faculty of Science, and of the University, in making our work possible.

I have been lucky enough to receive project funding from many organisations, and would like to thank them all for their generous support: NWO, KNAW, European Commission, Dutch government, United Nations, World Bank, World Resources Institutes, OECD, Cordaid, Bermuda Institute of Ocean Sciences, PBL, Deltares, Aalto University, and insurance companies SCOR and AXA.

Science is an international activity, and collaboration with international partners is essential. I have had the honour of authoring papers with over 500 authors from all around the world, and would like to extend my thanks to each and every one of those, and collaborators in various projects, conferences, meetings, and so forth, for their important contribution to my research. In particular, I extend a special thanks to Upmanu Lall for my unforgettable visit to Columbia University. Closer to home, much of my research over the last 10 years has been with the GLOFRIS consortium of IVM,

Deltares, PBL, Utrecht University, and our partners World Resources Institute in the USA. Huge thanks to all who have been involved in this wonderful adventure, and I look forward to more collaboration in the years to come. In particular, it has been my honour to work with my colleague and friend Hessel Winsemius, together pioneering the field of global water risk studies.

Through our regular hikes in the Yorkshire Dales and elsewhere, my parents instilled in me a great interest in the natural world. They, together with my grandparents and brother Robin also provided me with love and support throughout my childhood, school days, university, and thereafter, which has enabled me to take this adventure. I am forever thankful. Also, many thanks to my in-laws, for their support over the last 15 years, and to my father-in-law Henk for the wonderful illustrations that you have seen in this inaugural speech. I would also like to thank my friends for their support, and for providing an escape from the world of science.

A final, but massive, word of thanks goes to Dieuwke, my wife, for her love, support, and friendship. I look forward to many more adventures together!

Ik heb gezegd.

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