Modeling, Measuring and Pricing Flood Risk

Survey and Actuarial Perspective

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Executive Summary

This report has been prepared in response to a call from the Society of Actuaries Committee on Climate and Environmental Sustainability Research. A year or so ago the first two authors embarked on an initiative to establish the Risk and Insurance Studies Centre (RISC), a multinational and multidisciplinary research unit that would pursue a holistic approach to researching the general notion of insurance risk as well as the topics related to it. It was then that these authors became interested in the challenges presented by flood risk modeling, measurement and pricing. The breadth of the problem was one reason for the interest; indeed, flood risk has already drawn considerable attention from engineers, hydrologists, physicists, mathematicians, economists and actuaries, among others, and RISC boasts the needed expertise. Yet another reason for the interest arose from the first two authors' research expertise, which lies in dependence modeling and financial risk measurement, insurance and economic pricing; in this regard, these authors felt that recent advances in dependence modeling, for example, have not been realized in the area of flood risk modeling. The other three authors were invited to participate in preparing this report as a part of their undergraduate and graduate training in Actuarial Science at Purdue University, the U.S. and York University, Canada. The outcome is an initial, expository step on the path to learning the notion of flood risk, in general, and flood risk insurance, in particular. The conclusions are summarized here:

1. An efficient flood risk insurance framework starts with a thorough understanding of the notion of flood risk. As the subject is utterly diverse and multidisciplinary, this much-desired understanding requires considerable effort and the involvement of a variety of distinct parties. Communication and mutual respect are of primary importance.
2. Flood risk insurance exists within a more encompassing framework of flood risk management, and it is often treated as such. More specifically, flood risk insurance belongs in the *risk reduction* pillar of a successful flood risk management framework, where it typifies the response preparedness and recovery preparedness tools. Remarkably, however, flood risk insurance can (and does) impact all other pieces of the flood risk management puzzle. Specifically, it affects the response, recovery and even the risk assessment pillars of flood risk management. This last observation is not particularly obvious to the general public.
3. Even more remarkably, flood risk insurance may shape the societal attitude to the notion of flood risk. Namely, inadequately priced—that is, too cheap—flood insurance policies may arguably result in people underweighting the likelihood of the occurrence of floods. Also, when *priced to risk*, the mechanisms of insurance may raise the population's awareness of the importance of the notion of flood risk and/or raise the funds necessary for establishing vital mitigation venues.
4. The involvement of actuaries (theoreticians and practitioners alike) is very much desirable at all levels of the flood risk management process, and such participation is crucial in the context of developing efficient flood risk assessment models that are appropriate for valuing related financial losses. Much of the existing actuarial know-how can be translated with a little effort to serve the purpose.

Section 1: Introduction

Floods are, by far, the most frequent and destructive natural disaster in North America. In the U.S., they account for nearly two-thirds of all presidential disaster declarations over the period from 1953 to 2010 (Michel-Kerjan, 2010). Floods are particularly devastating because of their pervasive impact, widespread loss of lives and assets, and the level of the associated disruption to communities and businesses. Eight out of 10 catastrophes in the U.S. have been flood-related (Altmaier et al., 2017), and in the past five years all 50 states have experienced flooding with varying degrees of severity. The situation is very similar in Canada, where floods are recognized to be the most frequently occurring natural hazard. More specifically, the Canadian disaster database has recorded 241 flood disasters between the years 1900 and 2006, which is five times the number of wildfires, the next most common disaster in the country (Sandink et al., 2010).

Flood risk is not endemic to the U.S. and Canada only, however. It poses a similarly significant threat to other nations, with many studies recognizing the related losses have been on an increasing trend. For instance, a recent report determined that global flood risk contributes $104 billion to the global average annual loss. That is twice the public health expenditure in the Middle East and North Africa and 30% of the annual public education expenditure in Latin America and the Caribbean (Desai et al., 2015). The 2010 Indus floods in Pakistan, the 2011 Australian and Thai floods, and the 2013 widespread central European floods that devastated Germany, Czech Republic, Austria and other European nations registered significant economic losses and garnered extensive media coverage.

Predictions for the times to come are not easy to make. Indeed, it seems the future image of flood risk is uncertain. It can be tempting to conject higher magnitudes and frequencies of flood hazards as a result of climate change (Douglas et al., 2008; IPCC, 2012), and yet relatively low-grade statistical significance of such claims has been found so far (e.g., Kundzewicz et al., 2014). The multidisciplinarity of the notion of flood risk adds more complexity to the associated modeling, assessment, and management, and so does the fact that the flood risk is intricately interconnected with a number of factors that are highly stochastic by themselves, for example, environmental and socioeconomic factors, among others.

The need for the multidisciplinary exploration of the notion of flood risk is thus self-evident; nonetheless, the vast majority of the existing studies are not multidisciplinary and therefore are limited. Although there is a massive body of monodisciplinary literature focusing on the investigation of flood risk, the contribution of the actuarial community (theoreticians and practitioners) has been rather restricted. The reasons are multifaceted, and we mention the following three only: (1) flood risk possesses characteristics that make it significantly different from the risks that actuaries have experience dealing with; (2) flood risk models are highly specialized and therefore not easy to understand for someone who is not specifically trained; and (3) flood risk insurance treaties are often not price-to-risk contracts, which leaves less room to trigger actuarial expertise and involvement. We discuss in more detail these points and others in the following pages. Our major goals at this stage are (1) to sketch the landscape of flood risk management, in general, and flood risk insurance, in particular and (2) to draw the attention of the actuarial community to these subjects and the opportunities they present.

The rest of the report is organized as follows: As we are convinced that an efficient flood risk insurance framework starts with a thorough understanding of the notion of flood risk, we take a closer examination of flood risk in Section 2. In Section 3 we elaborate on the general paradigm of flood risk management, of which flood risk insurance is an important component. When the ground has been prepared, we investigate flood risk insurance in Section 4. In Section 5, we provide a high-level overview of the modeling and measuring techniques of flood risk; in the same section, we also suggest exemplary ways to augment the state of the art of flood risk management with tools borrowed from the actuarial knowledge toolbox.

Section 2: A Closer Examination of Flood Risk

Flood risk presents an important societal and generational challenge. The scope of the problem, as well as the impact of the flood events, require a systematic approach to developing effective, long-term, sustainable risk management strategies. The first step in doing so requires a recognition of the risk in all its facets as well as the different perceptions of said risk.

2.1 Defining Flood Risk

In academia, risk is often seen as a deviation from the expected. Remarkably, this is the approach that the Intergovernmental Panel on Climate Change (IPCC) takes when defining the general notion of disaster risk, of which flood risk is a particular example. Specifically, in a 2012 IPCC report, disaster risk is defined as

> *… the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.*

Hence, the definition emphasizes the idea that a disaster entails a social, economic and environmental impact in a manner that is a significant deviance from normal functioning of the affected communities. The elements of *hazard*, *exposure* and *vulnerability* serve as basic means to understanding potential social, economic and environmental impact associated with the risk.

Hazard, vulnerability and exposure repeat across a variety of definitions of flood risk (Koks et al., 2014), which is as a rule seen as a combination of the likelihood of an event happening and the consequences if the event occurred. A more detailed definition of flood risk has been given by the U.S. Army Corps of Engineers (USACE). In 2006, recognizing the importance of flood risk, the USACE decided to focus its policies, programs and expertise on the subject in what it called a flood risk management program. The USACE views flood risk to be a function of (1) hazard, (2) exposure, and (3) vulnerability, which is not surprising, but also of (4) performance and (5) consequences.

- **Flood hazard** is defined to be an event that may cause loss of life, injury or other health impacts, as well as damage and loss of property, infrastructure, service provision, and environmental resources. Flood hazard is described in terms of its frequency, stage, velocity, extent and depth.

- **Exposure** is defined to be the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by an event. Exposure typifies the scope of damage in terms of who or what may be damaged.

- **Vulnerability** is defined to be a propensity to be adversely affected, which observes the susceptibility of various stakeholders to damage when exposed to a given event.

- **Performance** is the capability of a flood risk management system to accommodate a single flood event.

- **Consequence** is the quantified damage associated with an event, measured in terms of economic damage, acreage lost, crops damaged and lives lost.

We have stressed hitherto that the scope of the risk of flood as well as the associated impacts invite an integrated and multidisciplinary risk management approach to tackle the problem. The breadth of concepts contained in the preceding definition speaks to this same point. The next section, which outlines how multifaceted the notion of flood risk is, strengthens the statement further.

2.2 Types of Flood Risk and Associated Risk Factors

In insurance practice, floods are typically classified as either inland or coastal. The phenomenon is, however, by far more delicate. In fact, one reason flood risk is so complex and daunting arguably lies in the diversity of the types of floods that may take place. This, in turn, implies that the solutions must be of a nuanced manner that requires a critical understanding of the types of floods, their sources and their dangers. According to the Federal Emergency Management Agency (FEMA), floods can be grouped into the following types:

1. **Riverine flooding.** Riverine flooding occurs when surface runoff introduced into a natural or constructed stream exceeds its capacity. The resulting water overflows the stream banks and spills into the adjacent low-lying area. Riverine flooding varies with terrain and can be further subdivided as follows:

    - **Overbank flooding.** This type of flooding occurs when water exceeds the volume capacity of the river channel and spills onto the adjacent floodplain. It is one of the most common flooding events in the U.S. Typical examples of overbank floods. are the great Mississippi and Missouri Rivers flood of 1991 and the Red River flood in 1997. Risk factors associated with overbank flooding include the geographic characteristics of river flow, channel, floodplain, groundwater and so on (Doble et al., 2014). In steep, narrow valleys, flooding lasts for a shorter duration, but flood velocity and flood depth are higher in comparison to flat floodplains. Furthermore, the larger the flood basin, the easier it is to predict timing and elevation of flood peaks.

    - **Flash floods.** Flash floods are characterized by a rapid rise in water, high flood velocity and large amounts of debris, which make them far more severe than overbank flooding. Influential risk factors include intensity and duration of rainfall, steepness of watershed and stream gradients. Flash floods occur in all 50 states and may be caused by excessive rain, dam failures and alluvial fans, release of ice jams and collapse of debris dams.

2. **Urban drainage.** Floods caused by urban runoff may occur when the runoff exceeds the urban drainage capacity. When time required for surface runoff to reach the stream is reduced by construction or straightening and lining of channels, flood peaks increase and flooding happens more quickly and to a greater depth. In addition to the environmental characteristics, factors such as storm intensity, capacity of drainage system and concentration of population and assets all have significant influence on the risk of urban flood (Morita, 2014). Urban floods are particularly concerning, as, for instance, in Canada around 82% of the total population live in large and midsized cities (census 2016 data). It is not surprising, therefore, that the July 2013 flood in Toronto caused around $950 million in insured damage.

3. **Ground failures.** Subsidence and liquefaction of soil may result in a ground failure, causing one of the following several types of floods:

    - **Mudfloods and mudflows.** Mudfloods occur when a flood carries heavy loads of sediment including coarse debris. Mudflow occurs when the dominant transporting mechanism has sufficient viscosity to transport boulders. These are a subset of landslides and typically impact floodplains along mountainous regions, the most prone of which include the Appalachian region, the Rocky Mountain region and the Pacific coast region (Wold and Jochim, 1989). Mudflows and mudfloods take place in areas denuded by forest and brush fires, where the subsoil layer consists of clay. Once the clay becomes saturated, mudflows take place. Mudfloods and mudflows cause severe damage due to the flow of debris. They often initiate future floods by filling drainage channels with sediment.

- **Subsidence.** Subsidence is a type of ground failure that results from the lowering of the ground surface. This in turn leads to increased and more frequent flood damage. It may occur either from natural factors such as weathering or consolidation or from anthropological activities such as groundwater extraction and fossil fuels removal.

- **Liquefaction.** Seismic shockwave triggered by earthquake can change a soil structure so that soils with water in the pore space will be transformed into groups of grains. With a certain level of steepness on the layer slope, soil, vegetation and debris along with liquefied material will flow downslope and cause soil movement on a large scale.

4. **Fluctuating lake levels**. Heavy rainfall and annual snowmelt can cause high water levels for a short term. The imbalance between inflow and outflow in closed-basin lakes may cause dramatic water level fluctuations over the long term, with associated flooding persisting for years.

5. **Coastal flooding and erosion**. Storm surges and wave actions result in coastal flooding with varying frequency and magnitude. Depending on the types of coastal floods, wind speed and wave height are the most commonly recognized risk factors. Sea-level rise and land subsidence are emerging factors that compound the damaging impacts of coastal floods. Historic events causing major coastal floods include Hurricanes Katrina, Ike and Harvey.

   - **Storm surge**. Wind action over a long stretch of open water can cause water-surface elevation above normal tide level, which leads to the inundation of a small area to more inland from the shoreline. The intensity of the storm is characterized by the minimum central pressure deficit, forward velocity and location at landfall.

   - **Wave action**. As important aspects of coastal storms, battering waves are a destructive phenomenon that can cause beach erosion and even destroy coastal structures.

When seeking a definition of flood risk, we must recognize it as a piece of an encompassing puzzle of disaster risks. Unfortunately, distinct pieces of this highly cumbersome puzzle are interconnected and so must be studied thoroughly too.

2.3 Understanding Flood Risk in the Context of Catastrophic Risks

Floods in, for instance, the U.S. are particularly devastating primarily because they are frequently associated with extreme hydrological events that involve consequential physical impact. Hydrological events can give rise to extreme impacts, like flooding, that typically last over several weeks and inevitably affect the natural physical environment, the ecosystem and the presiding society.

This is clearly evidenced in the context of hurricanes. Indeed, the subsequent floods have been notorious for the devastation they bring. Namely, the flooding that resulted from Hurricane Katrina was responsible for the highest insured losses to date; Hurricanes Harvey and Sandy come 2nd and 3rd, respectively. These hurricanes were not isolated incidents, with Ike, Ivan, Charley, Wilma and more recently Matthew, Hermine and Harvey all having taken place since 2000 (Altmaier, et al., 2017). Hurricanes Katrina, Rita and Wilma and their resulting storm surges in 2005 cost more than $180 billion (2011 combined prices) (Michel-Kerjan and Kunreuther, 2011).

Of the 10 most significant losses recorded by the National Flood Insurance Program (NFIP), nearly all were linked with hurricanes (Altmaier et al., 2017). Yet hurricanes are not the sole causal link to floods. One-in-1,000-year rains (i.e., rains with the chance of annual occurrence equal to 0.1%) have also resulted in significant flood damages in recent years (Stevenson and Schumacher, 2014). To be clear, the term *1 in 1,000 years* in no way implies that these events cannot happen more frequently. In fact they do, as a referee of this report emphasized.

The floods resulting from hydrological events are deemed to be a disaster once they surpass specific thresholds in at least one of three dimensions: (1) the degree to which damages can be restored from neighboring capacity, (2) the degree by which recovery is impeded by further damage, and (3) the intensity of the impact (IPCC, 2012). However, for the purposes of recording, most agencies recognize flood events to be a disaster once the agencies' expectations associated with total repair cost or mortality rate have been exceeded (IPCC, 2012).

2.4 Societal Perception of Flood Risk

Flood hazards are often utterly impactful and must not be neglected. The exposure and vulnerability are daunting (and according to a significant number of climate scientists, are going to increase), and yet numerous public surveys (Bubeck et al., 2012; FEMA, 2013) find that the public awareness of flood risk remains low. One paper that resulted from a nationwide study of flood risk awareness among U.S. households indicates that about 30% of survey respondents believe their communities are at risk, while only about 10% believe their residences are at risk (FEMA, 2013). Remarkably, the residents in the flood-prone communities demonstrate merely slightly higher awareness of flood risk than those outside of the areas. The perception of flood mitigation activities is also somewhat low. For example, Cigler (2017) reports that while the U.S. government spends about $400 per household annually in response to extreme weather events, only 4% of the spending is for preparation.

In comparison, average Canadians are even less cognizant of flood risks and the protection options. The latest survey, which was conducted in 2017 by researchers at the Interdisciplinary Centre on Climate Change together with the University of Waterloo (Thistlethwaite et al., 2017), finds that 94% of respondents are unaware of the risk and Canada's recent policy changes that aim to ease the heavy burden on the government disaster-assistance programs. This public unconsciousness is unfortunate, as the new approach has shifted more responsibility to homeowners in protecting their houses. When asked about the risks they face, only 6% out of 2,300 respondents who live in communities with high flood likelihood were found to be aware that their homes were located in a designated flood risk area; we note for completeness that 21% believe flood risk is going to increase over the next 25 years. That gives a reason for the low uptake of flood mitigation measures among households in Canada—only about 30% of Canadians are taking even minimal actions to protect their property from flooding.

The aforementioned underweighting of the risk of flood is somewhat puzzling. Recall that the widely accepted cumulative prospect theory (Kahneman and Tversky, 1979) states that people tend to attach higher weights to rare events, of which floods are an example. To elucidate, consider, for instance, Lichtenstein et al. (1978), who argue people tend to significantly overestimate the likelihood of rare-death events. We can only speculate about the reasons for the contradiction in the case of flood risk (and perhaps disaster risk more generally). We wonder whether the low insurance premiums (see Section 4) play a role in creating a myth of immateriality of flood risk. One way or another, a lot more has to be done to raise public awareness of the risk of floods.

Section 3: Flood Risk Management

In this section, we review the ongoing development of flood risk management programs around the globe; we confine the discussion in Section 3.4 to the flood risk management developments in the U.S. Speaking simply, flood risk management is a set of measures that aim at reducing the risk to life and damage to property caused by flooding. The importance of flood risk management is evident at many levels. Namely, at the governmental level worldwide, much legislation has been put forward to implement new or refine existing flood risk management frameworks (for instance, Biggert-Waters Act in the U.S.; Directive 2007/60/EC in the European Union). In academia, flood risk management has been recently granted its own dedicated journal, the *Journal of Flood Risk Management* (*JFRM*). *JFRM* publishes research in all areas of flood risk, and it has quickly become a first-rank journal in safety, risk, reliability and quality as indicated by the SCImago Journal Rank (SJR indicator).

Somewhat akin to the changes that the solvency accords have been undergoing globally, in response to the challenges presented by concurrent flood risk, governments of developed nations have pursued policies creating anticipatory flood risk management frameworks. Most notably, the United Nations General Assembly, in March 2015, adopted the Sendai Framework for Disaster Reduction, which calls for a culture of prevention and for investing in disaster reduction for resilience (UNISDR, 2015). Further, the Global Assessment Report (Desai et al., 2015) specifies the importance of managing risk along social and economic lines in a manner that is fundamentally different from traditional approaches to disaster risk reduction. It verifies the importance of taking a precautionary stance in disaster risk reduction, as it not only makes good long-term financial sense but also serves a prerequisite to the U.N.'s Sustainable Development Goals.

In a similar fashion, events in North America have shown the need for a shift in the approach to flood risk management. The failure of the flood protection infrastructure, disaster anticipation and disaster mitigation in response to Hurricane Katrina aggravated losses incurred and social vulnerability in New Orleans. Six years after the disaster, poverty rates stood at 29%, double that of the U.S. average (Desai et al., 2015).

The consensus paradigm is that concurrent flood risk management strategies must consider the perspectives of not only residents but also local governments, businesses and financial sectors across social and economic lines. Private and public investment in disaster mitigation and reduction across structural and nonstructural measures have become essential to supplement efforts at maintaining an equilibrium in economic, social, health and cultural reliance of all stakeholders. This has given rise to a host of challenges and opportunities to devising holistic solutions in meeting the said challenges.

3.1 Defining Flood Risk Management

Given that flood risk is a diverse problem, encompassing multiple social, environmental and economic perspectives and stakeholders (Section 2), a salient definition of flood risk management must adopt a vocabulary that reflects this diversity.

General disaster risk management can be defined as (IPCC, 2012):

Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, resilience, and sustainable development.

This definition, while it extends beyond the consideration of flood risk, integrates perspectives from several historically distinct research communities studying climate change and adaptation, long-term planning and decision making, prevention and preparedness, among many others.

Flood risk management is considered a focused perspective on disaster risk management, and its definitions reflect this. Prettenthaler et al. (2017) define efficient flood risk management as requiring a combination of risk reduction, risk retention and risk transfer. Surminski and Thieken (2017) view flood risk management as a means to improving society's ability to prepare for, respond to and recover from flooding. They advocate for a more anticipatory flood risk management approach, which begins with a systematic identification and analysis of risk, followed by prioritization of risk, mitigation of risk and, finally, monitoring and regular assessment of risk.

3.2 Value of Flood Risk Management

A tailored risk framework process, when applied effectively toward organizing flood mitigation and prevention efforts, may confer benefits that are sensitive toward social, fiscal and other considerations. The benefits we discuss in some detail in this section are (1) increased risk awareness and knowledge, (2) improved identifiability of the involved stakeholders and better quality control, and (3) supported economic growth.

Managing risk through a framework facilitates the development of risk awareness and risk knowledge. In turn, the development of understandable and actionable risk knowledge is crucial, as it may (1) contribute to better estimating the causes and consequences of risk generation and accumulation, (2) motivate a paradigm shift if felt necessary and (3) promote an increased sensitivity and awareness to risk that internalizes social, economic and environmental vulnerability. Then risk can be managed effectively through a consideration of multiple perspectives as well as a combination of corrective and compensatory disaster risk management practices.

For instance, current approaches to managing risk frequently compare replacement cost against the cost of reducing risk. A holistic risk framework would seek to expand this perspective so that it highlights the trade-offs implicit in each decision, including downstream benefits, environmental development, social progress and an understanding of the bearers of the costs and beneficiaries of the risk management efforts. Such a broad consideration to cost-benefit analysis can improve visibility and appeal of the flood risk management efforts, while maintaining long-term perspectives on the U.N.'s Sustainable Developmental Goals. It can help to isolate potential risks inherent in asset and risk portfolios, thus identifying and discouraging financial flows toward investments that increase flood risk. Principles in favor of including risk-reducing measures in recovery and reconstruction of essential public assets were introduced into Australia's Natural Disaster Relief and Recovery Arrangements. Following Cyclone Oswald in 2013, the Queensland and Australian government launched the AU$80 million Queensland Betterment fund with the purpose to finance the reconstruction of assets (Desai et al., 2015).

Through a risk management framework, stakeholders involved in investment decisions and risk-sharing mechanisms can be clearly identified and can thus be held accountable for their decisions. This in turn will improve sensitivity of social factors toward the causes of flood risk and responsibility for subsequent losses, which, by itself, sets the stage for further improvements.

An ideal flood risk management framework not only promises minimized disruption and expedited flood relief but also sets the stage for sustainable reduction in poverty and improvement in health and education by facilitating sustainable and equitable economic growth. Countries that have effective policy and regulatory frameworks as well as strategies and financial mechanisms in place to prevent new disaster risks can further transform development, knowing full well that necessary safeguards against risk have been established, which is vital to any progress-motivated, risk-averse society.

3.3 Frameworks of Flood Risk Management

Given the complex nature of flood risk and the diversity in the approaches to risk management, it is understandable that we also find a diversity in the types of flood risk management frameworks. Across these frameworks, however, there are common elements, which we outline and discuss here.

Surminski and Thieken (2017) suggest an anticipatory flood risk management cycle that involves four phases: (1) risk assessment, which involves acquisition of data, information and knowledge sharing necessary to identify and quantify risk, (2) risk reduction, which involves prevention, mitigation, protection, response preparedness and recovery preparedness, (3) response, and (4) recovery. Utilizing this elementary model, we disseminate contemporary risk management frameworks and examine specifics in their application.

Risk assessment is primarily carried out through the use of risk maps. In the U.K., risk maps are championed by the government. Some EU countries use a combination of flood risk and flood vulnerability maps in assessing risk. In the U.S., flood risk maps are mostly based on NFIP and USACE data. Flood risk maps identify the potential for damage in different flood risk areas as well as land-use practices that may impact vulnerability to flooding. Vulnerability maps, by comparison, help identify populational segments across various demographics and their relative vulnerability to flood events. In Canada, flood mapping is conducted using hazard maps, which are tailored to the purpose of land-usage planning, rather than to establish risk mapping.

Risk reduction is primarily pursued through the implementation of structural and nonstructural flood risk management measures. Structural measures aim to protect people and property through mechanisms that counteract the flood event, reduce hazards or influence the likelihood of occurrence of the event. In North America and Europe, dams, dykes and levees are common structural measures in active implementation. Nonstructural measures are mitigation or adaptation measures that seek to reduce damage without influencing the current of the flood event through large-scale defenses. Typical examples of nonstructural measures include, but are not limited to, relocation, flood warning systems, land-use regulations and flood insurance. As a rule, a hybrid of structural and nonstructural measures is utilized.

For instance, during early efforts of flood control, Canada mostly relied on structural flood measures, including dams, dykes, levees and other structures to control and mitigate flooding damages. With further developments, nonstructural measures, as supplements to structural measures, were introduced and supported by the Canada Water Act in the form of establishing government disaster relief programs, providing emergency preparedness assistance and initiating floodplain mapping (Sandink et al, 2010). For many low-income and lower-middle-income countries, risk reduction is a significant challenge primarily because the governments therein lack necessary capital to invest in structural measures in a manner similar to the case of high-income countries.

Improving society's ability to respond to and recover from flooding is the crux of any contemporary flood risk management framework. Typically, in most countries, response and recovery efforts are mostly led by the governments themselves. For instance, in Canada, response to flood events is a public responsibility. If flood damage occurs, arrangements exist whereby all three levels of the government work together to provide assistance to affected communities.

3.4 Flood Risk Management in the U.S.

Managing flood risk in the U.S. has undergone an evolution over time from flood control to flood damage reduction to flood risk management. The USACE has played an essential federal role in the development of flood risk management in the context of both the structural and nonstructural measures.

According to the USACE brochure *Value to the Nation: Flood Risk Management*, the USACE spends about 30% of its annual funding on flood reduction activities and has been responsible for the construction of some 383 major lake and reservoir projects, more than 8,500 miles of levees and dykes, about 90 major shoreline protection structures and hundreds of other flood risk reduction projects, such as temporary flow restriction structures.

The Flood Risk Management Program, pioneered by the USACE in May 2006, integrates various flood risk management projects and programs by authorities of federal agencies, state and tribal organizations, and regional and local agencies. This program also supports Silver Jackets teams, which are unique to each state and bring government and nongovernmental organizations together to work on flood risk management.

Over the past 30 years, the USACE has also contributed significantly to flood mapping by completing 3,000 studies for FEMA. However, a recent study (Wing et al., 2018) indicates that the flood risk in the U.S. is vastly underestimated when assessed using the existing FEMA maps. In this study, a research team used a high-resolution model combined with a two-dimensional representation of flood physics to estimate the flood risk across the entire conterminous U.S. According to the results, approximately 41 million Americans live within the one-in-100-year flood zone, which is more than triple the 13 million estimated by FEMA (Wing et al., 2018).

An obvious observation regarding the role of insurance in the context of flood risk management is that insurance, through its risk transfer function, contributes to the recovery preparedness, and so belongs in the risk reduction niche of the flood risk management framework described in Section 3.4. That said, we find this observation too simplistic. In fact, we are convinced that flood risk insurance can (and does) have impacts on all four pillars of the flood risk management framework (see Surminski and Thieken, 2017 for more details and examples).

Section 4: Flood Risk Insurance

Given the ample evidence that flood damages have been rising over the past few years, flood risk insurance has gained prominence across discussion forums and research papers alike. In particular, the lack of flood coverage has garnered much attention. As close observers have noted, the resulting protection gap offers significant opportunity for innovation to insurers, is of ongoing concern to governments that would otherwise be required to pay emergency relief and is an ever-present threat to property owners who may suffer ruin in the face of unaffordable flood-related losses. We discuss the notion of flood risk insurance in this section.

4.1 Defining Flood Risk Insurance

Flood risk insurance, like all insurance products at their core, offers the tool to transfer risk from one party (i.e., the insured) to another (i.e., the insurer) at the cost of a premium or premiums. The economic losses, as consequences of floods, at the heart of this risk can be classified into the following categories:

- **Direct tangible (physical) damage.** This is the most common, most important and best understood damage category. Direct tangible damages are typically quantified using the insurance payout via the average unit cost method. Stage-depth damage curves may also be used in the cases when the relevant data are sparse (see Section 5.2 for more details).

- **Indirect tangible damage.** In this category, the most common damage types are business interruption (for the commercial flood insurance coverages) and loss of use (for the personal flood insurance coverages). For the commercial flood losses, indirect tangible damages are typically measured using the percentage of the direct tangible assets, such that the indirect tangible component is assumed to be a percentage of the direct damage valuation. Alternatively, in the cases when sector-specific losses are realized, certain unit cost methods may be applied. Then the cost is calculated on an hourly or daily basis. In the context of personal flood losses, the measurement for loss of use is based on the length of time needed to rebuild or repair the damaged properties. Insurance products that are employed to protect against the loss of use are commonly referred to as the “part D coverage.”

- **Direct intangible damage**. Typical examples of direct intangible damage include environmental damage and loss of life. This category is most prominent in developing countries, since high rates in loss of life are observed during flooding events, particularly in the cases of coastal flooding, floods associated with failure of flood defenses and flash floods.

- **Indirect intangible damage**. This category comprises all other damage types that have not been included in the previous three categories and are difficult to quantify. Supply interruption of water and electricity are examples of the damages in this category. These are quantified based on the damages sustained by water treatment plants or transformer stations.

According to FEMA (2012), flood insurance is defined as *the commercial machinery that provides coverage against direct physical loss caused by floods.*

While flood insurance does not provide direct coverage toward the indirect or intangible damage, it should be viewed more broadly as a tool that interacts with the overall risk management framework while also shaping risk governance and influencing risk behavior (Surminski and Thieken, 2017). If constructed properly, flood risk insurance should facilitate flood risk sharing and distribution along a longer time frame. Also, flood risk insurance should offer opportunity for faster reconstruction and minimized welfare losses.

4.2 Salience of Flood Risk Insurance

In Section 3.4, we mentioned that a comprehensive flood risk management framework should comprise four major components, namely, risk assessment, risk reduction, response, and recovery. Traditionally, flood risk insurance is viewed as a risk transfer instrument that repays the replacement costs of the damaged property. Therefore, flood risk insurance is well accepted to play an important role in the after-flood response and recovery. Another contribution of flood risk insurance lies in risk reduction, where it is seen as a response preparedness and recovery preparedness tool. The connection of flood risk insurance to the risk assessment component of the flood risk management framework is arguably overlooked, yet hard to deny.

Indeed, assessing the risk of flood is a necessary precursor to pricing it. Hence the development of flood insurance implies involvement with flood risk assessment. The data generated from the day-to-day operation of the flood insurance business can feed into various flood risk models; this way the latter can benefit and improve.

The other direction in the link *flood risk insurance—flood risk assessment* is via flood maps. Flood maps, which are put together with the help of flood data based on advanced modeling techniques and augmented with the required information on exposures, are often employed to determine flood risk insurance premiums for the properties located in distinct flood zones. In addition, flood maps are a convenient tool that facilitates the communication of flood risk–related messages to a variety of stakeholders within the flood risk management framework.

4.3 The Way It Is Done: Policy Design, Underwriting and Pricing

The faces of flood risk insurance vary across countries. This is mainly so in the following dimensions: (1) publicly offered versus privately offered policies or hybrids, and (2) optional versus mandatory or bundled policies. We further provide a high-level overview of the ways in which flood risk insurance is designed around the globe. To this end, we consider the examples of France, Germany, and the U.K. The discussion on the flood risk insurance offering in the U.S. is given in Section 4.4.

France is one of only a few countries that has mandatory flood risk insurance offered through the so-called Cat. Nat. System, which is a French natural disaster insurance system that augments private flood risk insurance with a state-owned reinsurance (IBC, 2015; Sandink et al., 2010). Flood risk insurance in France is bundled with other natural catastrophes within a standard home insurance package and is offered at a flat rate determined by the government regardless of the risk differentiation of households. An expense of 12% is added as a surcharge on every homeowner's policy to help the Cat. Nat. program cover losses (Duong, 2013; Enjolras et al., 2008; Sandink et al., 2010). Interestingly, despite the fact that flood risk insurance is mandatory, private insurers may refuse to provide coverage for homeowners residing in high-risk zones. Also, private insurers may require homeowners residing in the moderate-risk zones to invest in mitigation measures (Sandink et al., 2010). The state-offered reinsurance is provided by a state-owned reinsurer, Caisse Centrale de Réassurance (CCR), and it is optional to private insurers. This imposes immediate complications as, for example, private insurers may choose the reinsurance option for high-risk policyholders only, thus increasing the financial burden on CCR (Sandink et al., 2010).

Flood risk insurance in the U.K. is similar to that in France in that the policies are offered by private insurers and backed up by reinsurance provided through a government-supported risk-sharing pool, this one called Flood Re (IBC, 2015). The U.K. case is different, though, in that the purchase of flood risk insurance is not compulsory. That said, flood risk insurance coverages in the U.K. are as a rule bundled within the standard home insurance package that is required for mortgage approvals. Consequently, the penetration rate of flood risk insurance policies in the country is very high and stands at 95% (IBC, 2015; Sandink et al., 2010). Another noticeable aspect of the U.K. flood risk insurance framework is that the premiums are risk-based. Subsidized policies are available for the residents of high-risk zones. To this end, the reserves of Flood Re are used; the funds to match the subsidy are collected through levy charges imposed on all other policyholders in the country (IBC, 2015).

Flood risk insurance policies in Germany are, like in the U.K., offered by private insurers; the difference is that the reinsurance can be sought on the international market and under minimal governmental involvement (IBC, 2015). In Germany, flood risk insurance policies are voluntary and are offered as an add-on to the standard home insurance at extra charges (Sandink et al., 2010). Premiums, subject to deductibles and limits, are set by insurers based on the risk levels determined by flood risk zoning maps, known as ZÜRS, which have four hazard zones: (1) very low, (2) low, (3) moderate and (4) high (Sandink et al., 2010). Private insurers can charge very high premiums or even refuse to insure the properties that are located in high-risk zones. The set-up explains low penetration rates of flood risk insurance in the country; it stands at about 30% (IBC, 2015).

4.4 Flood Risk Insurance in the U.S.

Flood risk insurance in the U.S. is mainly offered through the NFIP, which was created in 1968 and is housed in FEMA. The major goal of the NFIP program is to reduce the impacts of floods and encourage communities to implement regulations to govern floodplain development. Community participation with NFIP is voluntary, but the participation requires the enforcement of certain land-use control and construction codes. On a different note, federal flood risk insurance is mandatory for properties with federally backed mortgages.

In general, the NFIP offers three standard types of flood insurance: (1) dwelling policy, which is used to insure one to four family residential buildings or single-family dwelling units in condominiums, (2) general property form, which is used to insure five or more family residential and nonresidential buildings, and (3) residential condominium building association policy form, which is used to insure residential condominium association buildings. The NFIP's dwelling form offers coverages for building property, up to $250,000, as well as for personal contents, up to $100,000 (FEMA, 2018). Some policyholders may find these coverages are not satisfactory. Such policyholders may choose to purchase additional protections primarily through the surplus lines markets. According to the Wholesales and Specialty Insurance Association, as of the 2017 year-end, the flood insurance premium written on a surplus lines basis totaled $232.6 million in the U.S.

Flood Insurance Rate Maps (FIRM) have been developed by the NFIP (as well as by the US Geological Survey and occasionally the Army Corps of Engineers) for the sake of premium determination and to communicate flood risk messages to the public. FIRM identify flood-prone areas that may be inundated by flood events with certain percent chance on an annual basis (typically, 1% or 0.2%); the areas are further classified into various flood zones. Together with the flood maps, key determinants of the NFIP's flood insurance premium include flood zone, type of occupancy, characteristics of property, coverage amount, deductible offset and expected loss ratio adjustment loads rates. By using this underwriting procedure, the ultimate goal of the NFIP is to guarantee accessible insurance coverages to all flood-prone areas under reasonable prices with a certain extent of actuarial soundness. For the properties built before the implementation of FIRM, premium discounts and subsidies are provided (FEMA, 2018). Properties of this kind are also known as pre-FIRM properties, and they account for about 20% of the total NFIP properties.

In recent years, especially after Hurricanes Katrina and Sandy, the NFIP has been able to operate only by borrowing extensively from the U.S. Treasury to cover claim losses. As of this writing, the NFIP owes more than $20 billion to the U.S. Treasury. To remedy the financial challenges that the NFIP is facing, a few regulatory actions were taken in the Biggert-Waters Flood Insurance Reform Act of 2012. The act includes, for example, revision of policy types and premiums, up-to-date flood risk mapping, flood mitigation, privatization and reinsurance. Since January 2017, FEMA under the NFIP reinsurance program has enlisted the services of private reinsurers to reduce risk exposure and strain on reserves and to help the NFIP to be more financially sound. By January 2018, via reinsurance, the private market had shared $1.042 billion out of $7.6 billion in claim payments due to Hurricane Harvey (FEMA, 2018).

The crux of the Biggert-Waters Act is perhaps the shift toward a price-to-risk approach. The importance of the change is hard to underestimate. Specifically, it operates at a number of levels at once; we mention just a few here that are direct consequence of the proper actuarial pricing: (1) improved solvency, (2) more accurate flood risk awareness and knowledge within the crowd of policyholders and property owners, (3) an incentive to engage in mitigation behaviors and (4) funding for the development of mitigation measures that have long-term benefits in reducing the risk of flood.

Although the 2014 Homeowner Flood Insurance Affordability Act repealed some of the rate increases implemented under the Biggert-Waters Act, many proposed changes have been assumed. We refer interested readers to GAO (2015, 2016) for a more detailed discussion.

Last but not least, the NFIP has recently become enthusiastic about collaboration with experts from a variety of industries to develop new pricing methodologies (Chamberlain, 2018; FEMA, 2018c). The new rating models are envisioned to boast the following characteristics (among others): (1) graduated risk with complete geographic differentiation; (2) use of agile method; (3) reflection of risk mitigation actions; (4) automated underwriting process and (5) inclusion of broader hazard sources.

Section 5: Flood Risk Modeling and Pricing

Quantitative modeling of flood risk is a core component in an effective flood risk management framework in general, and in insurance in particular. Indeed, one important objective of flood risk management is to offer a sound understanding of the economic consequences of floods. To this end, the results of quantitative flood risk modeling are critically important from a number of insurance and socioeconomic points of view. From a (re)insurer's perspective, the estimation of flood losses is not only the building block for flood risk insurance underwriting and pricing, but also a necessary input for the portfolio and capital management. More broadly, flood risk models provide quantitative justifications for the related decision making. For instance, with flood risk models in place, a cost-benefit analysis can be carried out to assess the effectiveness of a variety of flood risk mitigation strategies by comparing the projected economic losses with and without these strategies. Also, flood risk models provide valuable insights into such topics as urban vulnerability and resilience analysis, land-use planning and flood risk mapping.

This section is devoted to the discussion of a few critical considerations for building and selecting appropriate flood risk models from a (re)insurer's perspective and the review of the state-of-the-art flood risk modeling frameworks.

5.1 Factors Prescribing Insurance Industry Standards

Modeling flood risk is an extremely complex process. The phenomenon is highly stochastic and driven by numerous interconnected financial and nonfinancial factors. On the one hand, such environmental characteristics as the watershed properties, topography and land use must be taken into account when modeling the frequency and severity of flood events. On the other hand, characteristics of the involved assets including, for example, the location, type and age of structure play a prominent role in predicting the financial loss under a given flood risk scenario. The relative scarcity of data related to flood losses adds to the complexity.

The difficulty involved in modeling flood risk has spurred intensive research to tackle the challenge. Nowadays, the compendium of distinct flood risk models is so vast and diverse that even if we planned to dedicate this entire report to its coverage, our efforts would perhaps be doomed to fail. Remarkably, some of the existing models have been put forward by insurance companies when seeking competitive advantage.

Despite the overwhelming number of existing models—a recent World Bank report (2014) collected and briefly discussed more than 80 open-access/open-source hazard models —it is still fair to state that the quantitative studies on the topic of flood risk are at present in the embryonic stage, and there is no consensus on the benchmark models that would be widely accepted across different regions and countries (Schröter et al., 2014).

5.2 Guidelines for Modeling and Pricing

In the state of the art, a general framework for modeling flood risk typically consists of the following three principal components, which are consistent with the definition of flood risk:

- **Flood risk exposure**, that is, the inventory of structure and valuation information for properties and infrastructures that are subject to flood risk
- **Flood hazard**, that is, the frequency of occurrence of floods with particular intensity over an extended period of time
- **Vulnerability**, that is, the susceptibility to sustain certain levels of economic losses given a set of flood hazard intensity metrics (e.g., flood depth, duration, velocity).

Flood risk exposure is critical for public decision makers when understanding the flood risk of a certain region on an aggregate basis. In this regard, Hazus, arguably one of the most comprehensive flood risk modeling software packages developed and managed by FEMA, contains a rich inventory of the exposure information in the U.S. (FEMA, 2014). However, when flood insurance pricing for a particular property is of major interest, the information about the exposure seems to be less important and necessary details can be obtained during the underwriting process. Consequently, we confine our discussion in Sections 5.2.1 and 5.2.2 to briefly reviewing the concepts of flood hazard and vulnerability models, only.

To conclude the discussion in this section, we note that statistical performance of a model is a quantitative way for assessing flood risk models, yet the selection of an appropriate flood risk model needs to be justified not only quantitatively but also qualitatively. We further outline a few qualitative considerations to bear in mind when seeking a desired flood risk model. The criteria outlined here are of utmost importance in the context of insurance applications and risk management (Rath and Borrel, 2015).

1. **Reconciliation and attribution.** For an ideal flood risk model, the formulation should be consistent with other catastrophic loss models used commonly by the insurance industry. For example, the outputs of such an ideal flood risk model should provide the assessment of both the frequency and severity of flood events. In fact, separate frequency and severity modeling is commonly viewed as the best practice in the context of property and casualty insurance. The advantages of modeling both the frequency and the severity include, for example, the power to reflect claims inflation, understand the impacts of policy modifications (policy deductibles and limits) and study the reinsurance needs. We refer the interested reader to Klugman et al. (2012) for a detailed discussion on the frequency and severity modeling in insurance. Moreover, ideal flood risk models should be designed in such a way that the attribution of each risk factor to the corresponding economic consequence is explicitly made. This guarantees the feasibility for risk carriers to conduct stress testing of their insurance portfolios under a variety of flood risk scenarios. The stress testing is required under the Solvency II regulatory accord and the Own Risk and Solvency Assessment (ORSA) paradigm (Klein, 2012; NAIC, 2011). Understanding the attribution of risk factors further contributes to the optimal flood insurance design, insurance capital analysis and portfolio risk management.

2. **Risk-informed prediction.** The estimated losses produced by a flood risk model should not be merely a deterministic expected value. Instead, flood risk models should produce the probability distribution of the potential losses, which reflects the quantitative information about the stochastic nature of flood risk. By reporting the potential economic losses in a probabilistic domain, the insurer can take the subjective risk appetite into account and quantify flood risk in accordance with the company's risk profile and business strategy. In a somewhat different yet relevant context, risk measures that are mandated by the recent insurance regulation for risk reporting purposes, such as the Value-at-Risk and Conditional Tail Expectation, require the input of the insurer's risk appetite (a.k.a., the confidence level). This type of probabilistic assessment of flood risk constitutes a critical component of capital analysis and optimal reinsurance design, and consequently it plays an important role in the implementation of risk-oriented management approaches as described in Solvency II and ORSA directives.

3. **Granularity.** In the context of portfolio risk management, the financial impacts associated with the simultaneous occurrences of devastating insurance losses are well known as the systemic risk. The effect of systemic risk is particularly pronounced when it comes to catastrophic insurance portfolios. Mathematically, the systemic risk is described by the degree of interdependence among the insured assets within a risk portfolio. Therefore, ideal flood risk models should offer a high geographical resolution risk estimation, with which the risk analysts can account for the dependencies of flood losses across different regions. In addition, this dependence information is necessary for the estimation of aggregated losses, capital reserve, capital allocation and risk reporting.

4. **Validation.** Best practices in the insurance industry require that insurers develop and use quantitative models containing sufficient technical soundness, transparent documentation and strict oversight of the model validation process. Many external flood risk models lack detailed documentation and operate as black boxes. This may impose considerable technical difficulties for validation. Therefore, models of this kind may not be directly suitable for insurance applications. Moreover, a benchmark flood risk model that is widely accepted by the insurance industry should be at least identified so that the comparison, analysis and enhancement of various alternative models can be supported in a coherent manner.

5.2.1 Flood Hazard Models

The primary aim for flood hazard models is to estimate the frequency and intensity of the damaging floods. Depending on the types of floods, their characteristics can be very different. For exposition reasons, in this part of the report we focus on riverine floods only, while similar frameworks can be adopted to study other types of floods. In the context of the riverine floods, the analysis of the flood hazard can be separated into two major modeling domains: the discharge models and the hydraulic models (Wright, 2015). Speaking loosely, the former models study the causes of the floods, whereas the latter ones study their evolution. Next, we discuss these two types of models in more detail.

In hydrology, discharge is the flow rate of water running through a given cross section of the river (Meals and Dressing, 2008). High levels of water discharge that cannot be accommodated by the stream channel lead to the overbank flood. The estimation of water discharge can be accomplished by using either a statistical model (if the availability and quality of data permits) or by simulation. In many regions water levels and discharges have been recorded for a relatively long period of time. A comprehensive related database in the U.S. is the United States Geological Survey (Rosen and Lapham, 2008). Nevertheless, changes in land use and land cover often occur within the data record period and can considerably harm the quality of data.

Having the desired records, flood risk analysts look to estimate the probability distribution of discharges. Common probability distributions used to this end are typically heavy-tailed, at least to an extent, including log-normal, log-Pearson and generalized Pareto (Wright, 2015). Heavy-tailed distributions are essential for counting the potential occurrence of extremal water discharges (Hao et al., 2015). We have already mentioned that the statistical modeling approach depends crucially on the availability and quality of relevant data. Often, therefore, the preferred statistical modeling methods are not feasible, and other directions must be pursued.

When historical discharge is not available or is of poor quality, rainfall data to estimate the discharge distribution may serve as a substitute. The resulting rainfall-runoff models, which are essentially simulation-based hydrologic models, map the rainfall intensity to discharge estimation. In this regard, the runoff of water from rainfall to stream discharge across the drainage basin forms a complex physical system that consists of a sequence of interlinked processes and storages modeled mathematically by a set of physical equations. Therefore, in addition to the rainfall data, applications of rainfall-runoff models also require other inputs such as land use, soils characteristics and topographical data, among others. The development of digital terrain models, which are used to manage the huge volume of geographical survey data, has shown significant progress in recent years, and these models serve as a building block for flood hazard mapping. Compared with the aforementioned statistical modeling approach, the advantage herein is that the rainfall data is relatively easy to obtain, and is, as a rule, of better quality. The disadvantage, however, is the required significant amount of technical effort and specialized knowledge of well-trained hydrologists. Additionally, certain topographical information of the rainfall-runoff landscape is necessary, which can be expensive to generate.

We have thus far discussed the statistical models that aim to generate the probability distribution of the water discharge in the event of flood. The estimated probability distribution of water discharge is one of the key inputs for the hydraulic models. Another important input is the topographical information managed by the digital terrain maps (DTM) (Sojka and Wróżyński, 2013). The output of the hydraulic models are the predictions of such flood intensity characteristics as flood extent, depth, duration and velocity (Wright, 2015).

A vast number of hydraulic models have been developed in the state of the art, and the methodologies behind them vary significantly depending on the model complexity and data requirement. The majority of the hydraulic models are based on computer simulation of the evolution of water evaluation. We refer the interested reader to, for example, Novak (2010) and references therein, for a comprehensive review of existing models. Generally, hydraulic models are classified into two categories: one-dimensional or two-dimensional models. We briefly elaborate on them in what follows:

- **One-dimensional (1D) models**. 1D models use a set of cross sections along the stream channel to represent the river and floodplain geometry. Typically, 1D models use the topographical information provided by the DTM and the time series of discharges as inputs. By solving the so-called 1D Saint Venant equations (Labadie, 1994), the 1D models simulate the flow processes and estimate the flood intensity at the output step. An example of a popular flood risk software that hinges on the 1D models is the HEC-RAS, developed by the U.S. Army Corps of Engineers (USACE, 2016). 1D models are considered somewhat simplistic, and as such, they are more suitable for modeling floodplains where the terrain is relatively uniform.

- **Two-dimensional (2D) models**. When the terrain of the stream channel and the floodplain is complex—for example, in the presence of estuaries, waterways, impediments or other areas where irregular flow may occur—the results provided by the 1D models are no longer reasonable. In such cases, 2D models may become more appropriate. Compared with the 1D models, in which the water flow must be in the same direction as the channel, the 2D models can calculate water flows that are parallel or nonparallel to the main flows. Examples of popular software packages that rely on the 2D models include HEC-RAS-2D and Hazus-MH (World Bank, 2014).

A rare improvement comes with no price. Namely, the greater sophistication of the 2D models imply more intensive computation and stricter data requirements. It has been a common agreement in the literature that water flows along the stream channel are adequately modeled by the 1D models, whereas the 2D models can provide appreciable improvement for modeling water flows on floodplains. Therefore, the practice now widely accepted by flood risk analysts is to use the 1D physical equations (i.e., the Saint Venant equations) to simulate channel flows, then use the 2D continuity equations to approximate the flow over the floodplain area. In so doing, the computational efficiency of the 1D models is preserved and the advantage on accuracy of the 2D models for floods over complex terrain is gained.

We conclude noting that three-dimensional (3D) hydraulic models have been developed in the literature, too. However, the implementation of the 3D models requires a significant number of data inputs, computational resources, and scientific expertise. Due to this complexity, the 3D models are rarely used to model flood risk. That said, along with the recent remarkable development in technology and computational power, the potential application of the 3D models has been growing in importance and popularity (World Bank, 2014). The interested reader is referred to World Bank (2014) for a comprehensive review of the toolbox of flood hazard models available today, and to Prinos (2008) for a more detailed technical review of the common flood hazard models.

5.2.2 Vulnerability Models

Once the intensity of the flood event has been estimated for a given floodplain under a particular flood scenario, the financial loss for a specific property can be assessed. The major objective of vulnerability models is exactly that: to estimate the economic consequences of floods at a given level of flood intensity. Although flood hazards can lead to a variety of socioeconomic losses, we mainly focus on direct tangible losses, which are also the most obvious and easy-to-quantify type of flood vulnerability. Depending on the application purposes, the outputs of vulnerability models can be in forms of absolute damage expressed in monetary units (Prettenthaler et al., 2010), or relative damage as the propensity to the total damage out of the total asset value (Dutta et al., 2003). A benefit for using relative models is that the vulnerability estimation can be conveniently translated to another property having similar characteristics. Nevertheless, working with absolute damage, the impacts of insurance cover modifications such as deductibles and limits are easier to incorporate.

In the state of the art, the so-called depth-damage curves are the classical flood vulnerability quantification tools that describe the deterministic relationship between the flood depth and asset damage. The depth-damage curves estimate the damage based on one flood intensity factor only; therefore, they are considered a univariate model. In addition to the inundation depth, the implementation of the depth-damage curves requires other inputs, such as building types (commercial, residential or governmental).

Although it has been an internationally accepted belief that flood damage is mainly influenced by the inundation depth, the inclusion of additional predictors of flood intensity metrics, for example, duration, flow velocity and contamination, as well as the asset's characteristics, such as building type, quality, number of floors should provide notable improvement of the prediction power of the vulnerability models. Vulnerability models that account for more than one predictor are considered to be multivariate.

Another implicit feature of the depth-damage curves is that they are deterministic models producing point estimators of the flood damage. As only those flood risk models that depend on probabilistic tools can be considered fully risk-informed, the implicit determinism of the depth-damage curves is rather unfortunate. Furthemore, 94% of the existing vulnerability models are deterministic. A few probabilistic vulnerability models have been put forward. For instance, Zhai and colleagues (2005) derives the flood damage probability distribution depending on the likelihood of a property to be affected by the flood, and Schröter and colleagues (2014) uses Bayesian networks to model the joint probability distribution of flood damage and a variety of floods' and assets' characteristics.

In summary, we have reviewed two quantitative components of the flood risk modeling, flood hazard models, which characterize the intensity of flood, and vulnerability models, which characterize the level of the resulting damage. As we have emphasized, the end output of a flood risk model should provide the probability distribution of the flood damage over a predefined interval of time. This probability distribution should reflect two random sources, where one comes from the stochastic nature of the flood events and the other is due to the uncertainty in the property damage. Based on the discussion in Section 5.2, only those flood risk models that hinge on probabilistic tools when modeling both hazard and vulnerability components can be considered fully risk-informed. This is a rare case in current practice, in which the majority of the vulnerability models are deterministic.

5.3 Discussion and Future Improvements

Although public flood risk insurance had been available in the U.S. since the 1970s, the need for its privatization did not draw much public attention until the past decade, when the federal insurance program started to present a larger and larger amount of financial deficit. Therefore, the original intent of the majority of the existing flood risk models was to assist regional officials in land-use planning, mitigation project assessment and emergency response. The direct applications of the existing flood risk models for private insurance practices are hence not straightforward. Rath and Borrel (2015) outline a number of practical limitations for the usage of the existing flood risk modeling framework in insurance applications against the qualitative criteria presented in Section 5.2. In what follows, we highlight some of these limitations and then propose possible involvement of the actuarial professionals in addressing the related issues.

- **Reconciliation and attribution.** Unlike many other property and casualty loss models, the existing flood risk models are as a rule not able to model claim frequencies and severities separately. In addition, the existing flood risk models are not able to provide insights into how marginal risk factors affect these frequencies and severities. Further actions are needed to address this important issue.

- **Risk-informed prediction.** The majority of the vulnerability models available nowadays provide a point estimator of the damage due to the flood event, rather than a probability distribution of such damage. A point estimator, as a single number, is barely insightful as to the stochastic properties of the damage, yet these properties are utterly desirable for risk analysis.

- **Granularity.** First, many flood risk models are area-specific, and therefore not generic. On the one hand, risk analysts should indeed select the best available model, yet, on the other hand, an application of flood risk models that vary by geographical region raises inconsistency in the aggregated risk management. Second, modeling the dependence of flood risks across different spatial and temporal dimensions is important for, at the very least, the sake of good modeling and also to reap its benefits by realizing the diversification effect, for example.

- **Validation.** Recent regulatory accords (e.g., Solvency II) require insurance companies to continuously monitor the validity of the insurance models in use. However, flood risk models contain complex mathematics methodologies and rely on a large volume of data, thus, as a rule, require extensive time commitment and personnel resources. Hence, flood risk models may not always reflect the most up-to-date climate, environment and landscape information.

Recall that we started this report reiterating the diversity and multidisciplinarity of the notion of flood risk. It is that noticeable breadth of the challenge that requires active involvement of a variety of distinctly trained parties. While conducting this study, we have discovered that the communication between these parties—engineers, geophysicists, environmental scientists—and actuaries is often missing or inadequate. As a result, we have found that often, sound understanding of the assumptions, methodologies and limitations of the existing flood risk models is not evident in insurance applications. We conclude this section by outlining three specific examples on how actuaries can be of significant help in not only tailoring the existing flood risk models to be successfully applied in insurance, but also in improving some capabilities of these models that are well beyond the classical actuarial zone of interest.

- **Example 1**: **Predictive analytics techniques for flood hazard modeling.** In Section 5.2.1 we mentioned that the statistical properties of the water discharge and rainfall data must be well understood, as these factors serve as crucial inputs for the flood hazard model. Water discharge and rainfall data are highly variable and exhibit complex seasonality patterns. Hence relevant statistical modeling often requires advanced skills in time series analysis. The machinery that actuaries have developed in order to determine patterns in time series data in the context of insurance claims can be utilized in the context of water discharge and rainfall data to make better predictions and identify connections (Frees and Velu, 1990).

- **Example 2: Predictive analytics techniques for flood vulnerability modeling.** Section 5.2.2 stressed the importance of the flood vulnerability step, as a natural consequence of the flood hazard modeling. It seems that the skill set of generalized linear models (GLMs) that actuaries have been using extensively for a long time to handle large data sets in property and casualty insurance ratemaking is of particular relevance and can be applied effortlessly (see Goldburd et al., 2016, for a comprehensive review of GLMs for insurance application). Possible directions for applying the actuarial know-how are perhaps (1) to use the GLM with mixed effects to develop probabilistic vulnerability models in which the randomness is concealed in both the stochastic nature of financial losses and parameter uncertainty (Jiang, 2007), and (2) to employ double-generalized linear models to model vulnerability data containing extremal losses (Paula, 2013).

- **Example 3**: **Sophisticated statistical modeling techniques for describing dependencies.** Interdependencies among notions of interest are of importance in virtually every step of the risk-informed flood risk modeling. One example is the framework of vulnerability models. We have already mentioned the usage of Bayesian networks to formulating the joint probability distribution of flood damage and related risk factors such as flood intensity, and characteristics of the property of interest (see Section 5.2). Copulas are an alternative way to tackle dependencies. In the context of insurance applications, copulas have become an important element of today's best practice, displacing in many contexts other, more conservative approaches to modeling dependence. Remarkably, many theoretical developments in the area of copulas stem from the actuarial community. One such development is of particular interest for the sake of flood risk modeling. More specifically, a recent invention, multiple risk factor copulas enjoy the interpretability of the well-known factor models and the flexibility of the margins-independent dependence modeling (Hua and Joe, 2017; Su and Furman, 2017). By involving multiple risk factor copulas, classes of multivariate probabilities models can be used to better study the attribution of risk factors of interest.

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