



Technical Notes

Methods in Flood Hazard and Risk Assessment



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BACKGROUND

This technical note provides an overview for authorities who wish to conduct flood hazard and risk assessments and who must develop a step-by-step plan for carrying out the assessment that is appropriate and feasible in the local context. It is important to keep in mind, however, that many aspects of flood hazard and risk assessment require specific expertise and experience. It is not advisable to conduct these assessments if your team lacks this experience, and this technical note does not provide specific guidelines, which can vary dramatically depending on local and regional conditions.

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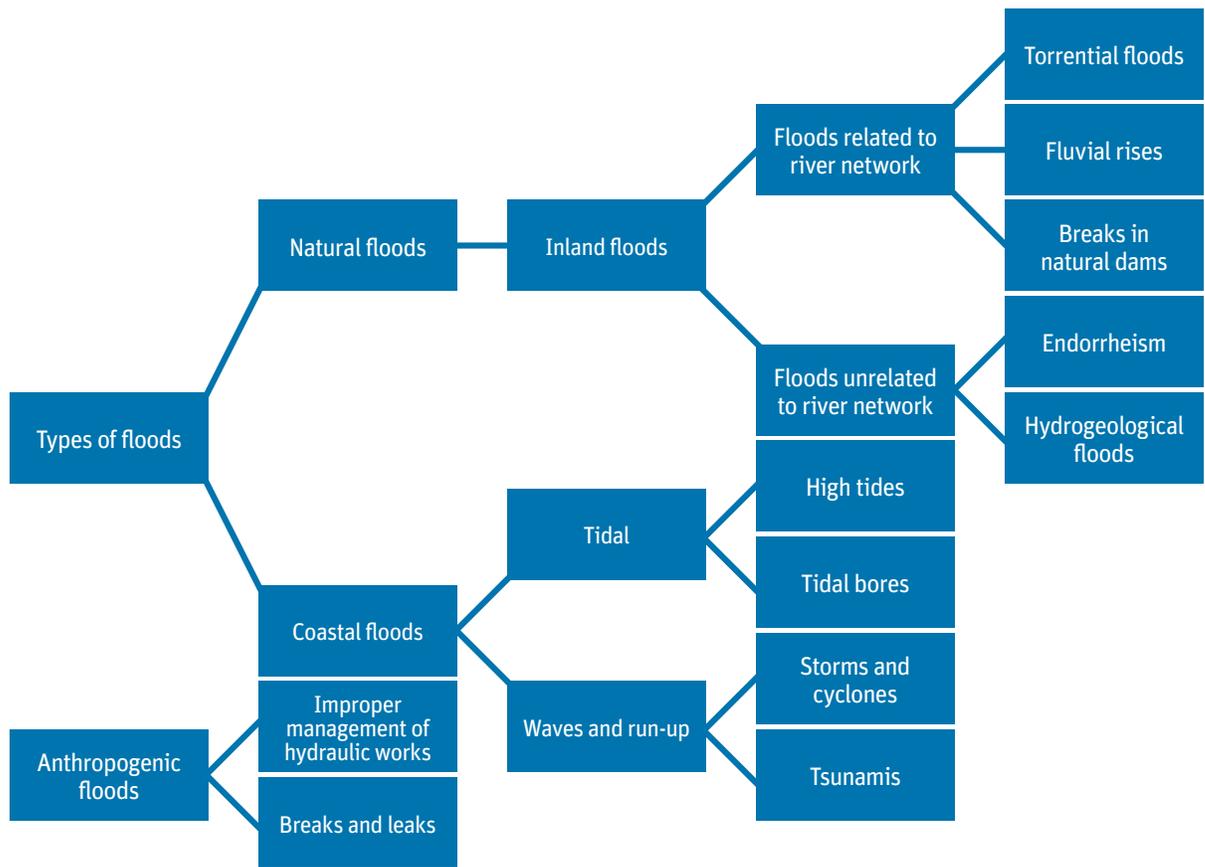
Technical review by Maria Carolina Rogelis, Senior Consultant on Flood Risk Assessment.

INTRODUCTION

Floods are amongst the most frequent and destructive type of disaster, causing significant damage and disrupting livelihoods throughout the world. There is a wide range of flood risk management methods available that can reduce this destruction, and managing flood risks requires the estimation of flood hazards and the impacts that they can cause. Proper estimation of risk is challenging and requires careful consideration of a number of factors, including watershed properties such as size, topography, and land use, the types and characteristics of storms that produce rainfall and flooding in the region, and the number, location, and types of buildings and other assets that could be damaged. Poorly-conducted hazard and risk assessments can lead to poor risk management decisions, from insufficient protection to the wasting of scarce finances on unneeded protection. Well-conducted flood hazard and risk assessments, on the other hand, can provide valuable support for a range of decisions such as land-use master planning, design of infrastructure, and emergency response preparation.

Different types of floods can be found in Figure 1. Before a hazard assessment is carried out, it is necessary to determine which types of floods are most common or destructive in the area, because in most cases the selection of hazard and risk modeling methods will vary depending on the type of flood. Detailed specifications for flood hazard assessment can be found in (FEMA, 2003a). While this technical note focuses on **fluvial floods** (i.e. floods in river systems), the general concepts are applicable for the other types of floods shown in Figure 1.

Figure 1 Types of flood hazards



Adapted from (Díez-Herrero, Huerta, & Isidro, 2009).

FLOOD HAZARD ASSESSMENT

Overview

A natural hazard is a potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation (UNISDR, 2004). “Potentially damaging” means that there are elements exposed to the hazard that could, but need not necessarily, be harmed (Gouldby & Samuels, 2005).

The goal of flood hazard assessment is to understand **the probability that a flood of a particular intensity will occur over an extended period of time**. Hazard assessment aims to estimate this probability over periods of years to decades to support risk management activities.¹ Intensity usually refers to the combination of flood depth and horizontal flood extent; although other intensity measures such as flow velocity and flood duration can also be important depending on the situation.

This relationship between the probability of a flood and its intensity gives rise to the concept of **return period (also known as recurrence interval)**, represented by the symbol T and expressed in terms of years. A T -year flood is the flood intensity that has a probability of $1/T$ of being exceeded in a given year. This probability is called the **exceedance probability**. For example, there is an exceedance probability of $1/10$ (0.10) that in a given year that a flood larger than the 10-year flood intensity will occur. Flood hazard assessments usually aim to estimate the flood intensity for a range of exceedance probabilities, for example from 0.1 to 0.001. It is important to point out that this definition of return period is contrary to what the term “10-year flood” or “100-year flood” would seem to imply, (i.e. the intensity of a flood that would occur once every ten or one hundred years). This is a major source of confusion and misunderstanding around the definition of return periods and can result in improper estimation or perception of hazard and risk.

Estimation of design discharge

This section focuses on the methods used to estimate **design discharge**, or the rate of the flow of water through the river or floodplain. The two most frequently-used approaches are outlined here—discharge-frequency analysis and rainfall-runoff modeling. While other methods are sometimes used, they typically supplement, rather than replace, one or both of these two approaches.

Discharge-frequency analysis approaches can be used to estimate **peak discharge**, or the maximum flow rate of water that passes a certain location during a flood. Rainfall-runoff modeling can also be used to estimate peak discharge and usually also a **design hydrograph**, or an estimate of the flow rate past a certain location over a period of time. Figure 3 demonstrates the relationship between a discharge hydrograph and peak discharge. A detailed review of riverine and coastal flood hazard assessment procedures, tools, and data can be found in (Prinos, 2008).

1. This contrasts with early warning systems, which aim to issue warnings over periods of minutes to days to facilitate emergency response actions.

Statistical Discharge Frequency Analysis

This approach relies on the existence of long records of accurate river discharge measurements. Usually, the highest recorded discharge record from each year is used in the analysis. For example, if there are 30 years of daily discharge measurements available at a particular measuring station, then 30 data points are used in the discharge-frequency analysis, each one corresponding to the largest daily discharge observation from one of the 30 years of record. These data points are referred to as **annual discharge maxima**. Once these data points have been identified, the analyst fits several statistical distributions (for example: log-normal, log-Pearson, or generalized extreme value) and selects the distribution that most accurately describes the data. Figure 2 illustrates this type of analysis performed using discharge measurements from a station in Puerto Rico. A partial list of tools for performing statistical analysis tools can be found at (FEMA, 2012). It must be emphasized that the proper application and interpretation of statistical procedures requires substantial experience and specialized knowledge.

Important considerations in discharge frequency analysis:

- The discharge records must be of good quality. Proper measurement of discharge requires maintenance of equipment to provide for continual automatic monitoring of water levels, as well as verification using field measurements of flow and river cross sectional profiles at a range of flow conditions at least several times per year (Buchanan & Somers, 1969).
- The discharge records must be sufficiently long to estimate the return periods that are required for the flood hazard analysis. There is no single guideline, but records should be at least 10 years in length to perform any sort of frequency analysis (Interagency Advisory Committee on Water Data, 1982), and longer if estimates of low exceedance probabilities are desired.
- The temporal resolution of the discharge record needs to be fine enough to measure the important properties of floods in the river. For example, daily discharge measurements are adequate on large rivers but not for steep mountain watersheds or in small urban basins, where automated measurements at time intervals of 1–5 minutes may be needed.
- The upstream area cannot have undergone significant changes in terms of land use such as urbanization, agricultural development, or deforestation over the period of the discharge record. If significant changes have taken place, the results of standard statistical analyses will not be valid. More advanced statistical methods exist that attempt to account for these challenges, but still have significant limitations and are generally not recommended for decision-making (Villarini, Smith, Baeck, Sturdevant-Rees, & Krajewski, 2010).

Figure 2 LEFT—Plot of annual maxima discharge observations from 1965–2011 for the U.S. Geological Survey discharge gage station on Rio Grande de Manatí near Morovis, Puerto Rico. **RIGHT**—comparison of statistical models based on the generalized extreme value and lognormal distributions for the annual maxima discharge observations on Rio Grande de Manatí near Morovis.

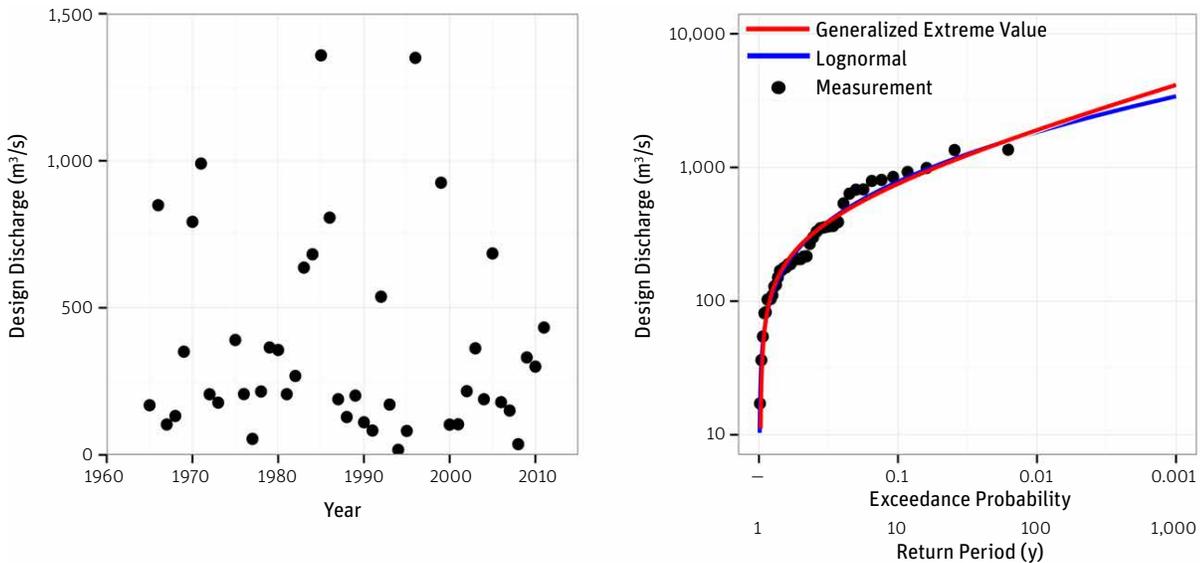
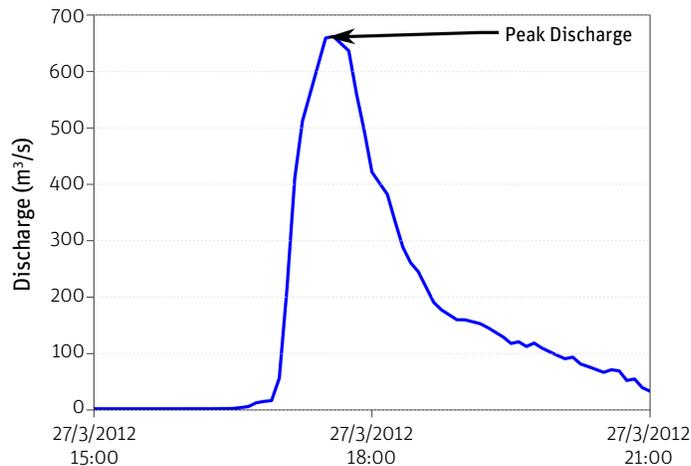


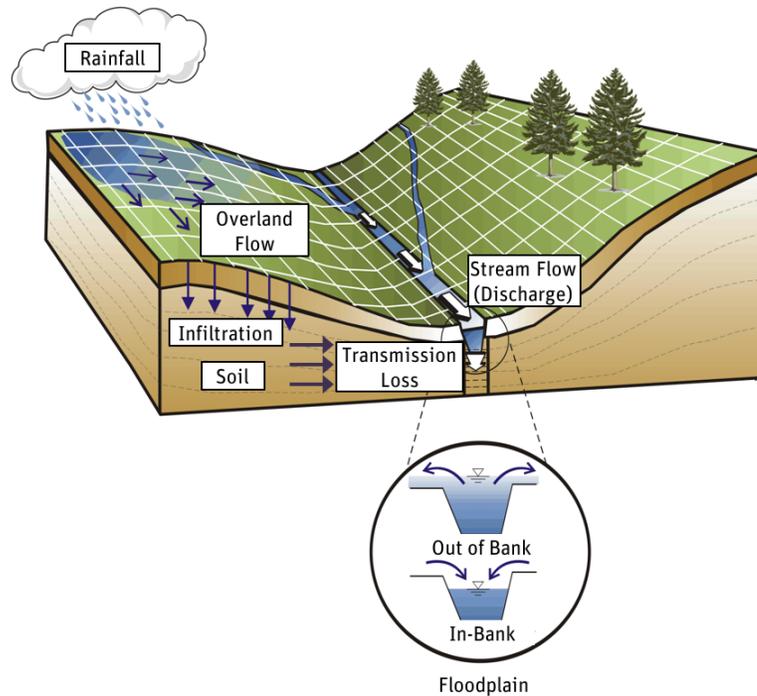
Figure 3 Example hydrograph and peak discharge value from a heavy rainfall event on March 27, 2012, measured at the U.S. Geological Survey discharge gage station on Rio Grande de Manatí near Morovis, Puerto Rico.



A design discharge obtained from discharge-frequency analysis is usually only valid in the vicinity of the measurement station, particularly if there are important tributaries or other discharge sources upstream or downstream of the station. Consequently, a relatively large number of measurement stations are needed to adequately estimate design discharges over a large or complex river system.

Rainfall-runoff modeling

Figure 4 Diagram showing the general components of grid-based rainfall-runoff model



Adapted from http://www.engr.colostate.edu/~pierre/ce_old/Projects/TREX%20Web%20Pages/TREX-Home.html (accessed 6 January 2014).

In many situations, discharge measurements are either nonexistent or of insufficient quantity or quality to be able to conduct a discharge frequency analysis as described in Section 2.2.1. In such situations, one of a broad class of tools known as **rainfall-runoff models** (also referred to as **hydrologic models**) can be used to convert estimates of extreme rainfall into design discharge estimates and design hydrographs. To do so, they must represent the movement of water across the landscape (a process known as **runoff**) and into the river channel. Some of the basic hydrologic processes that these models consider are shown in Figure 4. Many different rainfall-runoff models exist, each with certain advantages and disadvantages depending on a range of factors such as application, geographic setting, and data availability, and knowledge level of the user. A list of most commonly accepted models for flood applications can be found at (FEMA, 2014). It is extremely important to consider these factors when selecting a rainfall-runoff model. While some of these models are very simple and can involve simple hand calculations, most are complex, computer-based, and require specialized knowledge to be used correctly. The two main classes of rainfall-runoff models are:

- **Lumped:** Lumped models treat the watershed as a single unit. Calculations are performed using simplified, spatially averaged processes. The resulting discharge estimate only applies to the watershed outlet (the most downstream modeled point of the river network). Well-known lumped models include TR-55 and other unit hydrograph-based methods.
- **Distributed:** Distributed models use spatially varying input data for processes such as precipitation, infiltration, interception, interflow, infiltration, and base flow estimating discharge or other variables.

This kind of model demands more data than lumped models but are more flexible and can be more accurate. Distributed models are often intended for use at a particular scale range, such as small urban watersheds (SWMM, GSSHA, Vflo, OpenLISEM) or large river basins (VIC). Most distributed models, if properly used, can provide discharge estimates at various locations along the river network.

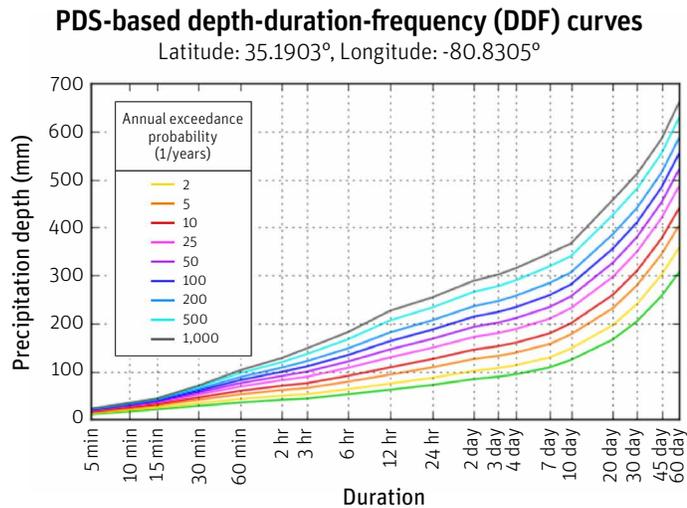
Some popular models, such as HEC-HMS, discretize the watershed into a number of subwatersheds, each of which is then represented using a lumped rainfall runoff model. The results of the individual lumped models can thus be combined to estimate watershed response at various points. This way, some of the advantages of lumped and distributed models can be combined.

In addition to the selection of a proper rainfall-runoff model, the suitability of this approach to flood hazard assessment depends on availability of high-quality local or regional rainfall datasets and other information to characterize the watershed such as topographic maps or digital elevation models (DEMs), land cover and soil information, and the location and properties of river channels and other water bodies. It is also crucial that measurements of rainfall and either flood discharge or flood extent are available for one or more past floods so that the model can be verified and adjusted to account for local conditions. The process of verification against local measurements is known as **validation**; the process of adjusting various components of the model so that the simulated results better match local measurements is known as **calibration**.

Once a model has been calibrated and validated, it can be used for estimating design flows. While more sophisticated approaches exist, the usual starting point is to conduct a rainfall frequency analysis on annual rainfall maxima. The rainfall frequency analysis procedure is similar to that described for discharge frequency analysis in Section 3.2.1, and is subject to many of the same general challenges. One important additional component in rainfall frequency analysis is that the rainfall **duration** must also be selected. Proper selection of rainfall duration is very important because floods in small urbanized or mountainous watersheds result from extreme rainfall lasting several minutes to several hours, while in large river systems, flooding can result from rainfall lasting several days to several weeks. Therefore, selecting the improper rainfall duration can lead to poor estimates of flood discharge. Guidance on the selection of rainfall duration can be found in most introductory hydrologic engineering texts (see for example (McCuen, 2005)).

Rainfall frequency analyses have already been conducted for some areas. In these cases, the results are presented as intensity-duration-frequency (IDF, also sometimes referred to as intensity-frequency-duration) curves. Examples of IDF curves are shown in Figure 5. Ideally, IDF curves are provided for multiple durations and for a wide range of return periods. If the desired rainfall duration or return lies between two IDF curves, the proper rainfall intensity can be linearly interpolated from the published curves. These curves can facilitate rainfall-runoff analyses, but have important limitations, especially in large watersheds and for long-duration rainfall (note, for example, that the rainfall durations shown in Figure 5 only extend to 60 minutes). More robust alternatives are available but not widely used (see, for example (Wright, Smith, & Baeck, 2014)).

Figure 5 Example IDF curves



Source: Bonnin, G. M., Martin, D., Lin, B., Parzybok, T., Yekta, M., Riley, D., (2006), NOAA, Atlas 14 Precipitation-Frequency Atlas of the United States Volume 2, Version 3.0: Delaware, District of Columbia, Illinois, Indiana, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, West Virginia, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, Maryland.

Once a rainfall intensity of a given return period is estimated, it is usually assumed that, when used as input to the rainfall-runoff model, the resulting simulated discharge has the same return period. For example, if the 12-hour duration 100-year rainfall intensity is estimated for the region containing the watershed and then used as input to the watershed rainfall-runoff model, the simulated peak discharge output is assumed to be an adequate estimate of 100-year peak discharge. This assumption is not strictly valid for several reasons and more advanced methods can be used to avoid it, but it is generally accepted in standard flood hazard practice (Wright, Smith, & Baeck, 2014).

There are several important considerations when estimating design discharge using rainfall-runoff models:

- The rainfall records must be of good quality. Proper rainfall measurement requires proper installation as well as frequent maintenance of equipment and its surroundings (Curtis, 1996; Sieck, Burges, & Steiner, 2007).
- The rainfall records must be sufficiently long to estimate the return periods that are required for the flood hazard analysis. There is no single guideline, but records should be at least 10 years in length to perform any sort of frequency analysis (Interagency Advisory Committee on Water Data, 1982), and longer if estimates of very low exceedance probabilities are desired.
- In addition to having sufficiently long rainfall records of the appropriate duration, it is usually necessary to have multiple rain gages over the region or watershed because there can be significant spatial variations in rainfall intensity within individual storms. Multiple gages allow for the characterization of this variation and for the interpolation of rainfall to fill in gaps between gages. There are no simple guidelines for how many rain gages are needed nor for how these gaps should be filled. Accounting for spatial variation in rainfall is particularly challenging in mountainous areas due to topographic influences on storm motion and rainfall generation. When available, rainfall estimates from weather radar or satellites can be used to assess spatial variations of rainfall, but significant experience is needed to properly use such datasets for flood applications.

- The temporal resolution of the rainfall record needs to be fine enough to measure rainfall at the durations that cause flooding in the watershed. For example, hourly rainfall measurements are insufficient to estimate the short-duration rainfall that causes floods in steep mountain watersheds or in small urban areas (Schilling, 1991; Berne, Delrieu, Creutin, & Obléd, 2004), but can be adequate for larger rivers.
- Depending on the region and the selected rainfall-runoff model, additional detailed information is needed. This information can include land cover data, the location and characteristics of river channels, and information to characterize soils and groundwater flow.
- It is difficult to perform rainfall-runoff modeling in watersheds that have significant regulation (i.e. manmade controls of river flows via reservoirs and other hydraulic infrastructure). Some rainfall-runoff models provide the capability to include these effects, to varying levels of detail. Even if a selected model has this capability, however, it is rare that the modeler has information regarding how this infrastructure will be operated during flood conditions.
- If flood hazard and risk estimates are needed at many points in a large watershed, it will be necessary to perform multiple simulations with different rainfall properties (i.e. different rainfall durations and intensities). This is because the rainfall duration and intensity that causes floods in the main river will be different than the rainfall duration and intensity that causes floods in the smaller upstream tributaries (Wright, Smith, & Baeck, 2014).

The challenges associated with rainfall-runoff modeling point to the necessity of trained hydrologists, preferably with previous experience in the region and with the specific rainfall-runoff model selected.

Hydraulic modeling and floodplain mapping

Once a design discharge (either a peak discharge value or hydrograph) has been estimated, it is transformed into an estimate of flood water elevation, known as **flood stage**, and an estimate of velocity using a **hydraulic model** (also called a hydrodynamic model). In the past, these models were often small-scale physical models, but now they are almost always computer-based simulation software. There are many hydraulic models that vary significantly in complexity and data requirements. A list of commonly-used models can be found at (FEMA, 2014). An experienced modeler can select the most appropriate model based on the location, the needs of the risk assessment, and the available data. The two most common classes of hydraulic models are:

- **1-Dimensional (1D):** 1D models are simplified models that characterize the terrain using a series of cross sections. At each cross section, the flow depth and velocity perpendicular to the cross section is computed. These models are well suited for areas where the flow direction is well defined. The best-known 1D model is HEC-RAS from the U.S. Army Corps of Engineers. HEC-RAS is free to download at <http://www.hec.usace.army.mil/software/hec-ras/>.
- **2-Dimensional (2D):** 2D models calculate the flow both parallel and non-parallel to the main flow. They are useful for modeling areas of complex topography such as wider floodplains or broad estuaries but require high quality data and can require long computation times. Examples of 2D models include TELEMAC 2D, SOBEK 1D2D, and Flo2D. Because of their greater sophistication, most 2D models are not freely available.

Some models, such as LISFLOOD-FP, are called quasi-2D, and combine some of the benefits of 2D models with some of the simplicities of 1D models. There are also 3-dimensional (3D) models, which have been rarely used for flood hazard assessment in the past due to their complexity and cost. However, the use of 3D models such as Delft3D is increasingly common, particularly for simulating coastal flooding due to storm surge.

Hydraulic models can be run in two different ways, depending on the application and the nature of the input design discharge. If the design discharge is a peak discharge estimate, then the models must be run in a steady flow mode. This is the least intensive mode from a computation standpoint. While steady flow mode is frequently used in flood hazard assessment, it may not capture the complicated flow dynamics in complex terrain such as urban floodplains. If the design discharge is a complete hydrograph, then the models may be run in unsteady mode, in which discharge rates and water levels across the model area can vary over time. Unsteady simulations can require significant computational resources in some cases, particularly when 2D or 3D models are used.

Accurate hydraulic modeling requires detailed information regarding the river channel and the floodplain. Some hydraulic models, such as the quasi-2D LISFLOOD-FP, rely on a single **digital terrain model (DTM)** consisting of regularly-sized square grid “cells” in which the channel and the floodplain are both represented.

Most 2D models also use make use of data from such a DTM, but require conversion from a regular square grid to a triangular mesh prior to simulation. As previously mentioned, most 1D models such as HEC-RAS make use of multiple cross-sections which are perpendicular to the predominant flow direction and which incorporate both river channel and floodplain geometry. This geometry can come from ground surveys or from aircraft-based instruments. Given the difficulty of conducting precise ground-based topographic surveys over large areas, aircraft-based instruments such as LiDAR (Light Detection and Ranging) are the most common method for collecting floodplain topographic information for large-scale flood modeling activities. For shorter river sections, however, field surveys are still commonly used. It should be noted that the collection and preparation of these data can be quite expensive and requires specialized expertise. A detailed procedure for commissioning a LiDAR survey can be found in (FEMA, 2003 (b)). Geometric information of river or lake beds or the seafloor, called **bathymetry**, requires field surveys or LiDAR and can be difficult to collect for large or deep water bodies. In some cases, bathymetric data are not necessary for flood hydraulic modeling in rivers because the channel features can be adequately represented by idealized rectangular or trapezoidal shapes. This decision should be made only by an experienced hydraulic modeler.

While the required accuracy of the DTM varies depending on the specific location and level of detail required by the study, vertical precision should be 1–2 meters or better. In some cases, vertical precision must be 5–10 centimeters. Consequently, freely available topographic datasets based on satellite observations such as SRTM or ASTER GDEM are not adequate for hydraulic modeling in many settings. The required horizontal resolution depends heavily on the specific application and on local conditions, and can vary from approximately 1 meter up to 100 meters or more.

In addition to topographic and bathymetric information, hydraulic models require the specification of the **hydraulic roughness**, or resistance to flow, of the river channel and the floodplain. The roughness is low in bedrock river channels that are free of vegetation or debris and high in a debris-filled river channel or a floodplain that has thick vegetation or buildings. Estimates of hydraulic roughness are usually based on expert judgment using visual surveys or aerial photography. Manmade structures such

as bridges, culverts, and levees or geological features such as rock outcrops that can impede flood flows can be very important for hydraulic modeling and usually require field surveys.

As with rainfall-runoff modeling, calibration and validation are crucial steps in hydraulic modeling. Usually this consists of adjusting model parameters (typically hydraulic roughness) while simulating past floods in an attempt to recreate observed water elevations and flood inundation extents. It is important, therefore, that flooded locations and maximum water levels be recorded during post-flood field damage surveys or using aerial or satellite photography (Gaume & Borga, 2008; Abhas, Bloch, & Lamond, 2012).

Once the hydraulic model is properly configured, calibrated, and validated, it can be used for flood extent mapping. An example of a 100-year flood extent map is shown in Figure 6. In this example, only flood extent is shown. In situations where flow velocity is high, both flood depth and velocity maps should be produced. Fortunately, all hydraulic models readily calculate both water level and velocity.

In the case of 2D models, the flood extent, depth, and velocity can be visualized directly in the model output. For 1D models, it is usually necessary to project the estimated flood water levels onto a DTM to estimate flood extent and depth. This DTM is often the same as that used to configure the model. If not, the two DTMs must share a common elevation datum and the same aforementioned precision and horizontal resolution requirements apply.

Historical flood information from major flood events can also be used to produce flood hazard maps. These maps can be the result of carefully-conducted field surveys, aerial photography, or more recently, satellite-based imagery. In order to estimate the frequency of flood hazard, flood extent maps from multiple past floods are available. These maps do not exist in many locations and thus, in practice, flood extent maps and imagery are more commonly used for hydraulic model calibration.

Figure 6 Example of 100-year flood extent map for River Eden in Carlisle, UK



Source: <http://web.sbe.hw.ac.uk/frmrc/index.htm> (accessed 6 January 2014, see https://web.sbe.hw.ac.uk/frmrc/downloads/teaching_materials/Licence.pdf for copyright information).

VULNERABILITY ASSESSMENT

Overview

The other major component of flood risk, aside from flood hazard, is flood **vulnerability**. The goal of vulnerability assessment is to understand how a system will be affected by floods. Examples of possible systems could include physical structures such as houses or bridges that could be damaged or destroyed, a business or service whose supply chain could face interruption, or a community that could suffer fatalities, property losses, and negative health impacts in the aftermath of a flood.

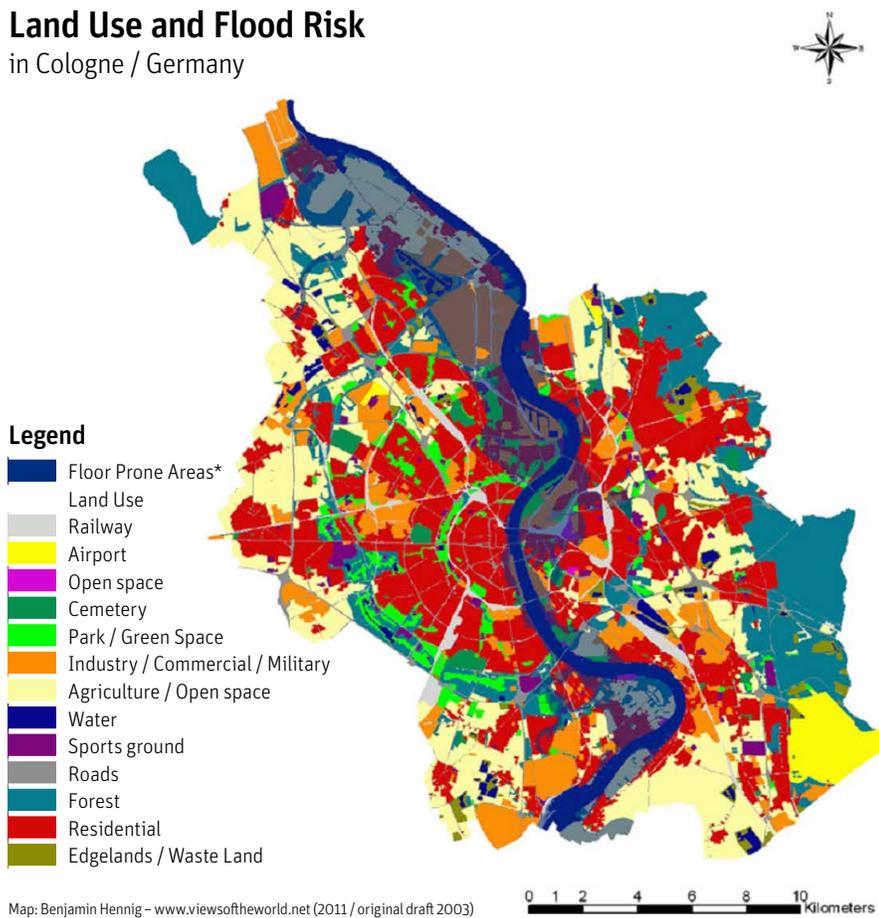
There are different classes of vulnerability. Some of these classes are briefly discussed below, but this document focuses mainly on physical vulnerability—meaning the vulnerability of the built environment to floods. The focus on physical vulnerability stems from the fact that it is the most obvious and easily quantified vulnerability class, and because in many situations it constitutes a large share of total flood vulnerability. For simplicity, flood risk studies and management efforts often only consider one or several of these classes. Regardless of the vulnerability class under consideration, mapping is a central element of any assessment. Expertise in mapping tools such as Geographic Information Systems (GIS) and Global Positioning Systems (GPS) is therefore critical.

Despite its importance, vulnerability assessment for floods and other natural disasters has received less attention than has hazard assessment (Changnon, 2003). There have been few efforts to standardize vulnerability measurement and estimation techniques, particularly in developing countries and for non-economic measures. Depending on the context, however, non-economic considerations can be extremely important. Because of this, it is important to involve flood vulnerability experts, preferably with previous local or regional experience. In general, finer-scale vulnerability assessment will yield more accurate estimates of flood risk but at greater cost.

Exposure

The flooded area shown in a flood hazard map usually does not display the flooded houses, factories, etc. nor their respective characteristics. **Exposure** analysis, therefore, aims to examine the economic assets and activities covered by the flood (Kang, Su, & Chang, 2005). Exposure is a geospatial mapping of the types of assets of interest relative to the flood hazard (i.e. flood extent). In addition, exposure information should include at least some basic characteristics of the assets in question. For example, a risk assessment of residential properties would require exposure on information on the locations of the properties, the type, the number of floors, the floor area, etc.

Figure 7 Example of land use map for flood exposure in Cologne, with flood prone areas superimposed



Source: Benjamin Hennig – <http://www.viewsoftheworld.net/> (2011), (accessed 28 May 2014).

*Erratum: Flood Prone Areas.

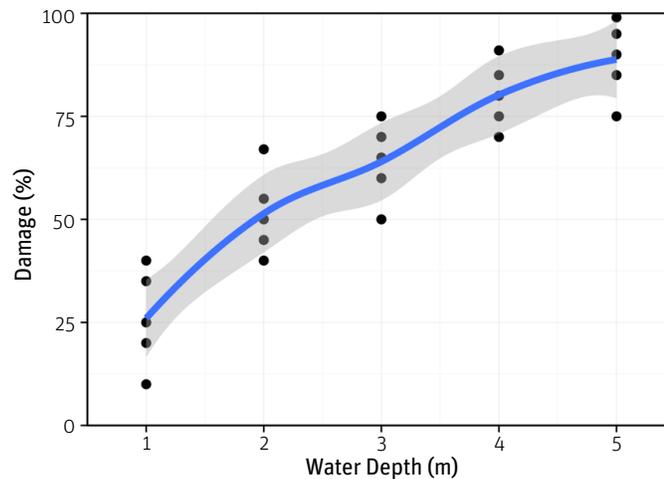
The scale at which flood exposure mapping should be conducted will vary depending on the needs of a particular flood risk assessment. Detailed mapping in urban areas can be conducted at the scale of individual buildings using handheld GPS or with aerial or satellite photography. For large floodplains, it may be preferable to model vulnerability at the scale of larger administrative units, such as lots or census tracts, or using existing land-use maps. Regardless of the chosen method, the data will be entered into a geospatial database using a GIS interface.

Physical Vulnerability

An important consequence of flooding is the damage to physical structures such as buildings, bridges, roads, and public utilities. Damage can be defined as the amount of money needed to restore the area back to its original condition before the disaster (Kang, Su, & Chang, 2005) and can be caused by lateral pressure forces, velocity forces, uplift, erosion of foundations, gradual weakening due to waterlogging, and other effects (Kelman & Spence, 2004).

Figure 8 Example of flood damage curve based on observations

The blue line is a best-fit to the observations. The gray area is an estimate of uncertainty (the 95% confidence bounds).

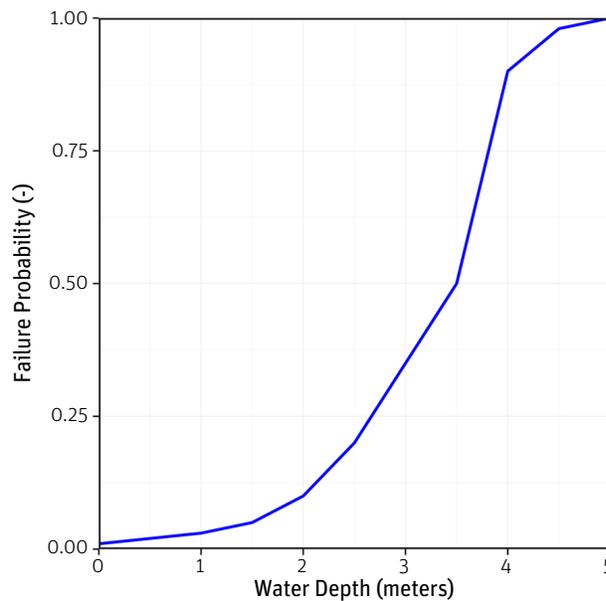


The impacts of flood forces on structures need to be understood and represented. These impacts are typically described by **damage curves** (also referred to as damage functions or vulnerability functions), such as the examples shown in Figure 8 and Figure 9. Figure 8 shows a damage curve for a structure. This curve ranges from 0% (no damage) to 100% (totally destroyed), describing the relationship between damage and flood characteristics such as water depth or velocity.

In the case of flood mitigation works such as levees, the resistance and effectiveness of infrastructure can be represented by **fragility curves** (also referred to as fragility functions). Figure 9 shows a fragility curve for a flood control levee, in which the probability of failure ranges from 0.0 at zero water depth to 1.0 at the maximum height of the levee (at which point the levee fails due to overtopping). Between these two water levels, the probability of failure is greater than 0.0 but less than 1.0 due to different failure modes such as rotational failures, piping, scour, etc. (Allsop, Kortenhaus, & Morris, 2007). It should be noted that damage can still occur to a flood mitigation structure even if the structure itself does not fail. For example, a levee may need to undergo repairs after a flood due to piping or scour damage, even if the levee is not overtopped. These repair costs could be represented as a function of height (and/or flood duration) by an additional damage curve.

Damage and fragility curves are typically assigned to particular asset classes or construction types. For example, separate damage functions should be developed for residential buildings, industrial buildings, etc. Likewise, brick houses will require separate damage functions than adobe or than wood houses. Similarly, masonry flood retaining walls will require different fragility curves than earthen levees. Determining these functions is a major challenge, as there can be significant variations in the construction type and quality even within the same structure class. In addition, there are usually very few measurements of damage based on local construction materials and practices. Structural analysis and expert opinion can help in the development of damage functions (Schultz, Goulby, Simm, & Wibowo, 2010). Estimates of economic losses will usually be very sensitive to the selected damage functions.

Figure 9 Example of fragility curve for a section of flood control levee



The most obvious direct economic impact is the cost associated with repairing or replacing damaged buildings and infrastructure. These impacts can be estimated by combining damage functions with estimated replacement costs. The replacement costs of contents such as a business's inventory or a family's possessions can also be significant and should be included in the analysis.

Nonphysical Vulnerability

In addition to the physical vulnerability of buildings and infrastructure, there are other important vulnerability classes.

The most commonly-considered nonphysical vulnerability is economic loss. There are multiple ways in which floods can have economic impacts, mostly related to the interruption of various activities that then lead to negative economic consequences. These indirect economic impacts are often much more challenging to estimate than are direct impacts to structures and building contents. Possible indirect economic impacts include:

- Lost business activity due to interrupted supply of utilities such as water or electricity.
- Lost business activity due to interruption of supply chains caused by large floods.
- Spoiling of agricultural products due to a damaged transportation network.
- Lost wages for employees due to any of the above impacts.

A detailed review of types of economic damage, several estimation techniques, and remaining challenges can be found in (Merz, Kreibich, Schwarze, & Thieken, 2010).

Social vulnerability can be another important vulnerability class. Floods can cause death directly via drowning, physical trauma, or secondary effects such as the failure of water and sanitation services, the spread of waterborne diseases and decreased nutrition (Abhas, Bloch, & Lamond, 2012). Even when death does not result, floods can cause injury, psychological trauma, negative health impacts, and stress stemming from loss of housing or employment. These impacts range in scope from individuals and families to entire communities. These impacts are oftentimes concentrated amongst the poor, who tend to live in flood-prone areas, have little access to flood warnings and evacuation services, and generally have fewer resources and services to draw upon to recover from a flood. Because social vulnerability has many different dimensions, there are many metrics that can be used to quantify it. A review of potential social vulnerabilities to flooding and some ways of measuring these vulnerabilities can be found in (Tapsell, Penning-Rowsell, Tunstall, & Wilson, 2002). Health impacts of floods are reviewed in (Few, Ahern, Franziska, & Kovats, 2004); (Ahern, Kovats, Wilkinson, Few, & Matthies, 2005). Social vulnerability is oftentimes not included in quantitative risk assessments, however, since it can be very difficult to quantify. This omission can lead to significant underestimation of overall risk.

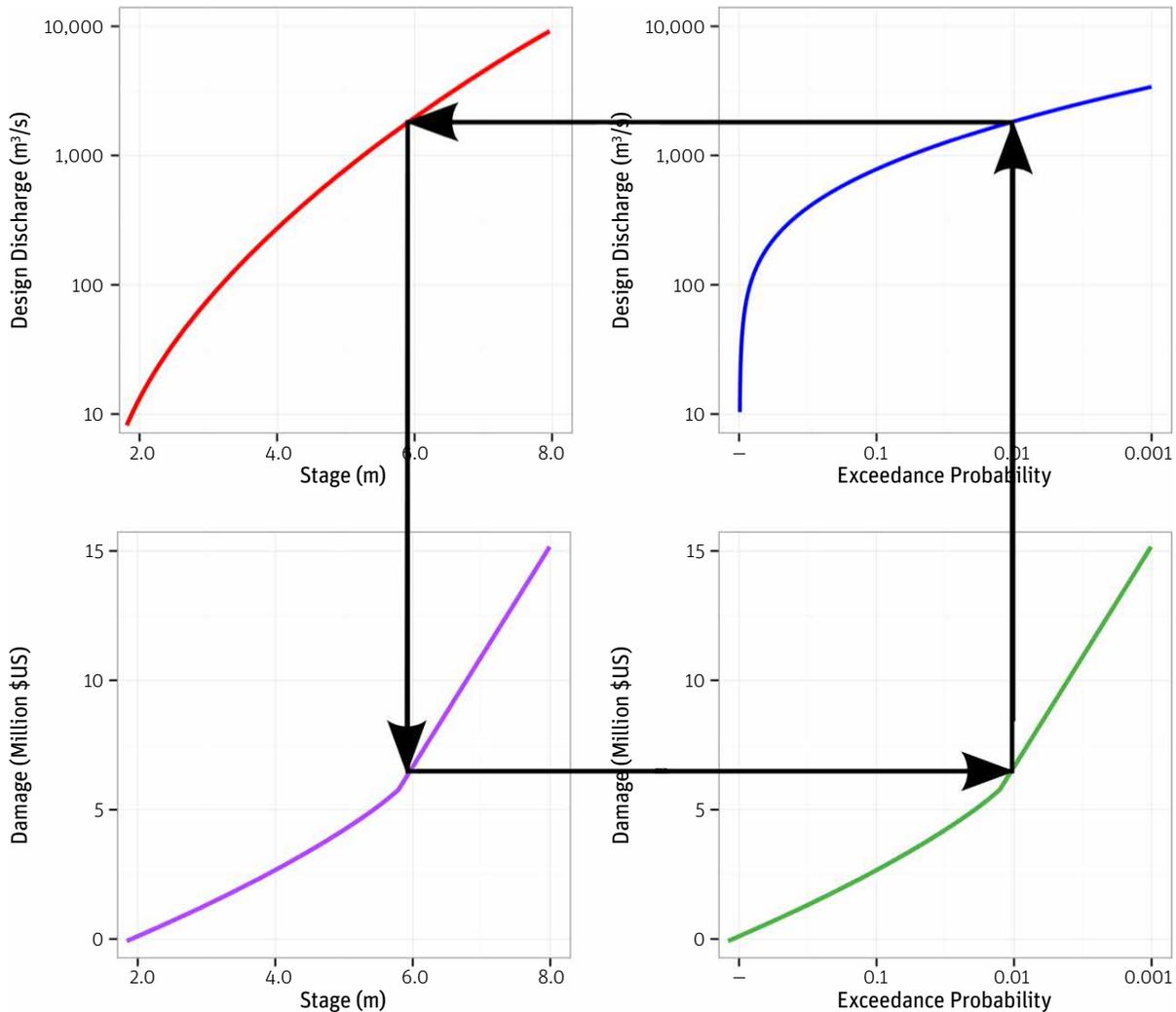
Floods can also have significant impacts on the natural environment. These environmental impacts can sometimes be beneficial, because the natural environment has adapted to the occurrence of floods over thousands of years. For example, rivers can carry large amounts of sediment during floods, which can help to rebuild delta regions, fish spawning areas, and agricultural soils. Floods help to replenish groundwater supplies. Seasonal floods signal fish and other organisms to reproduce or to migrate. In areas where flooding is caused by or exacerbated by human activities, however, the environmental impacts of floods can be very negative. This is because human impacts such as urban or agricultural development can alter the characteristics of floods, making them more intense and destructive than they would have been in the absence of human influence. For example, urban and agricultural development tends to increase the onset speed of floods because water moves more quickly across lots, streets, and drainage systems. The faster-moving water can carry more sediment, thus increasing scouring effects on structures and causing unnaturally large buildups of sediment in certain areas and intense erosion and landslides in others. Deforestation can further exacerbate these problems by limiting the landscape's ability to retain soil and absorb water.

Flood risk management projects can restore flood characteristics to more natural conditions, or at least minimize the additional negative environmental impacts. Environmental impact experts and ecologists can assist in the identification of possible positive and negative environmental impact and with the management of these impacts.

RISK ASSESSMENT

Once a flood hazard and vulnerability assessment has been completed, it is relatively simple to arrive at an estimate of flood risk. An example of the relationship between the different steps is shown in Figure 10. Firstly, a statistical or rainfall-runoff model is used to estimate design discharge for various exceedance probabilities, shown in the upper-right. Then these design discharges are converted into flood elevations (also known as flood stage), as shown in the upper-left, using a hydraulic model and floodplain mapping. The lower-left shows the damages associated with different flood stages. Finally the economic risk is shown in the lower-right, represented by monetary damage for various exceedance probabilities. A similar procedure could be used for estimating social, structural, or economic risks, as long as the different steps can be properly quantified.

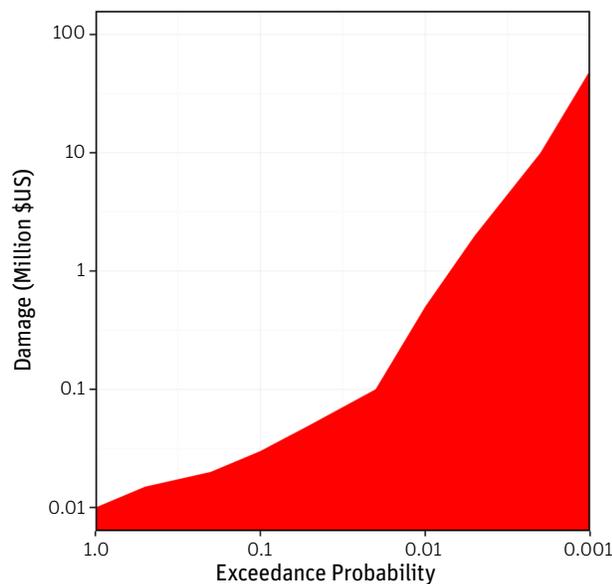
Figure 10 Conceptual diagram of how discharge estimates are converted into stage and economic damage estimates at a particular exceedance probability



The result of the final step in Figure 10 (the lower-right) is an example of what is called an **exceedance probability curve**. Another example exceedance probability curve is shown in Figure 11 This curve is very useful for decision-making purposes because it allows the estimation of a number of useful quantities. The most important of these quantities is the **average annual loss** (also known as expected annual loss), the average loss to occur per year over a long time period. The average annual loss is computed by finding the expected value of the loss across all return periods. The exceedance curve can also help guide decisions to reduce risks against very rare and intense floods. Note that exceedance probability curves and average annual losses could also be developed for non-structural damages. One could, for example, compute an exceedance probability curve for average annual inventory lost due to floods or an average annual number of people displaced due to floods.

It is clear that completely “correct” risk calculations can only be accomplished when the probability and the magnitude of the loss can be estimated with complete accuracy. This is impossible in practice due to the limited amount and accuracy of information. There are many situations in which flood hazard, vulnerability, or both are very difficult to quantify due to a lack of sufficient information. In such cases, one can either attempt to collect additional information to estimate hazard and vulnerability, or attempt to make risk management decisions without this information. Making flood risk management decisions with no or poor risk information can result either in too little or too much protection. Too little protection means that citizens or economic assets face continued exposure to flood impacts, while too much protection means that money has been unnecessarily spent on unneeded protection. Procedures for evaluating the costs and benefits of flood risk management measures can be found in (Medina, 2006) and (Johnson, Hansen, Warren, Reynolds, Foley, & Fulton, 1988).

Figure 11 Example of exceedance probability curve



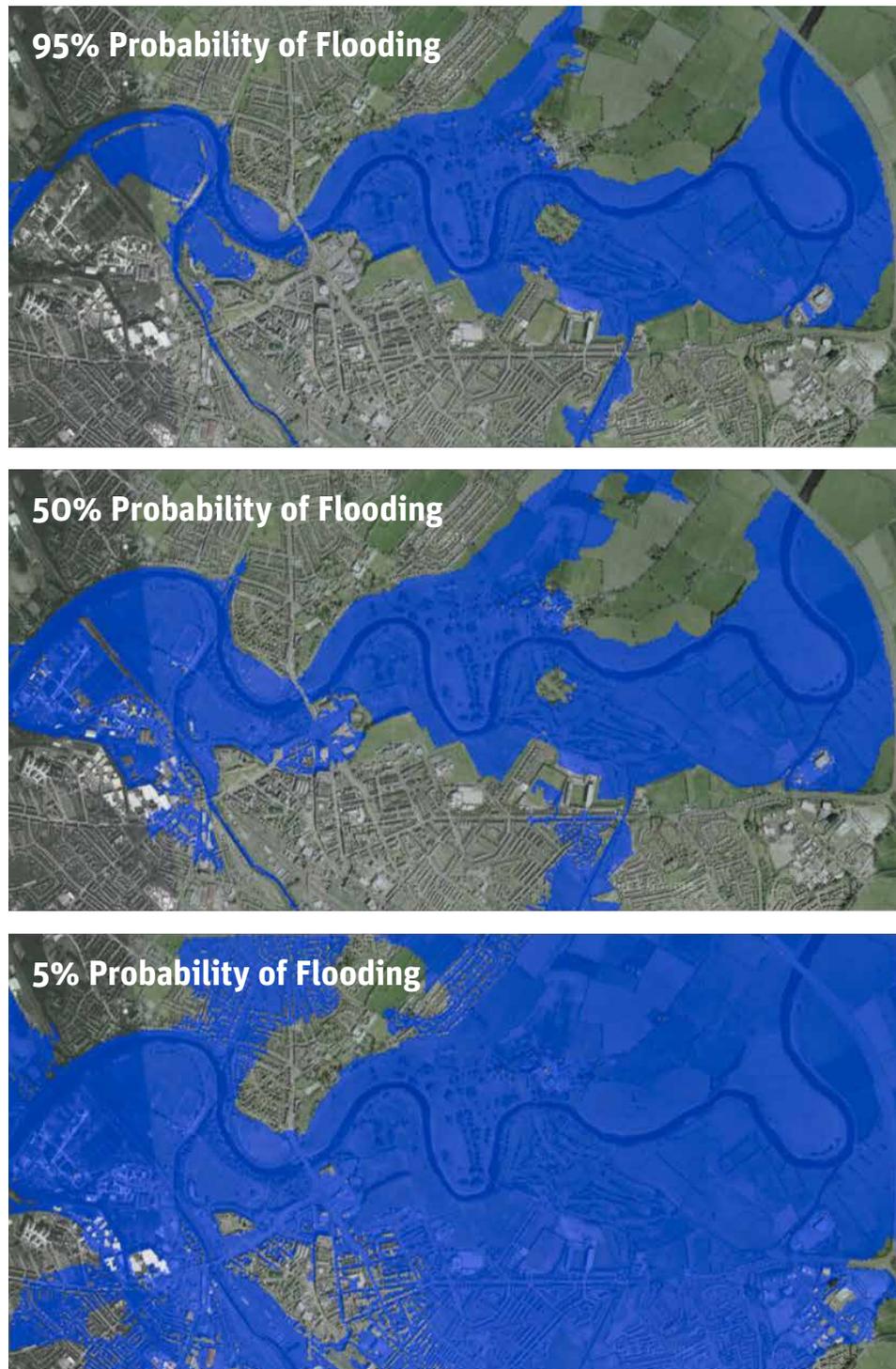
UNCERTAINTY IN FLOOD HAZARD AND RISK ASSESSMENT

Even when good information is available, it will never capture all of the details of flood hazard and vulnerability. A major challenge in flood hazard and risk assessment is to understand the uncertainties that exist at every stage of the process, and to decide how to incorporate these uncertainties into subsequent risk management decisions.

For example, the estimation of design discharges, whether done using statistical methods or rainfall-runoff models, always depends on the use of multiple assumptions, incomplete datasets, and imperfect models. This will lead to errors in design discharges, which will in turn lead to errors in the water levels estimated using a hydraulic model, which will combine with imperfections in the hydraulic model to affect the predicted spatial extent of flooding. Likewise, there are considerable uncertainties in vulnerability assessment. For example, variations in the characteristics of individual buildings cannot be captured using a single damage function, but it is impractical to create accurate damage functions for each individual home or business that might be affected. The inability to characterize building-level flood impacts will then translate into errors in estimated damage and economic losses.

Even the most careful analyses performed by leading experts cannot avoid such uncertainties. Though these uncertainties cannot be eliminated, their importance and impact on the decision-making process can and should be examined. In fact, flood hazard and risk experts put considerable efforts into understanding the various uncertainties and how they can affect risk estimates. An example is shown in Figure 12. These maps are taken from a demonstration by the Flood Risk Management Research Consortium (<http://web.sbe.hw.ac.uk/frmrc>) and show how the 0.01 exceedance probability (100-year) flood extent can vary for different levels of uncertainty. As can be seen in Figure 12, uncertainties in inputs to the floodplain mapping process can result in large variations in estimated flood extent. These variations can translate into significant differences in estimated economic and other types of flood damage and loss. These differences imply significant uncertainty in the decision-making required to reduce these damages. Uncertainties should be carefully considered when evaluating risk management investments. (Rogelis, 2012) provides a more detailed explanation of the various sources of uncertainty and how they can be incorporated into in flood hazard and risk assessment.

Figure 12 Example of how consideration of hazard estimation uncertainties can affect predicted 100-year flood extent



Source: <http://web.sbe.hw.ac.uk/frmrc/index.htm> (accessed 6 January 2014, see https://web.sbe.hw.ac.uk/frmrc/downloads/teaching_materials/Licence.pdf for copyright information).

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