Andrijana Todorović

Flood Risk Assessment

Accurate flood risk assessment is necessary to detect the most endangered zones in an area of interest. Hence, accurate flood risk assessment provides a foundation for effective flood risk management.

However, flood risk assessment is quite challenging. To start with, there is no generally accepted definition of flood risk. According to some definitions, flood risk is equivalent to the probability of flooding. Other definitions include, in addition to flood probability, taking flood consequences into account. Regardless of the definition, assessment of flood probability and (especially) quantification of consequences are complex tasks accompanied by considerable uncertainties.

Definition of flood risk

There are various definitions of the term flood risk. In Japan, for example, flood risk is related to the probability of flooding of certain area inferred from the flow forecasts [1]. According to some definitions accepted in the U.K., flood risk is related to the probability of flooding and four flood risk levels are recognised [2]. These four levels include the following: high, medium, low and very low risk, with probability of flooding from a river or the sea greater than 3.3%, between 1% and 3.3%, between 0.1% and 1%, and less than 0.1%, respectively [2]. Flood risk assessed in such manner is communicated to the public via online accessible maps [2]. Some insurance companies in Germany follow the ZÜRS system for flood risk assessment [3]. According to this system, high, medium and low flood risk levels are recognised. An area is categorised as high, medium and low flood risk if affected by floods of 10-year return period or below, by floods of 10- through 50-year return period, and floods of 50-year or greater return period, respectively (see Figure 1). Flood risk can also be considered with respect to associated health risks, i.e. the potential to threaten people's health and lives [4].

https://doi.org/10.36250/01052_06

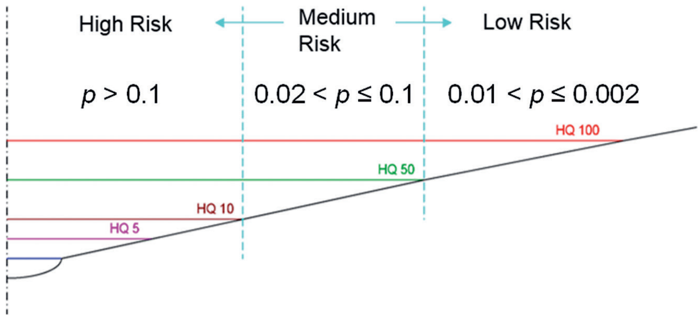

Figure 1. Flood risk classification in Germany according to the ZÜRS system [3]
Note: The probability of exceedance is given dimensionless and denoted with p

Flood risk assessment should not be related to the probability of flood occurrence only since potential consequences of floods are neglected this way. Hence, flood risk is defined as "a combination of the probability and the potential consequences of flooding from all sources – including from rivers and the sea, directly from rainfall on the ground surface and rising groundwater, overwhelmed sewers and drainage systems, and from reservoirs, canals and lakes and other artificial sources" [5]. The probability of flooding is referred to as hazard, while flood risk represents the combination of the probability of hazardous event (flood) and its consequences. In other words, flood risk corresponds to the probability of damages due to a flood event [6]. Flood consequences depend on vulnerability and exposure [7]. The former represents susceptibility to flood impacts, while the latter generally signifies the presence of people and assets in flood-prone areas [8]. Exposure can be mitigated to certain extend by implementing flood protection measures. Figure 1 shows the three components of flood risk: flood hazard, vulnerability and exposure (the latter two comprise flood consequences).

For the purpose of flood risk assessment, flood consequences are commonly represented by damages/losses quantified in monetary terms [3]. Such an approach to flood risk assessment is adopted and applied in many European countries (e.g. Germany, the Netherlands), and it is the basis of this course.

Figure 2. Components of flood risk [8]

To illustrate the outlined definition of flood risk, two hypothetical areas are considered: a flood prone area A, which is covered by forest and flooded on average once in two years, and area B, which is heavily populated with an industrial zone and heritage buildings. Area B is protected by dykes designed according to flow of 100-year return period. Regardless of being frequently flooded, damages in area A are negligible, whereas flood damages in area B would be enormous with potential casualties and impact to the historical/cultural heritage. According to the definition above, flood risk in area A can be considered low, and high in area B because of potential far-reaching and devastating consequences. However, flood hazard is considerable in area A, which is frequently flooded, and minor in area B (because of the dykes and low probability of flooding).

To assess flood risk, both flood probability and consequences represented by monetary value, have to be combined, as shown in Figure 3. The combination of these terms results in the expected annual damages (EAD) in the considered area. Imposing threshold values of the EAD, various flood risk levels are defined and assigned to distinct zones within the area of interest (e.g. high, medium and low). Flood risk can be fairly represented by flood risk maps, which are straightforward and can be easily understood by the public.

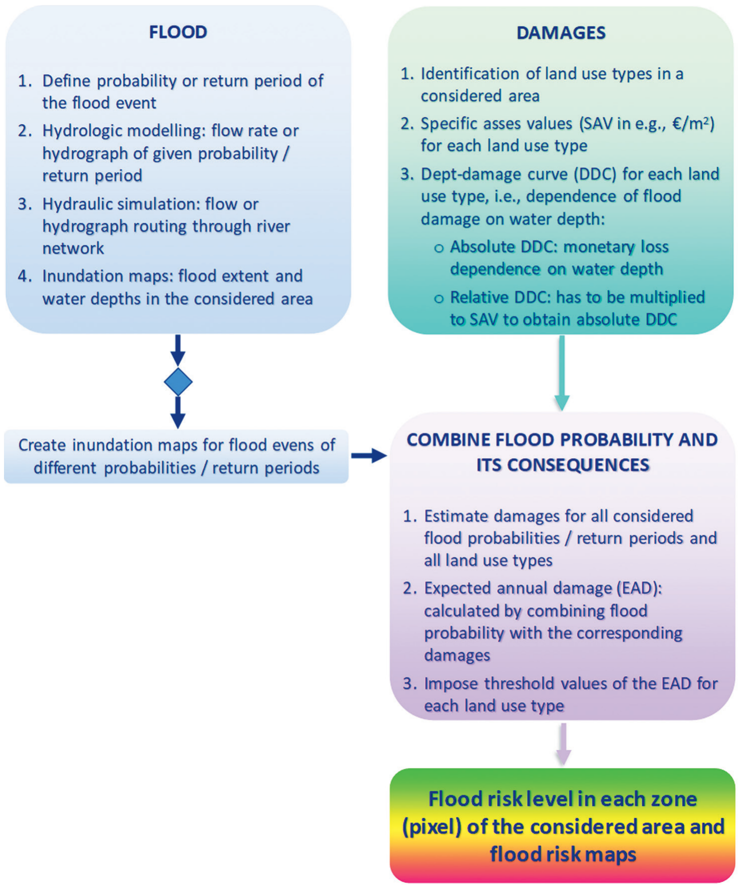

Figure 3. Methodology for flood risk assessment (compiled by the author)

Consequences of floods

Floods are by far the most frequent and disastrous events (see Figure 4). Flood consequences generally depend on the number of people in an area affected by the flood and asset values [6]. Floods make negative impacts on buildings, including public buildings, such as hospitals and heritage buildings, then industry, traffic, crops and livestock, and, most importantly, human health and lives. Some consequences are arisen immediately and are caused by a direct contact to the flooding water, while others are accompanying (e.g. costs of traffic disruptions). Some flood consequences can be easily quantified in terms of money, such as damages to buildings or infrastructure, while others are rather difficult to represent in monetary terms (e.g. casualties).

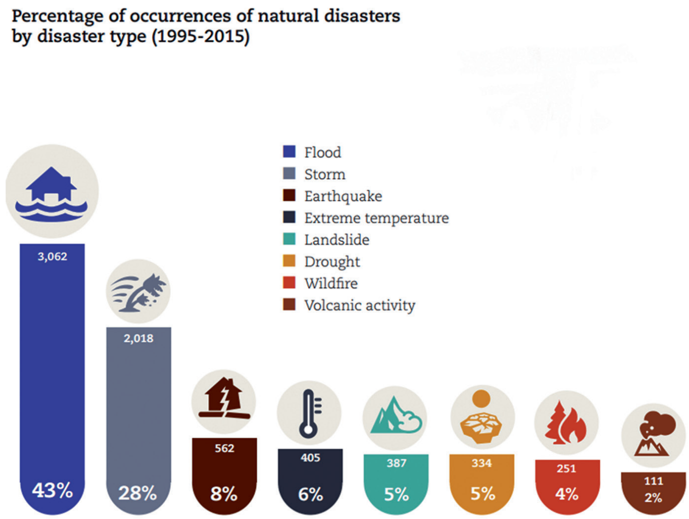

Figure 4. Frequency of natural disasters [30]

Hence, flood damages are generally categorised as follows [9]:

Direct and indirect: direct damages refer to the harmful effects due to contacts with flooding water. Indirect, secondary damages are not caused by flooding water itself, but by accompanying effects, such as loss of production because of flooding or costs due to traffic disruptions and power cuts. A thorough review of methods for assessment of indirect damages can be found in the literature [10].

Tangible and intangible damages generally can/cannot be easily quantified in terms of money, respectively. For example, the intangible damages include casualties, harmful health effects, damages to historical and cultural heritage, negative impacts on the environment. There are various methods intended to quantify intangible damages (for review see e.g. [9]), but these are generally not considered in flood risk assessment studies and, thus, they are beyond the scope of this course.

An overview of flood damages is given in Table 1.

Table 1. Classification of flood damages with examples (adopted from [9])

	Tangible	Intangible
Direct	Physical damages to assets: Buildings (structural damages) Infrastructure (e.g. roads, railways, etc.) Belongings and inventory Vehicles Losses of livestock Losses of crops	Loss of lives Negative health effects Harmful effects on the environment Damaging effects to historical and cultural heritage
Indirect	Loss in production (e.g. industrial, agricultural) Loss of incomes Costs of traffic disruption Loss of value added Evacuation and emergency costs Costs of post-flood clean-up Damages due to consequent landslides	Difficulties with post-flood recovery Increased vulnerability of survivors

To illustrate this classification of flood damages, a family dwelling is considered: direct damages refer to the building structure, furniture and assets, while indirect damages include e.g. clean-up and rehousing [11]. Figure 5 shows some of the consequences of the severe flood event in the Kolubara catchment in Western Serbia in May 2014. During this flood event, twenty-four casualties were reported. Many cities in this catchment suffered enormous damages to the buildings and infrastructure, including bridges and roads (direct, tangible damages). The agriculture of the area also suffered great damages (indirect, tangible). The thermal plant "Nikola Tesla" and local open pits of the coal mine that supplies the thermal plat were also flooded (direct, tangible damages), which resulted in the reduced supply of electric currency (indirect damages). Subsequent landslides caused additional (indirect) damages [12].

In addition to the asset values and number of people in a considered area, flood consequences also depend of flood characteristics, such as flood extent, water depth and velocity, flood duration, rate of the rise of water level, debris flow and waves [3] [8]. Damages also depend on the time of flood occurrence: for example, damages to agriculture, i.e. losses in crop production are the greatest due to floods during harvesting seasons [9]. Since flooding water is usually heavily polluted, damages also include far-reaching chemical and biological impacts on health and environment [11].

The larger flood extent, i.e. the greater area affected, the greater is the number of affected people and assets. Also, deeper water causes greater damages. For example, rather shallow water can be prevented from entering a building (e.g. by putting up shields), while deeper water reaches higher floors of buildings, augmenting damages manifold.

Figure 5. Devastating flood in the Kolubara catchment (Serbia) in May 2014: the city of Obrenovac [34] and losses in crop production ([35], top panels), power plant "Nikola Tesla" [36] and open pits of the "Tamnava" coal mine ([37], bottom panels)

These two flood characteristics are identified as the most important for flood damage assessment, i.e. a significant part of total flood damages can be explained by the flooding extent and water depth [9]. High water velocities can put people in danger, and can wash away moveable assets (e.g. vehicles), develop and enhance erosion. Table 2 shows impacts of different combinations of water depth and velocity on people. A combined impact of water depth and velocity is also illustrated in Figure 6. Longer flood duration implies longer exposure to water, which augments damages. For example, building fabric is particularly sensitive to long exposure to water [9]. Impact of flood duration on damages is shown in Figure 7. High rate of water level rise means shorter warning lead times, which further leads to higher damages [10].

This statement is supported by the figures in Table 3, which clearly indicate that increase in warning lead time can considerably mitigate flood damages. Longer warning lead times are necessary as they enable evacuation of more people and allow people to relocate/elevate their moveable belongings. High debris load can enhance mechanical impacts of flowing water, and, thus, deteriorate flood damages to buildings and infrastructure. Furthermore, debris deposits have to be cleaned-up after the event, increasing indirect damages. Most importantly, debris are one of the major causes of injuries and casualties due to floods [9]. Waves make mechanical impact on the building fabric, and also can cause injuries and jeopardise human lives. Strong wave impacts are generally associated to coastal floodings [9]. Various flood impacts on health and environment are elaborated by the U.S. EPA [13]. Some common consequences to health include diarrheal diseases and wound infections. Frequent animal and insect bites accompany floods, considering that animals are also being displaced. Health can also be threatened by exposure to various chemicals and pollutants, such as fuels, pesticides, paints, cleaning supplies, silica from construction materials, hazardous chemicals from the industry, etc. Figure 9 shows major impacts of polluted flooding water on health.

Table 2. Risk to human lives assessed from water depth and velocity [4]

Depth velocity (m2/sec)	Description	Risk to human lives
< 0.75	Shallow flood water or deep standing water. Caution is needed.	Low
0.75 < 1.5	Deep water or high velocity. Dangerous to vulnerable groups.	Moderate
1.5 < 2.5	Deep water or high velocity. Fatalities are mainly due to exposure to the flooding water. Dangerous to most people.	High
2.5 > 7.0	Extreme danger from deep, fast flowing water. Fatalities due to exposure to the flooding water. Dangerous for all.	Extreme
> 7.0	Extreme danger from deep, fast flowing water and risk of building collapse. Dangerous for all.	Extreme

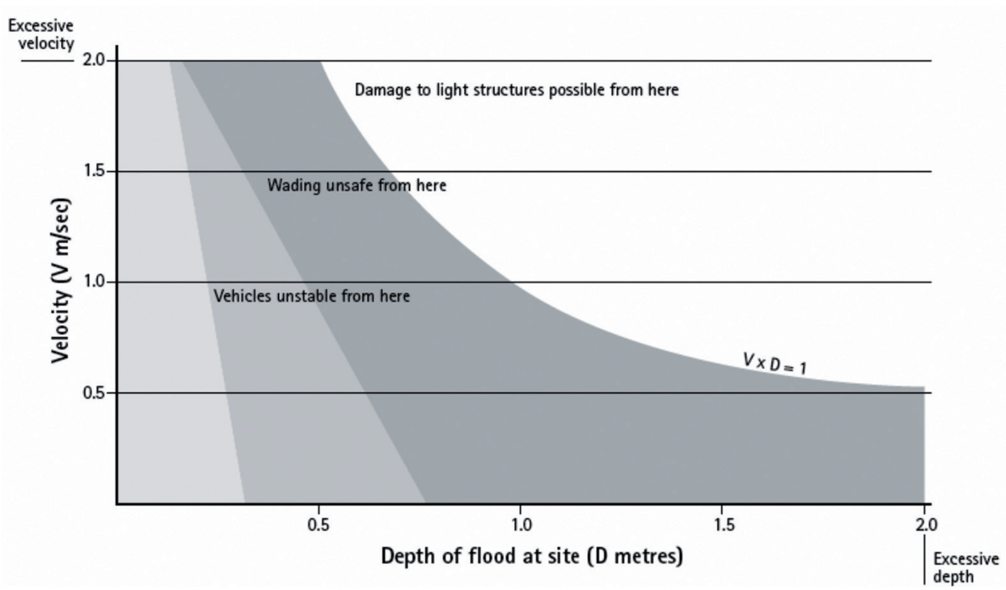

Figure 6. Combined impact of water depth and velocity [11]

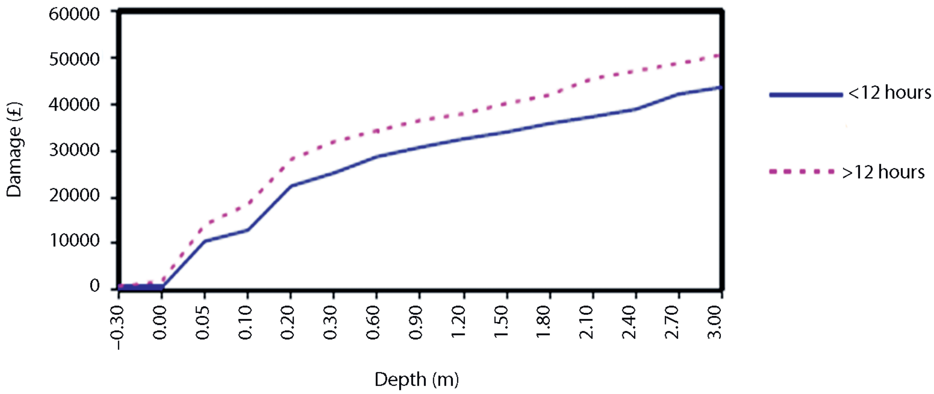

Figure 7. Impact of flood duration on damages [9]

Table 3. Impact of flood warning lead times on damages on residential properties [9]

Depth of flooding (m)	Flood warning lead times			
	Up to 2 hours	2–4 hours	6 hours	8 hours
	Damages avoided (% of the total damage)			
1.2	25.3	35.7	38.7	40.7
0.9	26.4	37.6	40.6	42.6
0.6	25.5	37.2	40.2	42.2
0.3	30.0	42.1	45.1	47.1
0.1	24.5	32.8	35.8	37.8

Figure 8. Impact of debris load during floods [31] [32]

Outline of the course

This course explains a methodology for flood risk assessment by combining flood hazard and flood consequences, assessed in monetary terms.

The following section explains in detail the assessment of both components: namely, how to obtain inundation maps due to flood event of a given probability, and corresponding direct, tangible damages, quantified in terms of monetary loss. Assessment of indirect and/or intangible damages is beyond the scope of this course. Damages are obtained from assessed asset values and water depth only. Based on flood probabilities and corresponding damages, computation of expected annual damages that combine these terms, is thoroughly elaborated. Finally, identification of different flood risk levels based on the expected annual damages is described.

Information on flood risk can be effectively visualised and communicated to the public and decision-makers by flood risk maps. The final section concisely explains how to obtain flood risk maps by employing GIS tools.

For the sake of clarity, a glossary explaining the key terms is provided at the end of this course material.

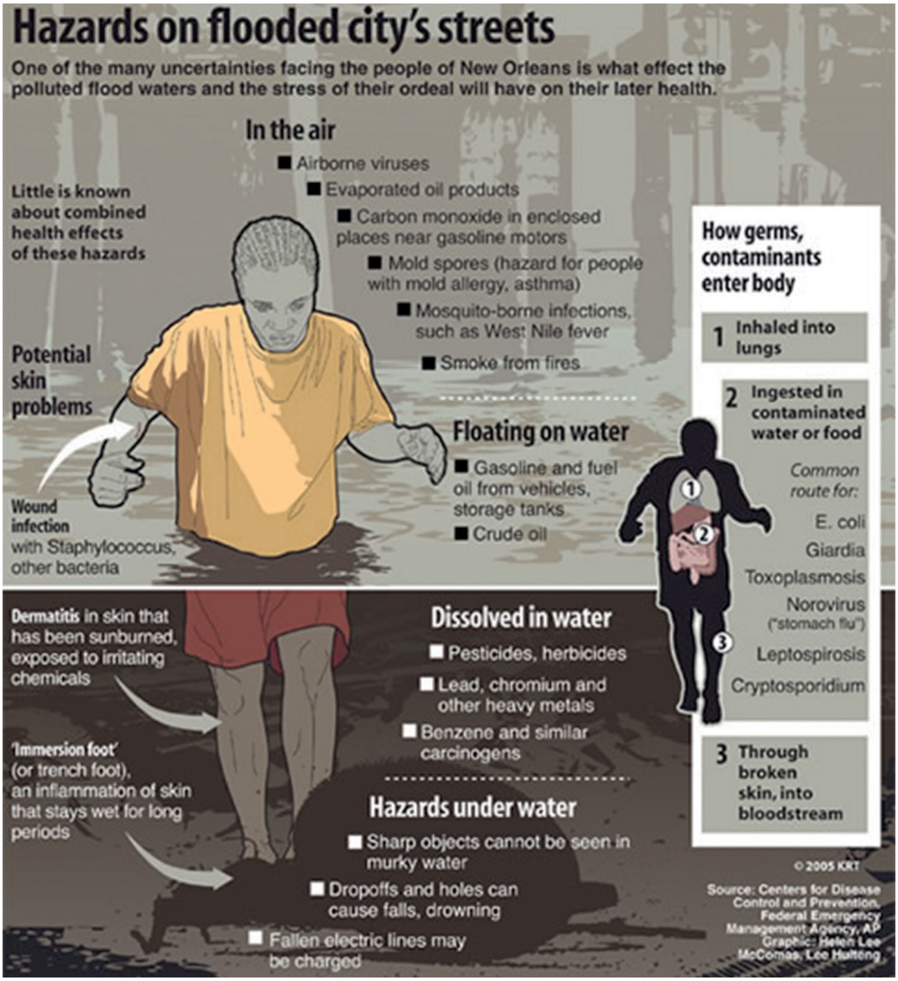

Figure 9. Health risks due to polluted flooding water [33]

Methodology for flood risk assessment

As explained in the previous sections, flood risk assessment comprises estimation of flood hazard and the consequent damages. Flood hazard (potential harm) is related to the probability of flooding: for example, great flood hazard implies flood prone areas. Section *Probability of flood – Hazard* explains how to obtain inundation maps for a flood event of a given probability of exceedance/return period. Assessment of monetary equivalent of direct, tangible flood damages is elaborated in section *Flood damages,* as well as how to combine flood probability with its consequent damages, resulting in expected annual damages (EAD, subsection *Expected Annual Damage [EAD]*). Identification of flood risk level from the assessed EAD is explained in section *Flood risk assessment.*

Probability of flood – Hazard

Flood hazard indicates the probability of flooding of a considered area. Methodology for flood probability assessment, which is the first part of the flood risk assessment methodology, includes the following steps (Figure 10):

Estimation of the flow rate or the entire hydrograph for the given flood probability or return period (e.g. 100 years).

Flow or hydrograph routing through a river network by using a hydraulic model.

Use of the hydraulic simulation results for inundation maps, which show flooding extent and hydraulic variables (e.g. water depth) within the flooded area.

Create inundation maps for various characteristic probabilities/return periods.

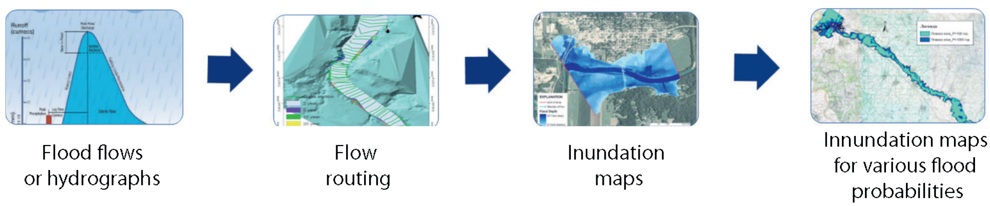

Figure 10. Inundation maps for the purpose of flood risk assessment (compiled by the author)

Flood probability

There are two approaches to flood flow estimation: namely, the statistical approach and the deterministic one (see Figure 11). The former is based on the application of statistical methods and requires observed flow series, whereas the latter approach relies on rainfall–runoff models and design rainfall [14].

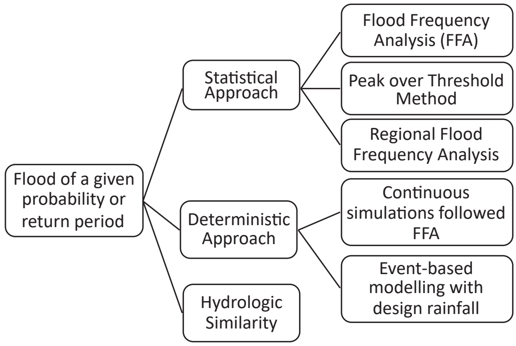

Figure 11. Approaches to flood estimation (adopted from [14])

Flows of a given probability/return period are commonly obtained by applying the Flood Frequency Analysis (FFA [15]) or Peak over Threshold method (PoT [16]). Flood frequency analysis is based on the series of annual flow maxima, and it is aimed to obtain the fittest model (i.e. theoretical distribution) to the empirical distribution of the observed annual maxima. However, application of this method requires that the flows are independent and identically distributed. These requirements are examined by applying statistical tests prior to the FFA. Steps of the FFA are outlined in Table 4. The PoT method comprises of probabilistic modelling of: 1. Flood occurrence, i.e. expected number of events exceeding the set threshold per year; and 2. Flood magnitude (i.e. peak flow rate). Discrete distributions are used to estimate the probability of flood occurrence, while flow magnitude is described with a continuous probability distribution. Unlike FFA, the PoT method is based on the flood exceeding a given threshold, meaning that several floods in one year can be taken into analysis, whereas maximum flows from some other years that do not exceed the threshold are discarded. For simplicity, the threshold is usually set to provide statistically independent flows. The mathematical model of the PoT method is more complex than the FFA, but, considering that the largest observed flows are taken into account regardless of the year of their occurrence, PoT is expected to yield more reliable quantile estimates than FFA. Additionally, there are quite complex PoT model versions that do not require independent data [16].

Application of statistical methods requires long-term and reliable flow observations. For example, for a reliable flood frequency analysis at least 25 years of flow observations are required [15]. Also, an empirical rule states that the Gumbel distribution can be applied for reliable flow quantile estimation for return periods of twice the length of the observed period or shorter [17]. If only a short data is available at a considered stream gauge, a regional flood frequency analysis can be applied. Specifically, annual maxima from several gauges within the same region are normalised (e.g. with respect to the mean flow at the gauge), and concatenated into single, long series, followed by the FFA. In this way, dimensionless flow quantiles are obtained. The quantiles at a gauge are calculated by multiplying the dimensionless quantiles with the mean flow at that particular gauge [14].

Table 4. Flood frequency analysis: an outline (compiled by the author)

Step	Procedure
0	Obtain annual maxima series from the available flow record.
1	Calculation of the sample statistics: mean value, standard deviation, skewness, etc.
2	Test for homogeneity and independence. The former is tested with e.g. z-test, Student, Man-Whitney or Mann-Kendall tests, and the latter with e.g. Bartlett test.
3	Calculation of empirical distribution by using e.g. Weibull probability plots.
4	Distribution fitting, i.e. calculation of parameters of probability distributions: (log-)normal, Gumbel, (log-)Pearson III, Generalised Extreme Value (GEV), etc. Various methods can be used for parameter estimation: method of moments, L-moments, weighted L-moments, maximum likelihood method.
5	Goodness-of-fit tests: Kolmogorov-Smirnov, Anderson-Darling, etc. Selection of the most suitable probability distribution.
6	Compute flow quantiles, i.e. flows of different probabilities/return periods by using the selected probability distribution.

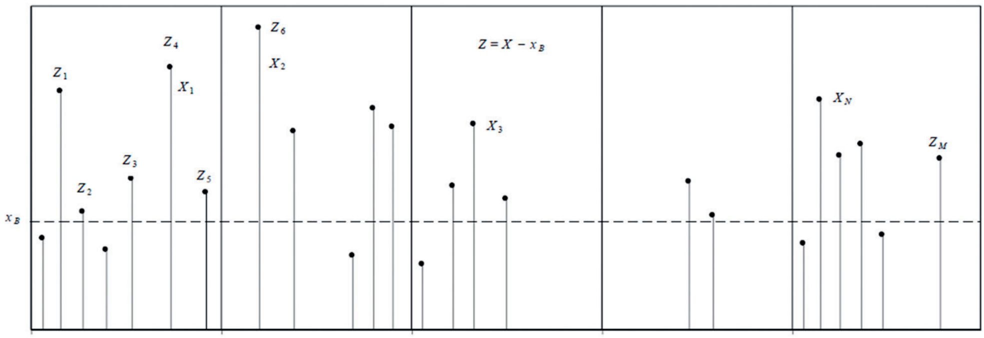

Figure 12. Peak over Threshold method: x_B – threshold, X – flows, Z – peaks over threshold [16]

Table 5. Peak over Threshold method: most frequently used models [16]

Number of occurrences distribution	Peak height distribution		
	Exponential	Weibull	Generalised Pareto
Poisson	P + E	P + W	P + GP
Binomial	B + E	B + W	B + GP
Negative binomial	NB + E	NB + W	NB + GP

Rainfall–runoff models enable flow simulations from input meteorological data (precipitation, temperature, potential evapotranspiration) and data on the considered catchment (e.g. area, hypsometric curve, land use types).

Rainfall–runoff (hydrologic) models simulate flows at a catchment outlet for given rainfall data and initial conditions in the catchment. Presently, there are numerous rainfall–runoff models that vary in complexity, spatial discretisation and data demands. Hydrologic models are generally classified as event-based or continuous. The former simulate catchment response to a single rain event (i.e. they simulate single flood hydrograph at a catchment outlet). The latter are used for long-term, continuous simulations that include periods during and in-between rainfall events [18].

For the purpose of flood frequency estimation, event-based models are usually applied. Runoff simulations with event-based models include: 1. Calculation of runoff volume; and 2. Runoff routing to the catchment outlet. Runoff volume (i.e. rainfall–runoff partitioning) is usually calculated by applying the SCS CN method [19], while runoff routing models include the rational method and various models based on the unit hydrograph (UH) theory [20]. The rational method is the simplest event-based model, and its application is limited to small, urbanised catchments [20]. Some of the commonly used UHs are Clark or Snyder [21]. These models consist of equations that comprise parameters, which have to be adjusted to provide the best possible fit to the observed flows, i.e. the models have to be calibrated before their application. The calibration is performed to achieve the best possible fit between simulated and observed hydrographs in terms of: peak flow magnitude and timing, runoff volume, rinsing limb slope and timing and recession limb. For model calibration, models are forced with the observed meteorological series. The event-based models can also be used for ungauged catchments that lack long-term, reliable flow observation necessary for model calibration. Synthetic unit hydrograph (SUH) models are employed for this purpose [22]. The SUH models are derived from topographic data on the catchment. One of the most frequently used is the dimensionless SCS SUH [21].

To obtain flows of a given return period, UH and SUH models are forced with design rainfall, derived from depth–duration–frequency curves and assumed hydrograph shape, i.e. change in rainfall intensity throughout the design event. Since uniform rainfall intensities result in lower peak flows, it is recommended to force the models with time-varying rainfall for the purpose of flood flow modelling. Such design rain event can be obtained by using e.g. the Chicago method. An underlying assumption in this approach to flood flow estimation is that the return period of the simulated peak flow is equal to the return period of design rainfall used for the model run.

Continuous hydrologic models can also be used for estimation of flood flows. This approach includes two steps: 1. Calibration (and evaluation) of a continuous model; and 2. Application of Flood Frequency Analysis over the series of simulated annual maxima [14]. The application of this approach can be justified by the fact that meteorological record series are usually considerably longer than flow observation. Hence, forcing the model with (longer) meteorological input series can provide longer flow series, which are expected to increase reliability of the flow quantiles. However, this approach to flood estimation is rarely applied, primarily because common calibration of continuous models leads to poorly simulated flow peaks (mainly their underestimation) [23].

Floods of a given probability/return period at an ungauged river cross-section can be estimated by applying the principle of hydrologic similarity [17]. The flood of return period T is calculated as follows:

$$\frac{Q(T)}{Q^*(T)} = \left(\frac{A}{A^*}\right)^{\alpha} \qquad (1)$$

where Q*(T) represents the flow of a given return period T at the point of the river with drainage area A*, while A is the area of the ungauged catchment. The recommended value of the parameter α is 1/3, although its value can be adjusted to fit available data [17].

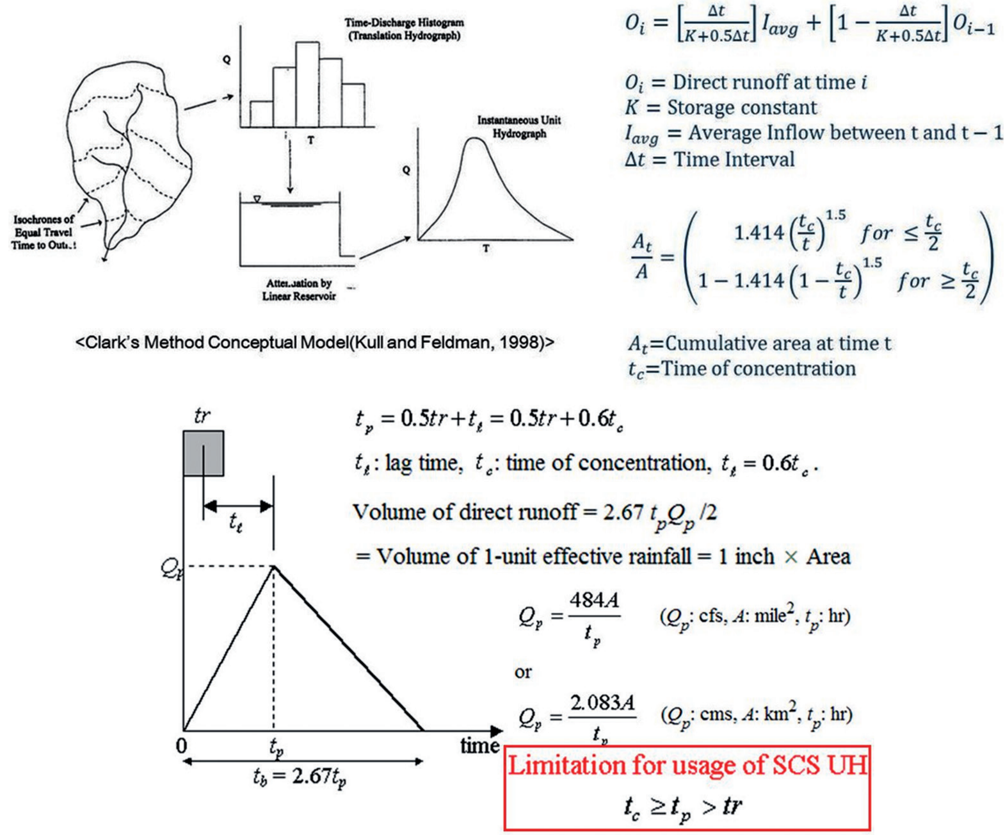

Figure 13. The Snyder UH (top panel) and the SCS SUH (bottom panel) [38]

Flood routing and inundation maps

Hydraulic simulations, i.e. flood routing enables the computation of flow rate and other hydraulic variables at any point of the river network and at any time, given the input flood rate or hydrograph, network geometry, initial and boundary conditions [20]. Water levels across the river network and in the inundation/flooded area of primary interest to flood risk assessment.

Flood routing can be steady or unsteady: the former implies routing of constant flow rate in time, while the latter denotes routing of an entire flood hydrograph (i.e. time-variable flow). Unsteady routing results in higher water level than steady flow routing [24], thus it is preferred for flood risk assessment.

There are parsimonious flood routing methods, such as the linear reservoir equation or the Muskingum method. However, accurate flood routing requires distributed routing models, which are based on the partial differential equations describing mass, momentum and energy conservation laws [20]. Some of the distributed flow routing models are e.g. kinematic, diffusion or dynamic wave models. To apply the distributed models, the geometry of the river network has to be specified, as well as initial and boundary conditions. Additionally, the partial differential equations embedded in these models can seldom be solved analytically. Specifically, analytical solutions are possible if strong assumptions on geometry are made and some terms in the equations omitted. Therefore, various numerical methods are applied for flood routing. Routing of flash flood poses a great challenge for numerical modelling due to sudden change in water depth that cannot be captured by commonly applied methods [20].

The routing models also vary according to flow direction that they can simulate. One-dimensional models are frequently used, while application of 2D models, which provide detailed description of flow, is constrained by considerable computational time [9]. Computational requirements are even higher for three-dimensional models, which are mostly applied to simulate complex flow in junctions and their immediate vicinity.

One of the most frequently used software for flood routing is HEC-RAS by the US Army Corps of Engineers [25]. This software is user-friendly (see Figure 14) and can be freely downloaded from the US Army Corps of Engineers HEC webpage (HEC).

Based on the simulated water level, inundation maps can be obtained. As shown in the bottom panel of Figure 14, inundation maps indicate flood extent, i.e. flooded areas, and show water depth within the flooded area. An example of inundation map is shown in the bottom panel of Figure 14. For the purpose of flood risk assessment, inundation maps are required for various probabilities/return periods (see subsection *Expected Annual Damage [EAD]*). Besides water depth, other hydraulic variables, such as water velocity, pressure force, shear stress can be shown as well.

Inundation maps are usually obtained by importing water levels into a GIS environment. For example, hydraulic simulation results obtained with HEC-RAS can be easily imported by applying the HEC-GeoRAS plug in. The version for ArcMap can be readily obtained from the HEC webpage. A similar tool is available as a plug-in for QGIS.

The application of hydraulic models for flood routing is a subject of the specialised course of this postgraduate programme, which explains hydraulic modelling in detail.

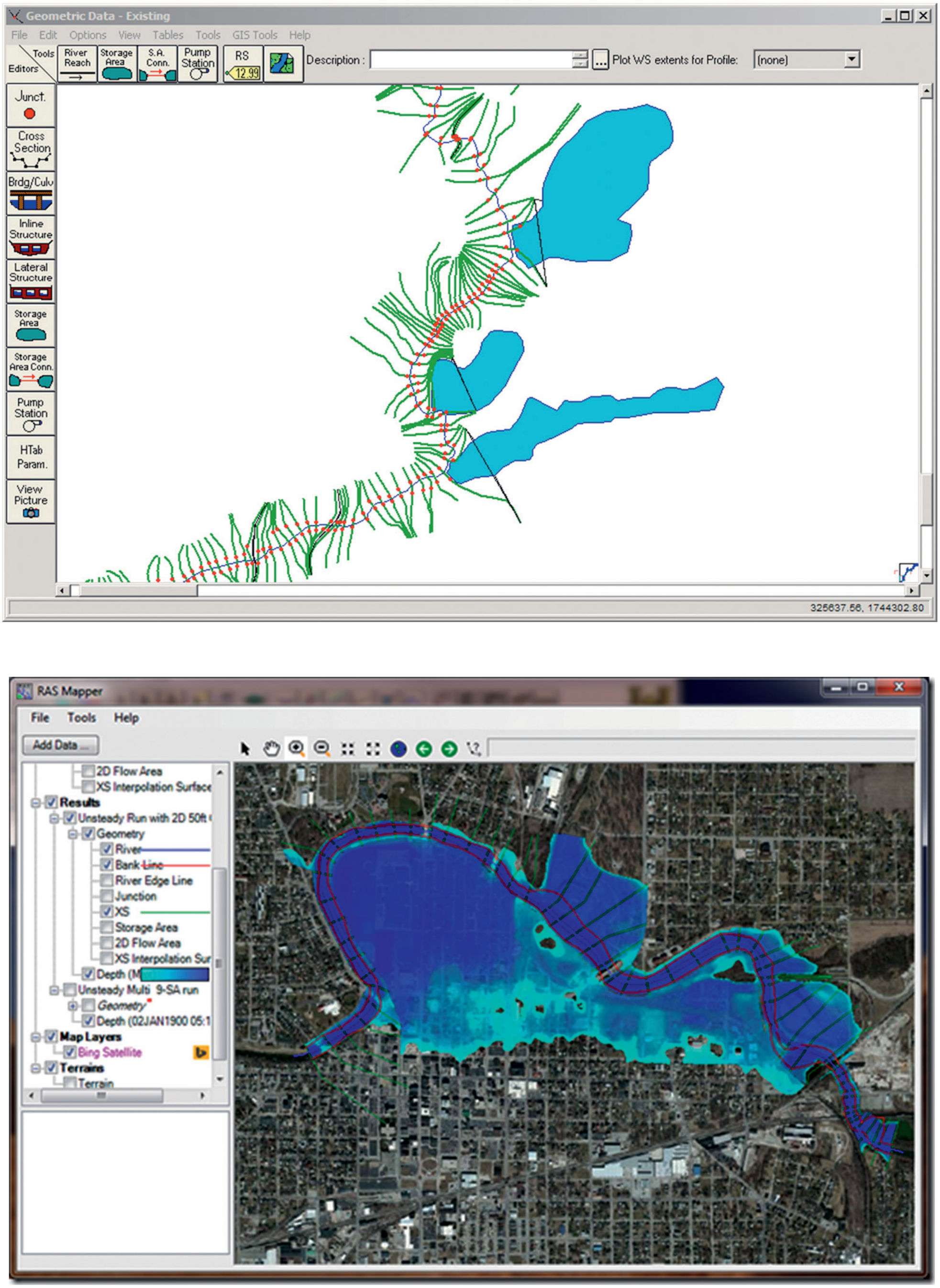

Figure 14. Hydraulic simulations with HEC-RAS: cross-sections in the HEC-RAS window (top panel, [39]) and inundation map (bottom panel, [40])

Flood damages

For the purpose of flood risk assessment, flood consequences are quantified in monetary terms [3]. This methodology for flood risk assessment recognises only direct, tangible damage (e.g. damages to buildings or infrastructure), whereas indirect and/or intangible damages are not considered here (see section *Consequences of floods*). Additionally, only water depth is considered, whereas other hydraulic variables, such as water velocity or flood duration, are neglected.

Estimation of flood damages includes the following (Figure 15):

- identification of land use types in the area of interest
- assess specific asset values for each LUT
- obtain depth–damage curves (DDC) for each LUT

Compute damage (in monetary terms) by combining water depth due to flood event of a given return period, degree of damage given the water depth, and information of asset value.

Figure 15. Assessment of direct, tangible damages due to a flood event of a given probability (compiled by the author)

Identification of land use types

For assessment of direct, tangible damages, land use types (LUTs) in a considered area have to be identified. Depending on the area and scope of the flood risk assessment study, i.e. required accuracy and spatial resolution, the number of identified LUTs varies from a few to several hundreds. For example, high spatial resolution and micro-scale studies imply a large number of LUTs. Categorisation of LUTs in the considered area should result in 1. Minimum variance within one LUT category; 2. Maximum variance among different LUTs. Additionally, LUT categorisation should be constrained by available depth–damage curves and data on asset values [9]. For example, setting an abundant number of residential LUTs with only one available DDC or with data on property values does not increases accuracy of the damage assessment. Generally, buildings within a residential area are all different: for example, they differ according to the number of storeys, presence of cellar, elevation of the ground flood, etc. Additionally, different buildings are differently furnished in terms of luxury, implying large variations in asset values. Bearing in mind these differences, several residential categories may be defined, depending on the scope of the study. Categorisation of LUT in the Rhine basin is shown in Figure 16.

Information on LUTs in the considered area can be obtained from primary and secondary data sources. The primary data sources are essentially field surveys. The secondary source includes LUT databases, cadastral maps or real estate market data, all of which provide aggregated data on LUTs [9]. Field surveys do provide most accurate information on LUT, however, they can be carried out only for small areas, i.e. for the purpose of micro-scale studies. Concerning secondary sources, there are some geo-databases with information on LUTs for each country. For example, LUT data can be obtained from ATKIS-DLM in Germany, or the GeoSrbija portal for Serbia. The Corine Land Cover [10] database that covers the entire Danube basin can be accessed via the link https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012?tab=mapview.

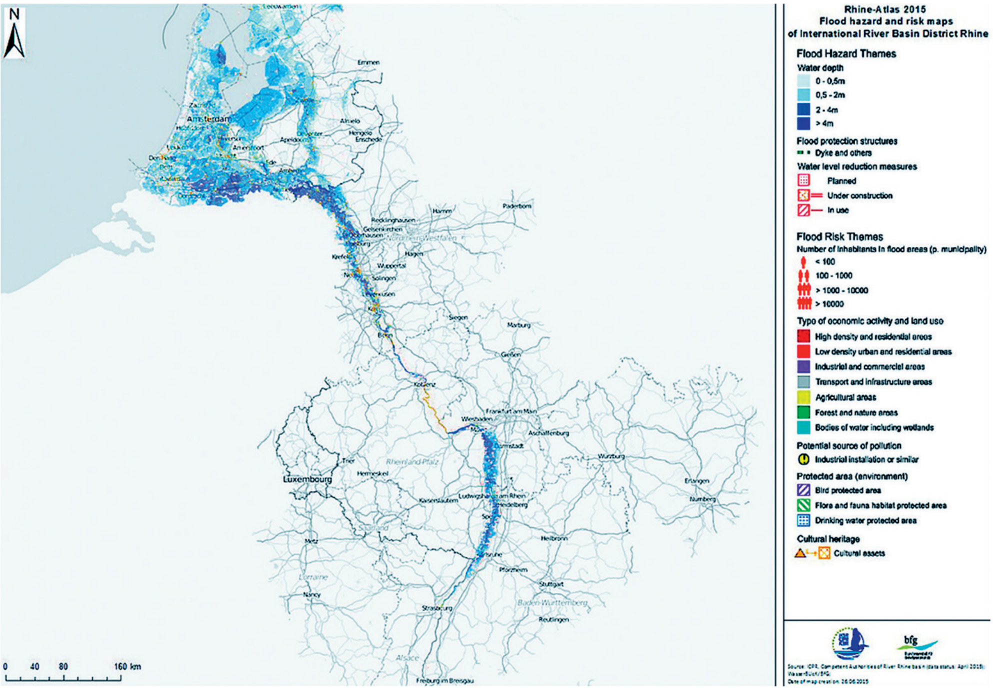

Figure 16. Rhine Atlas [26]

Asset value estimation

There are two approaches to asset value assessment: namely, assessment of value at purchase price and at the actual price [3]. The former concept does not take depreciation into account, and, basically provides full replacement value. As such, it provides overestimated asset values and, hence, should be avoided [9]. Additionally, even severe flood events do not necessarily cause total damage of buildings, particularly in case of reinforced concrete structures. The latter approach, which takes depreciation into account and provides realistic estimates of asset values, is preferred. Only one approach can be used for a flood risk assessment study: the combination of both approaches is strongly discouraged [9].

Assessment of values of buildings in residential areas should mandatorily include vehicle values. Value of infrastructure assets (e.g. road, railways, water supply or sewer systems, etc.) can be obtained from the construction costs that are usually made available in publications. Values of crops are equal to the investments to produce the crops, while value of livestock can be inferred from market price. A detailed guide on the asset value estimation can be found in the literature [9].

Flood damages assessments should refer to large areas (e.g. entire regions). On the other hand, asset values are often inferred over much smaller, "sample" areas: for example, value of dwellings is assessed based on a sample of individual dwelling within a smaller zone, assuming that this zone is representative for the entire considered area. To enable extrapolation to wider areas, asset values are given per unit area, i.e. as specific asset values (e.g. in €/m^2). For example, once a representative zone is selected, the number of buildings within such a zone is determined, and then multiplied by the mean estimated value of the building to yield the total asset value of the zone. The total value is then divided by the zone area, resulting in specific asset value. A similar calculation can be done for road and rail network: although values of these assets are regularly given per unit length, values per unit area can be calculated taking into account e.g. the road/rail track width [9].

Specific asset values greatly facilitate flood risk estimation, as explained in the sequel.

An example of specific asset values, assessed for the North Rhine region, are given in Table 6.

Table 6. Specific asset values for North Rhine-Westphalia [9]

Land-use category	Value of fixed assets (EUR/m^2)	Value of mobile assets (EUR/m^2)	Total (EUR/m^2)
Settlement	231	59	289
Industry	231	80	311
Traffic	263	2	265
Agricultural area	No differentiation	No differentiation	9
Forest	No differentiation	No differentiation	1
Other	No differentiation	No differentiation	0

Damage-Depth Curves (DDC)

Depth–damage curves (DDCs) represent dependence of damages on flooding water depth. As such, these curves provide a link between flood characteristics and flood consequences, i.e. damages that are essential for flood risk assessment.

There are two types of these curves: absolute and relative [9]. Absolute DDCs show damages in monetary terms versus water depth (at the abscissa, see e.g. the bottom panel of Figure 17). Relative DDCs show damages as the share of total asset value at the given water depth. Specifically, loss takes value between 0 (no damage) and 1 or 100% (total loss of the asset) [3]. Absolute DDCs can easily be converted into relative ones by dividing ordinate values by the estimated asset value, and vice-versa. Relative DDCs are convenient, since they can be easily transferred across different regions, and applied with site-specific asset values.

DDCs are derived for each land-use type in the considered area. The curves for forests or agricultural land are generally obtained from less detailed data than DDCs for residential or industrial areas, or road and rail networks [3]. There are two approaches to DDC derivation: from real survey data (ex-post) and from synthetic data (ex-ante, "what if" approach), i.e. expected values based on the assumptions on damage magnitudes [9]. The latter approach generally leads to overestimated damages, as even severe floods do not always cause total damages, i.e. total loss of assets.

Derivation of DDC is a quite challenging task. The following explanations about DDC creation are based on the example of DDC for a residential building. Figure 17 shows ex-ante derivation of the absolute DDC for a single two-storey residential building, considering the relative share of damages to the individual dwelling components into the total damage (Figure 18). Abrupt jumps in the DDCs in Figure 17 are noticed when the water stage reaches a level at which power sockets are put up, or the second floor of the building.

Similarly to the asset values, the DDCs have to be extrapolated to much wider areas (e.g. a region). In other words, DDCs have to be representative of many buildings of varying characteristics within the considered area. To this end, DDCs are created either by averaging data for numerous buildings, or by analysing data after flood events. For example, the flood damage data for the U.K. are available from the Flood Hazard Research Centre (FHRC), and for Germany from the HOWAS database [9].

Averaging data from numerous flood events and/or on numerous buildings results in smooth curves, without any abrupt jumps that are apparent in DDCs derived from synthetic data (ex-ante approach). Regional DDCs obtained for the Rhine and Elbe basins are shown in Figure 19.

Considerable variations in elevation, robustness of the building structure, presence of cellar and furnishing luxury [27] result in an extensive scatter in damage data, as shown in Figure 20. This means that, although DDCs derived either by averaging over numerous buildings or from the post-event survey data are considered representative of the entire considered region, they are accompanied by enormous uncertainties (see Figure 20). To take differences among the buildings into account, different DDCs are obtained for few distinctive residential building types in the U.K. based on the data from the FHRC (Figure 21).

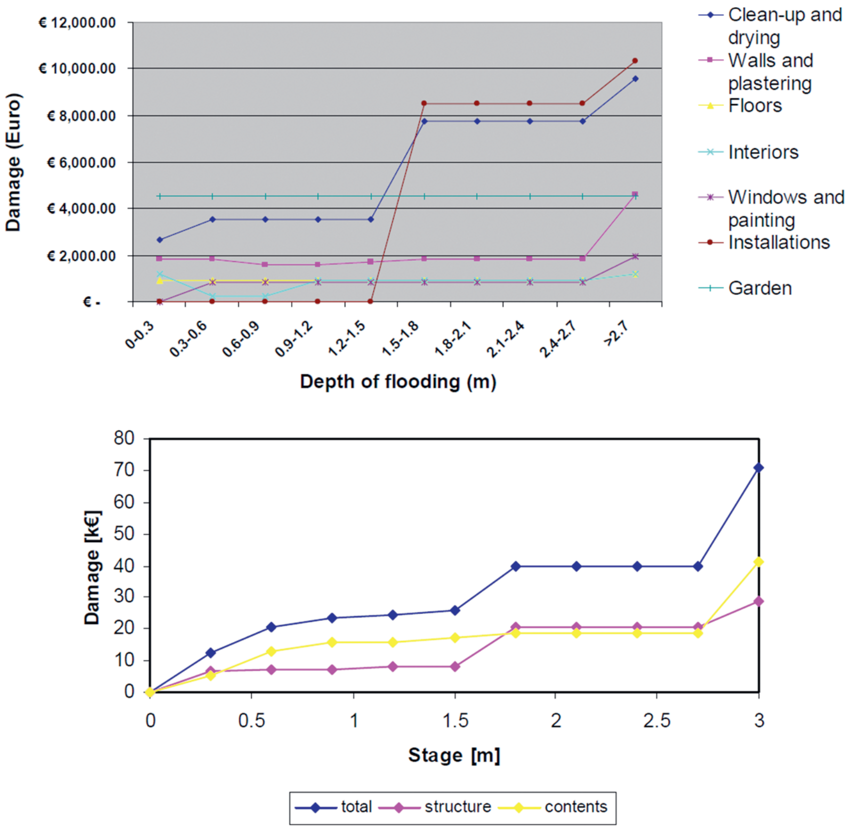

Figure 17. DDC for a two-storey house: development of absolute DDCs (top panel), individual damage components of the DDC (bottom panel) [11]

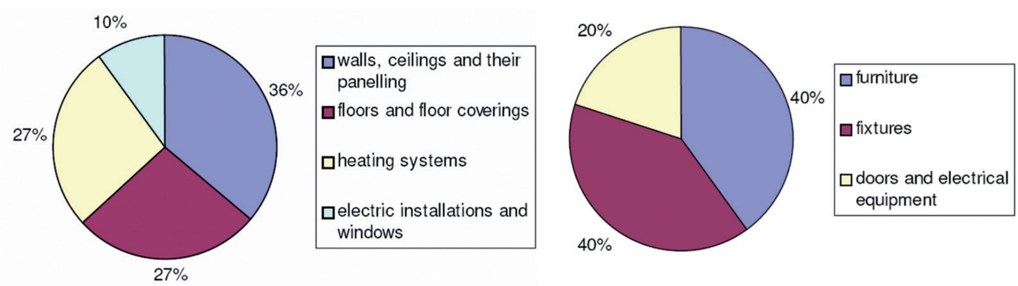

Figure 18. Damages to dwellings: structure (left panel) and properties (right panel) [11]

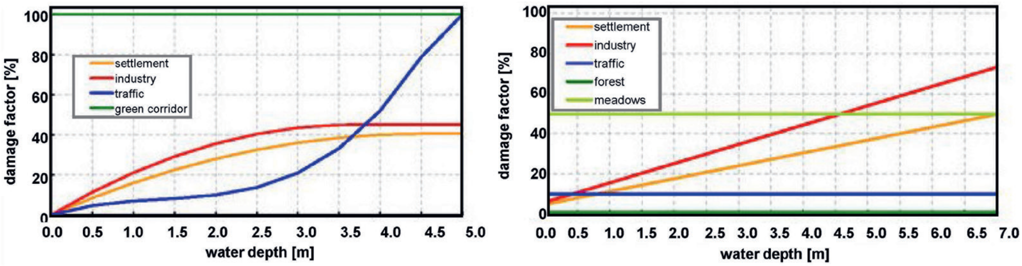

Figure 19. The IKSE (the Elbe River, left panel) and IKSR (the Rhine River, right panel) relative DDCs [3]

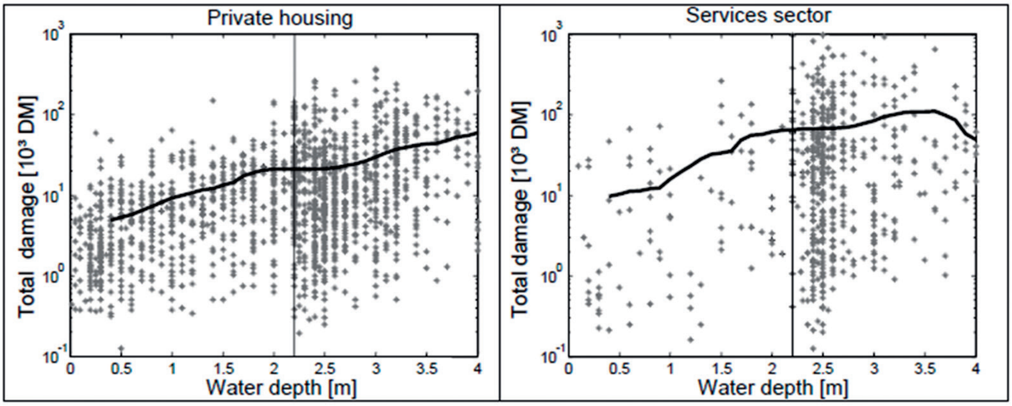

Figure 20. Scatter plots of depth–damage data [28]

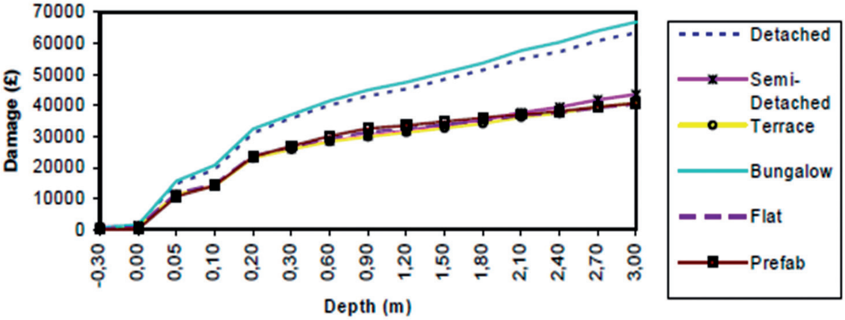

Figure 21. Absolute DDCs for different residential building types in the U.K. [9]

Expected Annual Damage (EAD)

One area can be affected by flood events of various probabilities/return periods (e.g. 50-year or greater). Each of these floods causes damages of different magnitudes. Therefore, consequences of floods of various probabilities should be taken into account for the purpose of flood risk assessment. To this end, expected annual damages (EADs), which combine the probability of flood events that affect the considered area, and the corresponding flood damages are computed [9]. This is in line with the definition of flood risk, which is a product of flood hazard, i.e. the probability of occurrence and flood consequences, represented in monetary terms (see section *Definition of flood risk* and Figure 3).

To calculate EAD, the product of flood probability P and consequent damages D is represented in an integral form as follows [6]:

$$\mathrm{EAD} = \int_{P_{\mathrm{crit}}}^{P_{\max}} P(h) \cdot D(h)\, dP \qquad (2)$$

where h stands for the water depth, and P(h) and D(h) denote the probability of a given water depth (i.e. flood event that results in a given water depth), and consequent specific damage quantified in monetary terms, respectively. Specific damage dependence on the flood probability is illustrated in Figure 22. The value of the integral in equation (2), i.e. the blue area below the function in Figure 22 represents EAD [5] [6].

The lower limit of integration Pcrit is the probability of the critical flood event that causes flooding of the considered area and triggers damages [3]. In other words, flood events of higher probability of exceedance (shorter return period), do not trigger flooding of the area, and, hence, do not cause any damage. The probability of the critical flood event should be defined bearing in mind that some minor flood events do not cause any measurable damage [9]. The upper limit of integration is set arbitrarily to a quite small probability of exceedance (e.g. 0.001 or 10,000-year return period). Flood damage at lower probabilities of exceedance cannot be calculated, and it represents residual risk [3]. The integration of equation (2) is performed by applying the trapezium rule, assuming a linear increase in damages in between two characteristic flood probabilities [3].

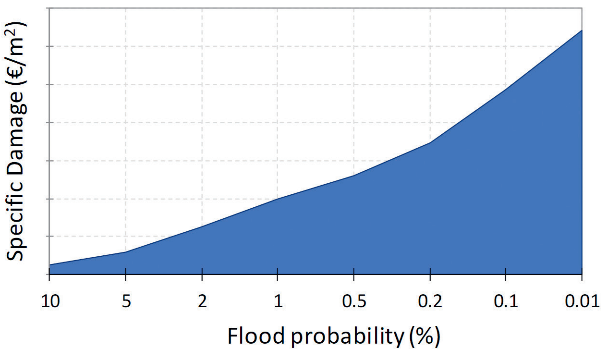

Figure 22. Specific damage as a function of the flood exceedance probability (compiled by the author)

To obtain the curve shown in Figure 22, specific damages have to be estimated for several floods of characteristic probabilities/return periods. For example, in Figure 22 damages are obtained for the following return periods: 10-, 20-, 50-, 100-, 200-, 500-, 1,000- and

10,000-year return periods. These specific damages should be computed for each LUT in the considered area, following the methodology described in the previous sections.

It should be noted that damages due to flood event do not represent actual damages, but rather rough assessments of the expected damages [9]. As stated previously, there are considerable uncertainties in DDCs, as well in the asset value assessment. Also, measures that can be taken prior to and during a flood event, such as relocation or elevation of movable assets, or putting up shields around a building or a property, are not accounted for in this approach although these measures can mitigate flood damages. Therefore, the EADs also represent approximations of average flood damages in a given year.

Flood risk assessment

According to this methodology, a level of flood risk is inferred from EAD, taking into account LUT. Additionally, for assessment of flood risk levels two things have to be defined: namely, risk levels (e.g. high, medium and low) and EAD threshold values that allow differentiation among different risk levels. For most LUTs, following three levels of flood risk are recognised: high, medium and low [3].

The threshold EAD values depend on the LUT, but also on the geographical region. Specifically, flood risk levels are related to costs of flood insurance per year, which, on the other hand, depend on EAD in a considered area. For example, the threshold for high flood risk should be EAD equal to the unacceptably high flood insurance costs. Considering that insurance costs and “unacceptable costs” considerably vary, there are no unique, generally accepted EAD threshold values.

For example, for residential areas, the EAD value of 0.1 €/m^2/year can be used to discriminate between low and medium flood risk, and EAD value of 1 €/m^2/year can be used to identify high risk areas (i.e. annual insurance costs of 1 €/m^2 can be considered prohibitive and unaffordably high by most citizens) [3]. The same principle is applied for flood risk assessment in agricultural areas. In these areas, only low and moderate levels of flood risk are recognised with EAD value of 0.012 €/m^2/year as the threshold EAD value [3]. Note that these EAD threshold values can vary with the region, depending on the economy of the region and insurance policies.

As stated in the previous sections, this methodology for flood risk assessment does not consider risks to human health and lives. However, flood risk to people can be readily estimated from the product of water depth and velocity, and by imposing threshold values given in Table 2.

Flood risk maps

Information on flood risk levels are easily obtained and communicated to the public and decision-makers via flood risk maps, which are obtained by using a GIS tool.

In addition to effective visualisation, GIS tools greatly facilitate the manipulation of different data (e.g. inundation maps, LUT and asset values) and they are essential for flood risk assessment. Flood risk maps are obtained following the methodology elaborated in the previous sections. The process of creating flood risk maps by using QGIS is described and illustrated with examples in this section. Being freely-available, QGIS is preferred over e.g. ArcMap.

The latter is certainly more user-friendly, and offers more features, however, it is not freeware.

Inundation maps. Flood flow rates or hydrographs are computed and routed externally, by employing appropriate hydrologic and hydraulic models. Simulated water levels during flood events of different return periods are exported from the hydraulic model to a GIS environment. For example, water levels simulated with HEC-RAS can be easily imported to ArcMap or QGIS by using appropriate plug-ins (as explained in section *Flood routing and inundation maps*), resulting in inundation maps.

Land use types. LUT layers have to be either imported in the GIS environment or created based on the e.g. orthophoto maps. Specific asset values can be appointed to each LUT as by adding a column in the attribute table and entering estimated values, as shown in Figure 23. LUT data are commonly made/available as vector shapefiles. For the purpose of flood damage computations, a raster version of LUT layer is required. A LUT layer can readily be rasterised e.g. with the Rasterise function (under Raster drop-down menu, command Conversion in QGIS).

Since DDCs differ across LUTs, pixels with one LUT have to be extracted, as shown in Figure 24. In this way, pixels with industrial LUT are assigned value 1, and the remaining value 0.

Damages due to flood event of a given return period. These damages (in monetary terms) are easily calculated by applying the Raster calculator, as shown in Figure 25. In this example, the IKSR DDC is applied to estimate damages due to 1,000-year flood in industrial zones. Note that the auxiliary raster layer enables that the damages are estimated for pixels with industrial LUT only. Damage computation should be repeated for all LUT and all return periods considered.

Expected Annual Damage (EAD). EAD is easily calculated from the estimated damages, by applying the trapezium rule (see subsection *Expected Annual Damage [EAD]*) with the raster calculator, as shown in Figure 26. Note that values in "Raster calculator expression" in Figure 26 correspond to differences between the flood probabilities (e.g. 0.005 is the difference between 1/100 and 1/200).

Flood risk maps. Based on the EAD and adopted threshold values for every LUT, flood risk maps are obtained. Initially, flood risk can be derived for individual LUTs, considering different threshold values or risk categorisation, and merged into a single raster file with the command Merge raster layers in QGIS environment.

The maps created for the purpose of flood risk assessment in the Resava catchment are shown in Figure 27.

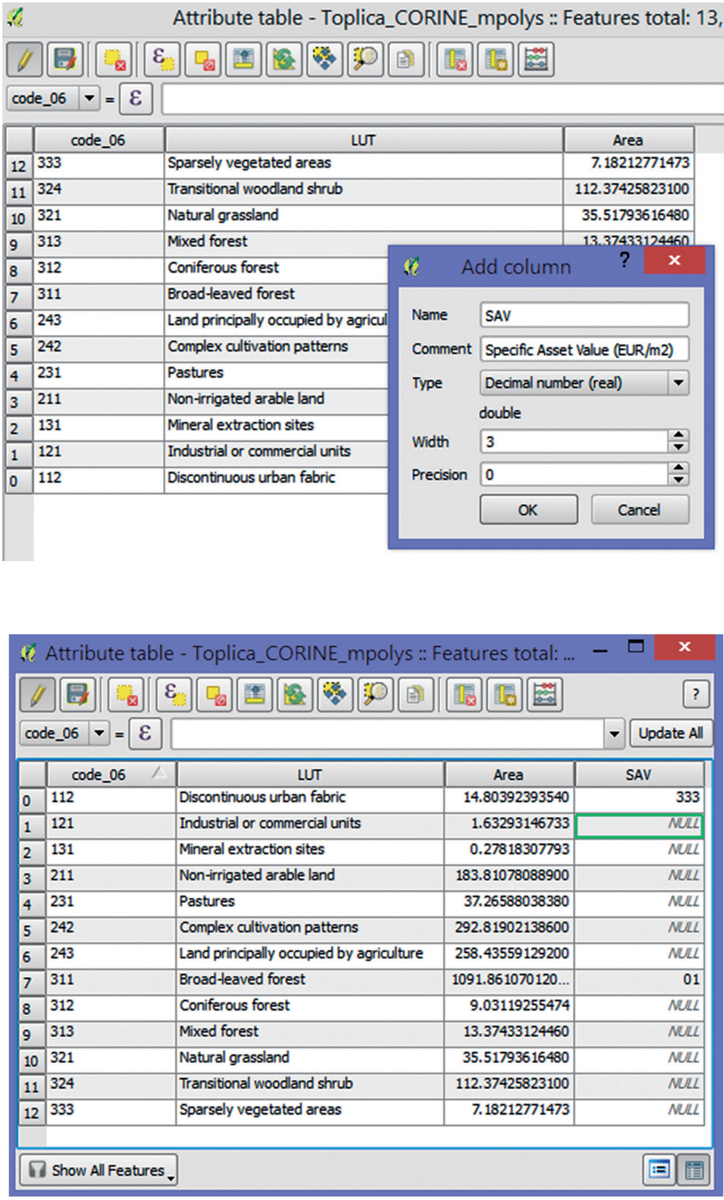

Figure 23. Appointing specific asset values in GIS environment to each LUT (compiled by the author)

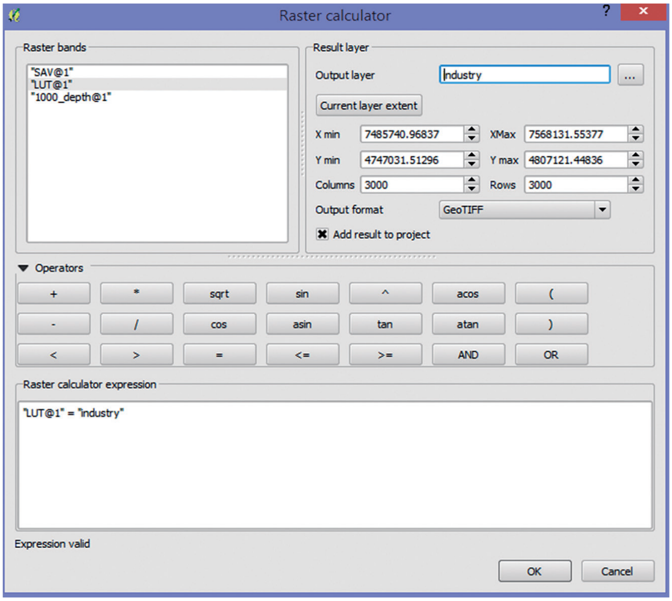

Figure 24. Identification of pixels with industry (compiled by the author)

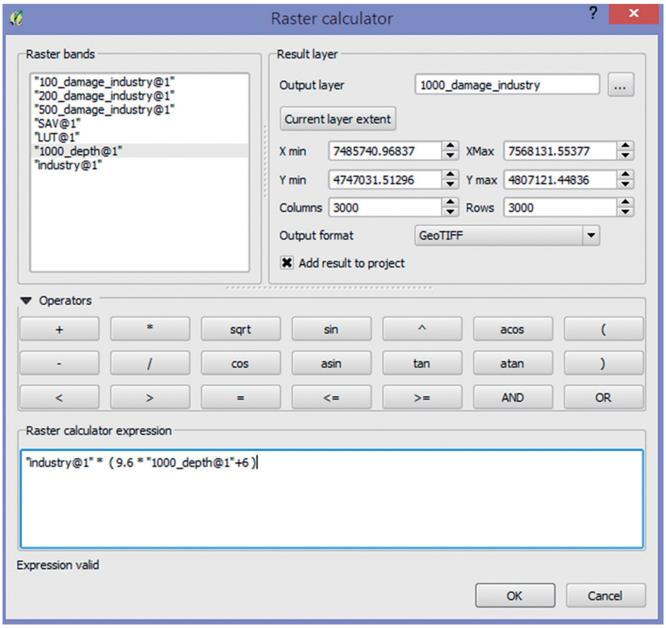

Figure 25. Calculation of damages due to 1,000-year event in industrial zones by applying IKSR DDC (compiled by the author)

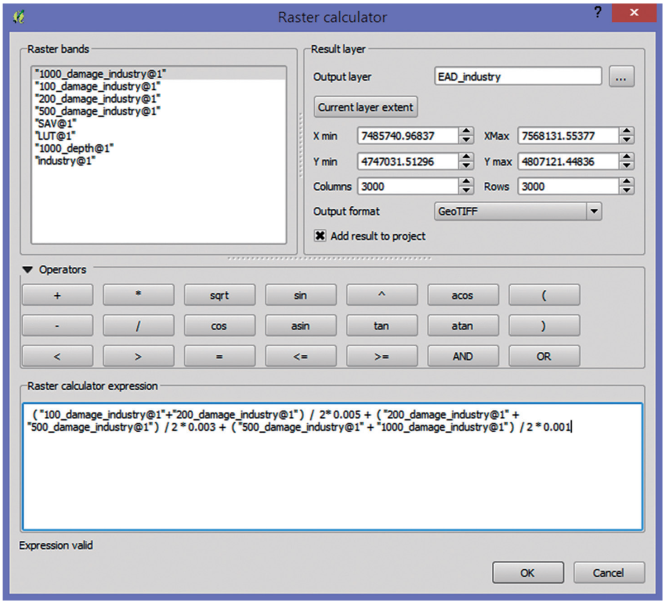

Figure 26. Calculation of expected annual damages by applying the trapezium rule to 100-, 200-, 500- and 1,000-year flood events in industrial zones (compiled by the author)

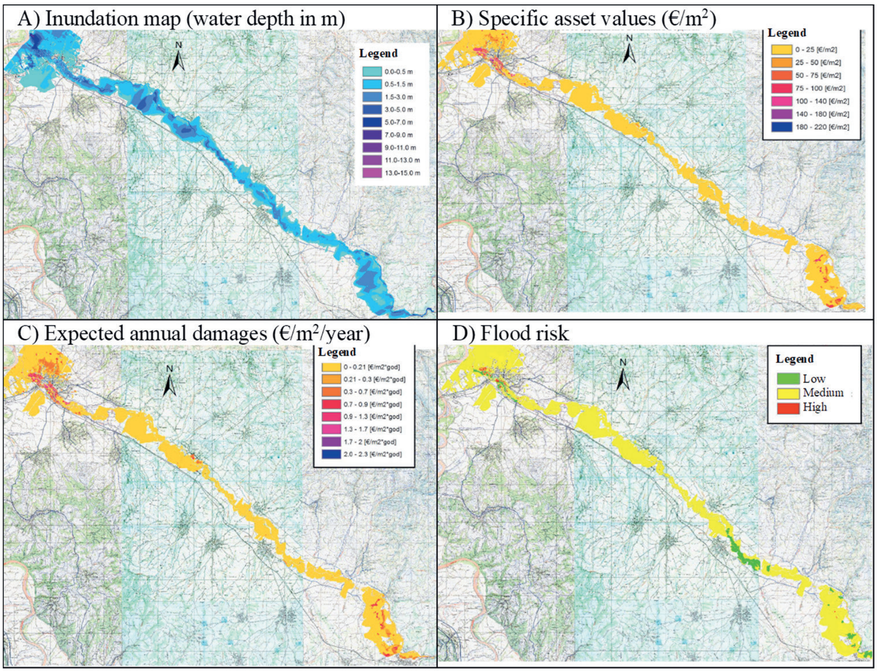

Figure 27. Flood Risk Mapping in the Resava catchment: A) inundation map (1,000-year return period); B) specific asset values; C) expected annual damages; and D) flood risk [29]

Glossary

Assets – represent entities of value in a considered area, such as houses, vehicles, inventories, infrastructural systems (e.g. traffic, water supply and sewer systems), etc.

Consequence – negative flood impacts, which generally include social, economic and environmental impacts. Consequences can be represented in terms of monetary loss or qualitatively (e.g. high, low). Only economic consequences are considered in this course.

Damages – losses due to flood expressed in monetary value. Here, only direct, tangible damages are considered.

Depth–damage curves (DDC) – functions showing dependence of damages on water depth for a considered land use type (e.g. residential or industrial areas, agricultural land, etc.).

Absolute DDC – show damages expressed in monetary value versus water depth.

Relative DDC – show damages in relative terms, as share of total asset value.

Direct damages – damages caused by direct contact with flooding water (e.g. damages to structures, industrial facilities, infrastructural systems, crops, etc.).

Expected Annual Damages (EAD) – specific damages in a considered area calculated by combining various probabilities of flooding (e.g. 50- through 1000-year return periods) and the corresponding damages, represented by their monetary value. EAD is given in €/m^2/year.

Exposure – the situation that people, infrastructure, housing, production capacities and other tangible human assets are being situated in a flood-prone area [8].

Flood – An overflow of a large amount of water beyond its normal limits, especially over what is normally dry land (source: https://en.oxforddictionaries.com/definition/flood).

Flood hazard – related to frequency of flooding. Flood hazard is great in flood prone areas.

Flood risk – risk is a function of probability, exposure and vulnerability. Here, it is calculated by multiplying of flood probability by its consequences, which are quantified in terms of monetary loss.

Flood risk assessment – procedure of estimation of flood risk in a certain area, according to the methodology adopted, including thresholds used to differentiate among different risk levels.

Flood risk maps – maps showing different degrees of flood risk across a region of interest. These maps clearly indicate high risk areas, and can be easily used by decision-makers and citizens.

Flow quantile – flow rate of a given probability of exceedance or return period. This value is estimated by applying statistical methods (e.g. Flood Frequency Analysis).

Hazard – a potential source of danger or a harmful event.

Flood hazard – probability of flooding of certain area.

Indirect damages – damages accompanying direct ones. Indirect damages are not caused by direct contact with flooding water. These damages include e.g. loss in production and income, loss due to traffic disruption, etc.

Intangible damages – damages that are difficult to represent in terms of monetary value [9]. These include e.g. loss of human lives, negative effects on health and environment, damages to cultural heritage, etc.

Inundation – flooded area that are otherwise dry.

Inundation maps – maps showing the flood extent and water depth in each pixel of the inundated (flooded) area for a flood of a given return period. These are obtained by overlying common terrain maps by the results of hydraulic simulations.

Inventories – household contents or, for businesses, stocks of outputs that are still held by the units that produced them [9].

Land use types – include e.g. residential zones, industrial zones, agricultural land, forest (deciduous or coniferous), shrubs, traffic, etc.

Probability – here, the term "probability" is used to represent the probability of exceedance, i.e. the reciprocal value of the return period.

Return period – mean time interval between exceedances of a specified flow. It is calculated as a reciprocal value of the flow probability of exceedance and is expressed in years [15].

Specific asset value – asset value per unit area (e.g. €/m^2). It is obtained by estimating the total asset value within a considered area, and dividing this estimate by the total area.

Tangible damages – damages that can be readily quantified in monetary terms. Tangible damages include e.g. damages to buildings or infrastructure.

Vulnerability – potential of a system to be harmed. According to UN, vulnerability is defined as: "the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards" [8].

References

[1] Real-time Flood Risk Map (2018). Available from: www.jma.go.jp/en/suigaimesh/flood.html

[2] Long Term Flood Risk Information (2014). Available from: https://flood-warning-information.service.gov.uk/long-term-flood-risk/risk-types

[3] Flood Risk Assessment (s. a.). Available from: http://daad.wb.tu-harburg.de/tutorial/flood-risk-management/flood-risk-assessment/sitemap-of-flood-risk-assessment/

[4] Priest S, Wilson T, Tapsell S, Penning-Rowsell E, Viavattene C, Fernandez-Bilbao A (2007). Building a Model to Estimate Risk to Life for European Flood Events. European Community, Sixth Framework Programme for European Research and Technological Development.

[5] Guidance: Flood Risk and Coastal Change (2014). Available from: www.gov.uk/guidance/flood-risk-and-coastal-change#flood-zone-and-flood-risk-tables

[6] Kron W (2005). Flood Risk = Hazard • Values • Vulnerability. Water Int. 30(1):58–68. DOI: https://doi.org/10.1080/02508060508691837

[7] Sato T (2006). Fundamental Characteristics of Flood Risk in Japan's Urban Area. In: Ikeda S, Fukuzono T, Sato T editors. Better Integrated Management of Disaster Risks: Toward Resilient Society to Emerging Disaster Risks in Mega-cities. Tokyo: Terra Scientific Publishing. p. 23–40.

[8] United Nations (s. a.). Disaster Risk Management. Available from: www.un-spider.org/risks-and-disasters/disaster-risk-management

[9] Messner F, Penning-Rowsell E, Green C, Meyer V, Tunstall S, van der Veen A (2007). Evaluating Flood Damages: Guidance and Recommendations on Principles and Methods. European Community, Sixth Framework Programme for European Research and Technological Development.

[10] CORINE Land Cover (2012). Available from: https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012?tab=mapview

[11] McGrath HD (2017). Web-based Flood Risk Assessment – Rapid, User-friendly Tools Leveraging Open Data. Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada.

[12] Stanić M, Todorović A, Vasilić Ž, Plavšić J (2018). Extreme Flood Reconstruction by Using the 3DNet Platform for Hydrological Modelling. J Hydroinformatics Jul;20(4):766–783. DOI: https://doi.org/10.2166/hydro.2017.050
[13] U.S. EPA (s. a.). Flooding. Available from: www.epa.gov/natural-disasters/flooding
[14] Smithers J (2012). Methods for Design Flood Estimation in South Africa. Water SA Sep;38(4):633–646. DOI: https://doi.org/10.4314/wsa.v38i4.19
[15] Kottegoda NT, Rosso R (2008). Applied Statistics for Civil and Environmental Engineers. 2nd ed. Oxford: Blackwell Publishing.
[16] Vukmirović V, Plavšić J (1997). Flood Flow Analysis Using Renewal Processes. UNESCO-IHP V Tech. Documents in Hydrology No. 11 (Annual FRIEND-AMHY meeting, Thessaloniki, 1995). p. 159–169.
[17] Montanari A (2016). Estimation of Design Peak River Flow and Flood Hydrograph. Available from: http://distart119.ing.unibo.it/albertonew/?q=node/56
[18] Beven K (2001). Rainfall–Runoff Modelling. The Primer. West Sussex: John Wiley & Sons.
[19] Yu BB (1998). Theoretical Justification of SCS Method for Runoff Estimation. J Irrig Drain Eng. 124(6):306–310.
[20] Chow VT, Maidment DR, Mays LW (1988). Applied Hydrology. New York: McGraw-Hill.
[21] Feldman A (2000). Hydrologic Modeling System HEC-HMS – Technical Reference Manual.
[22] Blöschl G, Sivapalan M, Wagener T, Viglione A, Savenije H (2013). Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales. Cambridge: Cambridge University Press.
[23] Mizukami N, Rakovec O, Newman A, Clark M, Wood A, Gupta H, Kumar R (2018). On the Choice of Calibration Metrics for 'High Flow' Estimation Using Hydrologic Models. Hydrol E Syst Sci Discuss. Aug;23(6): 1–16. DOI: https://doi.org/10.5194/hess-23-2601-2019
[24] Jovanović M (2008). Regulacija reka [River Regulation]. 2nd ed. Belgrade: University of Belgrade, Faculty of Civil Engineering.
[25] Brunner GW (2016). HEC-RAS River Analysis System. US Army Corps of Engineers, Davis, CA.
[26] Rhine Atlas 2015. Available from: www.iksr.org/en/documentsarchive/rhine-atlas/
[27] Gersonius B (2006). Flood Damage to Buildings. UNESCO-IHE.
[28] Merz B, Kreibich H, Thieken A, Schmidtke R (2004). Estimation Uncertainty of Direct Monetary Flood Damage to Buildings. Nat Haz E Syst Sci. 4(1):153–163.
[29] Cvijanovic N (2015). Flood Risk Mapping in the Resava River Basin. University of Belgrade.
[30] Myers J (2016). Which Natural Disasters Hit Most Frequently? World Economic Forum. Available from: www.weforum.org/agenda/2016/01/which-natural-disasters-hit-most-frequently/
[31] Hersher R (2018). More Rain, More Development Spell Disaster For Some U.S. Cities. Available from: www.wlrn.org/post/more-rain-more-development-spell-disaster-some-us-cities
[32] ABC News (2017). Hurricane Irma: Cuba Surveys Toppled Houses and Flooded Cities Left behind by Storm. Available from: www.abc.net.au/news/2017-09-10/cuba-surveys-toppled-houses-and-flooded-cities-in-wake-of-irma/8890152
[33] Ashmyn (2011). Hazards on the Flooded City's Street. Available from: https://ashmynslife.wordpress.com/2011/07/15/hazards-on-the-flooded-citys-street/
[34] Available from: https://mondo.rs/Info/Drustvo/a696171/Traga-se-za-jos-11-osoba-nestalih-u-poplavama.html (Accessed on 10th of July 2022)

[35] Available from: https://www.agronews.rs/tokom-poplava-nije-bilo-ugrozavanja-zivotne-sredine/#prettyPhoto/0/ (Accessed on 10th of July 2022)

[36] Available from: https://www.bastabalkana.com/2014/05/svetski-mediji-izvestavaju-o-poplavama-u-srbiji-2/comment-page-1/ (Accessed on 10th of July 2022)

[37] Available from: http://arhiva.alo.rs/vesti/reportaza-srbija/pogledajte-kako-izgleda-kop-kolubare-ispod-vode-ostao-citav-mali-grad-video/56276 (Accessed on 10th of July 2022)

[38] Cheng, K-S (2014). Presentation on theme: "Hydrology Rainfall - Runoff Modeling (II) Synthetic unit hydrographs". Available from: https://slideplayer.com/slide/5151854/

[39] Etkin D (2016). Applications of 2D Surface Flow Modeling in the new HEC-RAS Version 5.0 ASFPM Annual National Conference, Grand Rapids, MI Concurrent Session G. Available from: https://nanopdf.com/download/applications-of-2d-surface-flow-modeling-in-the-new-hec_pdf

[40] Godell, C (2014). Web Imagery for RAS Mapper in Version 5.0. Available from: http://lh6.ggpht.com/-fizZ-9_oCto/VAndX5G5-LI/AAAAAAAAMQo/FF3taOnoX3Q/image_thumb%25255B10%25255D.png?imgmax=800