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VULNERABILITY AND FLOOD RISK IN URBAN AREAS

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ABSTRACT

Flood risk management has been increasingly noticed over the years at the same time that population has settled in highly concentrated urban areas. Such areas, whenever they are in danger of suffering the effects of damaging natural phenomena (in particular, flooding), are likely to experience numerous losses. In this context, flood risk management (FRM) aims to carry out analyses that take into account all influencing aspects to determine the probable negative effects and, with this information, to take the appropriate measures to reduce risk up to a “tolerable” level of risk.

This paper focuses firstly on the explanation of the three main concepts intimately related with risk, which are flood hazard, flood risk and vulnerability. Although they seem clear concepts, it actually happens that depending on which source or science they are consulted different meanings can be attributed. Therefore a clear definition for each concept is presented with the purpose of leaving no space for misinterpretation. Moreover, a literature review is done to collect different available methodologies that express either of the these concepts so that similarities and differences can be noticed and compared.

A second part deals with the main tool that is used to represent vulnerability of elements at risk, which is called vulnerability curve or damage function. These functions are the key element within a flood risk analysis to determine total losses for different scenarios of flooding, also used for benefit-cost studies. A distinction is made between relative and absolute damage functions; a number of functions have been collected from available past studies in order to carry out an analysis of their behaviour, variability, patterns and critical levels of hazard in regard to the amount of damage. Moreover, the author presents a proposal of her own absolute damage function for building contents in residential areas (damage per property).

A third part of the paper regards the effect of flow velocity since it is most often neglected when assessing flood damage estimates. Considering a few past studies on the matter, a modified function is suggested which includes the damaging effects of water depth and flow velocity.

Key words: flood risk, flood hazard, vulnerability, damage curves, relative function, absolute function, velocity effect on damage functions

RESUMEN

Recientemente, el concepto de gestión del riesgo de inundación se ha generalizado a la par que han aumentado los niveles de población asentada en áreas urbanas muy concentradas. Estas zonas, que además estén en peligro de sufrir los efectos negativos de fenómenos naturales (en este caso particular, las inundaciones), son susceptibles de experimentar importantes pérdidas económicas. En este contexto, la gestión del riesgo de inundación tiene como objetivo analizar todos los aspectos que contribuyen a la determinación de las probables consecuencias negativas del suceso y, con esta información, decidir qué medidas son las más apropiadas para reducir el riesgo hasta un nivel “tolerable”.

Esta tesina está dedicada, en primer lugar, a explicar los tres conceptos principales relacionados con el riesgo: la peligrosidad, el riesgo de inundación y la vulnerabilidad. Aunque puedan parecer conceptos claros, se acaba comprobando que en realidad se les atribuyen diferentes significados o acepciones dependiendo de la fuente o ramas de estudio en que sean consultados. Por lo tanto, se procede a plantear definiciones claras con el propósito de no dejar margen a ideas erróneas. Además, se ha revisado la literatura disponible para reunir diferentes métodos utilizados para expresar estos tres conceptos, identificando similitudes y diferencias.

Una segunda parte del trabajo se centra en la herramienta más utilizada para representar la vulnerabilidad de los elementos expuestos a riesgo de inundación, llamada curva de vulnerabilidad o función de daño. Estas funciones son el elemento clave para la realización de un análisis de riesgo de inundación y determinar las pérdidas totales debidas a diferentes escenarios de inundación; también se utilizan en análisis de coste-beneficio. Normalmente se distinguen dos grandes grupos de funciones: relativas y absolutas. Se han reunido un número de funciones de ambos tipos con el fin de analizar sus comportamientos, comparar patrones e identificar valores críticos de calado. Adicionalmente, la autora propone una función de daños propia para estimar los daños de contenidos en edificios de zona residencial (daños por propiedad).

La tercera y última parte trata el efecto de la velocidad teniendo en cuenta que en la mayoría de estudios se omite durante la estimación de daños de inundación. Habiendo considerado los pocos estudios existentes sobre este tema, se sugiere un modo de modificar la función de daños para incluir tanto los efectos del calado como de la velocidad del flujo.

Palabras clave: riesgo de inundación, peligrosidad, vulnerabilidad, curvas de daños, funciones relativas, funciones absolutas, efecto de la velocidad

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1. INTRODUCTION

Flooding in urban areas are recurrent and have caused a great amount of damage throughout history (loss of life, economic damage, etc.). There have been developed many studies that characterize the probability of occurrence of such flood events that occur over areas which are exposed and vulnerable. But it is higher concentration of urban areas what increases the total loss since in those areas there are more susceptible elements and valuables at risk.

Most of the cities authorities have established regulations and policies based on probable water levels (flood hazard) for which there is a “tolerable” probability of suffering flooding, so that the severity of flooding effects can be limited. However, because of the potential and significant economic consequences of flooding, for some years already the approach of flood protection that was initially focused on flood hazard has shifted towards a flood risk management (FRM).

This new approach seems to fit better since it takes into account not only the probability of an area being flooded but also the elements that may be exposed along with their values and vulnerabilities. The FRM approach was established in the European Union in 2007 when the directive 2007/60/CE on the assessment and management of flood risks was approved. Their objective was to set a common framework for all countries that would need to work on the following: a preliminary flood risk assessment to identify areas with significant risk, the making of flood hazard and flood risk maps, and the production of flood risk management plans.

It is clear then, that situations of zero risk in vulnerable and exposed areas cannot be achieved. Many authors think the best way to reduce flood risk is to find a balance between structural and non-structural measures (such as early warning systems). But prior to the decision making, analyses of flood risk are carried out. A key step within the obtention of flood costs is the estimation of the degree of damage and losses due to inundation depths, and the elements that are at risk. Throughout literature a variety of damage functions can be found, which have been developed for several categories of land uses, building structures and building contents. Since damage functions aim to express the relationships between water depths and damages caused according to a few variables, a great deal of data is required for a proper analysis. However, both lack of information and time demanding processes usually prevent the realization of detailed studies.

Moreover, it is important to be reminded of the inherent uncertainties within several parts of the analysis; for example, water levels are estimated through simulation and modeling of flooding in study areas (1D or 2D). Knowing all this, many authors have stressed on the importance of developing damage models which are simple enough and that enable to represent real circumstances with the lowest level of uncertainty.

1.1 Objectives

Given the necessity of clarifying the three basic concepts in which further analysis are based on, the first part of the thesis is focused on its definitions -flood hazard, flood risk, vulnerability- and their evolution in time. Moreover, methodologies that express each of these concepts have been collected from agencies, authorities and articles of past studies. The question would be how more or less different are those methods in terms of the variables considered, the ranges of those variables, their applicability to certain areas, properties, or people, etc.

The second part of the thesis deals with the development of functions that aim to predict the average amount of damage under particular hypothesis. These damage functions started to become the object of many studies because of the increasing significance of flooding consequences. Depending on the range of the analysis (local or regional) different spatial scales need to be considered. Here the motivation is to gather a number of functions and, through their comparison and review, to make an analysis and identify repetitive patterns, coherent representation of the response to flooding, spot the critical water depths for which damages change its tendency, etc. Overall, the objective is to determine which level of variability is observed between a wide range of available functions from different sources developed in various places and within a long period of time.

Additionally, the author will manage to produce her own damage function for an average property in residential areas. The motivation is to compare this function with the ones that had been previously reviewed, and to point out the difficulties or uncertainties of producing damage functions. The function will be based on the author's estimation of representative items that are found in an average household, their market value and the item's degrees of damage according to water levels.

Then, another important component which is usually neglected in the assessment of flood damage is the effect of velocity flow. However, it is commonly attributed to be an important factor that determines the degree of damage caused: to building structures, stability of pedestrians, and level of destruction. The majority of damage functions refer to inundation depths; only a few studies have attempted to determine certain thresholds to define hazard levels of flow velocity, and to determine the relationship between velocity and flood damage. The author aims to suggest a methodology to include the effect of velocity by applying the proven relationship between damage and the energy of the flow.

2. FLOOD HAZARD

There are three key concepts intimately related with floods in the context of damage estimation: flood hazard, flood risk and vulnerability. It seems that a detailed explanation of those three concepts and its processes is necessary and suitable to leave out any misconceptions. This chapter presents a short presentation of typical flood types, and provides a brief literature review regarding the different methodologies used to express flood hazard; flood risk and vulnerability will be dealt with in further chapters.

2.1 Flood types

Some of the causes of flooding are events of heavy rain, tidal surges and the raising of groundwater levels. Smith and Ward (1998) stated that flooding occurs because of the interference with natural drainage processes, for instance, changes to river channels or blocked sewerage systems. Therefore, if extreme weather conditions are assumed, rivers and drainage systems are likely to reach their capacity and the ground becomes saturated. This means water cannot be retained so it follows the least resistant path or remains in low areas. Urban areas usually modify certain hydrological variables (water storage, infiltration) which makes flooding in those areas much more harmful.

There are five broad categories of floods that can be distinguished: coastal flooding, groundwater flooding, river flooding, flash flooding and pluvial flooding. Coastal flooding can happen under storm surges conditions or wave actions according to FEMA (Federal Emergency Management Agency, USA). The storm surges can increase the sea level above the normal tide level because of low atmospheric pressures in the center of the storm; on the other hand, waves breaking at the shoreline can be very destructive as well. For these reasons, low-lying coastal areas are susceptible to be inundated during severe storms.

Problems with high groundwater levels mainly take place in floodplains or low-lying areas. Kreibich & Thicken (2008) stated that changes of groundwater levels can be a consequence of high infiltration rates (due to flooding or heavy precipitation) into the aquifer, or a reduced withdrawal of groundwater. When there is a considerable change of the groundwater levels (which can be sudden or a long-term change), damage is likely to happen; for example, in urban areas, basements would be susceptible to be affected.

Floods in river valleys mostly happen on floodplains as the result of flow exceeding the capacity of the stream channel and overspilling the banks (Smith & Ward, 1998). Most river floods result directly or indirectly from events of heavy and/or prolonged rainfall.

A flash flood is a rapid and extreme flow of high water that goes into a normally dry area and it is mainly caused by heavy or excessive rainfall in a short period of time (less than six hours); dam failure can also cause flash floods. According to the National Weather Service these floods are usually characterized by torrents within minutes or a few hours of heavy rains and are able to sweep everything before them.

Lastly, Falconer (2009) referred that pluvial flooding results from intense rainfall when water that does not infiltrate into the ground, ponds in natural or artificial hollows or flows over the ground before it enters a drainage system or watercourse, if full capacity is not already reached. Typically, pluvial flooding is associated with short duration and high intensity rainfall, but it can also happen within lower intensity and prolonged rainfall conditions. The pluvial flood extent can be larger if the ground has low water permeability which takes place when the ground becomes saturated or is paved.

2.2 Flood Hazard concept

In general terms, Tsakiris (2007) defines hazard as a source of potential harm and a threat or condition that may cause loss of life or initiate any failure to the natural, modified or human systems. He explains that the causes that originate hazard can be external (earthquake, flood) or internal (defective section of a levee). Moreover, hazards can also be classified as natural or man-made events, for instance excessive rainfalls and deforestation respectively. In particular, flood hazard belongs to the hydrological category of natural hazards.

Flood hazard can be defined as the threatening natural event including its probability of occurrence (Kron, 2002). In the context of urban areas, flood hazard is related to the degree of danger induced by the natural event to people, properties and infrastructures of those urban areas. The severity of the floodwater characteristics is a direct consequence of the frequency of occurrence and magnitude of the event. A frequent rainfall event, for example one year of return period, will not cause flood since the magnitude will pass almost inadvertently. For a less frequent rainfall event, flooding can happen to a certain degree and cause some kind of damage due to a higher intensity of rainfall. And for a rare event, extreme conditions usually result in a very severe flood with possible catastrophic consequences.

The severity of flooding is correlated with the capacity of dragging and destruction of the water flow (besides the contact with the water itself), and so it can be translated into some of the flow and flood characteristics. This means flood hazard can be expressed through parameters like flood depth, flow velocity, expected inundation area and flood duration among others. Some of these parameters can be associated with the probability of occurrence of the flood event. Both -specific parameters and probability of occurrence- would be measures to describe flood hazard while the first expresses its concept in a more accurate and direct way.

The concept of flood hazard is quite accepted and similarly understood in the scientific literature. The question raises when it comes to how flood hazard should be quantified or categorized. As mentioned above, flood depth is the main variable usually considered, followed in importance by the velocity of the flow.

2.3 Flood hazard methodologies

There is relatively plenty of available information regarding the different methodologies used to express flood hazard: flood hazard maps, flood hazard ratings, diagrams, matrices, etc. Some of those methods are described below.

2.3.1 Flood hazard maps

Flood regulations concentrate on the reduction of flood hazard through the reduction of probability of occurrence and the intensity of inundations. Typically flood hazard studies focus on obtaining maps plotting water depth levels for a design flood event; the design flood event is one that can happen in any year with a certain probability of occurrence or of being exceeded. Between larger (less frequent) and smaller floods (more frequent), most times the design flood used is the 100 year flood. This means that flooding has a 1% chance of occurring or being exceeded in any given year.

Given the return period and using a calibrated hydraulic model, the design discharge is modeled and flood elevations are calculated which can be superposed to terrain maps to obtain the extent of flooded areas and its inundation depths. Figure 1 shows an example of flood hazard levels to people according to the NOAH project. Three levels of flood hazard are defined (high, medium and low) according to the inundation depth and assuming an average person's height to be 1.69m. No reference is made regarding the person's weight which certainly influences people stability in flooded areas.

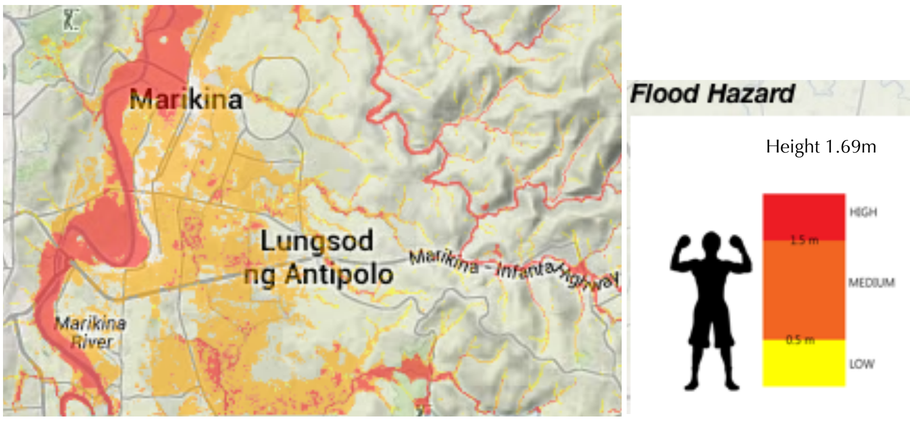

Figure 1: Flood hazard map of Marikina city, Philipines, for 100 year return period (NOAH project)

Flood maps are the most direct way of identifying flood-prone areas and their extent, so that local governments can plan appropriate measures to reduce potential flood damages and guarantee public safety. When considering floods along a river, the 100 return period is often used in city regulations as the limit for which development is prohibited or restricted. Sometimes there is a distinction between the floodway, where the water flow is mostly concentrated, and the flood fringe, where depth and velocity parameters are relatively low. Development under certain established standards is permitted in areas within the flood fringe.

2.3.2 DEFRA's flood hazard rating (UK, 2006)

The Department for Environmental Food and Rural Affairs (2006) presented a simple model of flood hazard to people based on depth, velocity and the presence of debris:

$$HR = d \cdot (v + 0.5) + DF \qquad [2.1]$$

where d is depth (m), v is velocity (m/s) and DF is the debris factor (0, 0.5, 1). The debris factor was added later to consider hazards due to the presence of floating debris; its value depends on the probability that debris would cause a greater hazard compared to the situation without debris. Also the suggested values are small enough so it is possible to distinguish the changes of the depth-velocity function.

Table 1 shows a guidance of debris factors for different flood depths and land uses: 0 for low water depths (and velocities) unable to transport debris; 0.5 for fluvial flooding in rural catchments; and 1 for fluvial flooding in urban areas. Later on, a simpler criteria was recommended when determining flood hazard to people: 0.5 for depths lower than 0.25m and 1 for depths over 0.25m. This second criteria is independent from the land use and assumes that the effect of debris on people should be always considered.

Depths	Pasture/Arable	Woodland	Urban
0 - 0.25 m	0	0	0
0.25 - 0.75 m	0	0.5	1
d>0.75m and/or v>0.2	0.5	1	1

Table 1: Debris factors (DEFRA, 2006, FD2321/TR1)

Regarding the depth-velocity combinations that are required to make people loose their stability during flooding (see Figure 2) some experimental work was done (Abt 1989, and RESCDAM 2000). Their results were used to produce a relation between the people's height and mass for several ranges of age. The expression that was found to be reliable for determining the threshold for losing stability is the following:

$$d \cdot (v + 0.5) = a \cdot h \cdot w + b \qquad [2.2]$$

where d is depth of flooding (m), v is velocity (m/s), h is height (m), w is weight (kg) and a, b are constants.

They emphasize that because of the variability of results of the experiments and the uncertainty of being able to reproduce real flood conditions, the determination of flood hazard classes was precautionary (Table 2). In the context of flood risk to people, flood hazard is used as a component that affects the proportion of people exposed during the flooding and that may result injured or killed.

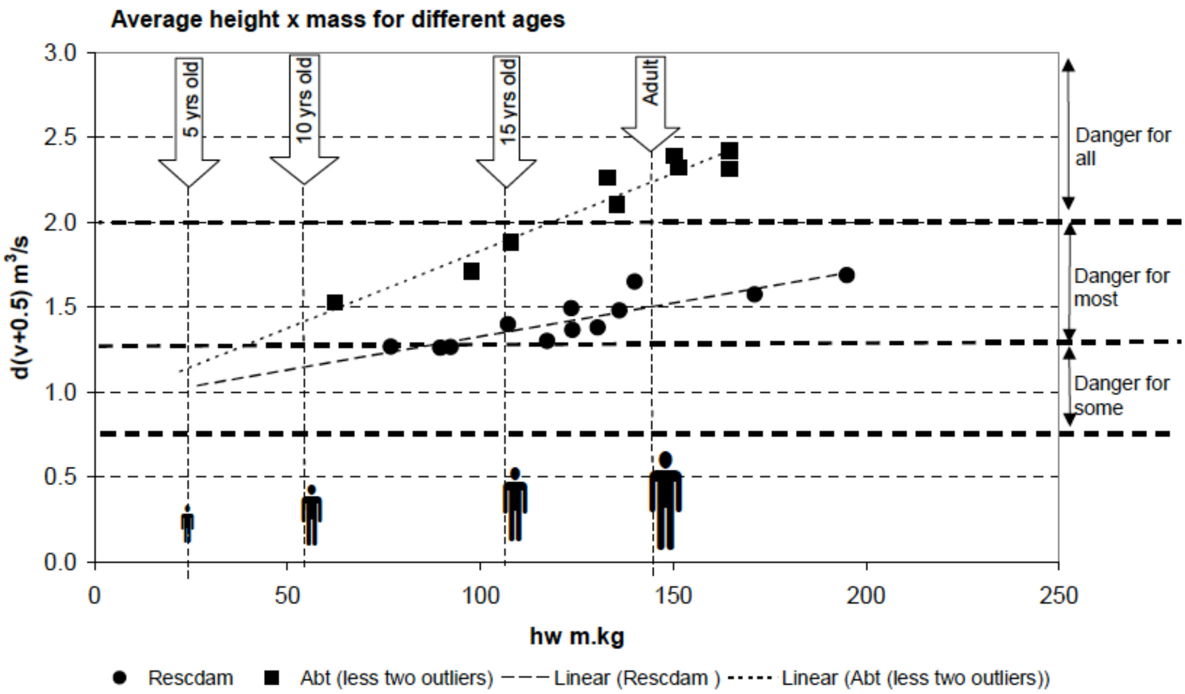

Figure 2: Interpretation of empirical data to define flood hazard categories (DEFRA, 2006)

Flood Hazard Rating $HR = d \cdot (v+0.5) + DF$	Degree of flood hazard	Description
< 0.75	Low	Caution - "Flood zone with shallow flowing water or deep standing water"
0.75 - 1.25	Moderate	Dangerous for some - "Danger: Flood zone with deep or fast flowing water"
1.25 - 2	Significant	Dangerous for most - "Danger: Flood zone with deep fast flowing water"
> 2	Extreme	Dangerous for all - "Extreme danger: flood zone with deep fast flowing water"

Table 2: Flood hazard categories to people (DEFRA, 2006, FD2320/TR2)

Regarding flood hazard to buildings, which are more resilient to floodwaters than people, some research has been done. The depth-velocity function used in the flood hazard rating for people, $d \cdot (v+0.5)$, was not appropriate for buildings since the relationship between its damage and the hazard rating was poor. Instead, the expression $d \cdot (v+2)$ was found to be a better fit. Figure 3 illustrates the results of the building damage level against the two mentioned depth-velocity functions.

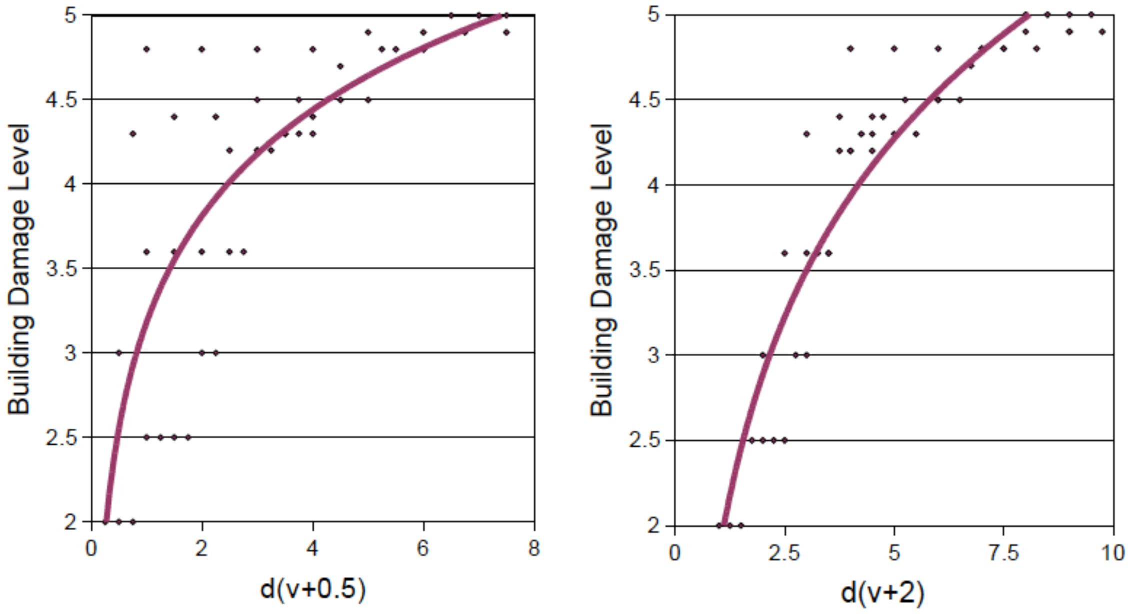

Figure 3: Depth/velocity function for people (left), and the improved function for buildings (right)

2.3.3 Spanish regulations

Flood hazard is considered as a function of the degree of danger and the probability of that hazard occurring. Here both flood depth and velocity are used to evaluate how potentially harmful the flood can be. The Spanish most recent regulation, Real Decreto 9/2008, states that assuming a 100 year return period event, significant amounts of damage to people and properties are likely to happen if any of the following criteria takes place:

- Water depth higher than 1m
- Velocity flow higher than 1m/s
- The product of depth and velocity higher than 0.5m²/s

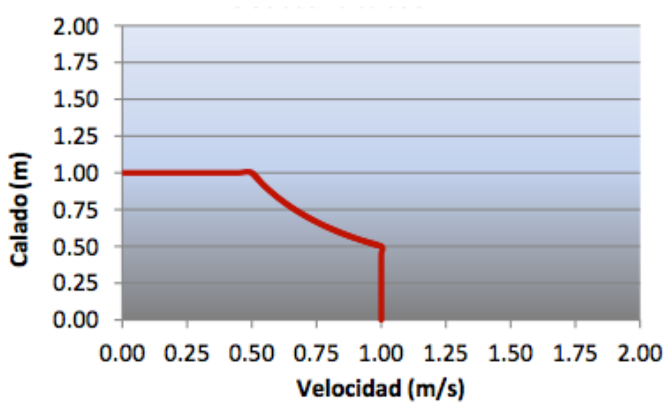

Figure 4: Flood hazard criteria for 100 year return period (Real Decreto 9/2008)

Later on, the Catalan Water Agency (ACA, Agencia Catalana del Agua) extended this initial criteria and came up with the flood hazard criteria shown in Table 3, and illustrated in figure 5. Five levels of flood hazard are defined: low, moderate, high, very high and extreme.

Usually there are three hazard levels but in this case the third one (high hazard) is further divided into three separate levels (high, very high and extreme). The extreme criteria is defined from 6m and 4m/s which seems unreasonable, especially in the context of urban areas, and is certainly not consistent with any of the flood hazard criteria from the rest of the sources considered in this work.

Hazard classification	Criteria description
Extreme	$h > 6m$ $v > 4m/s$ $h{\cdot}v > 2m/s^2$
Very high	$3.5 < h < 6m$ $2 < v < 4m/s$ $1 < h{\cdot}v < 2m/s^2$
High	$1 < h < 3.5m$ $1 < v < 2m/s$ $0.5 < h{\cdot}v < 1m/s^2$
Moderate	$0.4 < h < 1m$ $0.4 < v < 1m/s$ $0.08 < h{\cdot}v < 0.5m/s^2$
Low	$h < 0.4m$ $v < 0.4 m/s$ $h{\cdot}v < 0.08m/s^2$

Table 3: Flood hazard classification depending on depth, velocity and its product (Gracia et al.)

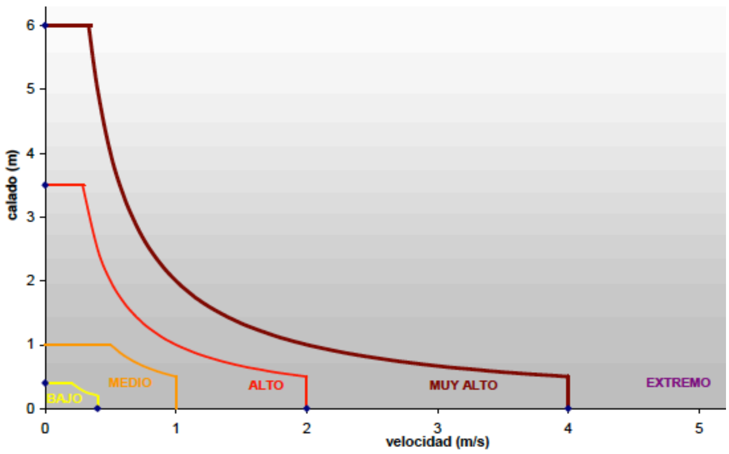

Figure 5: Flood hazard classification given flood depth and velocity (Gracia et al.)

Moreover, the ACA presents a methodology to determine the severity of a flood event by weighting the variables of depth and velocity depending on the return period, using the coefficients of Table 4. This is done to take into account the probability of occurrence. It considers the 100 return period as reference so that any flood that is likely to occur regularly, for example 10 years, is weighted higher, and the opposite is done for less frequent flood events. However, there are no clear explanations about the determination of these coefficients (they are not related with the probability of occurrence).

Return period (years)	10	50	100	500
Factor	2	1.5	1	0.5

Table 4: Weighting factors for depth and velocity given the return period

2.3.4 PREVENE (Prevención de desastres naturales en Venezuela)

In 2001, a Swiss methodology was presented in the PREVENE project which later on was accepted for general application throughout the country of Venezuela by the Ministry of Environment and Natural Resources. This methodology considers flood hazard to be a function of flood intensity and its probability of occurrence.

Regarding the flood intensity, two sets of intensity criteria were presented (tables 5 and 6), one for water flooding and another for water flows that carry more than 20% of sediments (mud, debris, etc.). Obviously, in the second scenario the intensity thresholds are stricter since the flow conditions are more dangerous. Three levels of intensity are distinguished using water depth, and its product with velocity; those levels are low, medium and high (see figure 6). Also, it should be noted that there are certain bounds under which the flow intensity level is considered insignificant.

Water flood event intensity	Maximum depth h (m)		Product of maximum depth h times maximum velocity v (m^2/s)
High	$h > 1.5\,m$	OR	$vh > 1.5\,m^2/s$
Medium	$0.5\,m < h < 1.5\,m$	OR	$0.5\,m^2/s < vh < 1.5\,m^2/s$
Low	$0.1\,m < h < 0.5\,m$	AND	$0.1\,m^2/s < vh < 0.5\,m^2/s$

Table 5: Flood intensity levels for water flooding (PREVENE, 2001)

Mud or debris-flow event intensity	Maximum depth h (m)		Product of maximum depth h times maximum velocity v (m^2s)
High	$h > 1.0\,m$	OR	$vh > 1.0\,m^2/s$
Medium	$0.2\,m < h < 1.0\,m$	AND	$0.2 < vh < 1.0\,m^2/s$
Low	$0.2\,m < h < 1.0\,m$	AND	$vh < 0.2\,m^2/s$

Table 6: Flood intensity levels for debris flow (PREVENE, 2001)

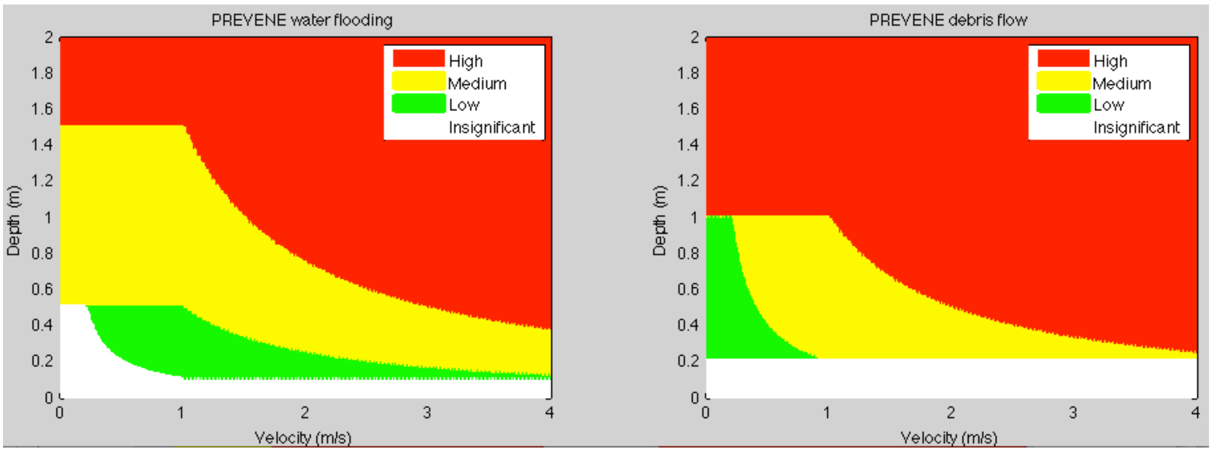

Figure 6: Intensity levels for water flooding and debris flow according to PREVENE (2001)

Regarding the probability of occurrence, three representative return periods are used: 10, 100 and 500 years. Then combining the intensity and probability criteria, three flood hazard levels are defined: low, medium and high (figure 7).

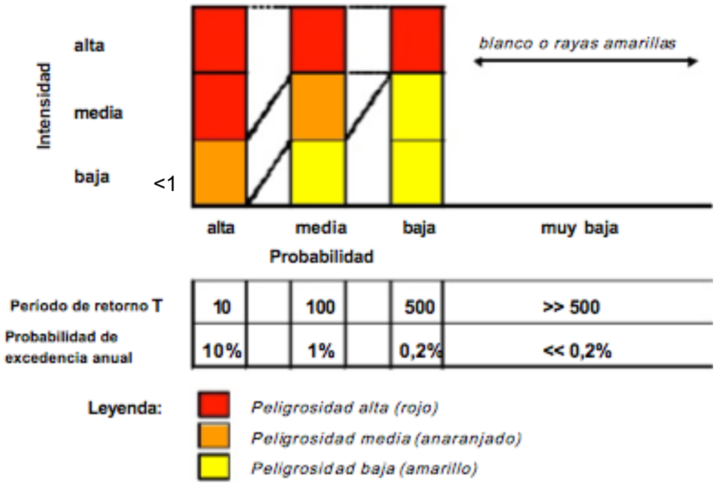

Figure 7: Flood hazard categories, function of intensity and probability (PREVENE, 2001)

Contrary to the ACA's methodology, PREVENE uses coefficients derived from the probability of occurrence to weigh up or down the intensity categories. For instance, a medium intensity along with a high probability of occurrence produces a high flood hazard since the event is likely to happen frequently; and a low probability of occurrence produces a low flood hazard as it refers to an event that will happen in rare occasions.

2.3.5 Matrices (Floodsite)

For modeling purposes, qualitative values are given to refer to flood hazard depending on the ranges of water depth and velocity. In the Floodsite website an example of flood hazard classification is presented in a matrix (figure 8). Various examples of the same kind may also be found. The flood hazard is determined by the intensity of the flood alone, not taking into account the probability of occurrence.

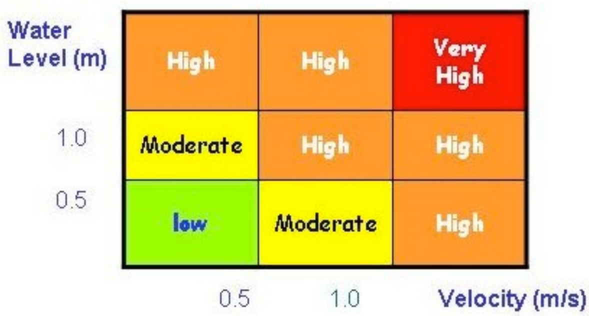

Figure 8: Categorization of flood hazard impact for population (Floodsite)

2.3.6 Hamilton City Council (New Zealand)

Their Catchment Management Plan program includes some computer modeling in order to produce maps in which flooded areas are identified and classified into three flood hazard categories: high, medium and low. Usually an extreme rainfall event of 100 years is used for the modeling of floods caused by the overflow of the Waikato river (the longest in New Zealand) crossing the city of Hamilton. Two sets of modeling are carried out separately, one for the river corridor and another for the sub-catchments of the city that deal with overland flowpaths and ponding flooding. Also, two different flood hazard criteria are defined respectively (figures 9a and 9b). Regarding the determination of the effect of floods on people an assumption was made; it was considered an average adult male whose height is 177cm, but no reference is made regarding the person's mass.

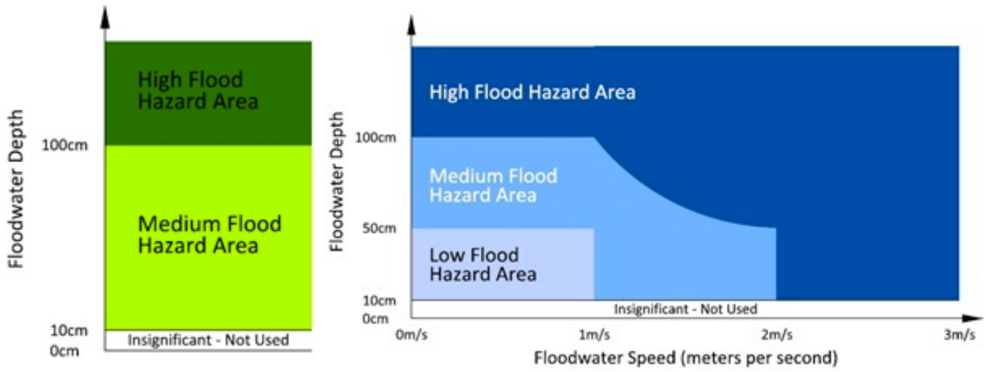

Figure 9: Flood hazard criteria for areas in (a) river corridor, (b) overland flowpaths and ponding flooding (Hamilton City, New Zealand)

Water depths and velocities are considered to be the key factors in determining the effects of flood water on people and property; those effects are detailed for each flood hazard category in table 7. It is noted that whenever the floodwater depth is lower than 10cm, the hazard is always considered to be insignificant both to people and property (similarly to PREVENE).

Floodwater depth	Floodwater velocity	Depth x velocity	Effect on people and property
0 to 10cm	Any velocity	-	At this depth, surface water is unlikely to be a hazard to people and unlikely to cause damage to property.
10 to 50cm	<1.0m/s	-	At this depth and velocity flood hazards are normally traversable by emergency vehicles and damage to property is minor to moderate. People can usually stand but more vulnerable people can be more significantly affected (e.g. children, elderly, injured, physically disabled). Scour/erosion of building foundations are unlikely to occur.
50 to 100cm	<2.0m/s	-	At this depth and velocity the stability of people in water is at risk. Damage to property can be financially significant.
>100cm	>2.0m/s	>1	At velocities greater than 2 metres per second the stability of buildings and their foundations can be significantly affected, as the force of the water can scour building supports. At depths greater than 1m significant damage to building and risk to life is very likely.

Table 7: Criteria for definition of flood hazard categories (Hamilton City, New Zealand)

2.3.7 CSIRO's approach for the Johnstone river (Australia)

Generally, the CSIRO (Commonwealth Scientific and Industrial Research Organization) refers to the degree of flood hazard as being a function of many factors: magnitude of flooding, depth and velocity, rate of floodwater rise, duration of flooding, evacuation problems, size of population at risk, land use, flood awareness, and effective flood warning time. Evidently these factors vary in space and time, adding complexity. However, four degrees of flood hazard are suggested: low, medium, high and extreme.

A particular approach was done for the Johnstone river floodplain considering its average specific flood characteristics: long duration of flooding (days), short warning times (6 hours), fast rates of floodwater rise and high flood awareness. Then, flood hazard classes were defined, shown in figure 10, based on the variation of depth and velocity of floodwaters. An extreme flood event of 100 years of return period was assumed. Table 8 gives a detailed description of each flood hazard category which refer to people stability and safety, as well as the damage to property.

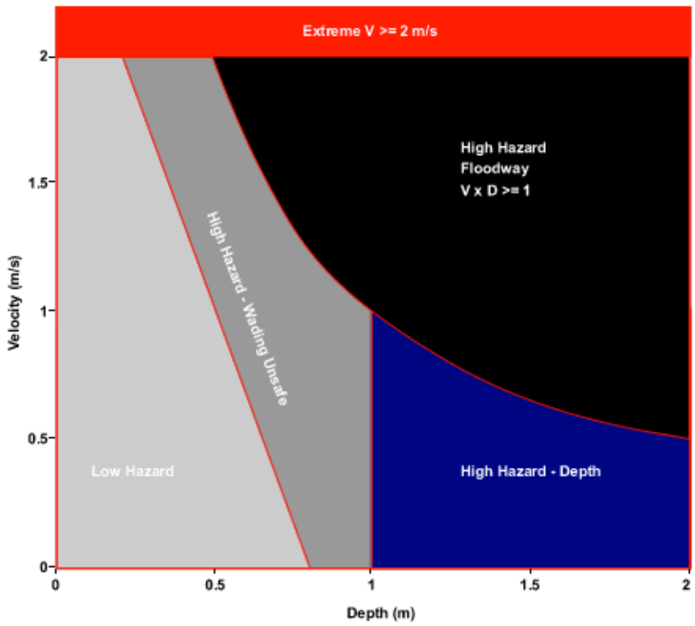

Figure 10: Recommended flood hazard categories for the Johnston river floodplain, 100 years

Hazard Category	Base Flood Event	Characteristics
Low	100yr	- Areas that are inundated in a 100yr flood, but the floodwaters are relatively shallow (typically less than 1m deep) and are not flowing with velocity. - Adult can wade.
High - Wading Unsafe	100yr	- The depth and/or velocity are sufficiently high that wading is not possible. - risk of drowning.
High - Depth	100yr	- Areas where the floodwaters are deep (> 1m), but are not flowing with high velocity. - Damage only to building contents, large trucks able to evacuate.
High - Floodway	100yr	- Typically areas where there is deep water flowing with high velocity. - Truck evacuation not possible, structural damage to light framed houses, high risk to life.
Extreme	100yr	- Typically areas where the velocity is > 2m/s. - All buildings likely to be destroyed, high probability of death.

Table 8: Flood hazard criteria recommended for the Johnston river (Australia)

2.3.8 Bureau of Reclamation (USA, 1988)

The Technical Memorandum nº11 was directed for dams whose failure implied a flood that would affect downstream population, although it should be used only for small dams (flood danger is obvious when large dams and catastrophic flooding are involved). It should be used for situations where the hazard depends only on an isolated flood situation where population may be in danger (in a house, vehicle, or in open air without protection). Three flood hazard categories are differentiated: low-danger zone, where the lives in danger are assumed to be zero; high-danger zone, where it is assumed that it is possible that lives are in danger; and the judgement zone, which represents the uncertainty of belonging to either of the previous two zones. Hazard classifications were presented for residents in houses built on foundations, mobile homes, passengers in vehicles, adults and children pedestrians. Figures 11 and 12 are shown to provide a qualitative idea of this methodology.

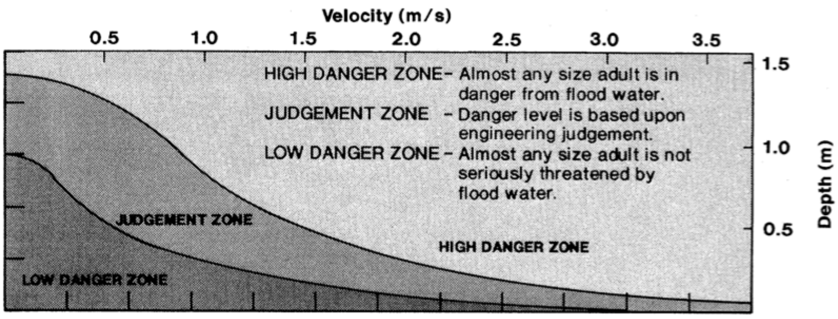

Figure 11: Flood hazard levels for adults (Bureau of Reclamation, 1988)

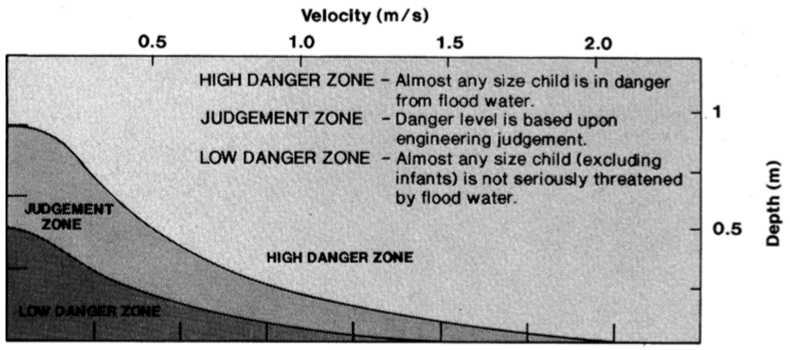

Figure 12: Flood hazard levels for children (Bureau of Reclamation, 1988)

2.4 Comparison of flood hazard criterias

From the criteria that have been presented above expressing flood hazard according to eight different sources, it can be extracted the following:

- Water depth is the first and most important variable used to describe the magnitude of flooding. All methods consider it although they differ in the definition of categories of flood hazard.

- Flow velocity is the second variable in importance when referring to severity of flooding. It is included in all methods except in the flood maps of the NOAH project. However, velocity maps can be also obtained.

- A combination of the two previous variables, named intensity, which is the product of water depth and flow velocity, is also used in quite a few methods. Its consideration provides a more likely criteria to include the effect of flow velocity since its importance is subjected to the occurrence of a certain inundation depth.

- The effect of debris (floating objects and sediments) is not generally taken into account, only within the DEFRA and PREVENE methods.

- Only two of the methods consider that the effect of probability of occurrence should be directly included in the obtention of flood hazard; its influence lies on weighting depth and velocity variables. Other methods do not state this effect but instead define the flood hazard method for a given return period, usually of 100 years.

- The basic flood hazard categories are three: low, medium or moderate, and high. Additionally, two methods (PREVENE and Hamilton) define an insignificant hazard category; also the high category is sometimes further divided (very high, extreme).

Table 9 shows a summary of all methods characteristics and the ranges of depth, velocity and its product for each category. Their values are variable depending on the source. Figure 13 illustrates the flood hazard criteria of all methods.

Method	h	v	h·v	Low	Medium / Moderate	High	Extreme
Maps	X	-	-	h<0.5m	0.5<h<1.5m	h>1.5m	-
DEFRA	X	X	X	$h < \frac{0.75 - DF}{v + 0.5} = h_{low}$	$h_{low} < h < \frac{1.25 - DF}{v + 0.5}$	$h_{med} < h < \frac{2 - DF}{v + 0.5}$	$h > \frac{2 - DF}{v + 0.5}$
ACA	X	X	X	h<0.4m v<0.4m/s hv<0.08m^2/s	0.4<h<1m 0.4<v<1m/s 0.08<hv<0.5m^2/s	1<h<3.5m 1<v<2m/s 0.5<hv<1m^2/s	h>6m v>4m/s hv>2m^2/s
PREVENE	X	X	X	**0.1**<h<0.5m 0.1<hv<0.5m^2/s	0.5<h<1.5m or 0.5<hv<1.5m^2/s	h>1.5m or hv>1.5m^2/s	-
Matrices	X	X	-	h<0.5m v<0.2-0.5m/s	0.5<h<1.5m 0.2-0.5<v<0.5-1	h>1.5m v>0.5-1m/s	-
Hamilton	X	X	X	**0.1**<h<0.5m v<1m/s	0.5<h<1m 1<v<2m/s hv<1m^2/s	h>1m v>2m/s	-
CSIRO	X	X	X	h<-0.275v+0.8 v<2m/s	h>-0.275v+0.8 v<2m/s hv<1m^2/s	hv>1m^2/s v<2m/s	v>2m/s

Table 9: Summary of the main characteristics of flood hazard methodologies

It is concluded that most methods consider both water depth and velocity to characterize flood hazard to people and properties. A qualitative idea of flood hazard to people has been provided to the reader through this review. However, it will not be further studied. The main focus will be given to quantitative damage to properties, structures and their contents.

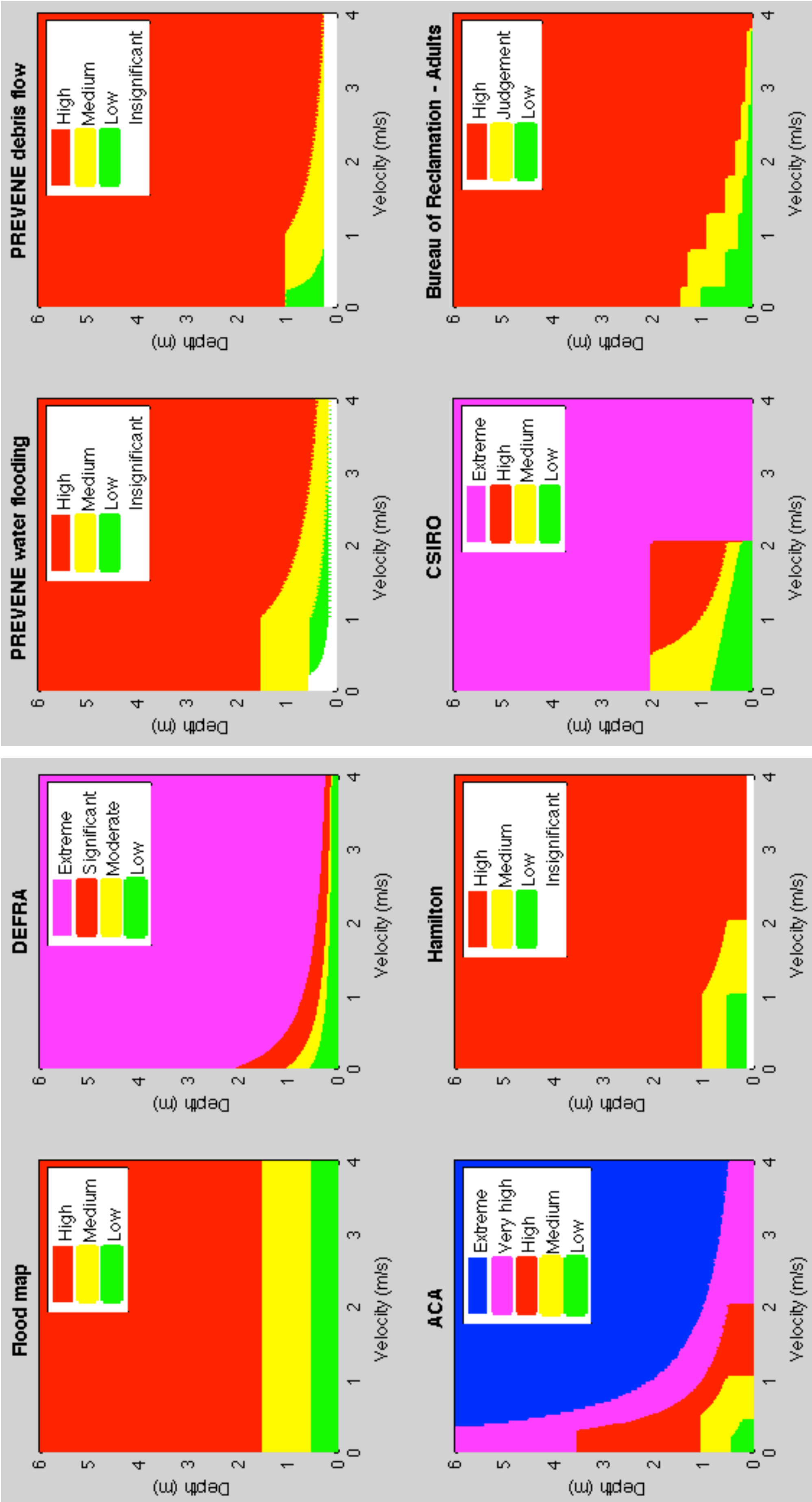

Figure 13: Flood hazard criterias (made by the author)

3. FLOOD RISK

This chapter focuses on the concept of flood risk. Sometimes, depending on the context, the words hazard and risk are used interchangeably. Therefore, a clear differentiation between these two concepts must be understood. Also, a couple of methods used to express and estimate flood risk are presented.

3.1 Flood risk definitions

Generally speaking, the difference between hazard and risk is found to be the following:

Hazard: the way in which an object or a situation may cause harm
Risk: the chance that some harm will actually occur

These definitions reflect a distinction between hazard and risk, also introducing the idea of exposure. When considering flooding, a certain area can be highly hazardous either because considerable water depths occur during flooding, or because the flooding itself happens frequently. But whether there exists risk in that area depends on the exposure, which determines the extent of the harm. If there is nothing susceptible to be harmed, then there is no risk. On the contrary, if that particular area concentrates valuables and goods, there is risk. Only when hazard and exposure occur simultaneously risk happens.

From a scientific point of view, risk was initially assimilated with hazard, focusing on the dangerous event, its degree to cause harm and its probability of occurrence. It was rather later when the concepts of exposure and vulnerability were introduced. In the flooding context, exposure is a factor that varies greatly in time and space: urban areas grow and increase their area extent; people are more likely to be at their homes at night, etc. Vulnerability, on the other hand, is a much wider concept that evolved through the years; it will be further explained in Chapter 4. Nowadays it is commonly understood as the amount of damage caused to an element exposed to a certain hazard that actually happens.

At the moment, risk can be commonly understood as the probability of some harm occurring but from the scientific point of view, and within this paper, flood risk is referred to as the economic valuation of the losses that result from a hazardous natural event, such as flooding, on the area that suffers its effects. Similarly, it is widely agreed that risk may be expressed as the product of a hazard and its consequences (Kron, 2002). Some other definitions found throughout the literature in the context of flooding are exposed in table 10:

Source	Definition
UNDHA, 1992, WOM, 1999	The expected losses (lives, people injured, property damaged, economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculation it is the product of hazard and vulnerability.

Source	Definition
DEFRA, 2005	A combination of the chance of a particular event with the impact that the event would cause if it occurred.
UN-ISDR	The probability of harmful consequences, or expected losses (death, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural hazards and vulnerable conditions.

Table 10: Definitions of flood risk

It is worth mentioning that sometimes the term 'social risk' may be found. Depending on the context, it is given different meanings; some refer to it as a measure to quantify the number of people at risk, especially the elderly and children. Others associate social risk to vulnerability on one hand, and the hazard to the physical environmental risk on the other hand. Whenever vulnerability is given a socioeconomic aspect it is a measure of how well prepared is the population to cope with flooding, their awareness, etc. Also, social perception towards flood disasters is taken into account during the decision-making process when protection measures need to be made.

3.2 Flood risk equation

There are two equations which are mostly used to represent risk. Equation [3.1] is conceptual and expresses risk in a qualitative way incorporating the various aspects of vulnerability and the capacity of the area to cope with the negative effects of flooding (qualitative ranges of risk can be defined). On the other hand, equation [3.2] quantifies the risk as the calculated cost of damages and losses due to the flood event. The equation can be evaluated with damage estimates (previous to the actual event) or with real damage data (after the event). Usually, risk is expressed in monetary units; however, certain losses such as human life are difficult to translate into costs. In both equations, the hazard component refers to the annual exceedance probability (AEP) of occurrence of flooding.

$$\text{Risk} = \text{Hazard} \cdot \text{Vulnerability} / \text{Capacity} \qquad [3.1]$$
$$\text{Risk} = \text{Hazard} \cdot \text{Vulnerability} \cdot \text{Costs of elements at risk} \qquad [3.2]$$

Regarding the equation [3.2] its components are defined as the following:

Hazard:	annual exceedance probability of the flood event (AEP)
Vulnerability:	degree of damage caused to an exposed element at risk
Elements risk:	quantification of types of elements at risk (properties, contents, people) and their estimated economic value

A few assumptions are often taken when calculating the risk; a) vulnerability is understood as physical vulnerability, leaving aside the social aspect of the concept; b) only direct tangible damage is computed (further explanations about the types of damage are given in Chapter 4).

Figure 14 shows all the elements of risk and their interaction as the equation [3.2] stated. Hazard is expressed through the AEP, and also appears implicitly in the damage calculation (vulnerability curves) through the water depth and velocity parameters. The exposure is implicitly considered since the damage is computed only when there are elements at risk exposed.

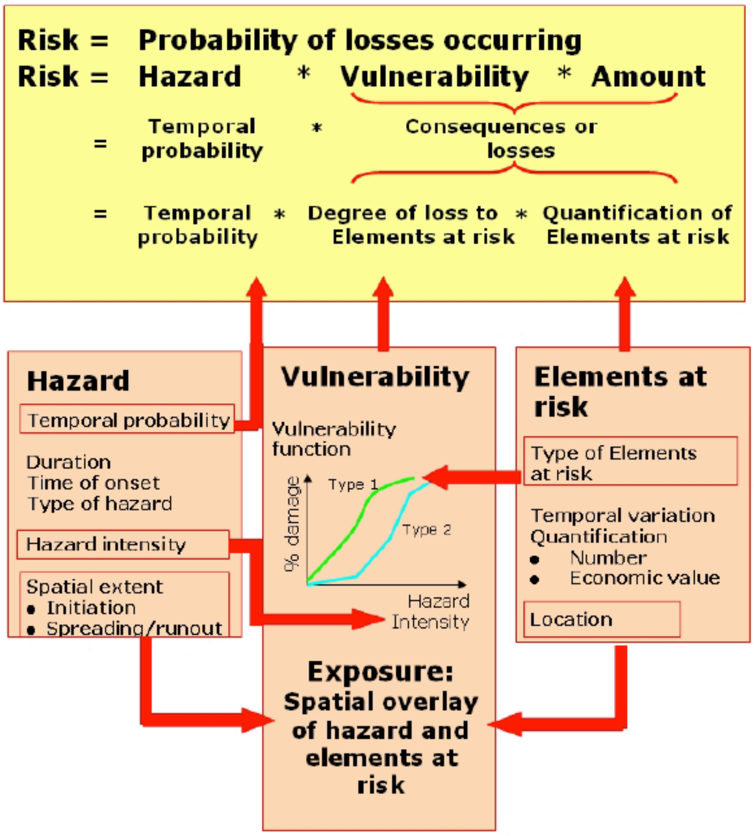

Figure 14: Definition of the concept of risk and its components

It is clear that most of the input data vary in space (the exposure and location of elements at risk) and time (for instance, market values of elements at risk may require an update from time to time). Depending on the scale study (city, region, country, etc.) the amount of work related with the degree of detail will be more or less time consuming.

3.3 Types of risk analysis methods

There exists an important and growing interest in assessing flood risk; a World Bank expert, Abhas K. Jha, reported in 2012 that economic losses had grown enormously in the last two decades even though flood deaths had declined in many parts of the world. He also stated that although it is impossible to completely eliminate flood risk even where disaster risk management is well established and understood, attention should be focused on designing efficient early warning systems, reducing social vulnerability and looking for alternative locations for populations in danger. In that way it is commonly accepted that risk reducing measures should contemplate both structural and non-structural measures, trying to find the right balance. But a previous and very important step is to determine the object of such risk-reducing measures, which in this case is to identify the areas at risk (and its quantification).

The existing methods to assess flood risk can be classified into two categories: qualitative and quantitative. It is convenient to mention that even though the flood risk is mostly understood as the economic risk expressing losses in monetary units, flood risk can also be expressed as population risk (number of fatalities and injured individuals) or property risk (number of buildings to be collapsed or partially damaged).

3.3.1 Qualitative methods

The qualitative approach is based on the experience of experts or based on indices that weight certain parameters for the two main components of risk, likelihood (or probability of occurrence) and impact (the consequences), so that their combination is translated into a number of risk categories: low, medium, high and very high. Figure 15 shows the risk rating matrix of the Scottish Government presented in 2007. Their risk guidance includes a qualitative description of the risk categories as well as for the four impact categories (health, social, economic and environment) and the likelihood of the event (annual probability).

This kind of method can be used in situations where a fast and cheap method is required to estimate the risk, or when either flood hazard, vulnerability, or both cannot be easily expressed in quantitative terms.

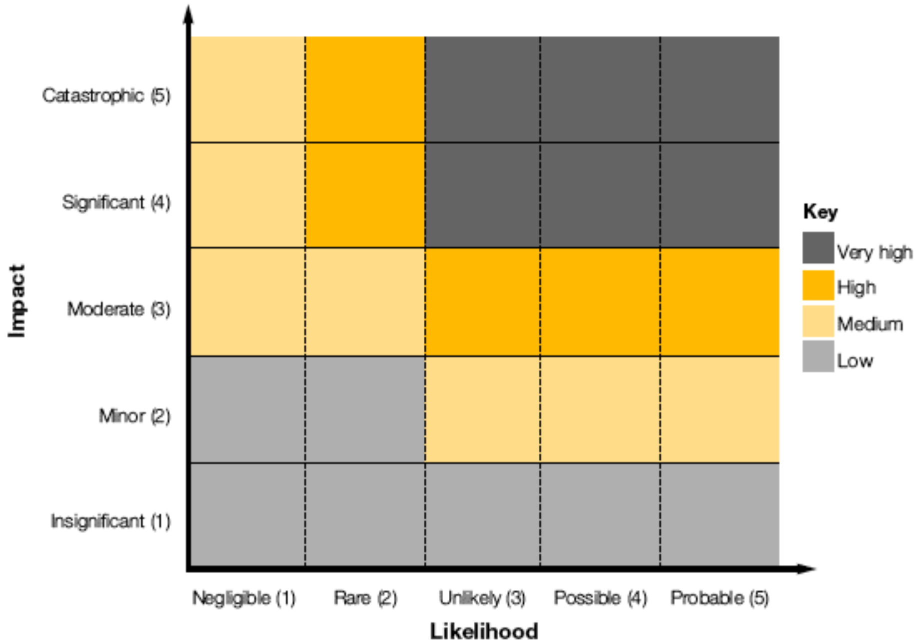

Figure 15: Risk rating matrix (Scottish Government guidance, 2007)

Another example is found within the INUNcyl (Civil Protection Plan for Flood Risk in the Province of Castilla y León, Spain). Flood hazard to people in the context of river overflow in floodplains is categorized into three levels (A, B, C) depending on the exposure of towns within flooded areas and the historical frequency of events affecting those areas. Moreover, the census of 2006 of those towns was consulted in order to establish a population risk matrix with three categories: low, medium and high (see figure 16).

		Población (INE 2006)		
		x≤500	500<x<1000	x≥1000
Nivel Peligrosidad	A	Medio	Medio	Alto
	B	Bajo	Medio	Medio
	C	Bajo	Bajo	Medio

Figure 16: Population risk matrix (INUNcyl, 2010)

These two examples shown above, explain how some institutions refer to the term flood risk when using methodologies that can be perceived as ways to express flood hazard (they pretend to estimate how much danger there is). In this sense, the use of 'flood risk' brings about confusion since it has been defined as the economic valuation of losses of a hazardous event. This stresses on the fact that according to different sources, the use of flood risk can be ambiguous.

3.3.2 Quantitative methods

These methods require enough information on each of the risk's components: flood hazard, vulnerability and the elements at risk. In order to assess flood risk due to a flood hazard it is needed to calculate the costs of the vulnerable elements at risk, and later damages and losses that are consequently originated. The following explanation summarizes the steps of the procedure that needs to be carried out to obtain flood risk results. A case study of Turialba City (Mexico) has been used as an example to illustrate each step of the methodology.

<u>Flood hazard</u>

In the previous chapter it has been seen that flood hazard is a measure of the degree of danger of an event according to certain flood characteristics such as inundation depth and flow velocity. Water depth is the most commonly used flood hazard characteristic. Whether the case study focuses on a past event or probabilistic scenarios (for several return periods), the aim is to obtain spatial information regarding the inundation depth and then to present the results (flood extent and water depth) as flood maps (figure 17).

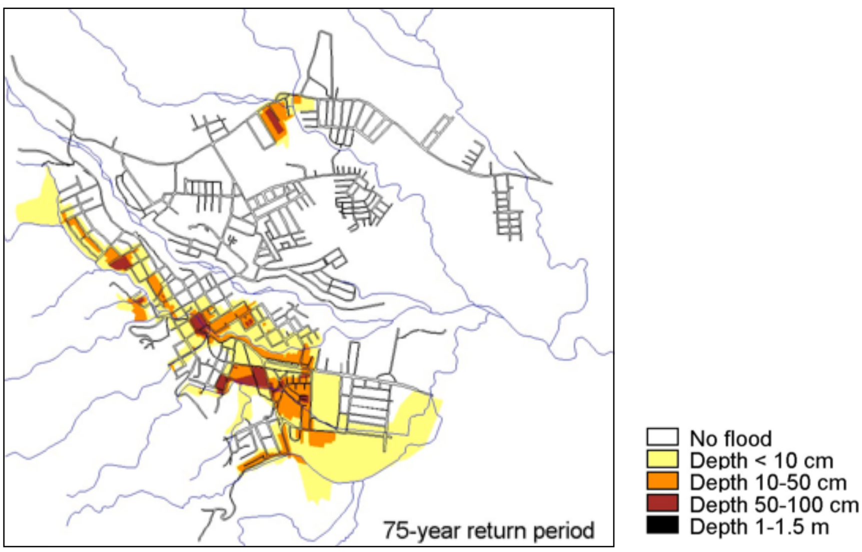

Figure 17: Flood depth map of Turialba City (Badilla, 2002)

Elements at risk

The next step consists on the collection of data of the study area, identifying the elements that are at risk, which relate directly on their exposure when the flood event happens. These elements are usually categorized into groups or classes of elements of the same kind and are represented by polygons (spatial information plotted as in figure 18). Examples of elements at risk are building structures, building contents, industry, agricultural or recreational areas. Moreover, some other attributes are included as additional information regarding land use, number of floors, age of structures and building material among others.

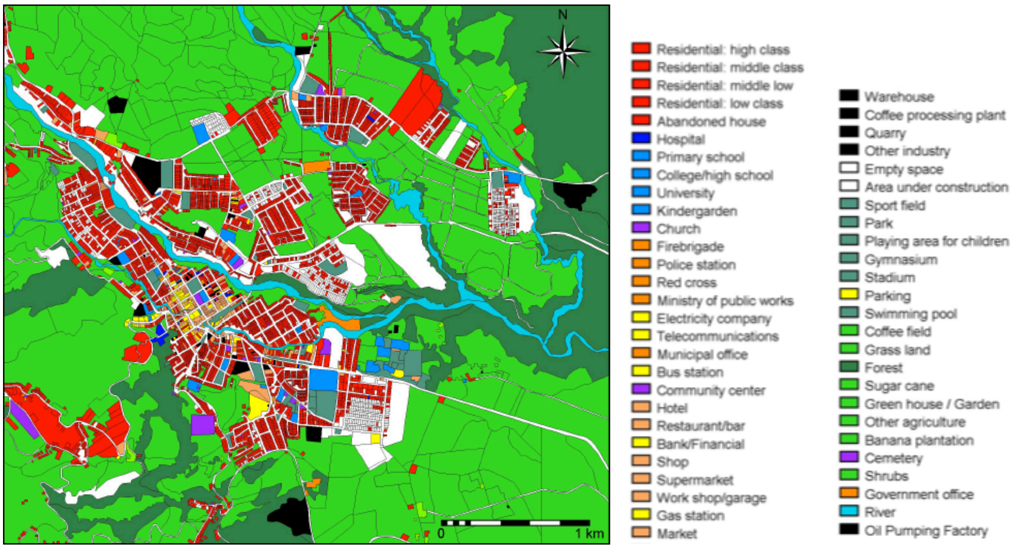

Figure 18: Attribute polygon map of the elements at risk showing land uses types (Badilla, 2002)

Vulnerability curves

The vulnerability curves, also known as depth-damage functions, relate the amount of damage and the flood depth for each category of elements at risk, or land use. Usually these functions define the damage as a percentage of the element's at risk value. Table 11 shows a group of functions used in the case study of Turialba City (Badilla, 2002). Figure 19 illustrates vulnerabilities grouped into four ranges. The next chapter of this thesis will be focused on a more detailed vulnerability assessment and the analysis of existing damage functions.

Landuse type or category	Vulnerability values			
	<10 cm	10-50 cm	50-100 cm	100-150 cm
Residential	0.15	0.35	0.50	0.80
Elementary education	0.02	0.30	0.45	0.60
High education	0.02	0.30	0.50	0.70
Fire brigade and Police	0.00	0.10	0.40	0.50
Red Cross	0.00	0.15	0.50	0.70
Government office	0.00	0.25	0.60	0.80
Bank/Financial	0.00	0.15	0.45	0.60
Doctor's practise	0.00	0.15	0.40	0.60
Hospital	0.01	0.08	0.15	0.20

Table 11: Depth-damage functions for types of land uses (Badilla, 2002)

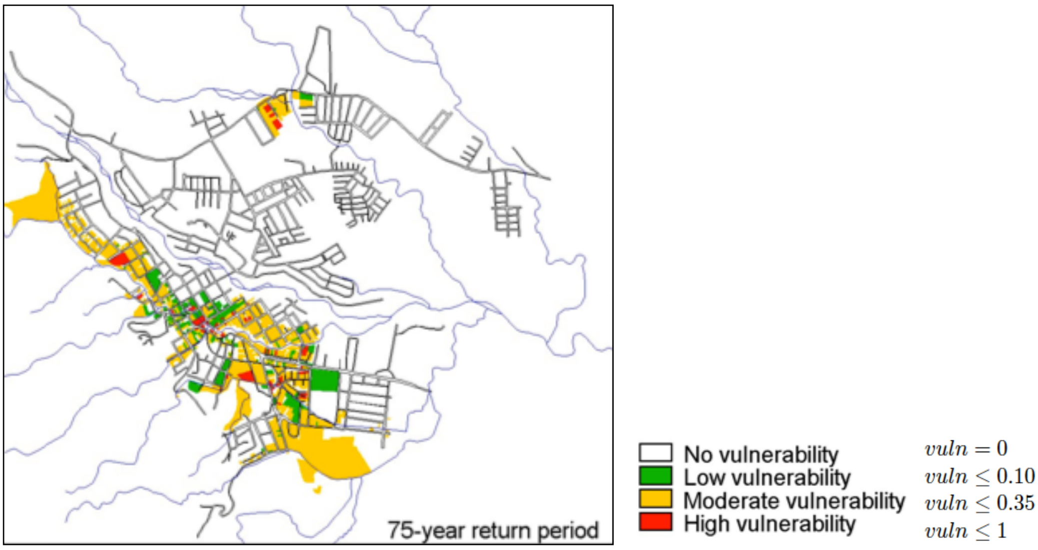

Figure 19: Vulnerability map of the study area (Badilla, 2002)

<u>Cost estimation of elements at risk</u>

Once a relation of the elements at risk has been produced, a value assignment is given to express their structure's and content's values. Different assumptions of content items are considered for buildings depending on their land use and other attributes. Figure 20 shows a map of the study area with spatial costs.

Estimation values are usually taken either from the market or from personal experience. Some studies choose to use the replacement value which assumes the cost of a new element to replace the damaged one. Other studies use the depreciated value instead, which takes into account the loss of value of the element at risk as time goes by. This point of view assigns a fraction of the original value as the cost originated at the time of the flood event.

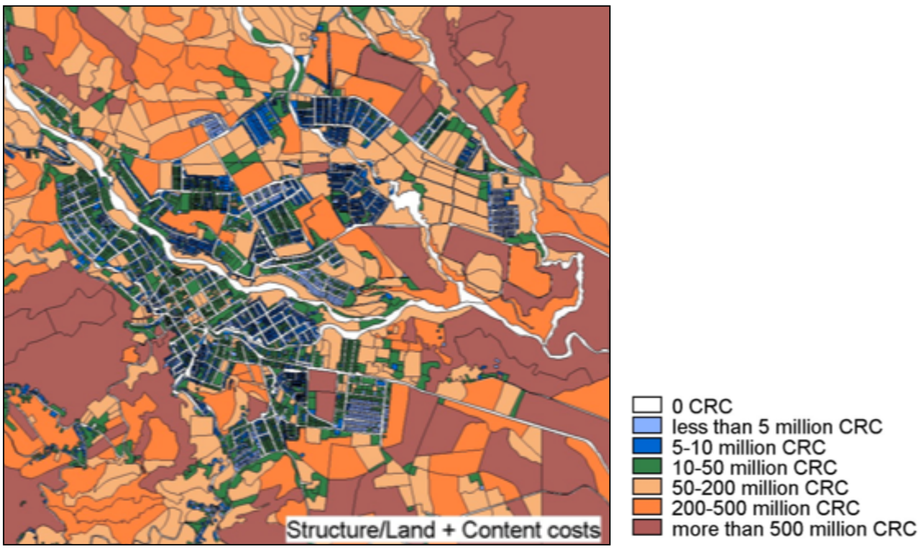

Figure 20: Map of costs of the elements at risk, units in Costa Rican Colones (Badilla, 2002)

Flood damage and flood risk

According to the definition of the economic valuation of flood risk, its assessment is done firstly by calculating the flood damage, and secondly by calculating the flood risk. Flood damage (or total loss) is obtained by multiplying the vulnerability values by the respective costs of the elements at risk within the exposure extent. Then flood risk is calculated by multiplying the flood damage times the probability of exceedance of the flood event. This process can be done for several return periods.

Flood risk is often called as the annual expected damage (AED). Table 12 shows the results of flood damage and flood risk for the case study example of Turialba City (Badilla, 2002) for three different return periods: 25, 50 and 75 years. Figure 21 illustrates the flood risk results in a map, grouped into four categories of risk.

Return period	Total loss (in millions of CRC)	Probability of occurrence (1/T)	Total risk (in millions of CRC)
25 years	313.2	0.04	12.5
50 years	330.2	0.02	6.6
75 years	361.6	0.0133	4.8

Table 12: Total damage and flood risk for three return periods (Badilla, 2002)

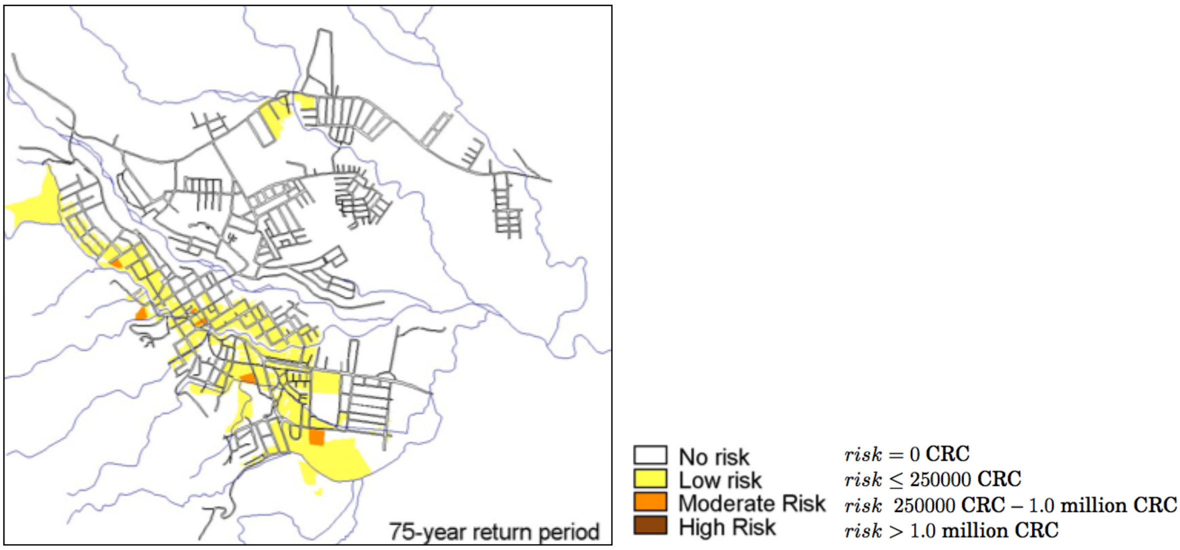

Figure 21: Map of flood risk, units in Costa Rican Colones (Badilla, 2002)

Once the risk calculation is done, it can be expressed through flood risk maps (as shown above) and flood risk curves. The results are expected losses, expressed in monetary units.

Flood risk maps

This is the most suitable way to present the risk results when the main interest is to determine the variability of risk within the study area and to find out which subareas are significantly sensitive to suffer more economic losses. Maps should be produced for several return periods so that variability of damaging effects are manifested as well. Another interesting application of flood risk maps for higher scales is that they allow to compare risk between cities, communities, and so on.

Regarding flood risk maps, a recent reference is found in the context of regulations in Europe. In 2007 the European Commission produced the latest European Directive (2007/60/CE) which stresses on the need to reduce and manage flood risk in all flood prone areas including urban areas, that can affect human health, the environment, goods and economic activities. For that purpose, it is suggested for all states members to follow a set of measures: initial flood risk evaluation, production of flood risk (and flood hazard) maps, and elaboration of flood risk management plans. Such maps would classify the risk into three levels (high, medium and low) and indicate the potential damage due to floods.

Flood risk curves

A flood risk curve, also called probability curve of exceedance, shows the relationship between the probability of exceedance of a flood event and the economic loss or total damage for a given probability of exceedance or below (see figure 22). The area under the curve (probability of exceedance times damage) is the annual expected damage or flood risk.

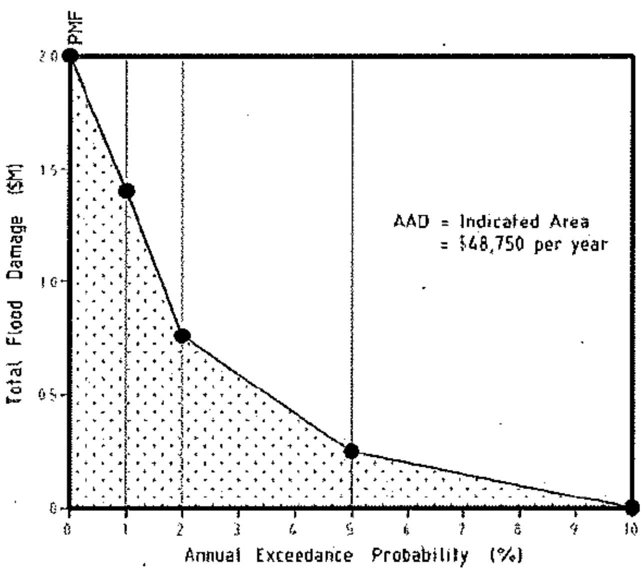

Figure 22: Flood risk curve

The resulting curve risk will definitely depend on the number of return periods used to develop the curve and, of course, on the data availability and accuracy regarding the amount of elements at risk and their cost estimation.

Regarding this methodology to determine the flood risk, Ward et al. (2011) examined how the choice of the return periods (which ones and how many) really affect the risk calculation and estimation. They took a case study and calculated the damage using all return periods between 2 to 10000 years (one year step) and derived a risk estimation that was considered as reference to compare with some other combinations of return periods.

Some of the results they obtained are summarized below:

(1) Effect of the selection of three return periods

The estimate based on three return periods (as it is required by the European Flood Directive 2007/60/EC) proved to overestimate the risk over 33%, which is the lowest overestimation obtained through various combinations of low, moderate and high probability. This means that because of the concave nature of the risk curve, a linear interpolation between three points always results in an overestimation of the risk.

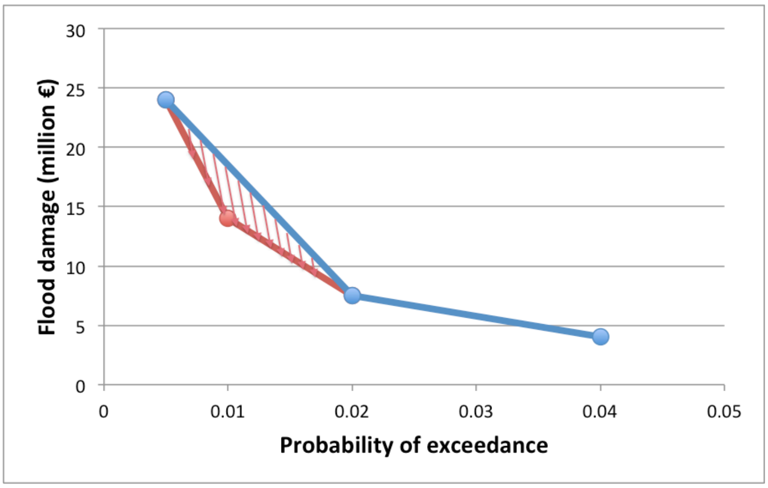

Figure 23: Flood risk curve - effect of the curve's concavity (made by the author)

(2) Effect of the choice of the lowest return period

The starting point of the flood risk curve is determined by the lowest return period used (highest probability). It was observed that the risk estimate is influenced considerably by such return period whenever the curve starts at a point where the damage is not zero. When a 10 year was used as the lowest return period (0.1 probability of exceedance), the risk was underestimated 33% compared to the reference estimate with 1.5 year as the lowest return period.

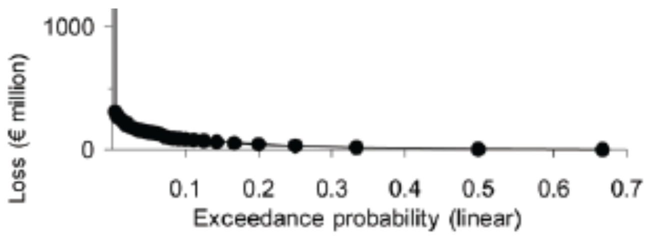

Figure 24: Risk curve with return period from 1.5 to 10000 years (Ward et al, 2011)

(3) Effect of the choice of the highest return period

Figure 25 shows how the risk estimates increase as the maximum return period used increases (from 2 to 10000 years). It can be observed that from a little over 1000 years the curve tends to stabilize. For 1250 years, the risk is 5% lower than the reference value reached at 10000 years. Also, it is made clear that the influence of low return periods is high since the curve is very steep for low values of maximum return periods, which means that low return periods are responsible for a large part of the total expected damage.

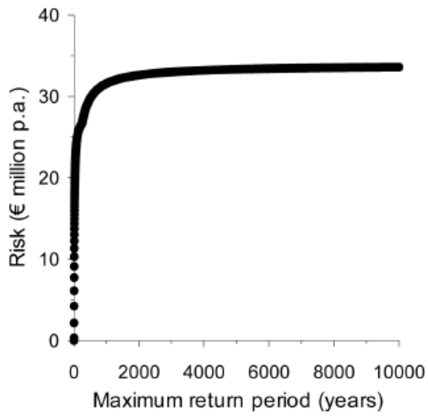

Figure 25: Flood risk using different maximum return periods (Ward et al, 2011)

(4) Estimation of risk using six return periods

The risk estimate that results from using six return periods and that is the closest to the reference estimate using the full curve, still overestimates the risk by 21%. Moreover, it has been proven that more accurate estimates are achieved when more return periods are used in the high probability end of the curve (lower return periods). So an extra return period in the low probability end of the curve (higher return periods) has little influence.

According to all these conclusions it is important to be reminded of the inherent uncertainties of the risk curve approach to estimate flood risk. Additionally, it should be noted that even though most research is usually focused on extreme events, the overall risk is greatly affected by the number of data used in the high probable end of the risk curve (lower return periods).

To conclude with the risk curves, another aspect worth mentioning is its shape, which provides an idea of how damaging flood events are distributed according to their frequency of occurrence. In figure 26(a), the dot line curve expresses high probability of frequent floods with lower damage, and almost no floods with catastrophic losses (it probably belongs to an area with very little exposure or content value). On the other hand, the black line shows a lower probability of frequent floods and a certain probability for extremely damaging floods (high density population and property exposure must be responsible for higher potential losses).

Moreover, it is possible for the risk curve to change over time. Typically, the flood risk curve is used for cost-benefit analysis of future protection or risk-reducing measures. Figure 26(b) allows to compare the present and future risk curves and then estimate how an investment is translated into benefits or loss savings, and whether the investment is profitable or not. If the cost of the protection measure surpasses the amount of losses saved by its implementation, such measure is not worth executing.

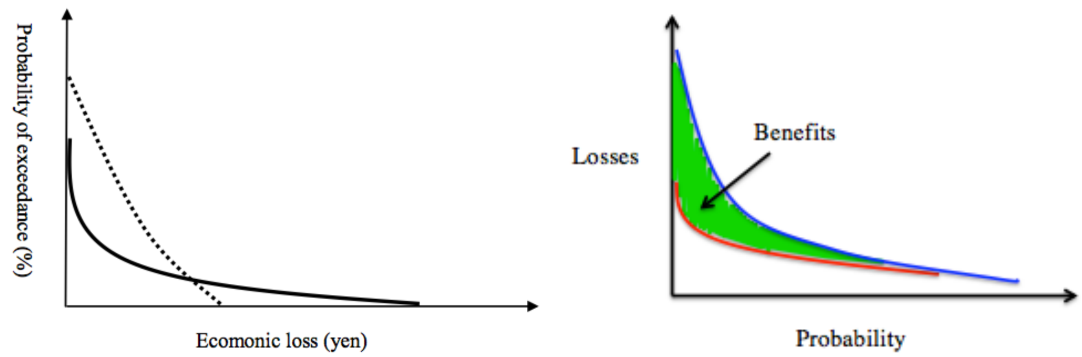

Figure 26: (a) Conceptual risk curves (b) cost-benefit flood protection measures (made by the author)

Comparatively with flood hazard, there are fewer flood risk methodologies, being the two most used the production of flood risk maps and flood risk curves; both provide a quantitative approach that estimate expected losses and damage through economic units. One the other hand, risk matrices are used when the previous methods cannot be pursued and provide a qualitative description of risk. It is important to remember that significant uncertainties are inherent within the calculation of quantitative methods, and a great deal of data is required.

4. VULNERABILITY

Regarding vulnerability, there is no definition widely accepted because of the multiple disciplines the concept may be used in. This chapter aims to expose the several aspects intimately related with the determination and quantification of damage due to flooding. Flood damage types, spatial scales, influencing factors and elements at risk will be outlined. Finally damage estimation approaches and methods will be presented.

4.1 Vulnerability concept and definitions

Vulnerability is probably the most complicated component out of the hazard-vulnerability-risk system because of the wide range of definitions and interpretations attached to this term. In the 1970s the concept of vulnerability was introduced within the social sciences when disasters were perceived from the natural hazards perspective. O'Keefe, Westgate and Wisner illustrated through empirical data that in the last 50 years the occurrence of disaster increased paralleled by an increase of loss of life. Since that time the concept of vulnerability has been the object of various disciplines, and therefore it has broadened. Birkmann (2006), who exposed the widening key spheres of the concept of vulnerability, stated the question of how we are supposed to measure or assess vulnerability when it can not be defined precisely in the first place.

Throughout literature, however, two main perspectives stand out from which vulnerability can be viewed, and also reflect the evolution that the concept has gone through. On one hand, the engineering and natural science perspective understands vulnerability as the amount of damage caused to a system by a particular hazard. This view responds to the origin of the concept when the perception of disaster risk overlooked the role and capacity of people to intervene and mitigate or prevent the impacts of flood hazards.

On the other hand, the social science perspective believes vulnerability is a state that exists within a system before the hazard happens. Here the focus is on determining the awareness, the coping capacity and the ability to resist and recover from the impact of a natural hazard.

While the first perspective focuses basically on the physical aspects, the second takes into account several influencing aspects such as physical, social, economic and environmental characteristics. Moreover, there are other approaches which state the need to include additional factors such as globalization and climate change. This shows that the broader the vulnerability assessment, the more interdisciplinary it is (Ciurean, 2013).

Some definitions of vulnerability are given in table 13. Some of them differ depending on the perspective from which they are explained.

Source	Definition
UNDRO, 1991	The degree of loss to a given element at risk or set of elements at risk, resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage)
Blaikie, Cannon et al. 1994	The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from impacts of a hazard
Pelling, 2003	Exposure to risk and an inability to avoid or absorb potential harm (it assumes physical vulnerability of the environment, and social vulnerability experienced by people)
UNDP, 2004	A human condition or process resulting from physical, social, economic and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard
UNU-EHS, 2006	The intrinsic and dynamic feature of an element at risk that determines the expected damage or harm resulting from a given hazardous event and is often even affected by the harmful event itself. Vulnerability changes continuously over time and is driven by physical, social, economic and environmental factors
UNESCO	The extent of harm which can be expected under certain conditions of exposure, susceptibility and resilience

Table 13: Definitions of vulnerability

Coping capacity and resilience are two concepts which arise in some of the definitions above. Resilience is not the absence of vulnerability but the capacity to resist the effects of an extreme event with a tolerable level of losses (Thywissen, 2006). Coping would refer to the strength and available resources of a community that can reduce the level of risk (UN-ISDR, 2004).

Some common features of vulnerability can be summarized as the following: it is multi-dimensional (each element or set of elements varies depending on various aspects), scale-dependent (the analysis unit can vary from individual to local, regional or national), dynamic and site-specific (the characteristic parameters change over time and space).

Regarding the first characteristic, five components or dimensions are clearly defined: (1) physical/functional, it relates with the predisposition of structures to be damaged, for example, same types of structures may show similar performances independently from their location; (2) social, relates with the presence of people, especially the handicapped, children and elderly, and their capacities to cope with, resist and recover; (3) economic, refers to the economic stability in danger of possible loss of production, business disruption or job loss; (4) environmental, refers to the capacity of ecosystems and their ability to tolerate hazard impacts; (5) and institutional, refers to actions as risk mitigation strategies that determine coping capacities and level of exposure to hazards.

Another aspect that should be considered are the spatial scales since flood damage assessment can be performed on three different scales: macro, meso and micro (Merz, 2010). The main differences between spatial scales relate to the spatial accuracy of potential damage analysis. Most detailed studies are confined to local areas; regional and higher scales, on the other hand, require less effort in precision of spatial data.

4.2 Physical vulnerability assessment

In this paper the role of hazard and its impacts along with the exposure of certain elements will be considered (physical aspect of vulnerability) while human intervention (social aspect) is neglected. In the engineering literature, physical vulnerability is usually defined on a scale from 0 (no damage) to 1 (total damage). Two main approaches of flood vulnerability assessment can be differentiated according to Ciurean (2013): (a) one focuses on the economic damage and is essentially a quantification of the expected or actual damages to elements or structures expressed in monetary units or through an evaluation of the percentage of the expected loss; (b) the other deals with the physical vulnerability of individual structures and the estimation of the likelihood of occurrence of physical damages or collapse of a single element (building). The first approach is the most used, especially because decision makers lean on benefit-costs analysis.

4.3 Types of flood damage

Flood damage refers to all varieties of harm caused by flooding (Messner and Meyer, 2005). When trying to assess the economic valuation of flooding, assumptions have to be made regarding the kind of damage that should be considered. It should be easily quantified and expressed in monetary units. The categories in which flood damage can be classified are described below.

4.3.1 Tangible and intangible damage

This is the most basic classification of flood damages. Tangible damages are the ones that can be expressed in monetary units. Intangible damage refer to assets which are not traded in a market and are difficult to transfer into monetary values (Merz, 2010). Intangible damages are real and represent a significant “cost” to flood-affected people. They are acknowledged in most flood studies although they are rarely quantified.

Tangible damages include the cost of repairing items damaged by floodwaters, the cost of clean-up and flood recovery, as well as the cost of traffic disruption. Intangible damage can be estimated by loss of life, injuries, trauma, loss of memorabilia (family photographs and documents) or negative effects on ecosystems.

4.3.2 Direct and indirect damage

Another independent classification is between direct and indirect damages. Direct damages are those which happen because of the immediate and physical contact of floodwater with people, properties or any other object. When considering tangible damage, some items might be capable of being repaired, then the damage is equal to the cost of repair plus the loss in value of the repaired item; other items will be damaged beyond repair, then direct damage is equal to the value of the item prior the event (it is a depreciated value; some choose to use replacement costs but those tend to overestimate the damage). Indirect damages are the additional losses caused by the flood, those which happen as a consequence of direct flood impacts and can occur outside the flood event in time or space. They include adverse impacts on the social well-being of a community and its economic activity.

The costs of direct impacts are generally much easier to quantify than indirect costs. The effects of the last one may have time scales of months and years. Although the differentiation between direct and indirect, and tangible and intangible damage is common, interpretations differ. But the important thing is that everything should be counted once and double-counting has to be avoided.

4.3.3 Potential, expected and actual damage

Leaving aside intangible and indirect damages because of their difficult assessment, the category of tangible direct damages distinguishes between actual, expected and potential damages. Actual damages are an estimate of the damages actually caused during a specific flood. These are detailed and object-specific estimations, and are calculated after the flood. Potential damages are the maximum possible damages that could occur considering the worst case scenario, that is, assuming that the inundation actually occurs and nothing can be done to remove susceptible valuable items from the flood-prone areas to locations out of reach of flood exposure. These damages estimations are made before the event and they refer to empirical data of previous after-flood damage estimations.

Variability of the relationship between potential and actual damage is shown in figure 27, along with the flood warning time. Flood awareness and experience of the affected population from past events is proven to be a damage-reducing factor. Awareness can provide available time for evacuating belongings from exposure areas, being crucial the first 12 hours. Also, experience increases the capacity of an effective damage prevention.

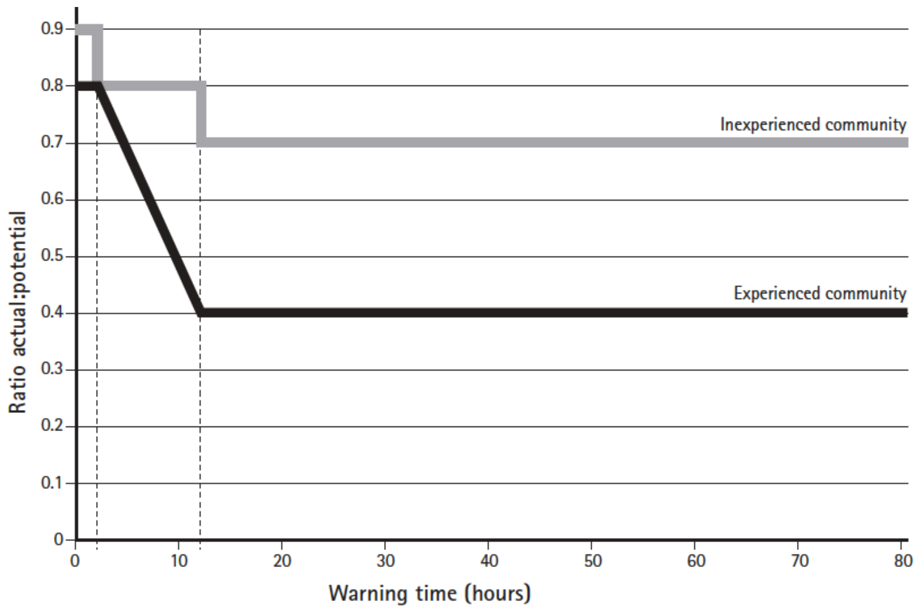

Figure 27: Relationship between actual and potential damage (Queensland government, 2002)

As for the expected damage, it refers to the damage which is expected to happen taking a number of assumptions. For example, if people have previous experience in coping with floods, then they may be able to save a portion of their property contents which would be damaged otherwise. Usually, when no assumptions are taken, expected damage is equal to potential damage.

4.3.4 Damage versus loss

Sometimes the words damage and loss are used interchangeably. Damage has been defined as all varieties of harm. Loss, on the other hand, is most commonly understood in the context of risk as the computed costs corresponding to all damage produced by flooding. Usually, the damage that needs to be considered is the direct tangible damage, and the potential or expected damage. Indirect damages are rarely taken into account because of the complexity they imply.

4.4 Damage influencing factors

The degree of damage produced after a flood event can be determined through the consideration of two groups of influencing factors: flood impact parameters, and resistance parameters (see table 14, from Merz, 2010). The first group depends on the nature and characteristics of the flood while the second group considers the characteristics of the flooded objects and areas. The number of factors is considerable, and having in mind that some of them are not independent (for example, an early warning is useless if people lack the sense of preparedness), damage analysis becomes complex. For this reason and because of their wide range in space and time, their difficult prediction and the limited information on their quantitative effects, the majority of these factors are neglected. McBean et al. (1988) also stated that “it does not seem possible to develop a simple and practical predictive tool that incorporates all these factors”.

Impact parameters	inundation depth, inundation duration, flow velocity, contamination, debris, inundation frequency and timing of the flood
Resistance parameters	land use, building type, building material, precaution, emergency response and early warning

Table 14: Impact and resistance parameters (Merz, 2010)

Based on the assumption that water level is the strongest influence on damage magnitude, most damage functions are depth-damage functions (Messner et al., 2007). Regarding the resistance parameters, a number of them are subjected to study their influence on damages. Next chapter deals with damage functions more extensively.

4.5 Classification of elements at risk

In most cases it is not possible to assess the damage for each single object separately, since such detailed assessment would require great effort (Sterna, 2012). Therefore elements at risk are classified into groups with distinctive characteristics, so that all elements of one class are treated the same way represented by an average element at risk. The classification also depends on the data availability and is based on different economic sectors: households, industry, public sector, companies, agriculture, etc. Merz et al. (2010) stated that detail of classification of a damage assessment should be directly related with the relevance of the objects or classes, especially regarding the sectors where a small share of flooded objects often causes a large share of damage.

Within one economic sector, whenever the elements at risk are very diverse, sub-classes are defined. One example is the building classification according to its structural characteristics: clay, prefabricated, masonry, reinforced concrete and flood resistant designed buildings (Schwarz & Maiwald, 2008). Another approach presented by Thieken et al. (2005) classifies buildings based on building types (single-family house, detached house and multi-family house).

4.6 Vulnerability estimation approaches and methods

Several vulnerability assessment methods have been developed within the risk analysis framework. There are three main groups of approaches and methods generally accepted to be used in flood damage assessment studies: analytical, empirical and synthetic (if convenient, a combination those can be another option). They produce vulnerability curves and damage functions, which later on are used to quantitatively estimate the flood risk. They are briefly explained below.

4.6.1 Analytical methods

Laboratory experiments are carried out while different flood parameters (duration, depth, velocity, etc.) are monitored so that their effects on the structures (and people) are quantified. Also, the probability of failure of a structure is tested using numerical models and computer simulation. These methods allow a better understanding of the relationships between flood intensity and the degree of damage for a specific structure. Inconveniences are that it is time demanding, costly and refer only to individual studies.

4.6.2 Empirical methods

Empirical approaches collect damage data through surveys after flood events when an important quantity of properties have been exposed. Such damage data is the actual data since it represents real losses experienced at a certain time and under specific circumstances. This means that whenever damage estimates are used for future damage assessments, the time and space difference should be taken into account. Transferability is an inconvenience and a source of uncertainty. Messner (2007) warned that flood damage may not be homogeneous when provided from different survey methods.

On one hand, the empirical methods are based on the analysis of observed consequences obtained through interviews, questionnaires and field mapping after the event. The main advantage of these methods is the use of real data. However, the results are very much dependent on the risk perception of people. Frequent events should be able to provide enough information on the degree of physical damage to buildings and infrastructures due to flooding. When affecting many buildings of a similar type, it is possible to make a correlation between the intensity of the flood hazard with the degree of damage and derive a vulnerability curve (see Figure 28).

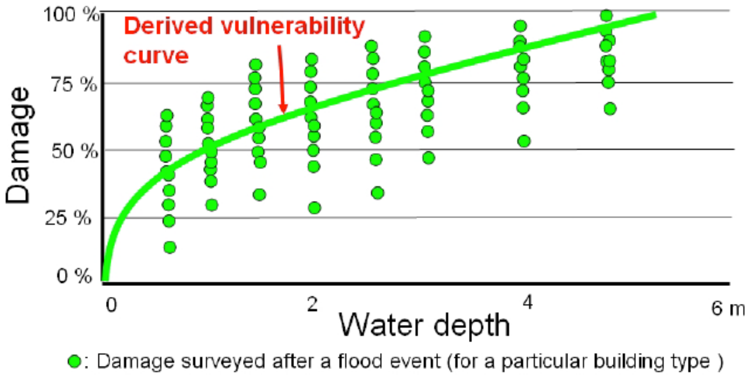

Figure 28: Generation of vulnerability curve through the use of damage surveys

On the other hand, in situations where there is no previous damage data or when classification of elements at risk are not comparable, to consult expert opinions on the matter (many experts should be asked) results to be a good choice. This involves asking about their opinion on the percentage of damage they expect for each structural type and for each hazard intensity.

4.6.3 Synthetic methods

Synthetic models collect damage data by answering what-if questions so that probable damage is obtained for an expected scenario, for example what would happen if the water depth reaches one meter. Damage is then estimated for standard and typical property types instead of actual properties. Therefore, this approach allows to calculate flood damage for any flood in any area, which is interesting whenever there is no empirical data available. Synthetic approaches return potential damage. The expected damage should be obtained by converting the potential damage, but its complexity usually leads to assume expected and potential damage to be equal.

The interaction between the flood event and the exposed elements at risk can be modeled using damage functions. Figure 29 shows three damage models (MURL, ICPR and Hydrotec) often used in Germany. They provide an expected share of damage for residential buildings according to the water depth.

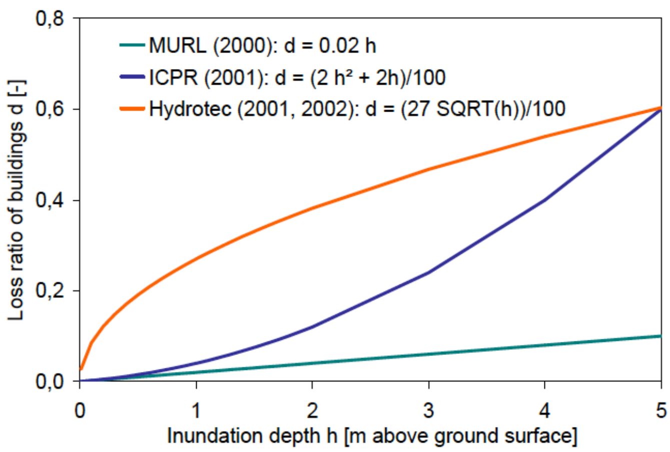

Figure 29: Relative depth-damage function models for buildings (HOWAS)

5. FLOOD DAMAGE FUNCTIONS

This chapter is dedicated to vulnerability (or damage) functions. A number of relative and absolute functions were collected from various sources with the purpose of carrying out an analysis and identification of patterns, variability of their shapes and depth thresholds that indicate change of susceptibilities. The majority of functions regard hazard intensity with flood depth, and various attributes of elements at risk are used to characterize vulnerability (land use, building types, building contents, social status, flood duration or warning time).

5.1 Flood damage curves and functions

It has been explained in the previous chapter that curves are produced via empirical approach while functions are obtained through synthetic methods. However, some authors use both terms, curve and function, interchangeably. Here, the term function will be used preferably.

Damage functions are an important component in the flood damage and risk estimation; they assign the degree of damage for each element that is exposed to a flood hazard and its intensity. Typically, these functions describe the relationships between damage and the inundation depth (stage-damage functions); velocity is also a very damageable factor but its impact is more difficult to assess quantitatively, as it was mentioned in section 4.4.

5.1.1 Relative and Absolute damage functions

There are two types of damage functions, relative and absolute. The choice of using either of them has to do with the kind of available data (Merz, 2010). Relative functions provide the percentage of damage suffered by an element at risk according to hazard intensities. Also the total value of those elements at risk needs to be determined, so that along with the damage ratio, total losses can be obtained by summing up the shares of every single element (or category of elements) at risk. Absolute functions, however, give directly the total amount of damage for each element since their value is already incorporated in the function. Then flood damage can be expressed in percentages or monetary units.

Both relative and absolute functions have advantages and inconveniences. Relative damage functions are better transferable in space and time, since they do not depend on the market value of assets. But those values are necessary, and their estimation is needed. Absolute damage functions do not need to estimate the asset values since they are included; the estimated monetary damage results directly. But since the function depends on the total value of the affected objects, a recalibration is needed from time to time to incorporate depreciation prices and to update the value of contents that are subjected to change over time.

5.1.2 Damage function patterns

Throughout literature a number of damage curves and functions (mostly stage-damage) have been produced. Figure 30 illustrates three typical examples of damage patterns: linear, quadratic and logistic. A fourth pattern would be the logit, the inverse of logistic function. These patterns show that relationships between damage and water depth are rather variable, especially at low depths which is most significant in the context of urban areas. The shape of a damage function is an excellent tool to identify the element's at risk susceptibilities, in this case under flooding conditions. In Arnell's paper (1989) another function which designates even higher susceptibilities was proposed and named Gompertz.

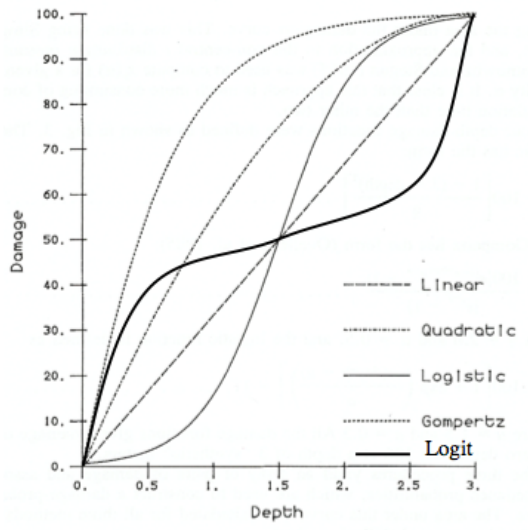

Figure 30: Damage functions patterns (Arnell, 1989, modified by the author)

From the mathematical point of view, a damage function should fulfill four properties:

- Monotonically increasing with the hazard intensity
- Continuous and differentiable
- Range from 0 to 1
- The shape represents the response of the phenomena

It is important to be reminded that damage functions are mean damage functions. There are uncertainties in the obtention of flood hazard intensities (hydraulic models), and in the process of establishment of damage relationships. Given the numerous sources of uncertainty, the goal is to estimate average damages and eventually losses with the least level of uncertainty.

5.2 Flood damage functions' collection

Flood damage functions have been developed in the past although relatively a few of them are publicly available. A group of easily available functions have been selected to carry out analyses and comparisons in this paper. Tables 15 and 16 provide two lists of the relative and absolute damage functions, along with the details of their sources and a general description for each one. A further explanation and their graphics can be found in Annexes 1 and 2.

Source	Year	General description
MURL, ICPR, Hydrotec	2000-02	Three models for residential land use.
The Rhine Atlas (ICPR)	2001	Land uses differentiation.
PATRICOVA (Province of Valencia, Spain)	2002	Damage function for general use.
USACE (U.S. Army of Corps Engineers)	2003	Structure and contents damage for building types.
FEMA (Federation of Emergency Management Agency)	2003	Buildings and contents damage functions.
Elsner et al.	2003	Damage functions for different asset categories.
MERK study (Ster et al.)	2005	Buildings and contents damage functions.
Flemish model (Vanneuville et al.)	2006	Land uses differentiation.
Netherlands (Klijn et al.)	2007	Land uses differentiation.
Cited in a Pistrika's article	2010	Structure damage for single-family residences.
A Taiwan's probabilistic model	2011	Comercial land use.
VIELCA ingenieros	2013	Generic function and agriculture land use.

Figure 15: Relative damage functions overview

Source	Year	Units	Description
Penning-Rowsell & Chatterton (UK), Blue handbook	1977, 2003	£/property, £/m^2	Damage estimation for different land uses, building types, inventory, social income.
McBean et al. (Canada)	1984	Canadian $	Total, structure and contents damage for several building types.
Badilla (Costa Rica)	2002	€/property	Estimation of contents damage for four social status.
Wang (Taiwan)	2003	$/m^2	Land uses differentiation.
Damage scanner model (The Netherlands)	2008	mill€/ha	Land uses differentiation.
Penning-Rowsell (UK), Multicolored handbook	2010	£/m^2	Collection of updated past manuals. Land uses differentiation.
Baró et al. (Mexico)	2011	Minimum salaries	Damage functions for different marginalization index and building types
Velasco et al. (Spain)	2013	€/m^2	Land uses differentiation.
Floodsmart.gov (USA)	-	$/property	Estimated losses for property contents.

Figure 16: Absolute damage functions overview

Absolute and relative damage functions need to be considered separately. Absolute functions are not easily comparable since their information is measured in different currencies from different periods ($, €, £,) and units (per property, per unit area). On the other hand, relative functions are more easily comparable. All functions refer to damage as percentages, that is, the degree to which 'something' is damaged at certain water depths (referred to the maximum possible damage).

From a first look over the flood damage functions that have been collected, at least six groups of vulnerability variables or attributes can be identified: land use, building structure types, building contents or inventory, social status (income level), duration of flood and warning time. Both types of functions are usually developed for these categories of elements at risk. Damage functions of single elements at risk are barely developed since the main interest is to obtain average damage per property or study area.

5.3 Relative damage functions analysis

In the estimation of relative damage relationships four vulnerability variables are considered in the functions that have been collected: land use, building types, building contents and warning time (which is a damage-reducing factor actually). Moreover, numerous functions are derived for sub-categories into which vulnerability variables can be divided. How damage is perceived by experts or those who establish damage relationships is essential. With all the collected data, an analysis will be carried out.

For comparison purposes, all functions have been transcribed into a *Matlab* script so that their manipulation is easier when comparison between different sources is addressed. Axis units have been unified; meters are used for water depths and percentages for relative damages. The following sections explain each attribute used to obtain damage functions, and the usual sub-categories that are typically defined, followed by an analysis.

5.3.1 Relative functions based on land uses

The most common variable used to establish damage functions is the land use. Because of the complexity that implies to carry a proper study that considers all elements at risk, the methodology is simplified. The usual approach is to estimate damage relationships for a number of representative elements at risk that are likely to be exposed within each land use. And from those functions, an average function can be derived with the mean damage relationship for a certain land use. However, for small areas it would be recommended to produce more detailed functions (although that goes with a more costly and time consuming process as it requires a previous and extensive research). The following table enumerates some land use categories:

Residential	Infrastructure	Forest
Retail/commercial	Agriculture	Grassland
Industry	Recreational	Greenhouses

Table 17: Categories of land use

In urban areas, damage functions are produced for several land uses although the residential and commercial ones are often the two most important land uses in terms of their density and degree of exposure. Other land uses may have not been subjected to such intense research and less functions are provided. To begin with, figure 31 shows the relative flood damage functions of several damage models or past studies for the residential land use.

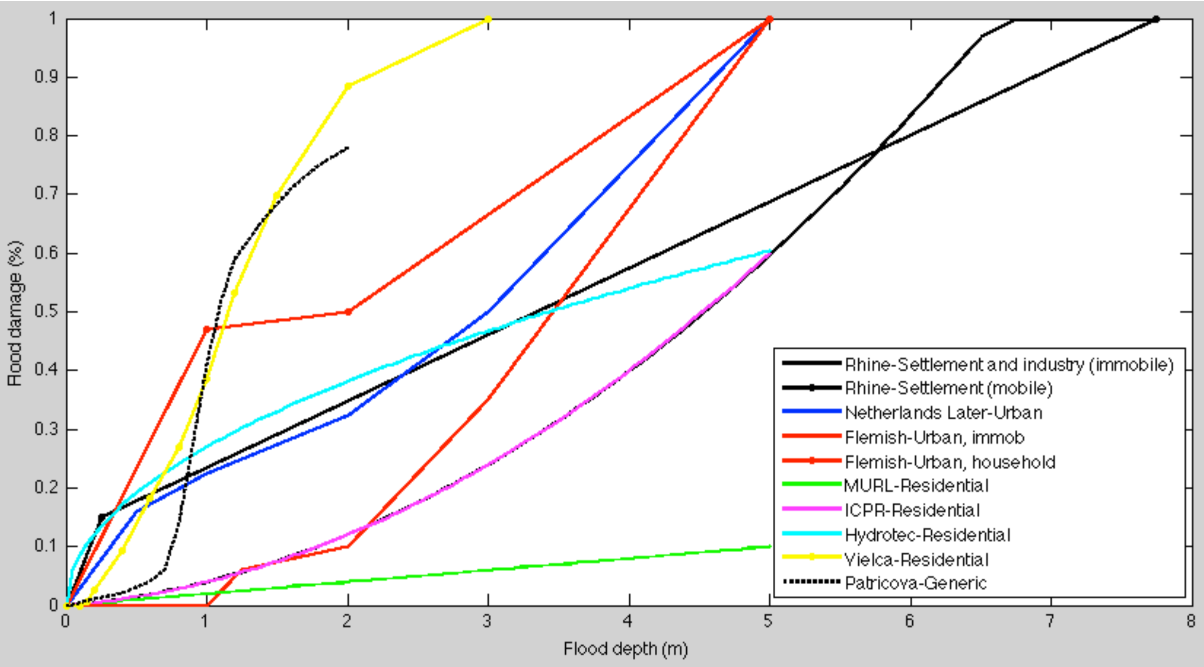

Figure 31: Relative flood damage functions for residential land use (made by the author)

Figure 31 shows that there is a wide spectrum of depth-damage functions. A direct consequence is that flood risk estimations (total loss) can be very variable for a given study area depending on which damage function is selected to describe its vulnerability. This gives an idea of the level of uncertainty it is assumed within the vulnerability component.

These functions' behaviour can be classified into the four representative patterns that were previously mentioned in section 5.1.2: linear (MURL) whose relationship is highly unlikely to represent how the actual damage is distributed in residential areas (or in any other land uses); quadratic (Hydrotec and Rhine-mobile) which starts with a quite rapid increase of damage at low water depths and then it grows but more gradually with depth; logistic (Flemish-immobile and Patricova) very little damage is caused at low water depths until a certain height from which damage increases rapidly for a range of water depths, and then damage is again affected very little by any higher depths; and logit (Flemish-household and Netherlands Later) whose behaviour is opposite to the logistic functions.

However, within the flood risk assessment in urban areas, the attention is directed towards the behaviour of damage functions at lower water depths, typically up to 1.5m (see figure 32). When looking at their behaviour at lower water depths two families of relative functions are clearly distinguished. A first group of functions (Rhine-Settlement mobile, Netherlands Later-Urban, Flemish-Urban household, Hydrotec and Vielca) describe a significant increase of damage for low water depths.

The second group (Rhine immobile, Flemish-Urban immobile, MURL, ICPR and Patricova) does not show the same degree of damage until higher water depths are reached. The first group assigns an average of 15% of damages for the first flooded 30cm and the second group does not reach that degree of damage until 2.5m are flooded (if neglecting the MURL function which assigns unrealistic levels of damage: 10% at 5m). Therefore, there is a remarkable gap at low depths.

Out of the five functions that assign low damage at low water depth, one is generic (Patricova) and two correspond to immobile functions (Rhine and Flemish). Both Rhine and Flemish provide two functions, mobile and immobile, using different elements at risk; and the mobile functions give higher damage ratios at low inundation depths.

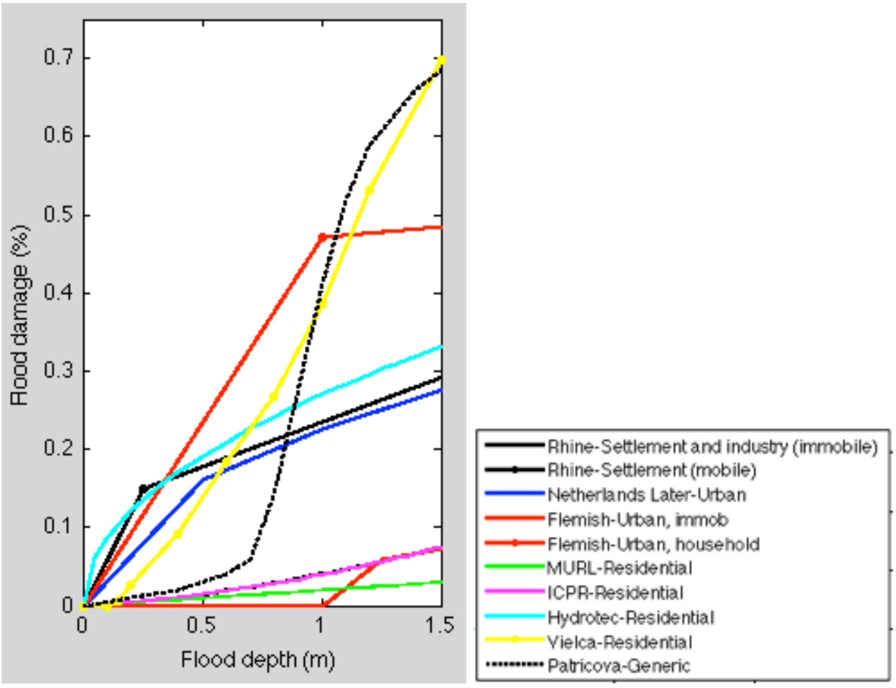

Figure 32: Relative flood damage functions for residential land use (at low depths)

Table 18 shows the values of inundation depths corresponding to three degrees of damage: 10%, 50% and 100% (although some functions do not reach total damage) for all the residential functions shown in figure 31.

Depth (m)	Rhine (mobile)	Netherl.	Flemish (mobile)	Hydrotec	Vielca	Rhine (immob)	Flemish (immob)	MURL	ICPR	Patricova
$H_{10\%}$	0.16	0.35	0.25	0.13	0.48	1.8	2	5	1.8	0.75
$H_{50\%}$	3.3	3	2	3.4	1.2	4.55	3.5	-	4.55	1.1
$H_{100\%}$	7.75	5	5	-	3	6.75	5	-	-	-

Table 18: Water depths for three damage levels (residential land use)

Variabilities have been extracted for the whole set of functions, and separately for the two families of functions that distinguish their behaviour at low water depths (table 19). Those variabilities are generally high, between 43% and 61%, if considering all the functions. But the group of functions that assigns higher rates of damage at low water depths, shows less dispersion for up to 50% of levels of damage (variabilities range from 4% to 27%). The other group of functions variabilities' are similarly high to the whole set of functions; the value of 22% resulting for 100% damage is misleading since there are only two functions out of five which reach total damage.

Variability	$H_{10\%}$	$H_{50\%}$	$H_{100\%}$
All functions	61%	43%	59%
High damage - low depths	4%	27%	59%
Low damage - low depths	53%	43%	22%

Table 19: Variabilities for three levels of damage (residential land use)

Some parameters to point out are the critical water depths for which different trends of damage are identified. There have been chosen four heights: hc_1 for depths where damage starts to increase rapidly; hc_2 for depths where damage starts to become rather constant or increases more gradually; hc_3 for depths where damage raises for a second time; hc_4 for depths where total damage is reached (table 20).

In the first group of high damage-low depths, damage raises rapidly from 0-15cm until depths between 25cm and 2m which represent from 15% to 88% of total damage. The two logit functions (Netherlands and Flemish-mobile) have another critical depth at 2m. Regarding the second group of low damage-low depths, the first critical depth is found between 70cm and 3m, while only the logistic functions (Flemish-immobile and Patricova) define a second critical depth around 1.3m. The fourth critical depth for which total damage is reached, varies from 3m to 7.75m.

Critical depths (m)	High damage - low depths					Low damage - low depths				
	Rhine (mobile)	Netherl.	Flemish (mobile)	Hydrotec	Vielca	Rhine (immob)	Flemish (immob)	MURL	ICPR	Patricova
hc_1	0	0	0	0	0.15	3	1	-	2.5	0.7
	0%	0%	0%	0%	0%	25%	0%		17%	5%
hc_2	0.25	0.5	1	0.5	2		1.25			1.3
	15%	17%	47%	19%	88%		6%			60%
hc_3	-	2	2	-	-		2			
		33%	50%				10%			
hc_4	7.75	5	5	5	3	6.75	5	5	5	2
	100%	100	100%	60%	100	100%	100%	10%	60%	78%

Table 20: Critical water depths for residential land use

The second land use that is presented next is the commercial, also called retail services. Figure 33 shows the four relative functions that have been collected. The one from The Netherlands is the most relaxed with less than 30% of damage for depths under 3m. The one from Taiwan shows a more likely depth-damage relationship except for the fact that there is no damage until water depth is 60cm, which seems unreal. The other two, Vielca and Patricova, are the same functions that were also included within the residential land use since they are generic, so that they are meant for general use. For that reason they should be given relative notice.

Regarding the patterns classification, the Taiwan function can be considered logistic (as well as the Patricova) although with a far more relaxed shape; the Netherlands can be categorized as logit (with a moderate first section) or linear with two different rates (slow increase of damage below 3m and rapid increase above 3m).

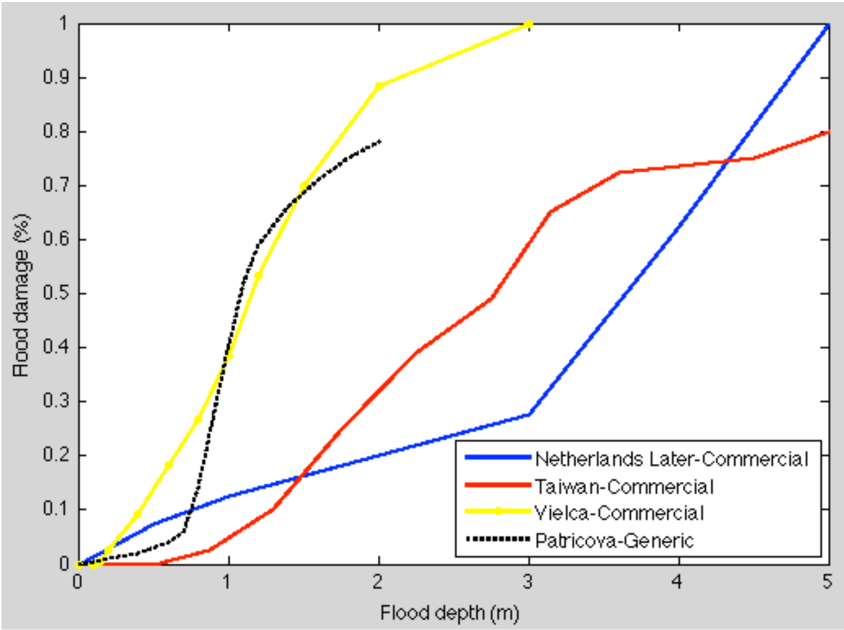

Figure 33: Relative flood damage functions for commercial land use

When looking at low depths (see figure 34), two pairs of functions can be differentiated regarding their response to damage. The Netherlands and assigns some occurrence of damage for low depths while Taiwan and Patricova delay the occurrence of damage. The case of Vielca is slightly different since no damage is assigned until 15cm, but then damage increases rapidly. However, the difference at low depths is not as evident as it was in the residential land use, where 15% of damage was reached at 30cm.

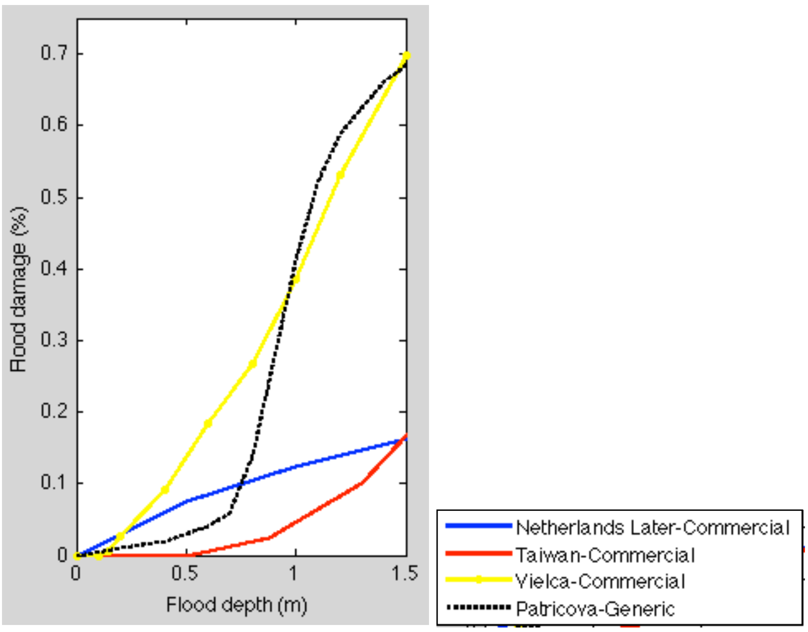

Figure 34: Relative flood damage functions for commercial land use (at low depths)

Similarly to what has been done for the residential land use, tables 21 and 22 gather some information from the damage functions for commercial land use. Table 21 shows the water depths for three levels of damage and their variability. Having in mind that there are only four functions available for commercial land use, variabilities are lower (from 18% to 50%) compared to the ones for residential land use. Contrary to what happens at lower degrees of damage, for higher damages (over 15%) two different pairs, Netherlands-Taiwan and the generic functions Vielca-Patricova, have similar shapes with a difference of value reflected through variabilities of 50% and 40%.

Depths (m)	Netherlands	Taiwan	Vielca	Patricova	**Variability**
$H_{10\%}$	0.75	1.3	0.4	0.75	18%
$H_{50\%}$	3.6	2.75	1.15	1.1	50%
$H_{100\%}$	5	-	3	-	40%

Table 21: Water depths for three damage levels and variabilities for commercial land use

Critical depths have been determined and presented in table 22. The first critical depth for which damage raises rapidly differ between the two mentioned groups defined at low depths (0-15cm and 55-70cm). However, from the second critical depths (and on) are very variable going between 50cm and 3.5m. The Netherlands function has a third critical depth at 3m from which point damage increases at a high rate until 5m of inundation depth.

Critical depths (m)	**High damage - low depths**		**Low damage - low depths**	
	Vielca	Netherlands	Patricova	Taiwan
hc_1	0.15	0	0.7	0.55
	0%	0%	5%	0%
hc_2	2	0.5	1.3	3.5
	88%	7%	60%	73%
hc_3	-	3	-	-
		27%		
hc_4	3	5	2	5
	100%	100%	78%	80%

Table 22: Critical water depths for commercial land use

The third category of land use is the industrial, and there are six functions shown in figure 35. After a first look two groups of functions are distinguished; on one hand both Rhine functions are very moderate, and on the other hand the rest of functions reflect higher susceptibility to experience damage. Identifiable patterns are quadratic, logistic and two-linear sections.

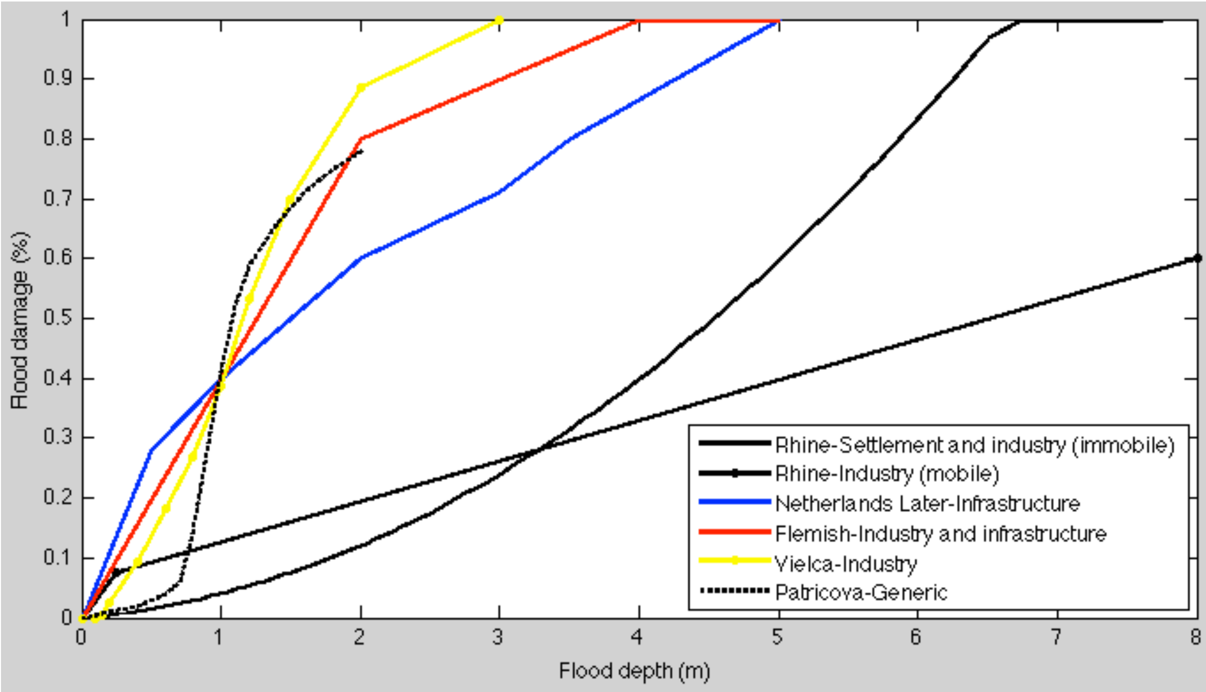

Figure 35: Relative flood damage functions for industrial land use

Similarly to what was observed in residential and (less evidently) in commercial land uses, two groups of functions are also distinguished at low water depths (figure 36). The Rhine-immobile and Patricova functions give lower damage values (5% at 85cm). The Rhine-mobile, Flemish and Netherlands assign higher rates of damage (5% at 20cm). The generic Vielca function describes an intermediate behaviour: damage starts at 15cm but increases rapidly 5% at 30cm.

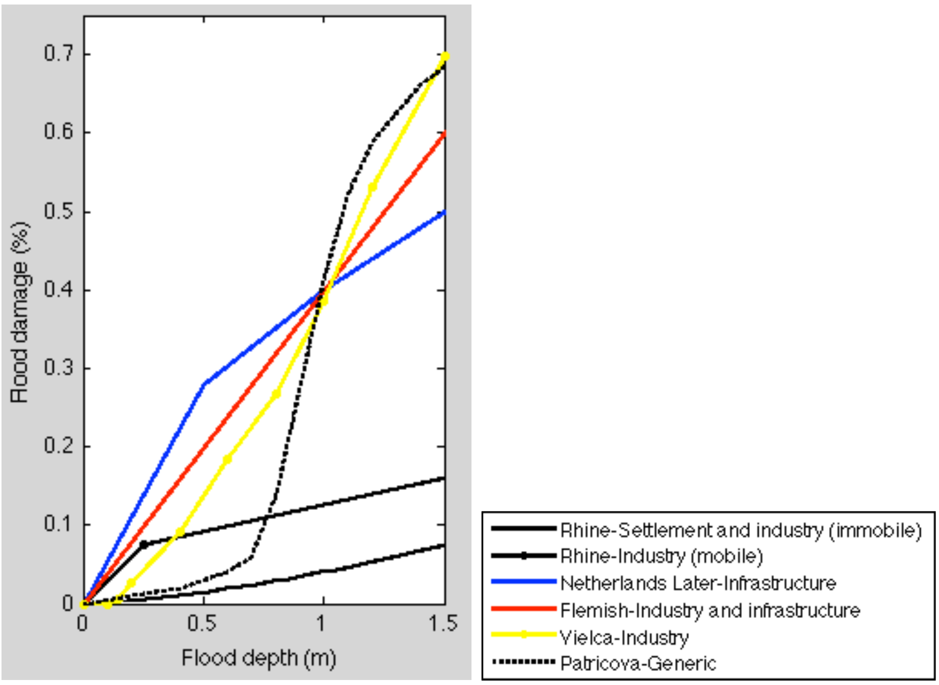

Figure 36: Relative flood damage functions for industrial land use (at low depths)

Table 23 provides variability numbers which range from 20% to 67%. The least level of dispersion is found in the 10% degree of damage while the most dispersion is at the 50% degree of damage. Maximum damage depths range between 3m and 6.75m. Similarly to what could be observed in commercial land use, Patricova and Rhine-mobile functions alternate behaviours; Patricova starts showing low susceptibility at low depths and from 0.8m it changes its trend, while the Rhine-mobile function indicates the opposite behaviour.

Depths (m)	Rhine (immobile)	Rhine (mobile)	Netherlands	Flemish	Vielca	Patricova	**Variability**
$H_{10\%}$	1.8	0.6	0.2	0.25	0.4	0.75	20%
$H_{50\%}$	4.55	6.5	1.5	1.25	1.15	1.1	67%
$H_{100\%}$	6.75	-	5	4	3	-	47%

Table 23: Water depths for three damage levels and variabilities for industrial land use

In table 24 three critical water depths have been pointed out instead of four since there are no logit functions. The first critical depth ranges from 0 to 70cm; the value of 3m (Rhine-immobile) was obtained as an approximate inflection point if simplifying the function into a two-section linear function but really there is no such critical depth, its damage grows gradually uniform. The second critical depth ranges between 25cm and 2m, and total damage is reached at very different depths (from 2m to 8m). Variabilities are quite acceptable for the first and second water depths.

Critical depths (m)	**High damage - low depths**				**Low damage - low depths**	
	Rhine (mobile)	Netherland	Flemish	Vielca	Rhine (immobile)	Patricova
hc_1	0	0	0	0.15	3	0.7
	0%	0%	0%	0%	25%	5%
hc_2	0.25	2	2	2	-	1.3
	15%	60%	80%	88%		60%
hc_4	8	5	4	3	6.75	2
	60%	100%	100%	100%	100%	78%

Table 24: Critical water depths for industrial land use

The final land use category is agriculture, illustrated in figure 37, which comprises several subcategories. The most surprising is the Rhine function that assumes there is almost no damage and it is constant. Opposite to that, two functions (Flemish-pasture and Vielca-farming) show almost immediate total damage (at 25cm and 60cm respectively). And in between there are another six functions. All kind of patterns can be identified: linear, quadratic, logistic and logit. In this case, at low depths the majority of functions assign a rapid increase of damage, except for the Rhine, Vielca-woodland and Patricova (which already was mentioned to be a generic function, therefore not so representative). As an order of magnitude, the majority gives 10% of damage at 15cm and the rest about 10% at 90cm.

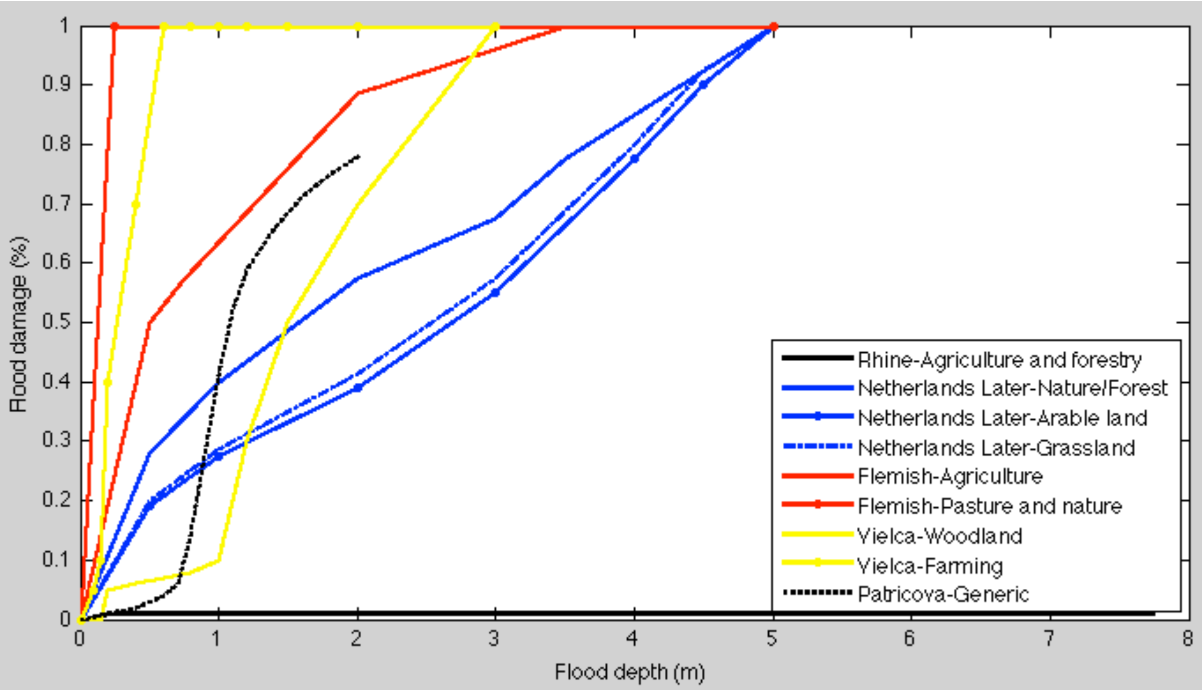

Figure 37: Relative flood damage functions for agriculture land use

Depths (m)	Rhine	Netherlands			Flemish		Vielca		Patricova
		Forest	Arable	Grassland	Agriculture	Pasture	Woodland	Farming	
$H_{10\%}$	-	0.18	0.25	0.25	0.1	0.05	1	0.15	0.75
$H_{50\%}$	-	1.6	2.75	2.6	0.5	0.1	1.55	0.25	1.1
$H_{100\%}$	-	5	5	5	3.5	0.25	3	0.6	-

Table 25: Water depths for three damage levels for agricultural land use

From table 26, it is seen that variabilities go from 19% to 95%. It has already been explained the extreme behaviour of the functions Flemish-pasture and Vielca-farming which are responsible of causing enormous dispersion of values at total damage (from 25cm till 5m). But for lower degrees of damage variability remains smaller.

	$H_{10\%}$	$H_{50\%}$	$H_{100\%}$
Variability	19%	53%	95%

Table 26: Variabilities for three levels of damage (agricultural land use)

Regarding the critical water depths, they are shown in table 25. If compared with the results for industrial land use, they are very similar. The first critical depths go between 0cm and 70cm; the second from 50cm till 2m; the third between 1m and 3m; and the fourth between 2m and 8m. It needs to be reminded that within agricultural land use numerous sub-categories have been included, so that not every function estimates damage under the same assumptions.

Depths (m)	Rhine	Netherlands			Flemish		Vielca		Patricova
		Forest	Arable	Grassland	Agriculture	Pasture	Woodland	Farming	
hc_1	-	0	0	0	0	0	0.15	0	0.7
	-	0%	0%	0%	0%	0%	0%	0%	5%
hc_2	0	0.5	0.5	0.5	2		0.2		1.3
	0%	27%	20%	20%	88%		5%		60%
hc_3	-	3	2	2	-	-	1	-	-
		67%	39%	42%			10%		
hc_4	7.75	5	5	5	3.45	0.25	3	0.6	2
	1%	100%	100%	100%	100%	100%	100%	100%	78%

Table 27: Critical water depths for agricultural land use

Figure 38 zooms the damage functions for agriculture land use at water depths between 0m and 1.5m. In this case it is more difficult to identify families or groups of functions since all of them constitute a wide spectrum of functions that range from one extreme to the other. But it can be observed that the majority of functions' behaviour (six out of nine) assign considerable -to-high damage and it increases more or less rapidly, while the other three functions assign much lower damage until 80cm.

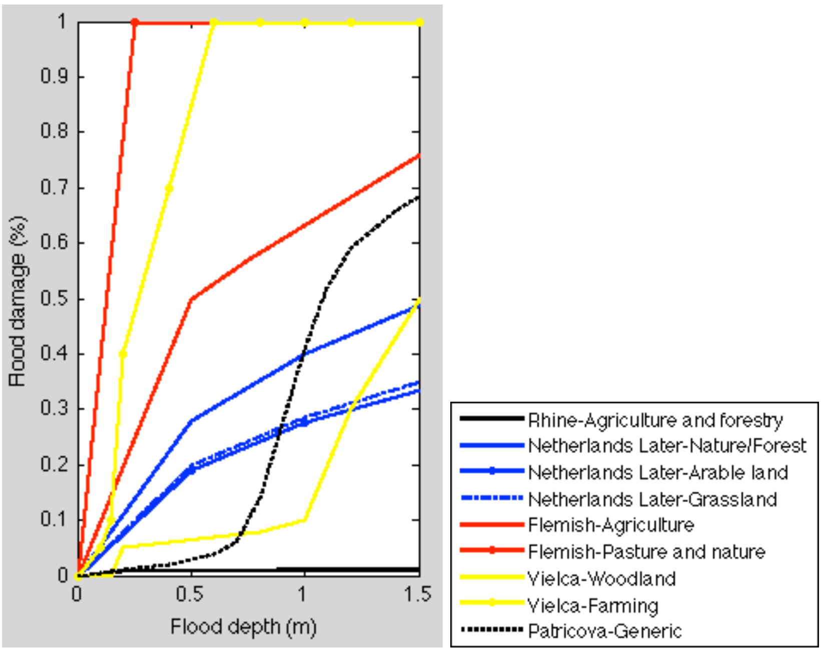

Figure 38: Relative flood damage functions for agriculture land use (at low depths)

Lastly, in order to see a general picture of all relative functions from every land use, all of them have been included in figure 39, one color for each land use. The majority show a higher damage rate for lower depths although the number of functions which express low susceptibility for quite a range of depths is not negligible. It has been seen that within each land use class there is wide spectrum of patterns, and thresholds for which damage starts to become significant as well as variability of water depths for a given degree of damage.

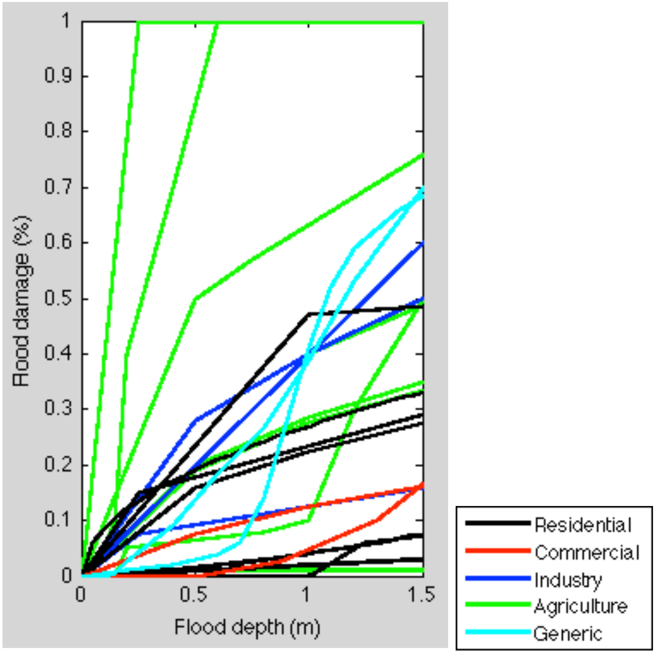

Figure 39: Relative damage functions of all four land uses (at low depths)

5.3.2 Relative functions based on building structure types

Many studies have focused on buildings as a single element at risk which potentially can entail significant losses in urban areas due to flooding. Therefore the interest lies in trying to determine the conditions under which buildings become damaged (and to what degree) or even collapse. The U.S. Army Corps of Engineers (USACE, 1996, 2003), FEMA (Federal Emergency Management Administration) and Penning-Rowsell & Chatterton (1977) are the three main sources which have collected extensive data regarding flood damage functions for several building types (see table 28). Regarding relative functions, the specific sources are USACE, FEMA, Merk (2005) and Pistrika (2010). Moreover, they distinguish separate functions to represent structure damage, contents damage and total damage. In this section, structure damage is the object of study.

Detached	One storey, no basement
Semi-detached	Two or more stories, no basement
Terrace	One storey, with basement
Bungalow	Two or more stories with basement
Flat/apartment	Building hall

Table 28: Categories of building types

Figure 40 shows a set of nine functions that estimate the structure damage for several building types. USACE and Merk provide several functions for different categories of buildings (one floor, two or more floors, building hall; with and without basement). On the other hand, FEMA's function is generic and does not differentiate between building types while Pistrika's function responds to a single-family building. The latter can be barely considered as a proper damage function because of its discrete nature but has been included to give an idea of all public available functions.

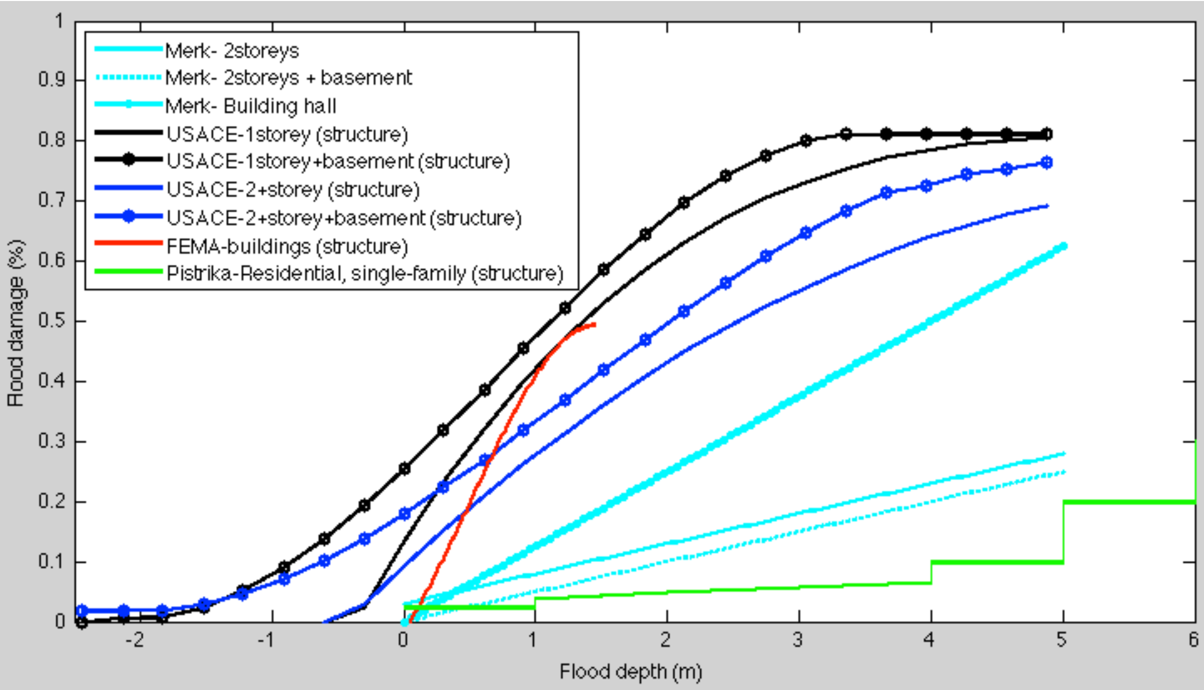

Figure 40: Relative flood damage functions for building types

Regarding the shapes of these functions, two different groups of functions can be distinguished. One group (Merk and Pistrika) show linear and discrete relationships which seem to be too conservative and unlikely to express a fair depth-damage relationship for buildings (especially the discrete function, where damage remains constant for ranges of 1m). The second group (USACE and FEMA) present quadratic and logistic patterns. FEMA's function only considers water depths up to 1.5m. USACE functions consider negative depths for buildings with and without basement, which shows that hydrostatic forces and their damaging effects upon the building's walls are considered.

There is a clear distinction of behaviours at low depths; the USACE functions already assign a considerable degree of damage; Merk and Pistrika express a general low susceptibility; and FEMA, as a logistic function, raises its degree of damage very rapidly reaching levels of USACE functions (figure 41).

In tables 29 and 30 a relation of depths for certain degrees of damage and its variabilities can be found. Variabilities range from 33% till 65%. At initial water depths, dispersion is basically given due to the presence or absence of basements in buildings although buildings without basements also present negative water depths (-60cm). Variability for 10% of damage is 65% but if Pistrika is neglected it would be 24%. For higher degrees of damage dispersion lies with the Merk building hall function.

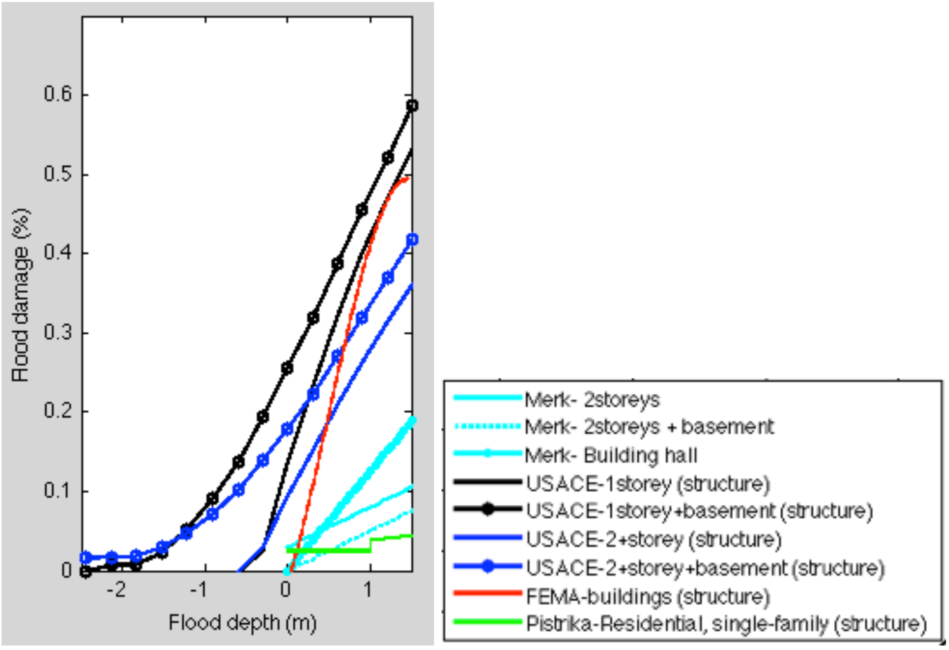

Figure 41: Relative flood damage functions for building types (at low depths)

Depths (m)	Merk			USACE				FEMA	Pistrika
	2s	2s+b	Hall	1s	1s+b	2s	2s+b		
$H_{0\%}$	<0	0	0	-0.6	-2.5	-0.6	<-2.5	0	<0
$H_{10\%}$	1.4	2	0.8	-0.125	-0.85	0	-0.6	0.25	4-5
$H_{40\%}$	-	-	3.2	0.9	0.7	1.8	1.5	1	-
$H_{70\%}$	-	-	-	2.75	2.1	5	3.6	-	-

Table 29: Water depths of structural damage for building types

	$H_{0\%}$	$H_{10\%}$	$H_{40\%}$	$H_{70\%}$
Variability	33%	65%	33%	38%

Table 30: Variabilities of structural damage for building types

Critical water depths are specified in table 31. In general, damage relationships initiate with a slow increase of damage (second critical depth); then half of them express a rapid raise of damage (third critical depth); finally, buildings with basements have another critical depth (the fourth) for which damage stabilizes. Variability between degrees of damage that refer to the maximum depth is 56%. None of the functions reach total damage, which is the collapse of the building. For that to happen the effect of velocity needs to be taken into account; attention will be given to this matter in Chapter 6.

The dispersion generated between the presence or absence of basement in terms of damage ranges from 5% (at 1m) to 14% (at -0.6m); when considering buildings with one storey and two or more, damage ranges from 0% (at -0.3m) to 19% (at 2.75m). Also, the proportion of damage for one-storey buildings is greater than for two or more floors according to USACE.

Critical Depths (m)	Merk			USACE				FEMA	Pistrika
	2s	2s+b	Hall	1s	1s+b	2s	2s+b		
hc_2	0	0		-0.6	-2.5	-0.6	-2.5	1.23	0
	3%	0%		0%	0%	0%	2%	48%	2%
hc_3	-	-		-0.3	-1.2	-0.3	-1.2	-	4
				3%	5%	3%	5%		10%
hc_4					3		3.6		
					80%		71%		
hc_5	5	5	5	4.9	4.9	4.9	4.9	1.5	6
	28%	25%	62%	81%	81%	69%	76%	50%	30%

Table 31: Critical water depths of structural damage for building types

5.3.3 Relative functions based on building contents

The contents damage is the share of the total damage caused to a building that considers the particular items of properties, shops, offices, etc. Usually there is no explicit classification of the inventory for damage estimations, although in the blue manual of Penning-Rowsell & Chatterton (1977) they presented a great deal of items that can be found in each typical building (household, shops, offices), but those are absolute functions. Most studies do not show that level of detail and probably take the most representative items to obtain relative depth-damage relationships. Figure 42 shows contents damage functions being a percent of the structure damage. The origin of structure and content functions is different so these building contents functions' applicability should be subjected to the use of their respective structure functions.

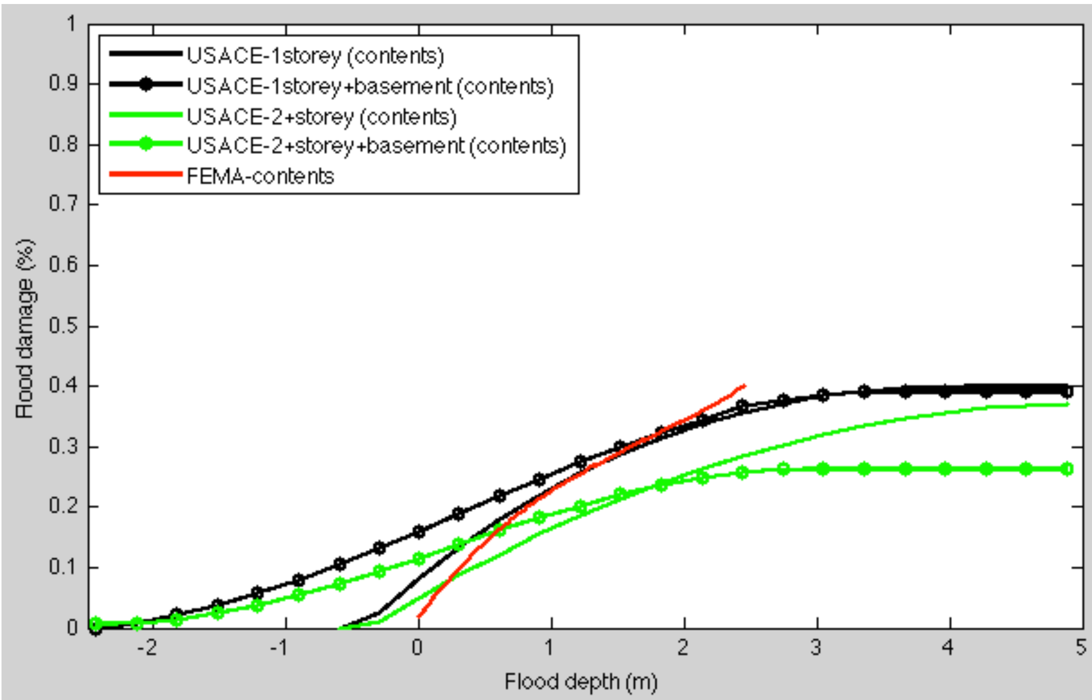

Figure 42: Relative flood damage functions for building contents

These functions show quadratic behaviours. At low depths a difference can be pointed out between buildings of one or more storeys, and with or without basements. The presence of basement assigns higher damage than buildings without basement although for depths above 1.75m the difference is smaller.

Table 32 presents quite moderate variability values for four levels of damage (from 15% to 33%). Dispersion is bigger at initial water depths because of the presence of building with basement. One detail worth mentioning is that contrary to what was observed in structure damage, the contents function for two or more stories without basement surpasses its homolog with basement at 1.75m (this is surprising because the one storey functions with and without basement are more or less the same from 1.75m).

Water depths (m)	USACE				FEMA	Variability
	1s	1s+b	2s	2s+b		
$H_{0\%}$	-0.6	-2.5	-0.6	-2.5	0	33%
$H_{10\%}$	0.1	-0.7	0.4	-0.25	0.3	15%
$H_{30\%}$	1.7	1.5	2.75	-	1.6	17%
$H_{40\%}$	3.75	4	-	-	2.45	20%

Table 32: Water depths and variabilities of contents damage for building types

To finish with, table 33 provides information related with the critical depths. The behaviours are identical to the ones presented for structural building damage. The differences are the degrees of damage at which the critical depths are situated. Variability between degrees of damage that refer to the maximum depth is 14%.

Critical water depths (m)	USACE				FEMA
	1s	1s+b	2s	2s+b	
hc_2	-0.6	-2.5	-0.6	-2.5	1
	0%	0%	0%	0%	23%
hc_3	-0.3	-1.2	-0.3	-1.2	
	3%	14%	1%	10%	
hc_4		2.4		2.2	
		36%		24%	
hc_5	4.9	4.9	4.9	4.9	2.45
	40%	40%	37%	26%	40%

Table 33: Critical water depths of contents damage for building types

Next, in figure 43 the building contents functions are plotted for low water depths, along with some of the functions of the residential land use (the ones that assign high damage at low depths). It can be observed that except for the Flemish-urban, the rest of functions present a similar behaviour with the FEMA and USACE function (one storey) for positive water depths.

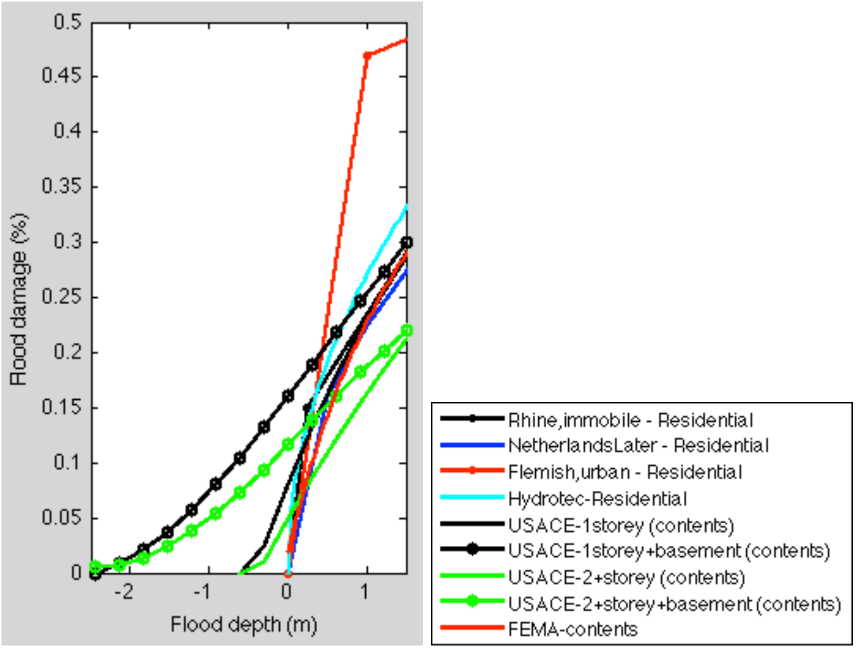

Figure 43: Relative flood damage functions for building contents and residential land uses

5.3.4 Effect of warning time on relative functions

The possibility of early warning times can be decisive when it is possible for people to secure a portion of their belongings and avoid their potential damage. Some functions are able to reflect how much money on damaged items is likely to be prevented due to early warning times; figure 44 shows some functions extracted from Chatterton (1979). For depths under 3m, it is given the percentage of damage that can be saved for total damage (line), inventory damage (dot line) and for several warning times: no warning, two hours warning and four hours warning.

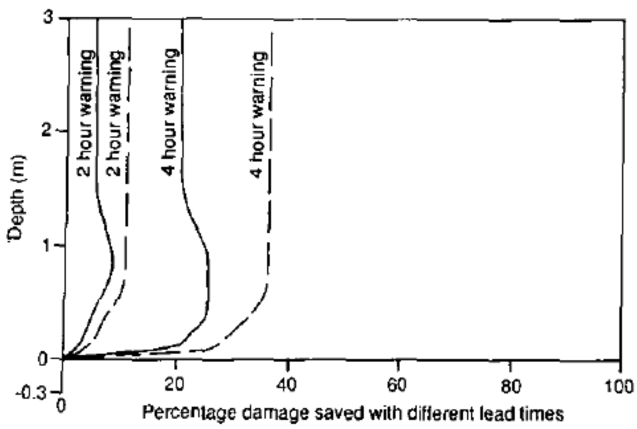

Figure 44: Damage reduction due to early warnings for one-storey residence (Chatterton et al., 1979)

Previously in section 4.3.3 there was presented another function (figure 27) which also expressed damage coefficients according to warning times. Next figure (45) compares both set of functions. The order of magnitude is similar, but the Queensland Government (2002) coefficients for experienced population assign higher reducing factors. Also, their coefficients are constant, while a distinction is made for the value of water depths in Chatterton (1979). It is assumed that damage reduction occurs for higher depths since certain damage cannot be avoided at low depths. And for total damage (black line) it is strange how the reducing factors decrease at depths higher than 1.5m.

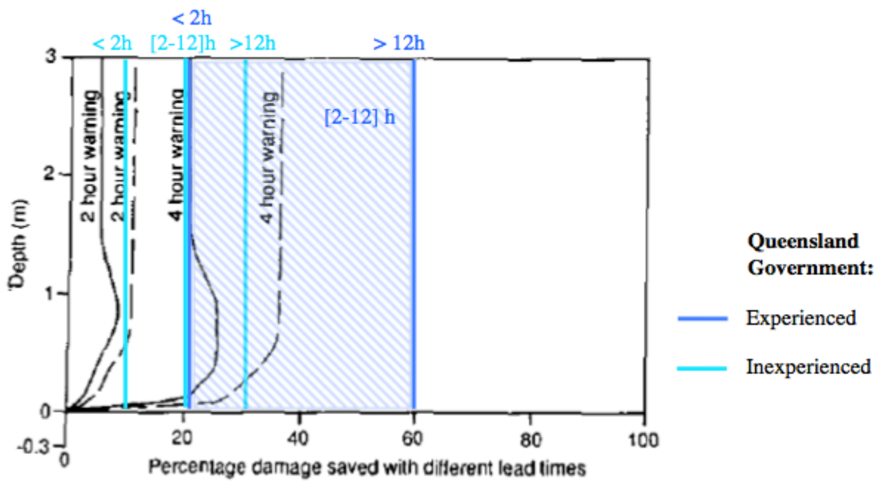

Figure 45: Damage reduction according to Chatterton (1979) and Queensland government (2002)

5.3.5 Discussion of results

Having presented a number of relative damage functions according to several vulnerability attributes, it has been seen the wide range of behaviours within each category. However, at low depths, which are interesting from the point of view of studies focused on urban areas, there are usually two families of functions, that assign either high or low damage at low water depths. But the majority (and having neglected the generic functions for their lack of representativity) respond to a behaviour of high damage at low depths. Above all, this type of damage function seems to be more coherent.

Among the damage functions corresponding to the four land uses (residential, commercial, industry and agriculture), it does not seem likely to recommend a certain damage function since dispersion of their values are more or less considerable.

Regarding building structure and building contents functions at low and positive water depths, the range of their behaviour is considered acceptable. In the case of building contents, and its comparison with functions of residential land use, it has been verified their similarities despite the fact that the first is produced from building structure damage functions.

5.4 Absolute damage functions analysis

The last section aimed to bring some light into the various relative damage functions. Those provide the potential damage that can happen according to hazard intensities. Now the absolute damage functions are usually obtained through empirical methods after the event. Since the absolute functions refer to different time scales and economic units (dollars, euros, pounds) the data has been translated into euros at the present time (2014) in order to be able to compare all the functions. An analysis of absolute functions is presented below.

5.4.1 Absolute functions based on land use

The following figure shows the total economic damage per unit area (m²), including all the available functions for residential areas. From the absolute functions (figure 46a) it is noted that the most damaging functions are in the following order: Penning (updated, 2010), Netherlands (high and low density, 2008), Velasco (2013), Taiwan (2003) and Penning (1977). The only function which takes into account negative water depths is Penning (1977).

It is clear that the maximum values of damage of the absolute functions differ in the order of magnitude even though they are expressed under the same currency reference. This has to do with the local estimation of costs considered within the obtention of the functions. In order to compare how the flood risk (total damage) is distributed along the range of water depths, a second figure has been created by plotting all the absolute functions on a scale from 0 to 1, where 1 equals each respective maximum of the function. Therefore, the functions in figure 46b are referred to as the “relative” absolute functions (not to be confused with the relative functions studies in the previous section).

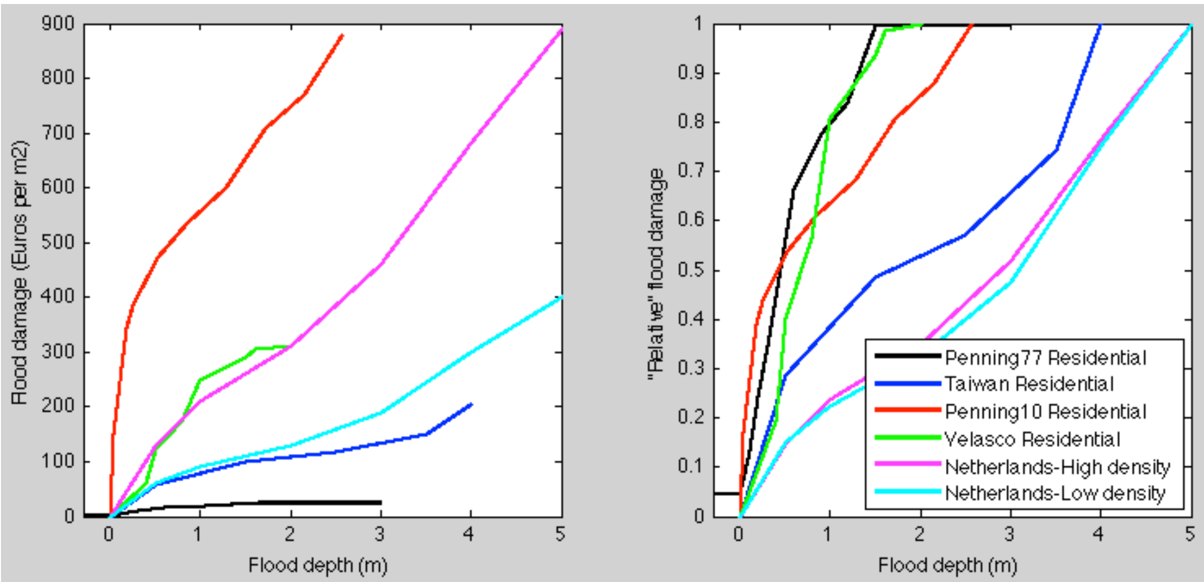

Figure 46: Absolute (a) and “relative” (b) flood damage functions for residential land use

Figure 46b can also be thought of as the dimensionless losses per square meter distribution. It can be observed that all the functions, although in some different degree, assign a considerable percentage of total losses at low depths (20% at 80cm for the Netherlands functions and at 17cm for the rest). Therefore, there is no distinction of two groups of functions with different behaviour at low water depths, contrary to what happened with the relative damage functions. As water depth increases, so does variability of functions; variability of the water depths that are assigned to express maximum losses is of 70%.

Behaviours like Penning (2010), for which there is no reference of a relative damage function, show that half the total loss is reached at 0.5m (see figure 47) which means either that there are many items which are damaged at low depths or that damage at those depths is costly. The Netherlands functions for high and low density show an identical distribution of losses, although of course the absolute losses are more than doubled for high density residential areas.

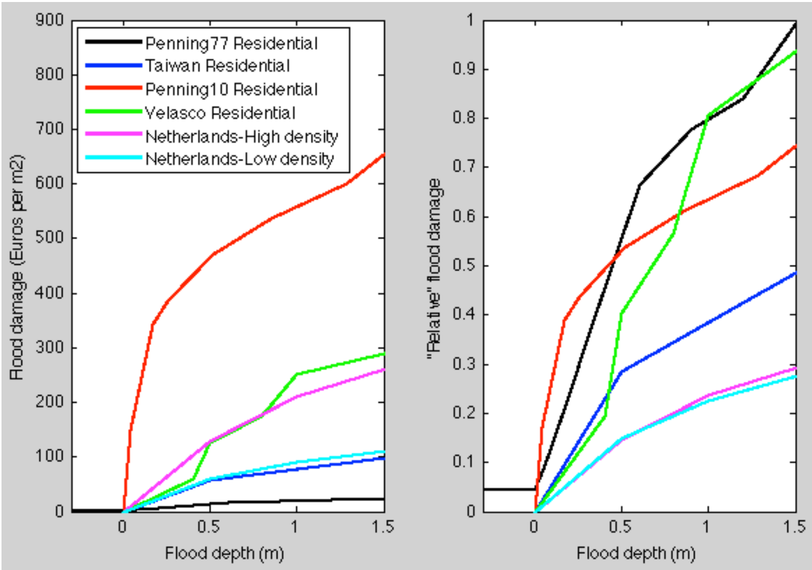

Figure 47: Absolute (a) and "relative" (b) flood damage functions for residential land use (low depths)

Table 34 shows the values of total flood damage in economic units, and the "relative" damage in percentages corresponding to absolute functions in residential areas. Four levels of water depths have been chosen. Variabilities have been determined and range between 51% and 69% for total damage, and between 43% and 73% for "relative" damage. It has been explained that variabilities of total damage are understandable due to their various origins; regarding the "relative" damage, variabilities are considerable but it is stated that all functions agree on high damage at low depths.

Total (€/m^2) and "Relative" (%) damage	Penning (1977)	Taiwan	Penning (2010)	Velasco	Netherl. (high)	Netherl. (low)	Variability
h = 0m	1.6	0	0	0	0	0	0.17%
	0.045	0	0	0	0	0	4.5%
h = 0.5m	11	60	470	140	140	60	51%
	0.58	0.28	0.54	0.41	0.15	0.15	43%
h = 1m	30	80	560	255	220	95	59%
	0.8	0.38	0.63	0.8	0.24	0.23	57%
h = 1.5m	36	100	660	295	260	110	69%
	1	0.49	0.75	0.94	0.29	0.27	73%

Table 34: Total and "relative" levels of flood damage (absolute functions - residential land use)

Next land use is commercial which functions, from the same sources of residential land use functions, are shown in figure 48. Most sources assign greater losses to commercial land use than those assigned to residential land use, except for the Netherlands function. Again, this has to do with the number of elements that are considered per unit area and their value. It makes sense that in commercial land use, density of goods and their values are high.

From figure 48b, showing the "relative" flood damage, it is clear that the distribution of the loss is almost unanimous except for the Netherlands: 70% is due to water depths under 1.3m. Therefore critical water depths are 0m (for the majority of functions) and 2m (for the Netherlands). Variability of depths for which maximum losses are reached is slightly lower, 60%. Figure 49 zooms the functions at low water depths (up to 1.5m) to see their behaviour more in detail.

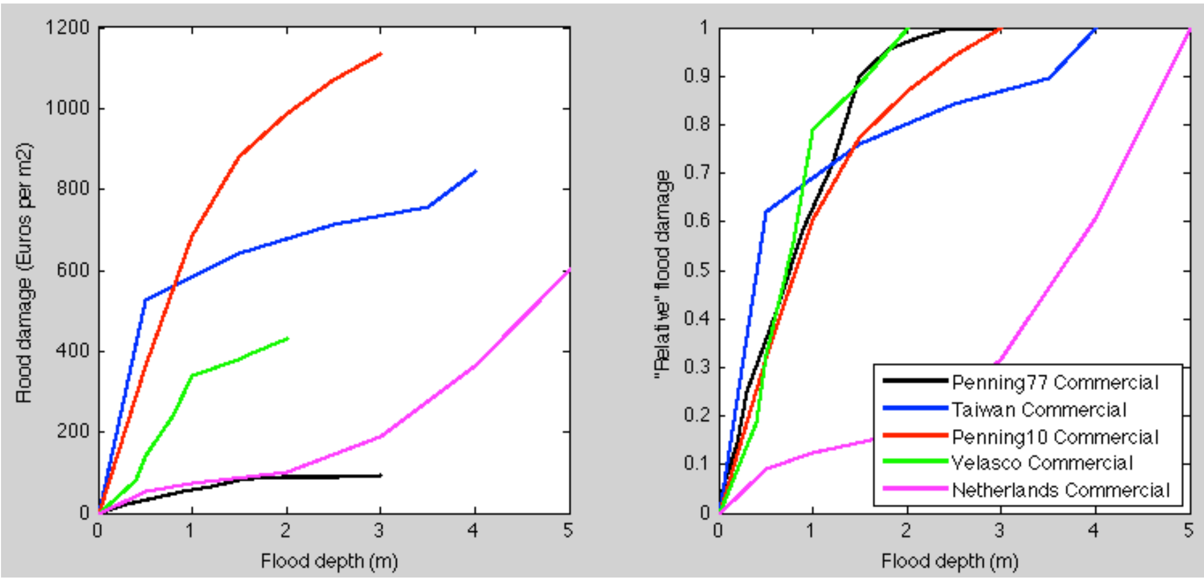

Figure 48: Absolute (a) and "relative" (b) flood damage functions for commercial land use

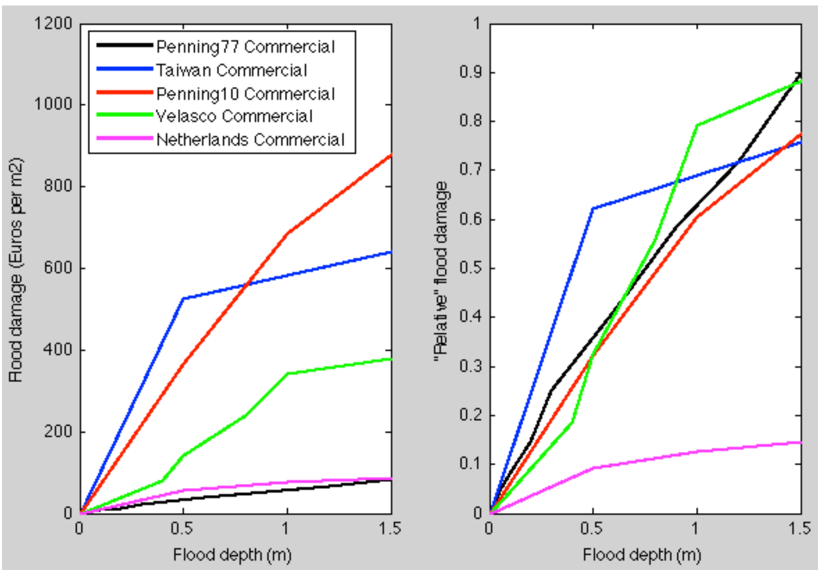

Figure 49: Absolute (a) and "relative" (b) flood damage functions for commercial land use (low depths)

Table 35 shows the values of total flood damage in economic units, and the "relative" damage in percentages corresponding to absolute functions in commercial areas. Variabilities have been determined and range between 43% and 68% for total damage, and between 54% and 76% for "relative" damage. Variabilities of total damage are slightly lower than those of residential land use, even though their absolute damages are higher. Regarding the "relative" damage it seems to be higher than of residential, but this is due to the Netherlands function which behaviour is very different. If this function is neglected, the variability values then go from 27% to 15%. Therefore, a clear representative behaviour of "relative" damage could be proposed.

Total (€/m^2) and "Relative" (%) damage	Penning (1977)	Taiwan	Penning (2010)	Velasco	Netherlands	Variability
h = 0.5m	35	530	360	140	60	43%
	0.37	0.63	0.33	0.33	0.09	54%
h = 1m	55	580	700	350	80	56%
	0.64	0.68	0.61	0.8	0.13	67%
h = 1.5m	90	620	880	380	95	68%
	0.9	0.75	0.77	0.88	0.14	76%

Table 35: Total and "relative" levels of flood damage (absolute functions - commercial land use)

The third land use category, industrial, is presented in figure 50. In this case the absolute damage values are more or less the same or lower than in residential land use. The difference between the updated Penning function (2010) and the rest of functions is considerable. In figure 50b, all functions agree on giving an average of 20% of losses at around 30cm. Again, the Netherlands is the function that delays the most the occurrence of higher percentages of damage as well as low absolute damages. Variability of depths for which maximum damage is reached is the lowest out the three land uses, 40%.

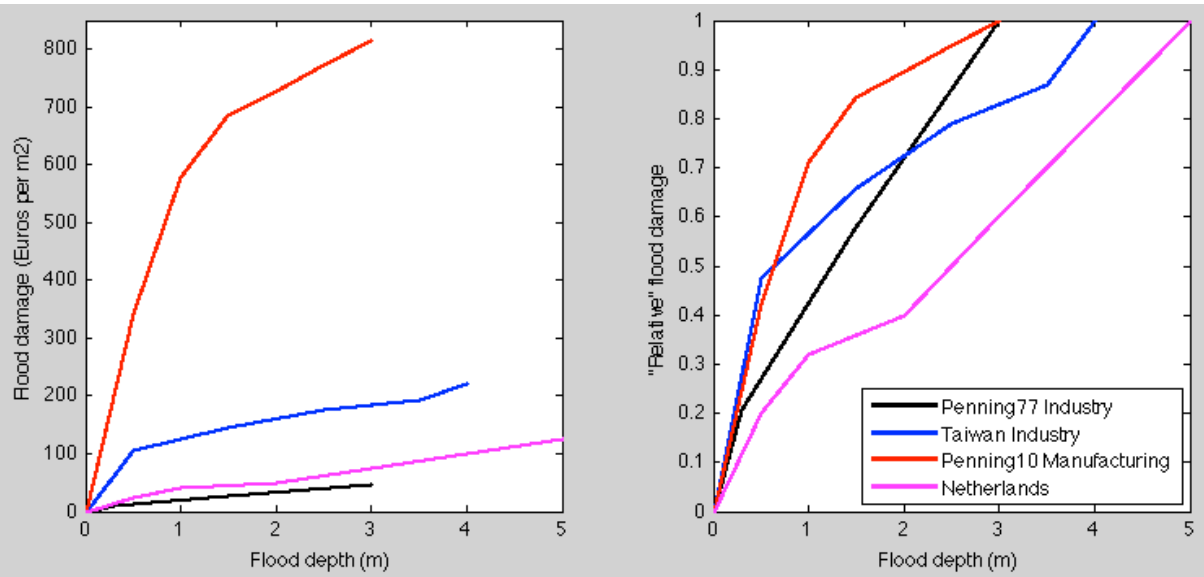

Figure 50: Absolute (a) and "relative" (b) flood damage functions for industrial land use

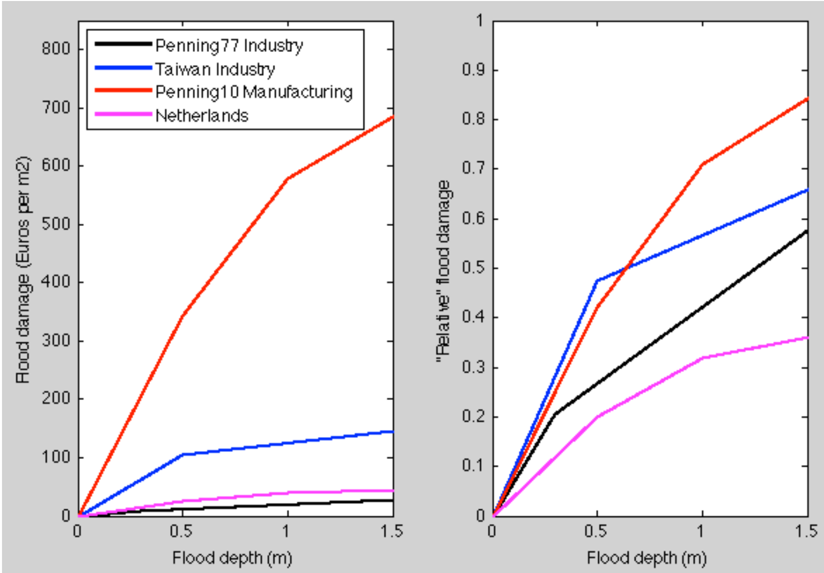

Figure 51: Absolute (a) and "relative" (b) flood damage functions for industrial land use (low depths)

Table 36 shows the values of total flood damage in economic units, and the "relative" damage in percentages corresponding to absolute functions in industry areas. Four levels of water depths have been chosen. Variabilities have been determined and range between 42% and 82% for total damage, and between 28% and 49% for "relative" damage. It has been explained that variabilities of total damage are understandable due to their various origins; regarding the "relative" damage, variabilities are higher than those of commercial land use but still up to 1.5m theres is clear representative "relative" damage function at low depths.

Total (€/m^2) and "Relative" (%) damage	Penning (1977)	Taiwan	Penning (2010)	Netherlands	Variability
h = 0.5m	10	110	350	25	42%
	0.27	0.48	0.44	0.2	28%
h = 1m	15	125	570	40	69%
	0.43	0.57	0.72	0.32	40%
h = 1.5m	20	140	680	45	82%
	0.57	0.65	0.84	0.35	49%

Table 36: Total and "relative" levels of flood damage (absolute functions - industry land use)

Regarding the agricultural land use, no available absolute functions have been found. It has been seen that absolute functions differ more or less depending on the land use and because of the valuation of each country or local areas. However, the "relative" functions are quite similar at low depths (under 1m), especially for commercial land use.

5.4.2 Absolute functions based on building structure types

There are three sources that provide structural absolute damage for building types: Penning-Rowsell & Chatterton (1977), a canadian article (1984) and a mexican study (2011). They also provide contents and total damage functions. Similarly to was presented in the relative functions analysis, the categories of buildings consider one and two or more stories, presence and absence of basement, as well as particular building types: mobile homes, detached, semi-detached, terrace, flat, bungalow or prefabricated.

Figure 52a shows all the absolute functions; after a first look three families of functions can be differentiated in regard with their absolute damage values. The Penning updated functions (2003) assign higher absolute damages: a first group of detached and bungalow building types, and a second group of semi-detached, prefabricated, flat and terrace. Then the rest of the function (Penning, 1977, Canada and Mexico) constitute a third group of functions. Within the third group, split buildings and buildings with basement show higher damages as well. One storey buildings are more costly than two or more stories.

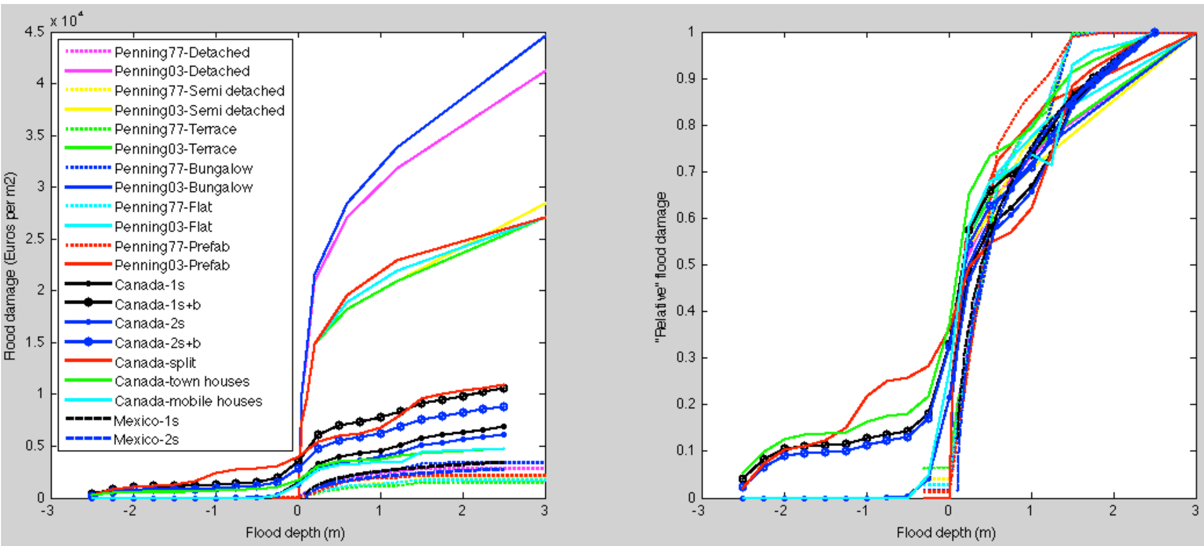

Figure 52: Absolute flood damage functions for building types

However, in figure 52b which shows the distribution of total damage along water depths, illustrated how similar are all the “relative” functions for positive depths, especially at low depths where 55% of total loss is reached at 50cm. The functions that also assign damage at negative depths differ some more. Losses are accounted in negative depths for Canada functions in buildings with basement, town houses and split level houses. Variability of depths for which maximum loss is reached is 25%.

Table 37 shows the variability values corresponding to the “relative” whole set of functions, and only the functions that assign damage at positive depths (in order to neglect the dispersion effect of the functions that give damage at negative depths). Three levels of damage are considered: 10%, 50% and 100%. For all the functions, variabilities range between 43% and 26%, and between 3% and 47% for the positive depths’ functions. Clearly a representative “relative” damage function can be proposed at low depths.

Variability	$H_{10\%}$	$H_{50\%}$	$H_{100\%}$
All functions	43%	9%	25.5%
Functions at positive depths	3%	16%	47%

Table 37: Variabilities for three levels of damage (building structure types)

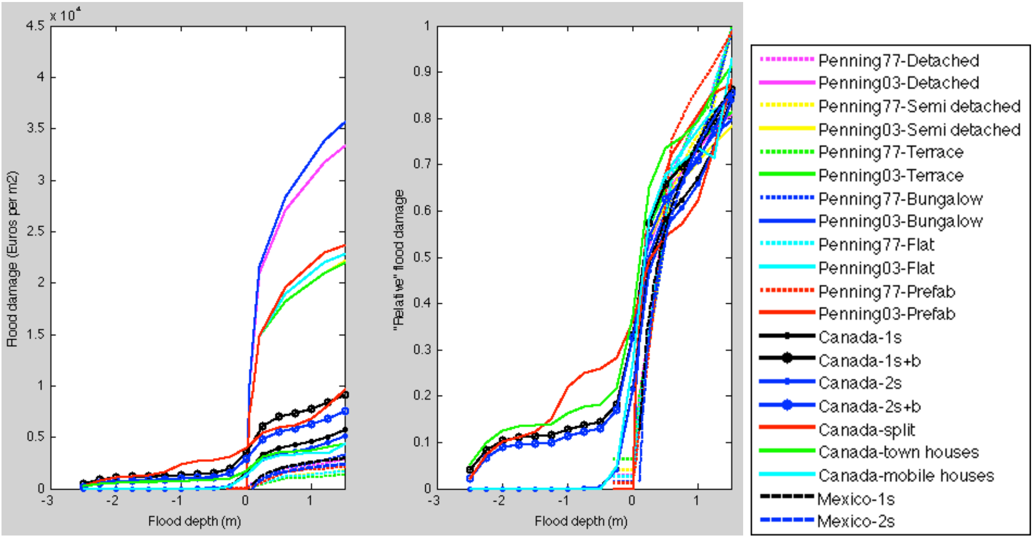

Figure 53: Absolute (a) and "relative" (b) flood functions for building structure types (low depths)

5.4.3 Absolute functions based on building contents

The same sources that provided absolute damages for structural damage, also present some results for contents damage. Moreover, an additional two functions are considered: Badilla (Costa Rica, 2002) who proposed several contents damage functions according to four social status, and a singular case, the website of FloodSmart, that provides a virtual tool that allows the user to evaluate the potential losses for different water depths assuming a number of representative items that usually belong to an average property (they define two functions for two household sizes).

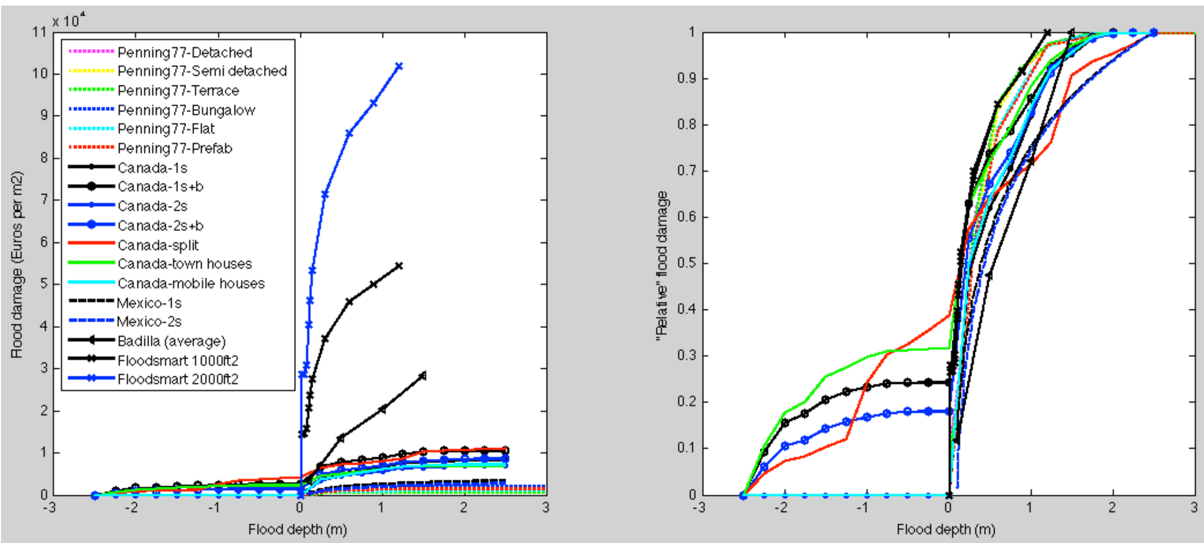

Figure 54: Absolute flood damage functions for contents

In figure 54a, it is seen that the FloodSmart functions only consider water depths under 1.2m; its absolute damage is the highest followed by Badilla. The Canada and Penning functions relatively conserve the same behaviour shown building types although their absolute damages have been reduced; contents are considered as a percentage of structural damage.

Figure 54b shows, similarly to what was observed for structural building damage, that most functions at positive depths are agglutinated at very low depths and then dispersion grows as depths increase, reaching a variability of depths for maximum loss of 22%. Behaviours at negative depths are slightly different assigning more losses than for building types (an average of 30% damage is attributed to negative depths for certain Canada functions).

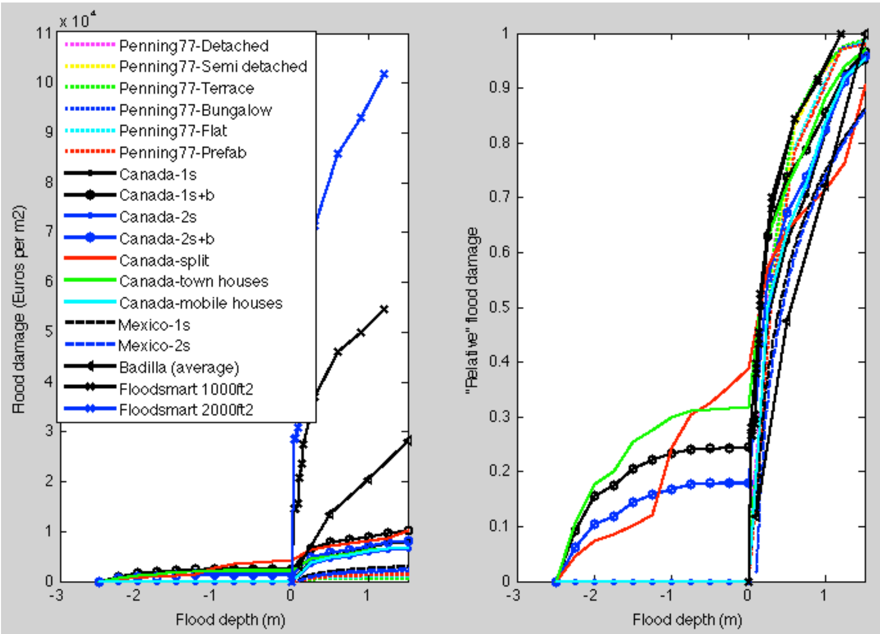

Figure 55: Absolute (a) and "relative" (b) flood functions for building contents (low depths)

Table 38 shows the variability values corresponding to the "relative" whole set of functions, and only the functions that assign damage at positive depths (in order to neglect the dispersion effect of the functions that give damage at negative depths). Three levels of damage are considered: 10%, 50% and 100%. For all the functions, variabilities range between 43% and 32%, and between 3% and 58% for the positive depths' functions. These values are slightly higher than the ones corresponding to building structure types. The same way it happened for building types, clearly a representative "relative" damage function can be proposed at low depths for building contents.

Variability	$H_{10\%}$	$H_{50\%}$	$H_{100\%}$
All functions	43%	7%	32%
Functions at positive depths	3%	13%	58%

Table 38: Variabilities for three levels of damage (building structure types)

5.4.4 Absolute functions based on social status

It is not often but some absolute damage functions take into account the factor of social status. In those cases, different levels of social income are considered so that a particular item (when assessing contents) has different values in each of those social levels. Higher incomes are likely to have a wider variety of belongings and more costly than lower incomes. Both cases may present the same degree of rates of damage given the same water depth although losses (total damage) will be more significant for higher incomes. This is why relative damage functions can not consider the effect of social status since they only measure the susceptibility of items to be more or less damaged, the rates of damage. But in flood risk analysis and during the evaluation of total damage, social status is a factor that can be considered.

Figures 56 (a,b,c) shows three sets of absolute functions corresponding to three sources: Penning-Rowsell & Chatterton (1977), Badilla (2002) and Mexico (2011). While the behaviour of first two functions present linear sections, the Mexico functions are quadratic. All of them seem to describe homothetic functions which differ on the absolute damage function, so the higher the social status the higher the damage.

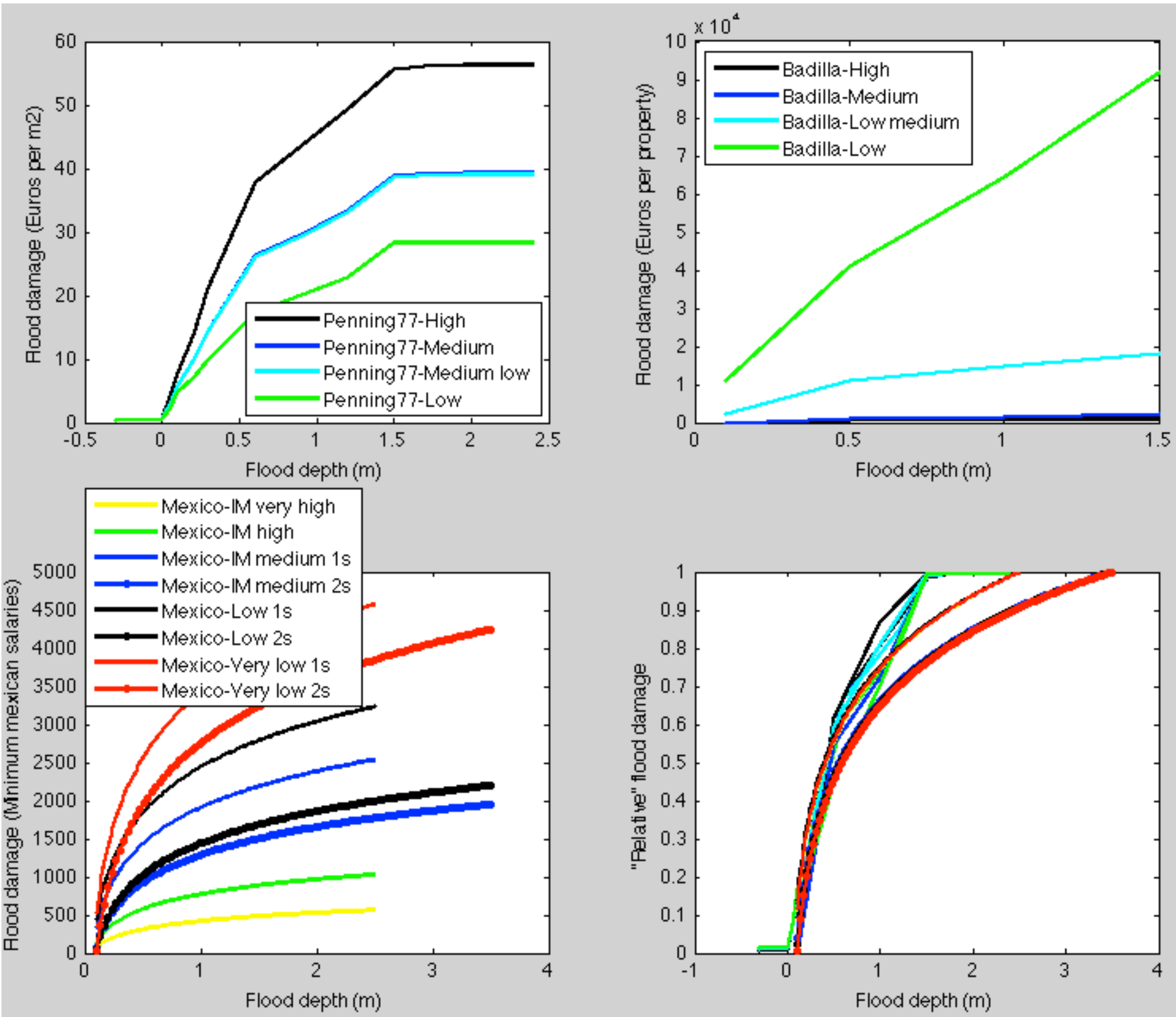

Figure 56: Absolute (a,b,c) and "relative" (d) flood damage functions for social status

Figure 56d, however, demonstrates that the distribution of total damage is practically identical for all the functions at low depths despite the difference of behaviours. For depths over 1.5m the functions are more variable though. Variability of depths for which total damage is reached is of 57%. What can be concluded is that differences correspond to absolute losses, not the behaviour, so a representative “relative” damage function can be defined for social status.

5.4.5 Effect of flood duration on absolute functions

Surely the effect of flood duration makes a difference. The longer an object remains wet, the more damage is likely to be produced. For example, for agricultural land use duration can be a significant factor that means either some of the production can be saved, or it will be lost. Typically durations below 12 hours or over are used and compared. Even though it seems attention should be given to flood duration, absolute functions that include its effect were only found in the blue manual of Penning-Rowsell & Chatterton (1977). Figure 57 (the function updated in 2003) describes which effect has duration in terms of damage savings. For water depths over 20cm the negative increments are quite constant and of 16%.

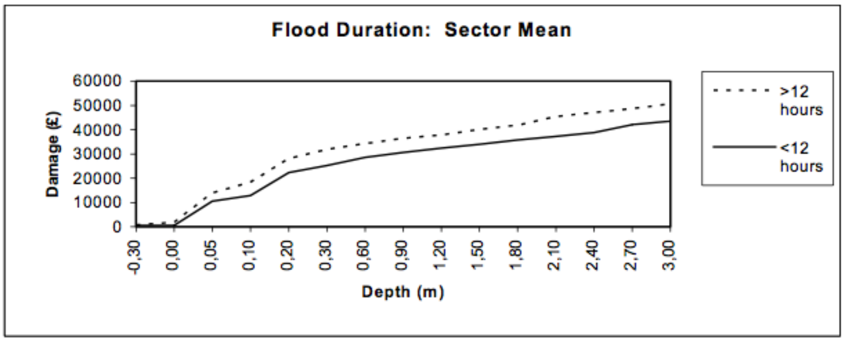

Figure 57: Effect of flood duration on damage functions (Penning-Rowsell et al., 2003)

5.4.6 Discussion of results

In this section, a number of absolute damage functions have been presented regarding vulnerability attributes of land use, building structure types, building contents and social status. It has been proven that the variability of absolute functions in all cases is high, and deduced to be related with the local cost estimation of damage.

Moreover the “relative” damage functions have been produced as the dimensionless absolute functions, which describe how the total damage is distributed among the range of water depths. It has been found that despite the difference of absolute functions, in some cases a representative “relative” damage function can be clearly defined. This happens for building structure types, building contents and social status. As for the land use, this feature is less noticeable although all their functions present a similar behaviour at low depths (high damage - low depth) contrary to what happened in the relative functions.

5.5 The author's own building content absolute damage function

Here the author aims to produce a damage function of her own for property contents taking as reference her dwelling. This has been done in order to compare the results with other damage functions elaborated in a similar way: FloodSmart, Badilla (2002) and Velasco (2013). All these absolute functions were produced by estimating the rates of damage for several representative items due to different inundation water depths, as well as estimating the respective elements at risk's values.

5.5.1 Assumptions

The following assumptions are considered for the production of the relative damage functions for property contents:

- Water levels are referred to the ground level of the one-storey property
- Property size of 90m^2
- Tangible and direct damage only
- Degrees of damage for each water depth are estimated
- Average social status is considered for the estimation of content values (average prices are used)
- Replacement costs (market values) and depreciated values (average remaining values) are used

5.5.2 Procedure and results

The first thing is to gather a relation of the most representative contents or belongings that are usually found in an average property. In this case, the author's household has been taken as reference. References from FloodSmart.gov, Aris (2002) and insurance valuation forms have been considered to produce a list of goods for which damage rates have been estimated.

The next step is to estimate the content values for each item. This can be done following two assumptions: to consider replacement values or depreciated values. The first assumes that damaged items are replaced with new items while the second takes into account the loss of the item's value due to time. In the Floodsite guidelines (2006) for assessing flood damages, it is recommended to use depreciation values or the average remaining values. Its consideration will prevent overestimation of damages.

Here absolute functions have been derived for both cases. Replacement costs have been taken as average market values and depreciated values are considered as an average of 50% for all items.

Figure 58a shows the results of the two functions that have been obtained along with the FloodSmart function, the Badilla function for a medium social status and the Velasco function (damage is expressed in euros at the present time). It can be observed that the majority of these functions resemble the same behaviour according to water depth (over 15cm) except for the Velasco function. They differ in the absolute damage values depending on the values estimation criteria and the region where items are valued. Under 15cm the FloodSmart and the author's functions describe a jump of damage.

The spanish function (Velasco) shows a different behaviour: a more relaxed estimation of losses and with two jumps at 40cm and 80cm, compared to the rest where damage generally increases gradually after the first 15cm of inundation depth.

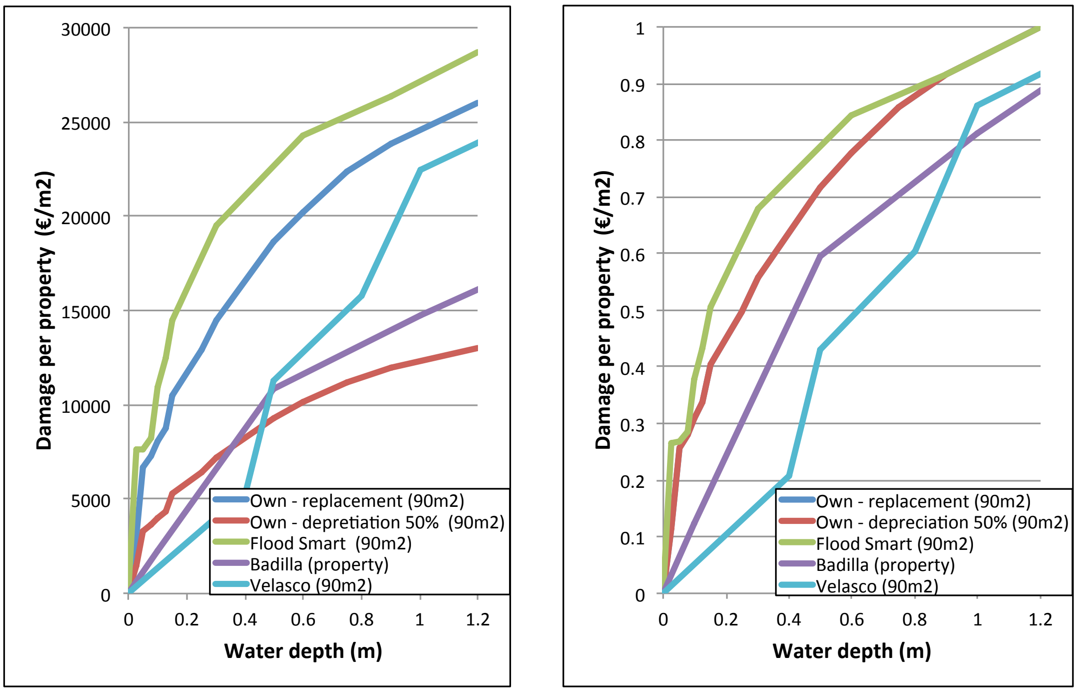

Figure 58: (a) Absolute and (b) "relative" damage functions for building contents

Figure 58b shows the corresponding "relative" functions which present two kind of functions. The FloodSmart and the author's assign 40% of total damage at 15cm, while the Badilla and Velasco assign 40% of total damage around 40cm. Additionally, Velasco assigns 20% of damage when the water raises to 40cm. For some reason important losses are attributed to happen at higher depths.

To conclude, it has been seen that the author's absolute function agrees with the representative curve that was deducted for "relative" damage functions.

6. FLOW VELOCITY

This chapter pretends to give some attention to the damaging effect of velocity and to deduce a coherent and realistic way to modify structural damage functions of buildings so that they include the effect of velocity. Assumptions from previous studies will be taken into account.

6.1 Effect of flow velocity on flood damage

In the context of damage to buildings structure, moving floodwaters generate hydrodynamic and impact forces that depending on the conditions may be able to collapse structures. The importance of these loads lies on the magnitude of flow velocity which determine the dragging forces, its capability to produce erosion of the soil around the foundations and the presence of floating debris which impact can be destructive.

It has been mentioned that flow velocity is considered to be the second most influencing factor on flood damage after water depth. In the flood hazard chapter, most of the flood hazard methodologies that were presented included the flow velocity and/or its product with flood depth (also called intensity) as criteria to define levels of hazard to people and properties. Therefore it is commonly accepted flow velocity aggravates flood consequences, however there still is relatively very little research to describe quantitatively such affirmations. Through literature review most authors refer to the flow velocity damaging effect but abstain from trying to assess its effect because of lack of available data. However, a few references have been found that attempt to predict intensity thresholds for which buildings are likely to experience failure.

6.1.1 Black (1975)

An article from Smith (1994) reported critical combinations of water depth and flow velocity from Black (1975) who stated that above those thresholds residential buildings would collapse. The possibility of failure is also related to the construction material and type of building. No further analyses were made to quantify damages by developing damage functions.

6.1.2 Clausen (1989)

A study of Pistrika and Jonkman (2009) mentioned the Clausen (1989) structural damage criteria for brick and masonry buildings (figure 60) based on empirical data from the case study of a dam failure that flooded the city of Sheffield in 1864. Later on more information was collected of other dam breaks and high-velocity flood events so that initial conclusions could be tested. This criteria was then applied in the after floods of the hurricane Katrina event, and it was found that the relationship between the observed and the predicted damage was poor. An adjustment was done to the criteria to improve its response (the condition of $v>2$m/s was eliminated); it resulted that the prediction was closer but still missed discrete areas of high damage values.

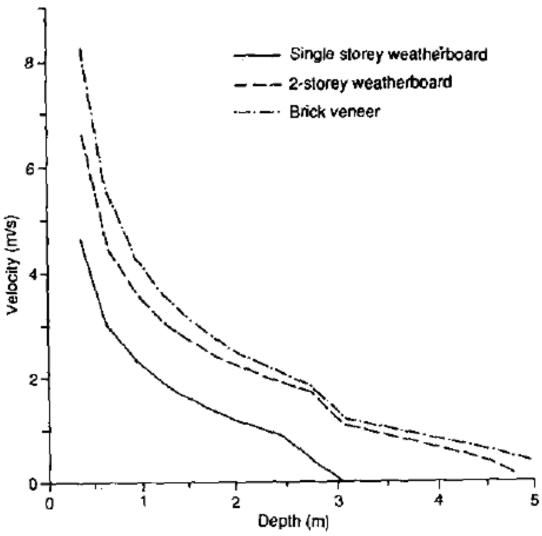

Figure 59: Critical velocity and depth for building failure of residential buildings (Black, 1975)

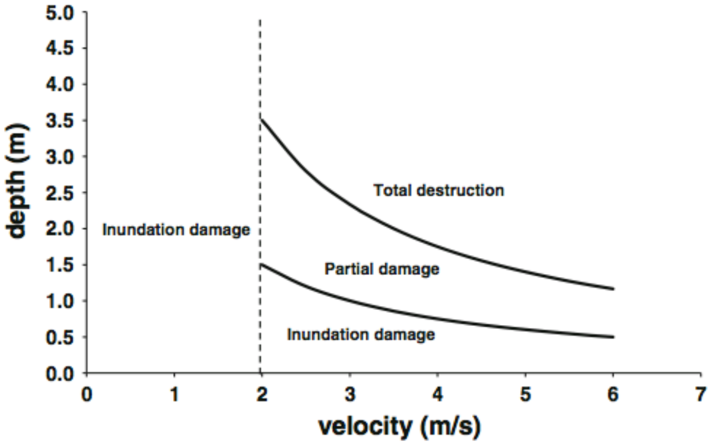

Figure 60: Structural damage criteria for brick and masonry buildings (Clausen 1989)

The author has drawn both of the criteria shown above in figure 61 to compare them. It can be observed that the 'single storey weatherboard' function can be considered as an inferior bound of damage to buildings according to depth and velocity.

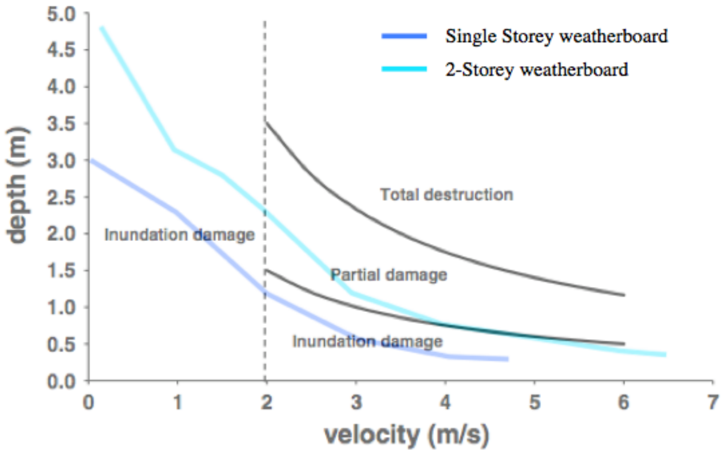

Figure 61: Structural damage and building failure (Clausen 1989, Black 1975)

6.1.3 Kreibich et al. (2009)

A recent study of Kreibich et al. (2009) analyzed how significant is the flow velocity in flood damage modeling, considering both structural damage and absolute monetary loss to residential buildings, road infrastructure and business disruption. Three parameters were selected in order to contemplate the effect of flow velocity: the energy equation (Bernoulli), an indicator of flow force and the flow intensity:

$$\text{Bernoulli's energy equation} = h + v^2/2g \quad [\mathrm{m}] \qquad [6.1]$$

$$\text{Flow force indicator} = h \cdot v^2 \quad [\mathrm{m^3/s^2}] \qquad [6.2]$$

$$\text{Flow intensity} = h \cdot v \quad [\mathrm{m^2/s}] \qquad [6.3]$$

They plotted all the depth-velocity of their database and the three equations with the same contribution of depth and velocity (figure 62); it was obtained that only in 1%, 4% and 7% of cases respectively flow velocity dominated the three parameters over water depth.

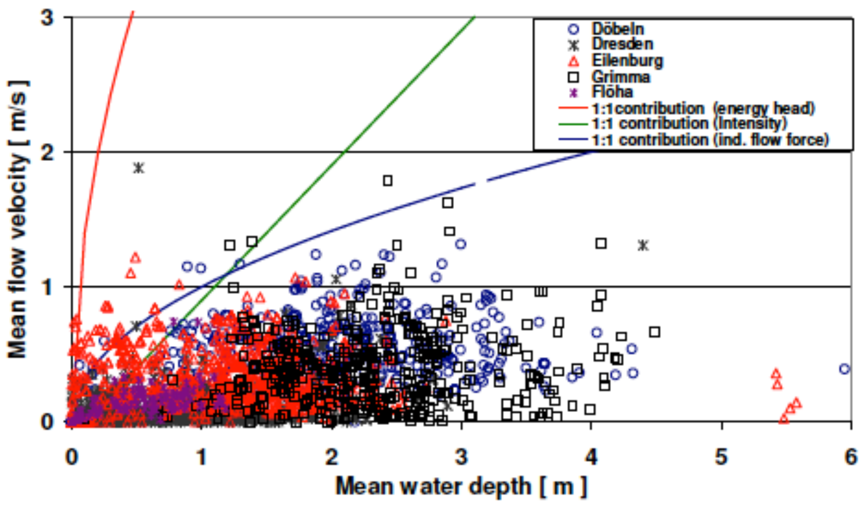

Figure 62: Equal contributions of flow velocity and flood depth

In order to study the influence of flow velocity and the three parameters on flood damage, they defined five categories of damage (D_i) and classified all data into those five groups. They concluded that, on one hand, the impact of flow velocity on structural damage is not independent from water depth, and on the other hand, that correlations between water depth and the energy parameter were high while with the indicators of flow force and flow intensity correlations were weak. Also, it could be deducted a critical lower impact parameter bound for the occurrence of severe structural damage (Kreibich et al., 2009). Past references refer to flood intensity and agree that such critical level is a flow velocity of 2m/s, so that for smaller values collapse should not be expected. But the definition of those critical impact levels needs to differentiate building types. Moreover, it seems that perhaps such critical threshold should refer to the energy parameter since in the context of floods, building collapse results from the combination of water depth and flow velocity (flow velocity alone is minor correlated).

However, a more detailed research should be carried out with larger number of cases and especially higher velocity values (velocities over 2m/s), distinguishing building types in order to derive demonstrated critical bounds.

Regarding absolute monetary loss to residential buildings, only water depth and energy showed significant correlations; flow force and intensity correlations were weak. They also concluded that other factors apparently have greater influence on the monetary flood loss than flow velocity, for example, significant loss reduction can be achieved by early warning, flood experience or private preventive measures.

6.2 Proposed damage function that includes the effect of flow velocity

Given the brief reviews that have been presented regarding the effect of flow velocity, the author pretends to suggest a possible way to modify damage functions so that they include both the effects of water depth and flow velocity. Assumptions are taken from former conclusions about their correlation with damage. It will refer to structural damage of residential buildings and will not differentiate between building materials.

Firstly, it is assumed that water depth and the energy parameter are correlated (as it was found in Kreibich et al., 2009) as well as significant differences of flood damage are shown for both depth and energy. Equation [6.4] gives the relationship between energy, depth and velocity:

$$e = d + \frac{v^2}{2g} = d + \Delta y = d + d(v) \qquad [6.4]$$

The contribution of velocity can be translated in terms of depth as an increment of depth that varies according to the Bernoulli's energy equation. Therefore it should be possible to modify stage-damage functions by considering those increments of depth, for several velocity values. Table 39 shows the increment values for various velocities:

	v=1m/s	v=2m/s	v=3m/s	v=4m/s	v=5m/s
Δy (m)	0.05	0.2	0.46	0.82	1.28

Table 39: Increments of depth for five velocity values

Several relative functions for structural damage of buildings have been selected to test how the application of those increments of depth would affect the original functions. The USACE functions assign damage for some negative depths due to the consequences of hydrostatic forces of rising groundwaters; for those depths the function does not need to be modified since there is no flow velocity underground. So, the functions have been changed by adding the increments of Δy for all positive water depths. Figure 63 illustrates the results for one-storey buildings functions with and without basement.

It can be observed that the functions are translated to the left, therefore assigning more damage compared to the function that considers still waters, with no velocity. At low depths there is a significant impact of the velocity effect while at high depths its effect is less noticeable. This behaviour is dependent on the shape of the original depth-damage function. Figure 64 shows the effect of flow velocity applied to two relative functions (FEMA and Merk) with two distinctive trends.

FEMA's function assigns high rates of damage for low depths while Merk's function assigns lower rates of damage even for higher water depths. Both functions have a more or less constant slope and it is easy to evaluate the variability of the velocity effect in both cases; table 40 shows the results.

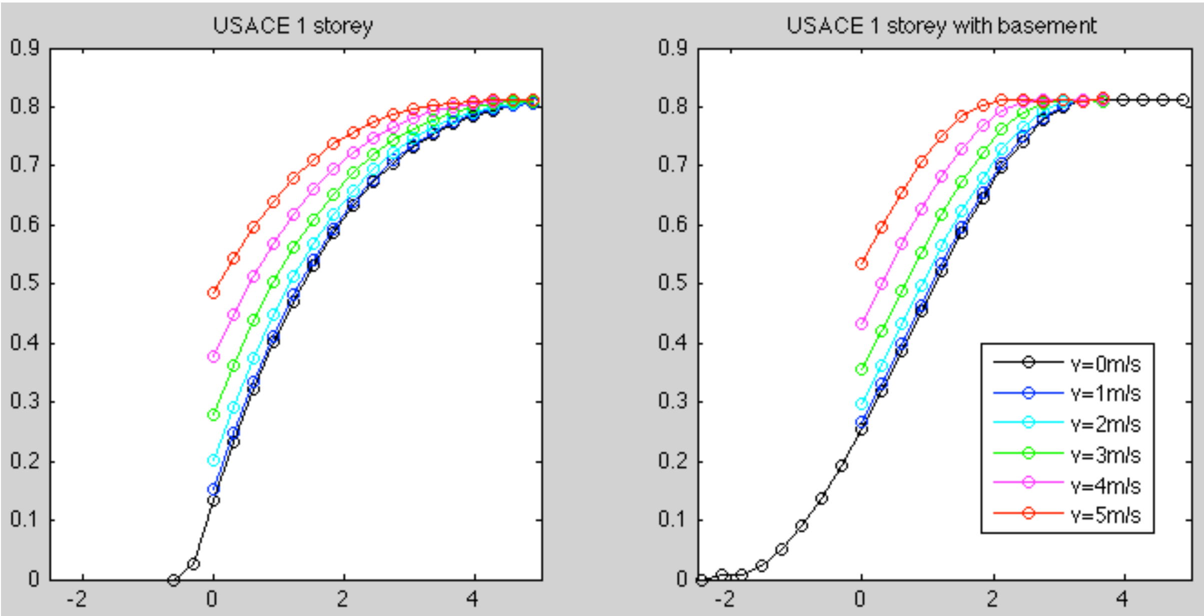

Figure 63: Modified USACE relative damage functions for several velocities (v=1,2,3,4,5 m/s)

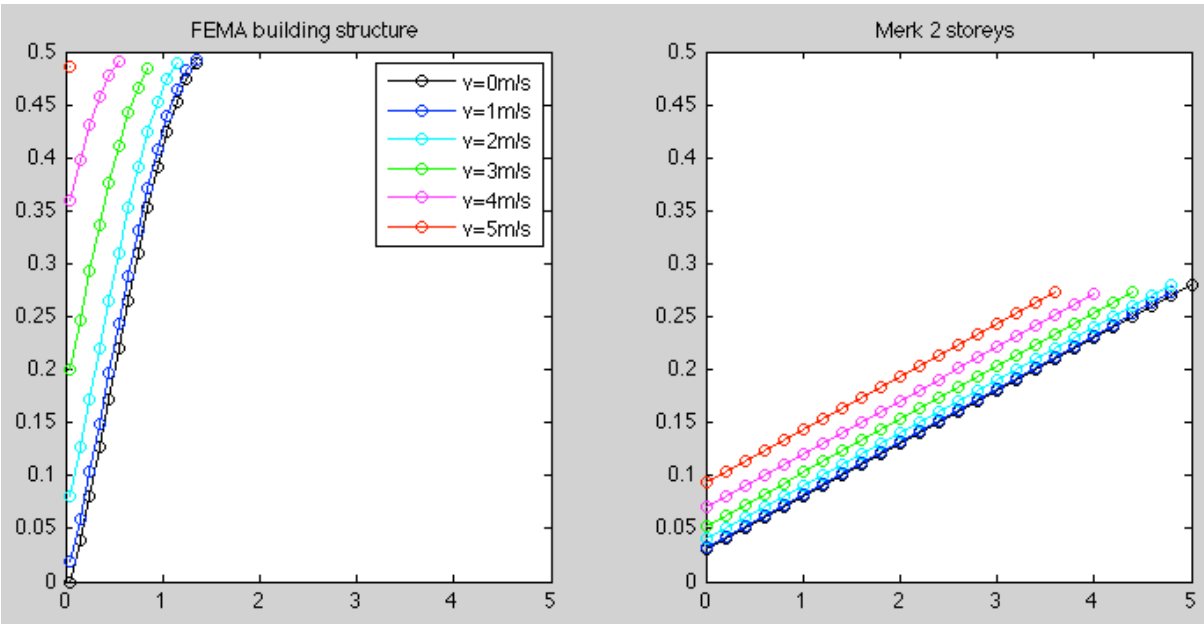

Figure 64: Modified FEMA and Merk damage functions for several velocities (v=1,2,3,4,5 m/s)

	Slope (%/m)	$\Delta Damage$ (%)				
		V=1m/s	V=2m/s	V=3m/s	V=4m/s	V=5m/s
FEMA	42	1.9%	8.2%	20.1%	36%	48.6%
Merk	5	0.25%	1%	2.3%	4.1%	6.4%

Table 40: Increments of depth for five velocity values

It is clear that the quicker damage is estimated by the function to occur (in terms of water depth), the greater is the effect of flow velocity. Also, the increment of damage grows accordingly with higher velocity values and their respective increments of depth.

The final modified function can be determined considering that the effect of velocity from 30cm of the ground level (figure 65). In Kreibich et al. (2009) they suggested that the energy parameter is suitable for reliable forecasting of structural damage to residential buildings above a critical impact level of two meters of energy or water depth. This assumption would leave out considerations regarding the effects of velocity due to hydrodynamic forces. An example of how velocity can be damaging at low depths is that while water depth may not reach the electrical equipment, the presence of rapid waters increase the chance of damaging such equipment with water depths below the equipment's level.

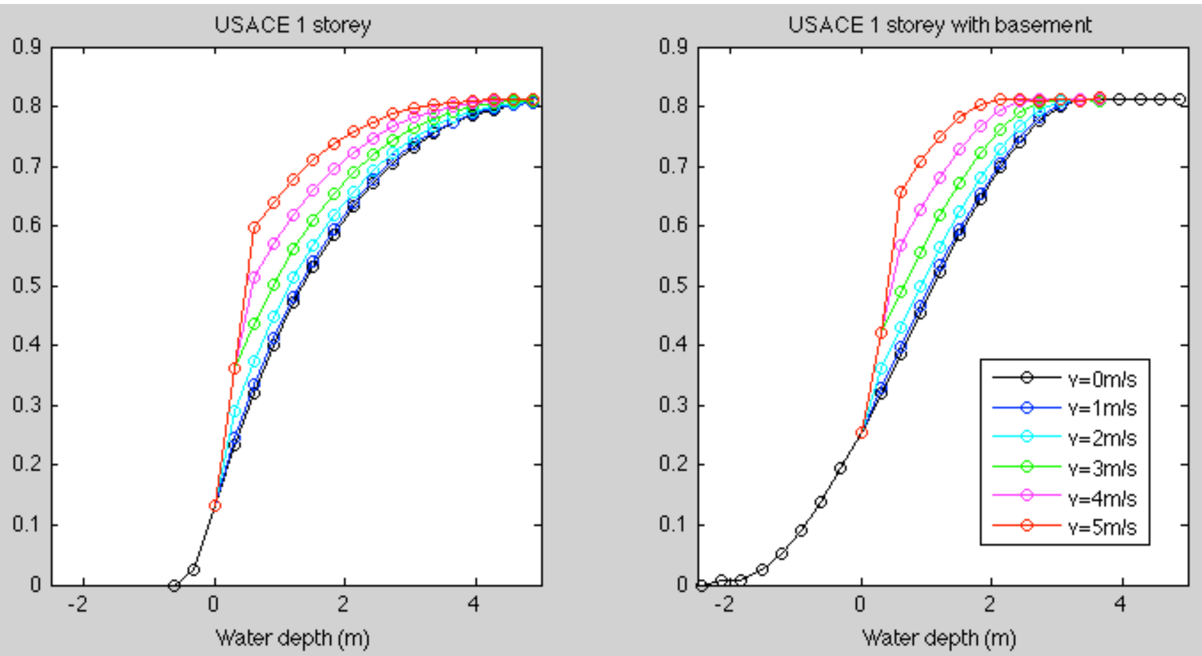

Figure 65: Final modified USACE relative damage functions for several velocities (v=1,2,3,4,5 m/s)

To conclude, it is important to note that there is certainly a need to carry out further and more extensive research of cases affected by high flow velocities in order to establish a bound from which the effect of velocity is significant.

7. CONCLUSIONS

It has become clear that this kind of methodology of damage function estimates and flood risk analysis should be taken into account out during the economic valuation of projects. In this sense, not only flood hazard should be evaluated (what is being done at the moment) but it is necessary to go further and calculate flood risks and the total damage that is consequently originated.

Also, the behaviour of depth-damage functions at low depths is of the most importance in the context of urban areas since damage happens most often within that range of depths; only rare floods experience extreme inundation depths and it has been stated that higher return periods do not influence flood risk as much. For this reason, whether there are significant differences of behaviour at that low stage of depths is important.

Regarding relative damage functions, significant differences of their curvature at low depths have been identified, which reasons are not clear. Even though the majority of functions present high damage rates at low depths, there are some for which damage is not attributed until higher depths. Further research should be undertaken to clarify this question.

From the analysis of the absolute damage functions, high variabilities have been observed regarding the total damage. This should be correct since each function is site-specific developed, and therefore subjected to the local estimation costs. However, a clear representative shape of the “relative” damage functions can be proposed based on the analysis results, and especially for building structure types, building contents and social status. It has been seen that the majority of functions are very similar at low depths, which is the range of depths to be used in urban areas.

In respect to the local damage functions developed in Spain, Patricova (Valencia) and Velasco (Raval, Barcelona), it can be mentioned that further research should be done. Patricova is meant to be for general use when it is very clear that each vulnerability attribute responds differently to damage. Velasco seems close to fit the representative “relative” function for residential areas.

As for the effect of the flow velocity, it is important to incorporate it in the flood damage analysis. For that purpose more studies should be done with high velocities in order to establish modified damage relationships.

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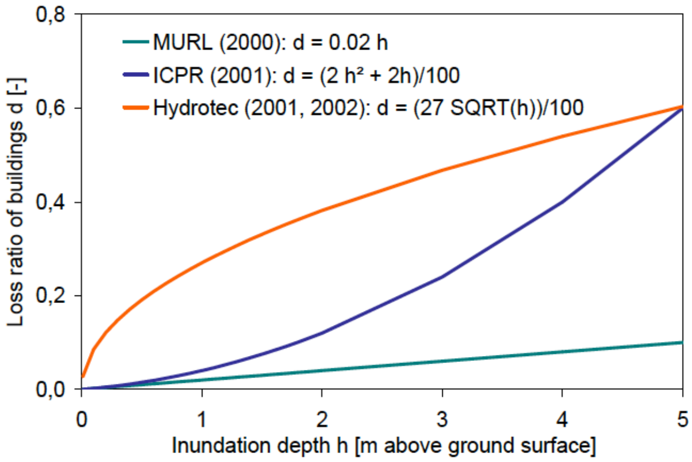
ANNEX 1: Relative damage functions

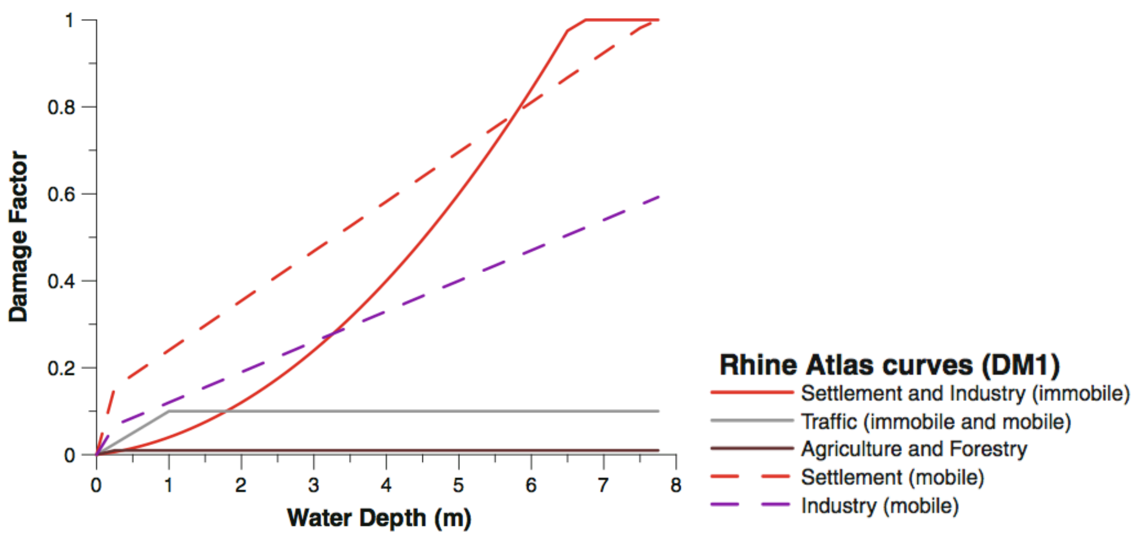
MURL, ICPR, Hydrotec (2000-2002)

These are three damage models often used in Germany. The HOWAS database contains data from nine floods from 1978 until 1994; data is classified into eight sectors: households, infrastructure, service sector, mining and building industry, manufacturing industry, farming buildings, agriculture and undefined. HOWAS database was used to derive damage functions for residential sector: MURL (2000), ICPR (2001) and Hydrotec (2002).



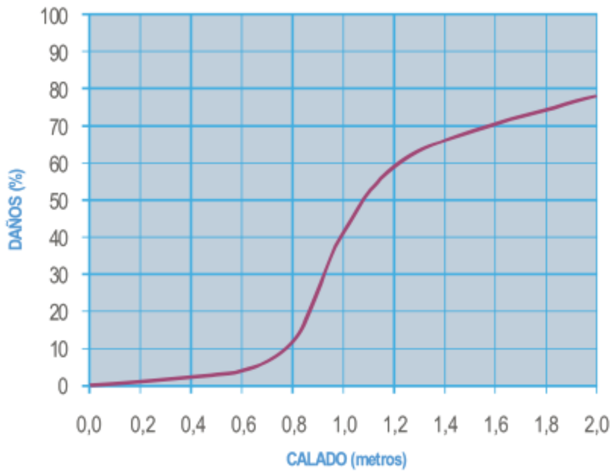
The Rhine Atlas (2001)

A meso-scale damage model that was developed by the International Commission for the Protection of the Rhine (ICPR, 2001). It has been used in low-lying areas in North-Western Europe. Six damage categories are considered to characterize the land cover. For three of them, residential, industry and infrastructure, two damage categories are distinguished: immobile (real estate) and mobile (building goods). Damage to vehicles, indirect damages and costs of emergency services are not considered. Loss calculation is carried out using a number of elements at risk and their values, which are based on market values (not replacement values).



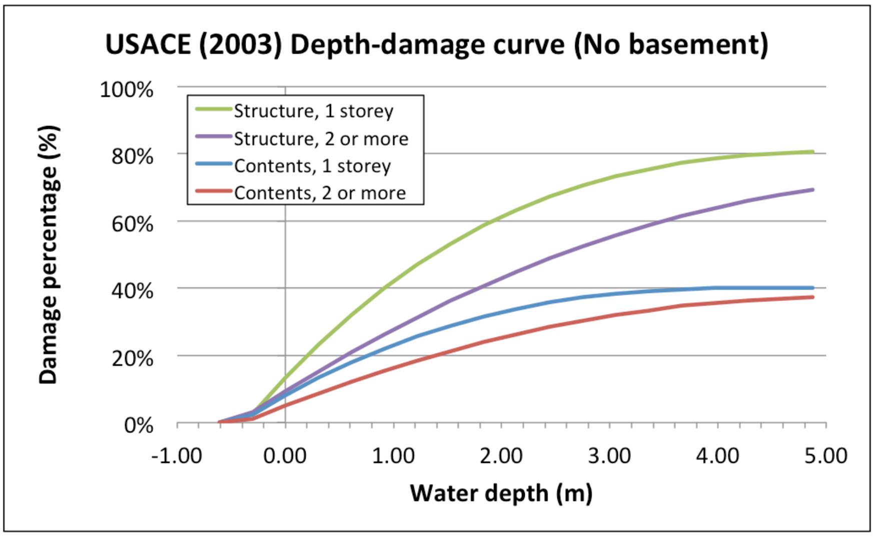
PATRICOVA (Plan de Acción Territorial sobre la prevención del Riesgo de Inundación en la Comunidad Valenciana, 2002)

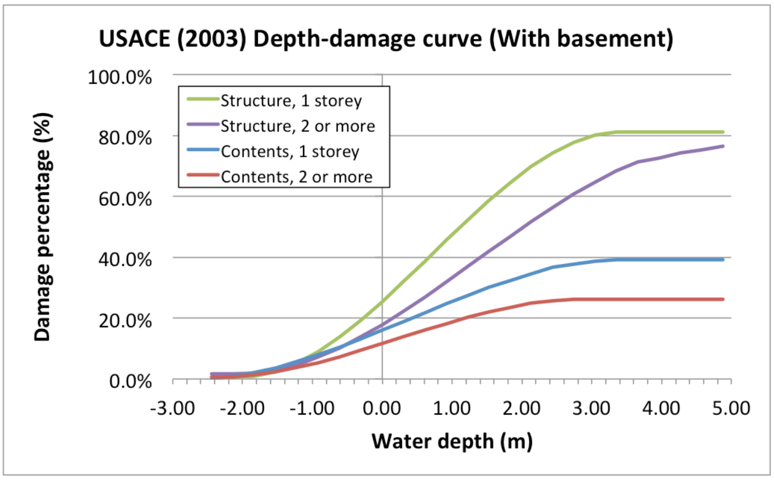
A guidance for the relationship between inundation depth and damages. There is no distinction made for structural and contents damage. They provide a function for general use. The classification of land use (and its density) is supposed to be taken into account through the variety of economic values and types of elements at risk, different for each land use.



USACE (U.S. Army of Corps of Engineers, 2003)

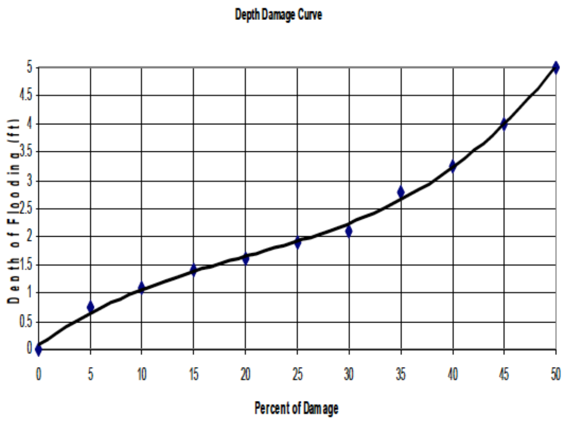
They developed methods for the rapid determination of residential potential flood damages. The Baltimore Office produced synthetic depth-damage data from an analysis of 90000 urban properties in the Susquehanna river basin. The idea was to provide nationally applicable data so that the time consuming properties interviews could be eliminated. They proposed several stage-damage functions (2000, 2003) for single family residential buildings. Relationships are given for building structures and its contents separately, with and without the presence of basement. Structures are divided into two categories: one story and two or more stories. Values for structures need to be estimated; contents damage were modeled as a percentage of the structure value (instead of using content values).

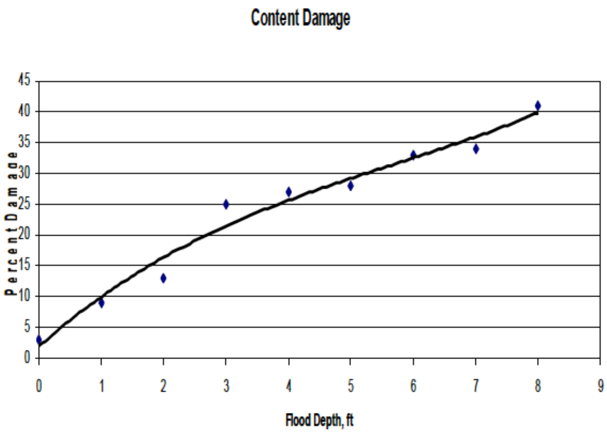




FEMA (Federal Emergency Management Administration)

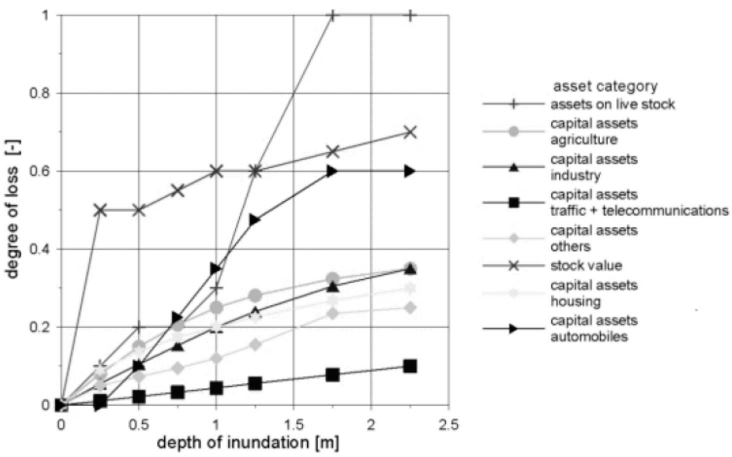
Flood damage functions were developed for buildings, contents and streets. The monetary value for buildings needs to be estimated. The monetary value of contents is assumed to be a percentage of the building structure value (30%).



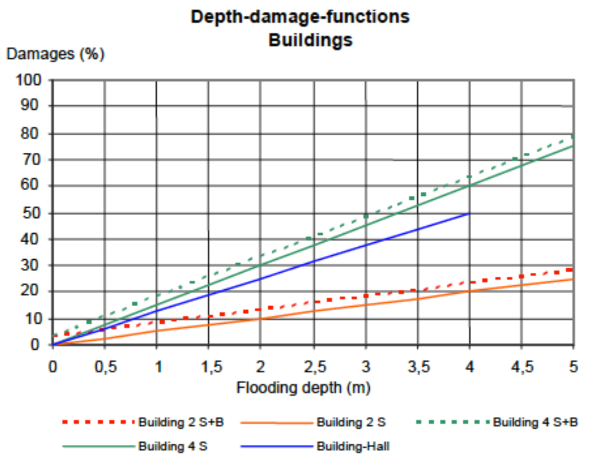


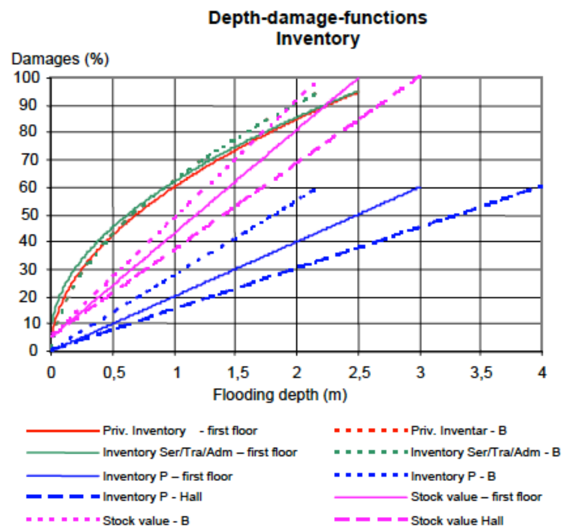
Elsner et al. (2003)

A set of damage functions were presented for several categories of elements at risk. They based on the previous work of Klaus and Schmidtke, 1990.



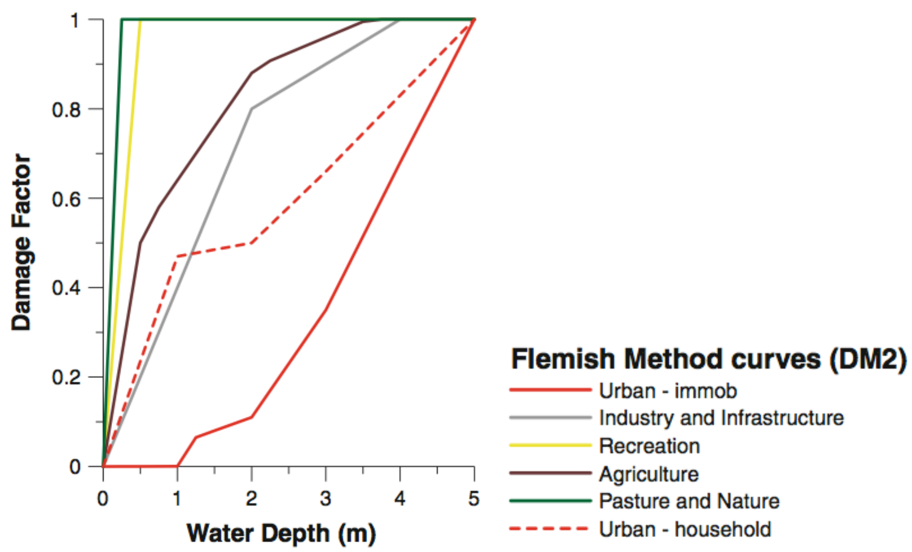
MERK study (Ster et al. 2005)



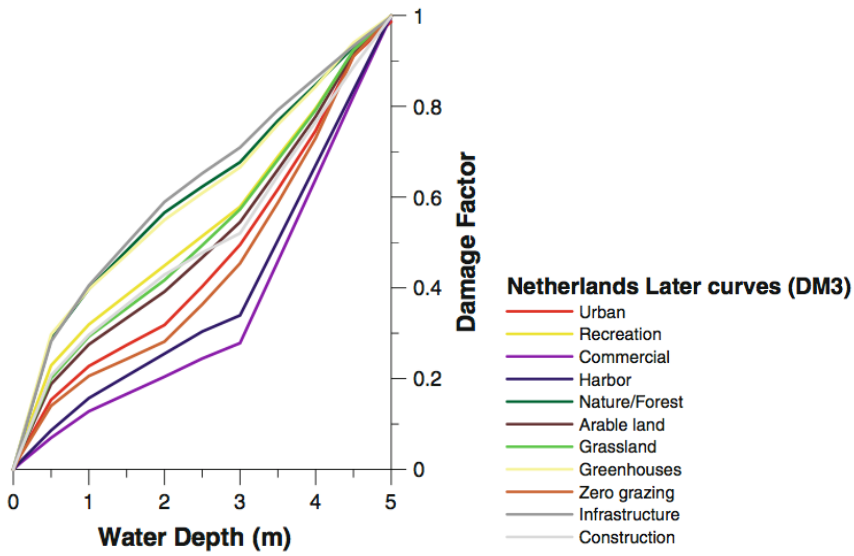


Flemish model (2006)

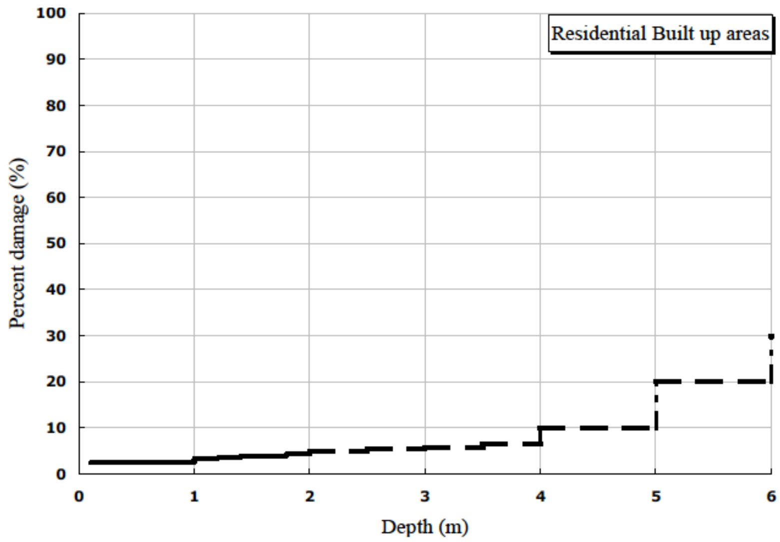
A damage model created for the Flemish Environmental Agency (Vanneuville et al., 2006). It has been employed in low-lying areas in North-Western Europe. The model calculates flood losses based on land use classes and some assets. Eight land use categories and their respective relative functions have been distinguished. Market values are used to derive the value of elements at risk; values are given per square meter except for the residential category which uses a value of 100000€/house (densities of 90, 40 and 10 houses per hectare are considered). Besides direct damages, an additional factor is used to represent indirect damages for some land use classes.



The Netherlands Later (2007)
This damage model was developed by Klijn et al. in 2007 as a derivative of the HIS-SSM (Kok et al., 2005). It distinguishes up to eleven land uses. The damage curves have been derived using a limited amount of damage data and expert judgement and the element values are based on market values. The model also includes in its estimation about 5% of indirect damages (such as business interruption, traffic interruption and loss of crops).

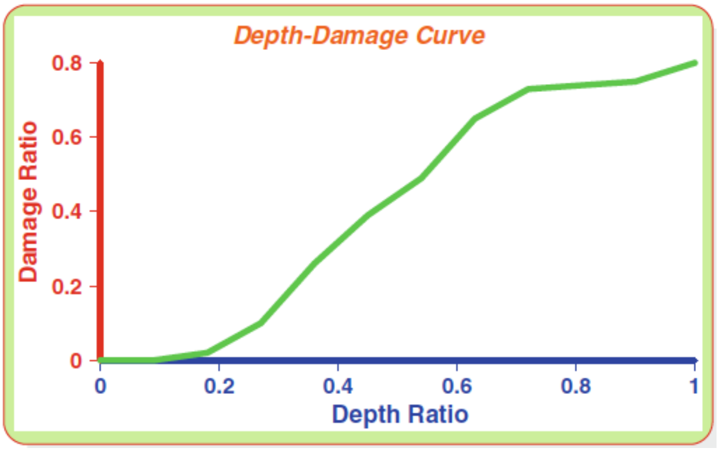


Pistrika (2010)
Based on expert judgement and analysis of past damage functions studies, the author obtained three sets of local depth-damage functions for built-up areas, one of which was the structural damage estimation to single-family, two storey residences made of concrete walls with average quality of structure.



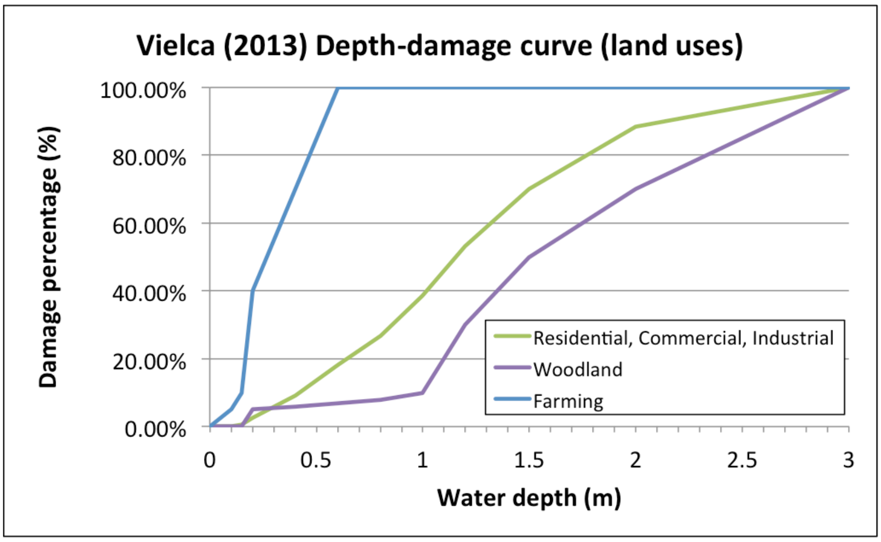
A Taiwan's probabilistic model (2011)

A probabilistic method was developed based on historical events to assess flood risk and be used as a reference for making effective flood risk management strategies. There are four modules, one of them regards to vulnerability and includes a number of vulnerability curves that define relationships between inundation depth and damage. Land use and population distribution are the influencing factors considered. The commercial land use damage function was presented as an example. The depth ratio is the ratio of the inundation depth to the average height of one floor.



VIELCA ingenieros (2013)

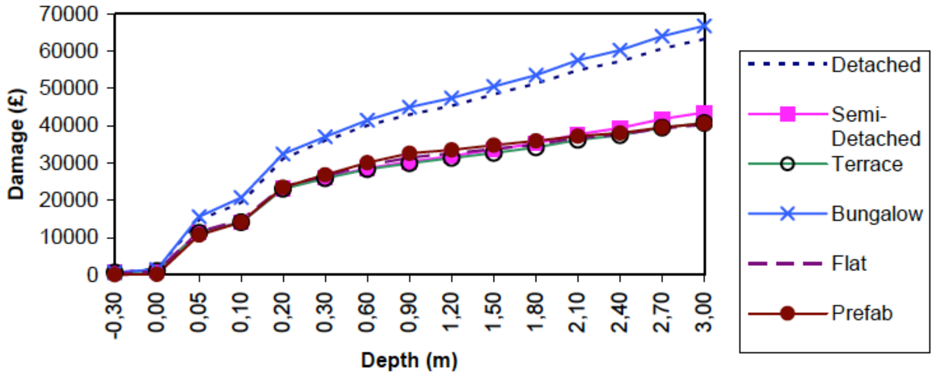
This consultant company developed a set of relative damage functions for a particular urban area. They assumed a common damage function for residential, commercial and industrial land use since heterogeneity of activities would require extensive and detailed work otherwise. For agriculture land use, two categories were distinguished. For residential land use a number of single elements at risk were given a specific function as well.



ANNEX 2: Absolute damage functions

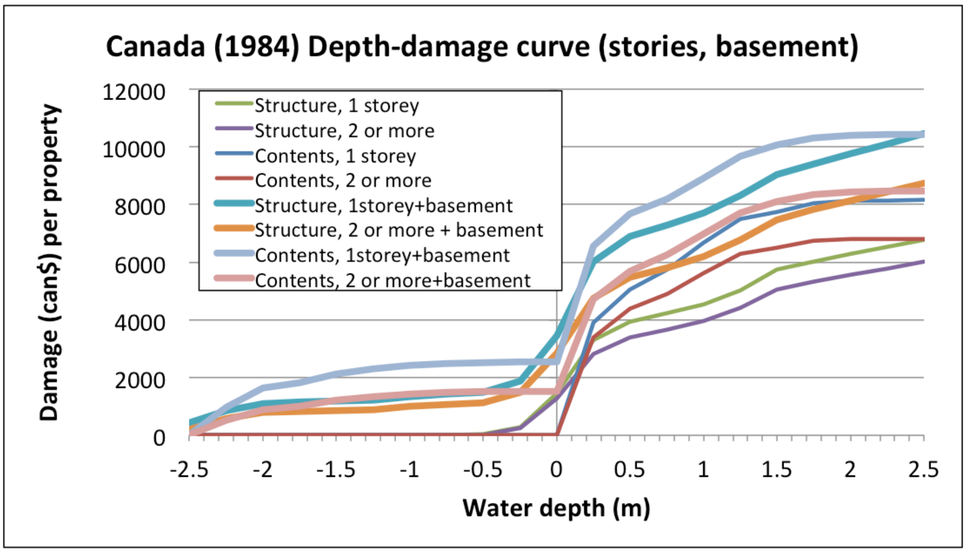
Penning-Rowsell&Chatterton, UK, Blue handbook (1977)

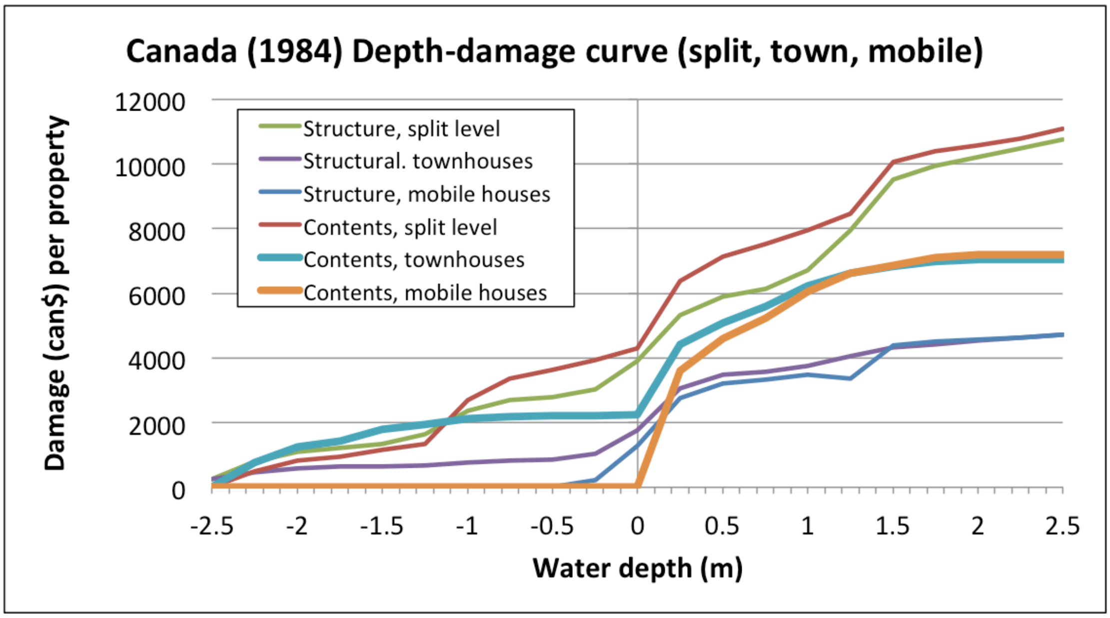
Extensive damage data was collected through surveys, interviews and empirical studies, so that it was possible to produce absolute standard damage functions for several categories: land use, building types, building contents and social status. The effects of flood duration and percentage of damage saved due to early warning times were considered. In 2003 some damage functions were updated considering new market values. Units in pounds per square meter.



McBean et al., Canada (1984)

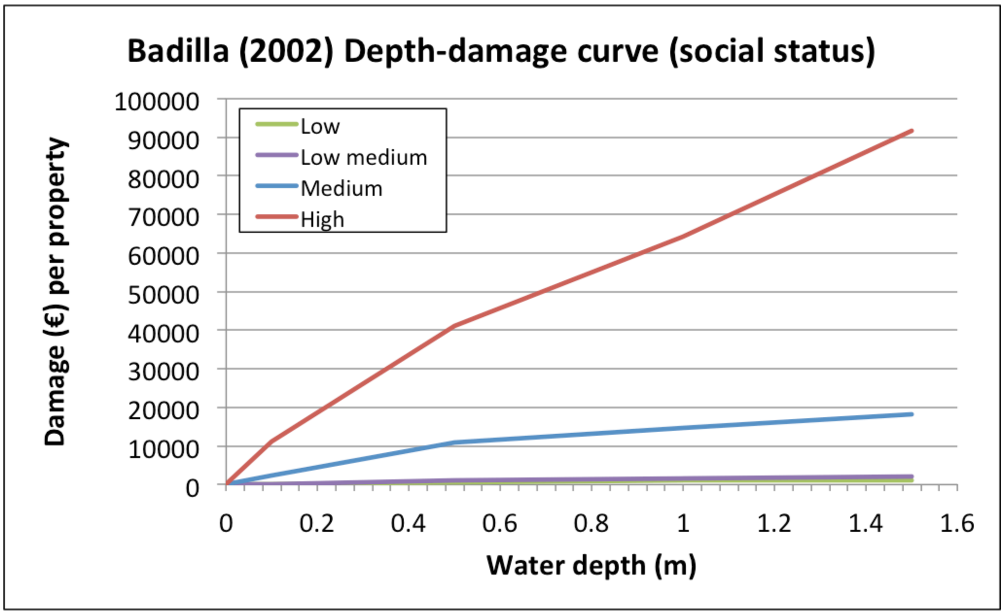
Depth-damage curves were calculated for each residential structure in which an interview was done. Data was divided into categories: total, structural and contents damage. For each category, mean damages were obtained (as well as the minimum and maximum) and used to create damage functions. Properties were classified into five classes. Another sub-category was the presence or absence of basements in properties. Units in canadian dollars per property.





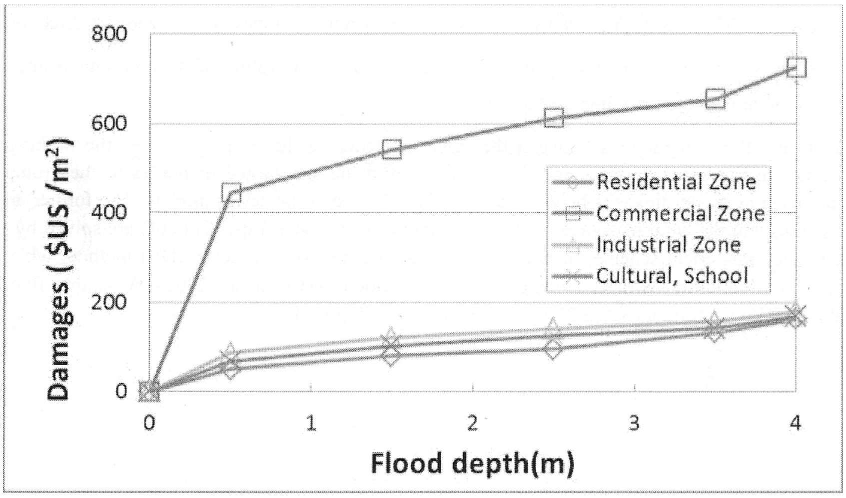
Badilla, Costa Rica (2002)

The author obtained damage functions for single households in urban areas considering four water depth stages and four classes of social status. For each social status, a certain number of representative items were selected. The estimation of the belongings' values depended on the social status as well. Units in euros per property.



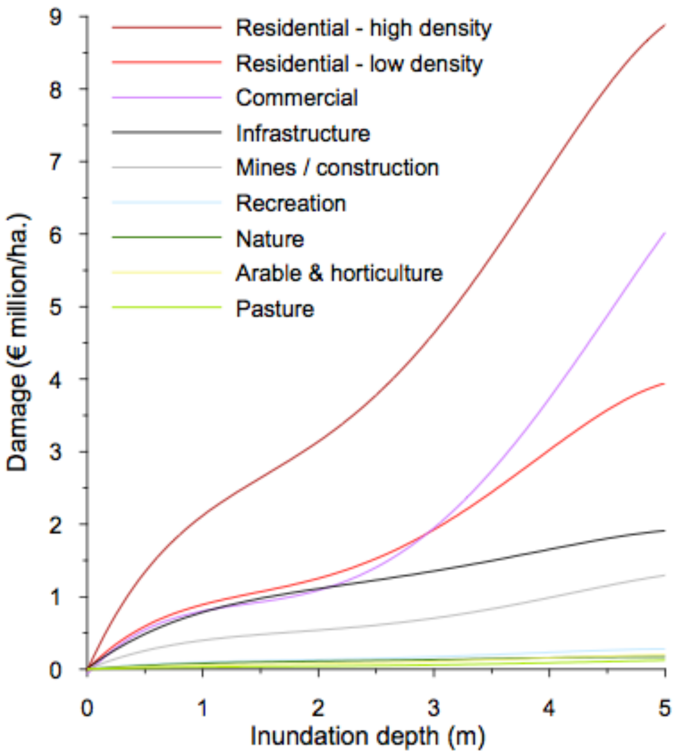
Wang, Taiwan (2003)

Collection of damage functions for diverse activity categories developed in 2003 by Wang and based on flood damage data collected after Typhoon Nari cause a major damage in the Taipei Metropolitan in 2001. Units in dollars per square meter.

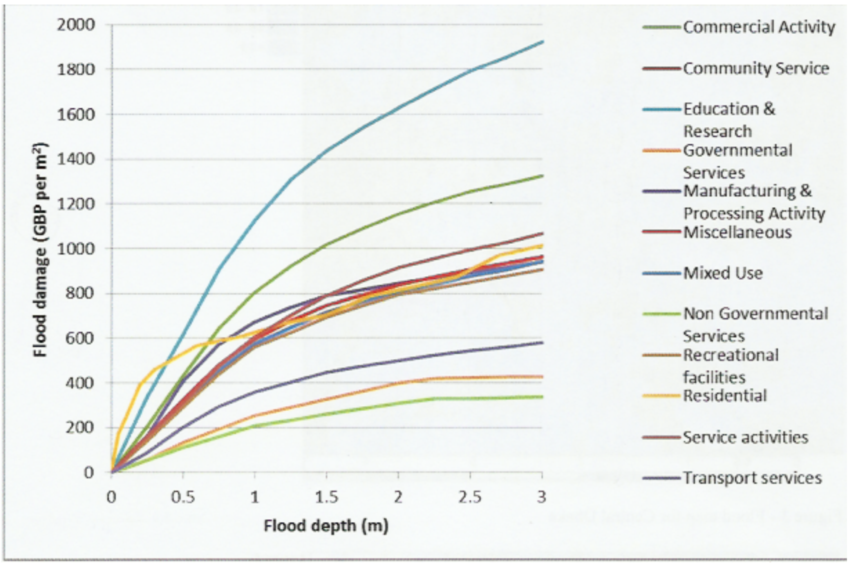


Damage scanner, The Netherlands (2008)

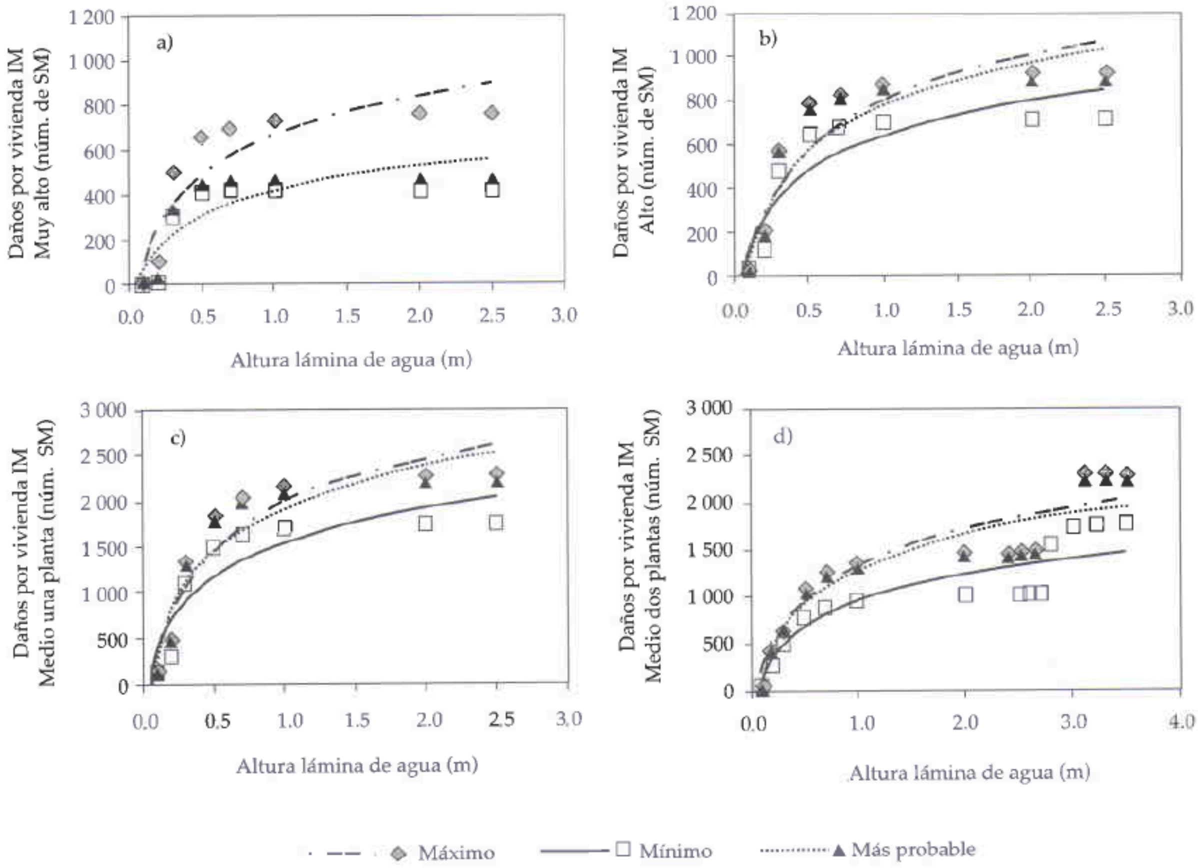
In this model (Aerts et al., 2008; Klijn et al., 2007) damages are not assessed per object but per land use, therefore it is not necessary to collect information about certain objects. This model only requires information about land use maps and inundation maps. The damage values for each land use category were derived from the HIS damage module. A group of nine stage-damage functions were selected. Units in euros per square meter.

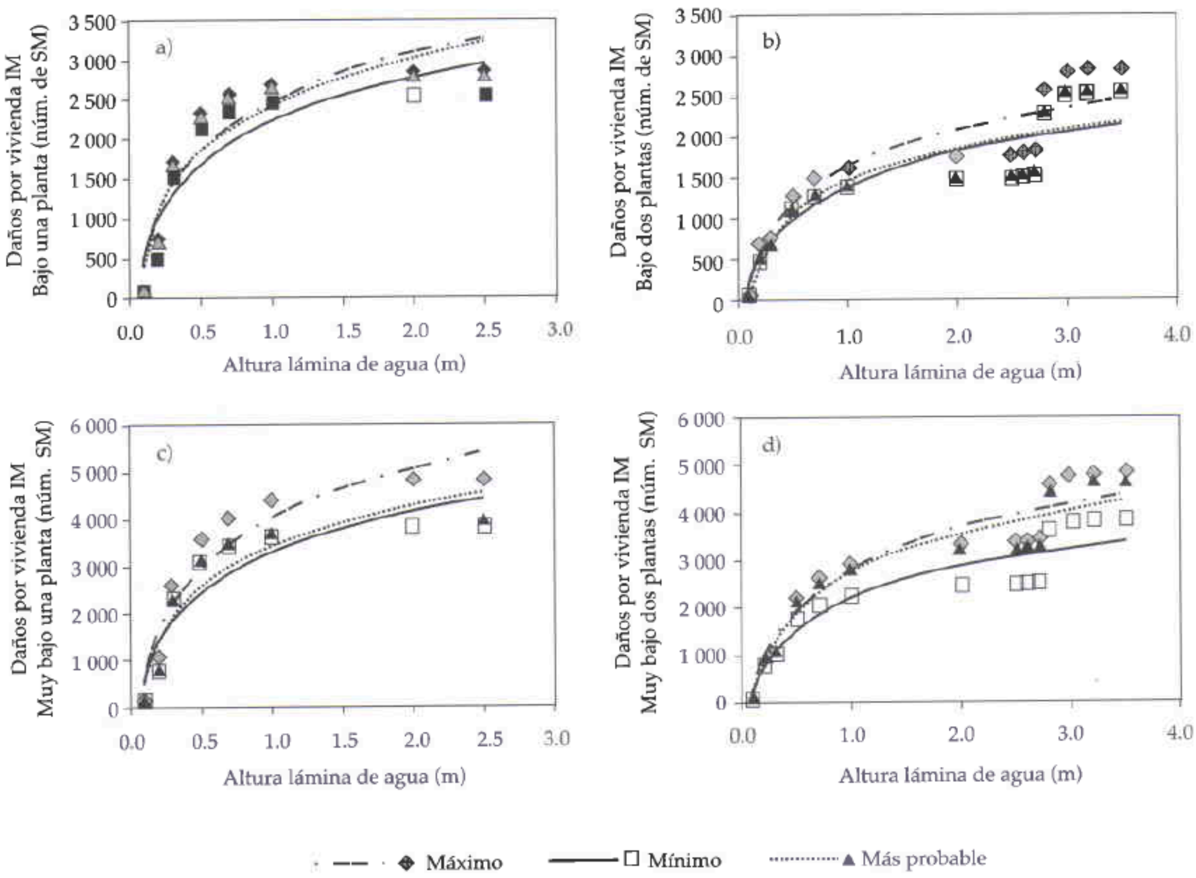


Penning-Rowsell, Multicolored handbook (2010)
These functions were developed in the UK as a further step from the previous work compiled in the blue manual (1977). A relation of ten building-use categories were chosen with their respective depth-damage functions. Units in UK pounds sterling (GBP) per square meter.



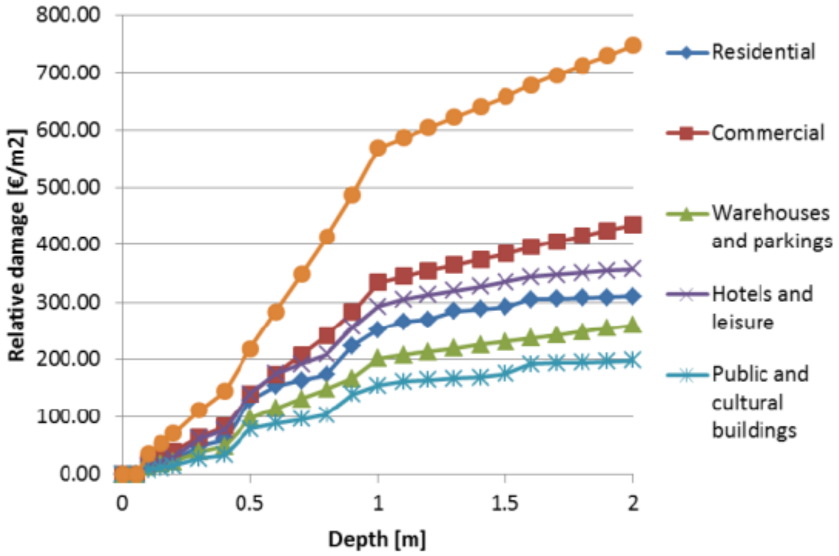
Baró et al., Mexico (2011)
A new method was proposed in this study; damage curves were produced for several urban marginal indexes (very low, low, medium, high and very high). For each marginal index an average property was associated with its belongings and their estimated values. Then percentage of damage for the affected elements at risk was analyzed to produce damage functions, which were presented in numbers of minimum salary.


a)
Daños por vivienda IM
Muy alto (núm. de SM)
Altura lámina de agua (m)
b)
Daños por vivienda IM
Alto (núm. de SM)
Altura lámina de agua (m)
c)
Daños por vivienda IM
Medio una planta (núm. SM)
Altura lámina de agua (m)
d)
Daños por vivienda IM
Medio dos plantas (núm. SM)
Altura lámina de agua (m)
Máximo
Mínimo
Más probable


a)
Daños por vivienda IM
Bajo una planta (núm. de SM)
Altura lámina de agua (m)
b)
Daños por vivienda IM
Bajo dos plantas (núm. de SM)
Altura lámina de agua (m)
c)
Daños por vivienda IM
Muy bajo una planta (núm. SM)
Altura lámina de agua (m)
d)
Daños por vivienda IM
Muy bajo dos plantas (núm. SM)
Altura lámina de agua (m)
Máximo
Mínimo
Más probable

Velasco et al. (2013)

A recent work carried out in the Raval District of Barcelona (Spain) tried to assess expected damages due to floods while considering climate change impacts. For that purpose, depth damage curves were developed and five types of land use were differentiated: residential, commercial, warehouses and parkings, hotels and leisure and public and cultural building. Units in euros per square meter.



Floodsmart.gov

The american website of the National Flood Insurance Program, FloodSmart.gov, provides an easy an quick way to estimate the total average losses of flooding given the user's particular scenario. Losses are given for a single property; two different sizes can be chosen. Within the calculation the model takes into account a number of assets that represent the contents of an average household, and then estimate to which degree they are damaged for every flood height. Units in dollars per property.