Urban flood impact assessment: A state-of-the-art review

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Flooding can cause major disruptions in cities, and lead to significant impacts on people, the economy and on the environment. These impacts may be exacerbated by climate and socio-economic changes. Resilience thinking has become an important way for city planners and decision makers to manage flood risks.

Despite different definitions of resilience, a consistent theme is that flood resilient cities are impacted less by extreme flood events. Therefore, flood risk professionals and planners need to understand flood impacts to build flood resilient cities. This paper presents a state-of-the-art literature review on flood impact assessment in urban areas, detailing their application, and their limitations. It describes both techniques for dealing with individual categories of impacts, as well as methodologies for integrating them. The paper will also identify future avenues for progress in improving the techniques.

Keywords: Urban flooding; Resilience; Impact assessment; ; Urban water management.

Introduction

Cities are social hubs, and life in cities is reliant on a number of services and functions such as energy and water provision, transport links, housing, education and employment. Urban flooding can cause significant disruption to these services, and wider impacts on the population. There have been many recent notable examples, including flooding in Brisbane in January 2011, widespread flooding in Thailand that inundated Bangkok during the 2011 monsoon season, and flash flooding caused by extreme rainfall in Beijing in July 2012.

A number of trends suggest that the problem of urban flooding is likely to increase. The first of these is the growing number of people that live in cities; the world's population is becoming increasingly urban. The United Nations (UN) recently reported that the world's population living in urban areas has overtaken the rural population, and it is projected that the world's urban population will grow both in absolute terms, and as a fraction of a growing global population (United Nations Department of Economic and Social Affairs/Population Division 2012). Between 2011 and 2050, the world population is projected to increase by 2.3 billion, from 7.0 billion to 9.3 billion. At the same time, the population living in urban areas is projected to increase from 3.6 billion in 2011, to 6.3 billion in 2050. This represents a growth from 51% to 68% of the global population. As more people move to the cities they inevitably turn green areas into impervious areas, increasing urban runoff, and as more people live in densely populated urban areas, often situated on flood plains and low-lying coastal areas, their exposure to flood hazards is increased.

The second trend arises from the possibility for climate change to lead to more extreme rainfall. Some studies have already shown statistically significant trends in extreme rainfall in the past century in Denmark (Arnbjerg-Nielsen 2006), and in North America (Peterson *et al.* 2008). However, these trends are variable both across temporal and spatial scales. As for future projections, a Special Report of the Intergovernmental Panel on Climate Change reports that “it is likely that the frequency of heavy precipitation … will increase in the 21st century over many areas on the globe”, although recent analyses have “highlight[ed] fairly large uncertainties and model biases” (Field *et al.* 2012).

If cities are to become more resilient to flooding, innovative and adaptable strategies and measures are needed. Although there are many different concepts of resilience, most authors are in agreement that a flood resilient city will have low flood consequences if and when flooding occurs. Therefore, to build flood resilience, planners need to understand the impacts of flooding. In the short term, these can include the risk to life, property damage, and failure of infrastructure such as transport and electricity networks. In the short to medium term, contaminated flood waters increase the risk of the spread of diseases such as diarrhoea, and stagnant water provide breeding grounds for mosquitoes, which can increase the risk of malaria and dengue fever. In the longer term, the disruption caused by flooding can have economic consequences that extend beyond the immediately affected region. For example, Thailand’s Gross Domestic Product grew by only 0.1% in 2011 (following the severe flood disaster), compared to 7.8% in 2010, and 6.5% in 2012 (GDP fell in the 4th quarter of 2011 by an annualised rate of 9.0%) (Office of the National Economic and Social Development Board 2012).

This article presents a state-of-the-art literature review on flood impact assessment, focusing specifically on urban flooding. Urban flooding can include pluvial, fluvial, groundwater and coastal flooding. Pluvial flooding results from urban drainage that is in adequate with respect to the rainfall in an urban area. Fluvial flooding results from the overtopping or bypassing of flood defences adjacent to rivers. Groundwater flooding results from high groundwater levels, and coastal flooding is due to tidal surges and waves (Saul *et al*. 2011). As a result, categories such as impacts on agriculture will be ignored (although agriculture is not always absent from urban areas, its contribution to overall impacts is considerably less than other categories). Examples of theapplication of flood impact assessment techniques will be described, along with their limitations. This survey builds upon previous reviews and brings them up to date, such as those undertaken as part of the FLOODSite project (Messner *et al.* 2007), but also aims to cover all the impacts of flooding, such as the intangible impacts, which have been neglected to some extent in earlier work (Merz *et al.* 2010). This review will focus on *ex-ante* assessment techniques, which produce estimates of expected damages (in contrast to *ex-post* assessments, which are based on observed damages).

The relationship between flood impact assessment and resilience

Flood impact assessments can serve a variety of purposes. For example, local or national governments use them for decision making and risk management, so that resources can be allocated to finance structural and non-structural flood mitigation measures. Insurance and reinsurance companies use flood impact assessments to understand the value of assets at risk, and to price their policies accordingly (Vetere Arellano *et al.* 2003). The diversity of the purposes of flood impact assessments, combined with differences in the availability of data and access to resources mean that there are many different flood impact assessment techniques (Messner *et al.* 2007). In the European Funded Collaborative Research on Flood Resilience in Urban Areas (CORFU), flood impact assessments have an important role in studies that aim to improve urban flood resilience (Djordjević *et al.* 2011).

Resilience is a concept that has emerged as a way to understand how systems prepare for, respond to, and recover from shocks (Zhou *et al.* 2010). Many practitioners consider increasing or building resilience an important objective in flood risk management, and resilience is often described as a desirable attribute for cities (Godschalk 2003). However, several challenges remain for transforming the concept of resilience into an operational tool that can be used for policy and management purposes.

The first challenge is to provide a clear understanding of the concept, in the context of urban flooding. There is an extensive literature on the development and application of the concept of resilience (Rose 2004, Gallopin 2006, Manyena 2006, Zhou *et al.* 2010). Resilience originally became prominent in ecology, where Holling (1973) defined it as a measure of the ability of an ecological system to absorb changes and persist. This multi-equilibrium concept has been contrasted with engineering resilience, which relates to the stability near a unique equilibrium, and where the resistance to disturbance and speed of return are used to measure it (Holling 1996). Variations on this definition of engineering resilience have become prominent in water resources systems analysis (Hashimoto *et al.* 1982).

Adger (2000) extended this concept to social systems, while recognition of the links between social and ecological systems has led to the growth of research on social-ecological resilience (Gallopin 2006).

The fields of natural hazards, disaster risk reduction, and flood risk management have adopted some of these concepts. Gersonius (2008) specified resilience in more concrete ways to identify the system attributes that are to be resilient, and to what kind of disturbances. It was argued that flood resilience incorporates four capacities; to avoid damage through the implementation of structural measures, to reduce damage in the case of a flood that exceeds a desired threshold, to recover quickly to the same or an equivalent state, and to adapt to an uncertain future. This echoes the definition developed by the United Nations International Strategy for Disaster Reduction (UNISDR 2011), and therefore, we adopt herein the definition that a flood resilient city is one with the ability to "resist, absorb, accommodate to and recover from the effects of a flood hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions". The development of flood resilience will require an understanding of how cities respond to flooding across varying spatial and temporal scales (Zevenbergen *et al.* 2008).

The second challenge is to quantify flood resilience, which links naturally with the consequences of flooding and therefore impact assessment. Two broad techniques can be found in the literature. An indirect method to quantify resilience is to use indicators that measure the characteristics of a system, which may lead to the system being resilient. One example is the Disaster Resilience of Place (DROP) model, developed and applied in the US, which uses several indicators to explore the dimensions of resilience: The dimensions of resilience are considered to include social, economic, institutional, infrastructure, and community capital factors. For example, social resilience was quantified by variables that included the percentage of non-elderly residents and the percentage of the population with access to a vehicle (Cutter *et al.* 2008, 2010). Similarly, Prashar *et al.* (2012) developed a Climate Disaster Resilience Index to investigate the resilience of different districts in Delhi, India to disaster risks, covering five dimensions.

In contrast, some authors have applied direct measures of resilience, which attempt to quantify how the system of interest responds to extreme events. Bruneau *et al.* (2003) argued that a resilient system would have reduced failure probabilities, reduced consequences from failures, and a reduced time to recovery, and used a system function to quantify these three properties. de Bruijn (2004) considered resilience and resistance to be distinct concepts, where resilience is the ease with which a system can recover from floods, and resistance of the ability of a system to prevent floods. The resilience of a lowland river system to flooding was quantified using three parameters: the amplitude of the reaction to flood waves, using the expected annual damage and the expected average annual number of casualties; the graduality of the increase of the impacts with increasingly severe flood waves, using a function of the slope of the discharge-damage relationship; and the recovery rate, using a combined set of indicators related to physical, economic and social factors that speed up recovery. The resistance to flooding is quantified by the reaction threshold, or the maximum flood discharge before flooding occurs. In the context of urban flooding, this can be the design standard for any flood defences or drainage infrastructure. The approach of de Bruijn (2004) suggests that there is some disagreement as to whether resistance is part of resilience, as per the UNISDR definition, or a distinct concept.

Both the approach of Bruneau *et al.* (2003) and de Bruijn (2004) consider that a resilient city will observe low flood impacts, in common with many other resilience approaches. It is thus, necessary to classify and quantify flood impacts in a consistent framework.

Understanding the impacts of flooding

Flood impacts are typically classified using two criteria. The first criterion distinguishes between tangible and intangible impacts. Tangible impacts are those that can be readily quantified in monetary terms (Smith and Ward 1998). These include the damage to property or the loss of profits if a business is disrupted. An alternative expression of this definition is whether a market exists for the asset in question (Bureau of Transport

Economics 2001). This is contrasted with intangible impacts, which cannot be readily quantified in monetary terms. Examples of intangible impacts include the loss of life, the negative impact on the mental well-being, and impacts on the environment, such as the loss of recreational environments, and contamination.

The second common distinction is between direct and indirect damage. A direct damage is defined as any loss that is caused by the immediate physical contact of flood water with humans, property and the environment. In contrast, indirect damages are induced by the direct impacts and may occur – in space or time – beyond the immediate limits of the flood event. Jonkman *et al.* (2008a) referred to direct losses as occurring within the flooded area, and indirect damage occurring outside of the flooded area. Messner *et al.* (2007) stated that direct damage is usually measured as a damage to stock values, whereas an indirect damage relates to interruptions to flows and linkages, and therefore as the loss of flow values.

There is some disagreement in the literature as to the precise nature of the distinction between direct and indirect losses. Some authors distinguish between direct losses (as already defined) and primary and secondary indirect losses. In the European funded FLOODSite project, the definition of indirect losses included both the loss of production by companies directly affected by the flooding, and the induced production losses of their suppliers and customers (Messner *et al.* 2007). Van der Veen (2003) maintained this definition, but distinguishes between primary and secondary indirect losses, and defines primary indirect losses as business interruption costs that relate specifically to flooded businesses, whereas secondary indirect losses refer to multipliers in the economy. In contrast Rose and Lim (2002) define losses that "pertain to production in businesses damaged by the hazard itself" as direct losses. This difference of opinion was recognised in the European funded FP7 CONHAZ project, and placed business interruption costs as a separate category to both direct and indirect costs (Meyer *et al.* 2013).

Some authors have made further distinctions, to include primary, secondary, and even tertiary impacts to describe impacts at greater and greater causal steps removed from the immediate inundation (Smith and Ward 1998, Parker 2000). However, few authors have adopted these distinctions, and it is not clear how these may differ from the distinction between direct and indirect losses.

Meyer *et al.* (2013) also included the costs of risk mitigation as an additional class of costs. However, in this review, the view is taken that these costs should be considered in the cost-effectiveness of different resilience measures.

Impacts on infrastructure can be classified as both direct and indirect. For example, floodwaters can directly damage infrastructure elements such as electricity substations or railway links. Failure of these elements can lead to indirect impacts in the wider system. Research on the vulnerability of infrastructure is relatively limited, although there is a growing body of literature on the topic (e.g. Rogers *et al.* 2012)). Infrastructure elements are typically highly specialised, and infrastructure networks are complex. As a result, in this review the impacts of flooding on infrastructure will be described separately.

Within this review, the following cost categories are described:

- Direct tangible impacts
- Business interruption and indirect tangible impacts
- Impacts on infrastructure
- Intangible impacts

Direct tangible damage

Direct tangible damage includes the physical damage caused to property and contents in both residential and non-residential sectors as well as infrastructure through direct contact with flood waters. It is the most commonly studied and best understood class of flood impacts. In many flood impact assessments, only direct tangible impacts are considered at the expense of other categories such as intangible impacts (Oliveri and Santoro 2000, Ward *et al.* 2011).

The principal technique adopted in direct tangible damage estimation is to develop and apply damage or susceptibility functions that relate the expected damage to the flood characteristics, such as depth and flow velocity, for particular asset classes. Merz *et al.* (2010) described three steps in the calculation of direct tangible damage. First, the elements at risk should be classified and pooled into homogeneous classes. The detail of these classes can vary, depending on the availability of data, the scale, and the resources available for the study. In the UK, the National Property Dataset allows for the classification of individual properties by their age, the social class of residents, and types of buildings (detached, semi-detached), and damage functions have been developed that can be applied to all of these categories (Penning-Rowsell *et al.* 2005). At the other end of the scale, broad classes such as residential, commercial and industry property can be used, even though there may be vast differences within these classes. In one analysis of the flood risk in Dhaka, seven broad property classes were identified (agriculture, residential, commercial, industrial, institutional, transport, and others) (Gain and Hoque 2012).

The second step is to undertake an analysis of the assets and their exposure, describing the number and types of elements at risk, and estimating their asset value. Thirdly, a susceptibility analysis is conducted that relates the damage of these elements at risk to the characteristics of the flooding. If the second and third steps are conducted separately, the damage functions are calculated relative to the total value of the assets. Relative damage functions have been applied for example, in Dhaka (Gain and Hoque 2012). Otherwise, the second and third steps can be combined, where absolute damage functions are developed and applied. Such absolute damage functions are used within the UK Multicoloured Manual (Penning-Rowsell *et al.* 2005).

It is beyond the scope of this review to describe in detail how the flood characteristics are obtained. It is sufficient to state that there has been significant progress in hazard assessment techniques, enabling more accurate and faster flood simulations in hydraulic models. Such models range from surface water models that ignore or vastly simplify drainage processes, to coupled 2D-surface / 1D sewer models that represent the interaction between sewers and surface models. These hydraulic models are capable of producing depth, velocity and contamination concentration flood maps (Henonin *et al.* 2010).

The damage relationships can be functions of a number of damage influencing factors. A distinction has been made by Merz *et al*. (2010) between *impact parameters* and *resistance parameters.* The former includes the characteristics of the flood that causes the damage, whereas the latter includes those parameters that relate to the resisting object.

In the simplest case, flood damage functions can be stated as a binary function of whether the asset is flooded or not, although this method is typically applied in large scale modelling as in a study on Mumbai (Ranger *et al.* 2011). In practice, much of the focus on estimating the damage caused by flooding has been on the flood depth, dating back to the work of Gilbert F. White, who introduced the concept of stage-damage curves (White 1945). Depth-damage or stage-damage curves have been adopted in multiple locations around the world (Smith 1994), and is a standard technique within flood risk management. Merz *et al.* (2004) studied nine flood events in Germany from 1978 to 1994, and reported that the variation in flood damage to properties could not be explained by inundation depth alone. This means that there is significant uncertainty when assessing flood damage, and that other factors must be important. In one study, the influence of velocity was only found to be significant on structural damage to road infrastructure, although this study was only focused on one catchment in Germany (the Elbe) and one flood event, and so the transferability of these conclusions are limited (Kreibich *et al.* 2009). Other factors studied include the presence of a flood warning system, prior flood experience, flood duration, and family income (Merz *et al.* 2010). An example of typical depth-damage functions can be seen in Figure 1.

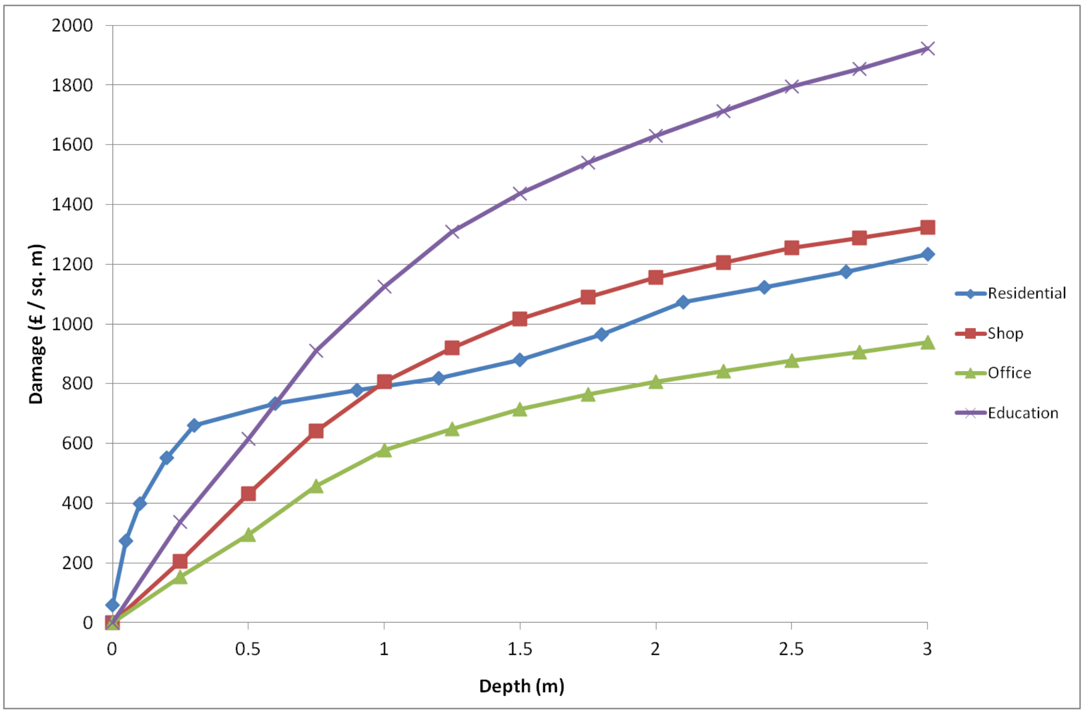

Figure 1 - Typical depth-damage functions (adapted from UK Multicoloured Manual (Penning-Rowsell *et al.* 2005))

There are two main approaches to developing damage functions. The first of these is through the use of real flood damage data, or survey data. This is often referred to as the *empirical* method. The second approach, the *synthetic* approach, is a hypothetical analysis based on land cover and land use patterns, type of objects, information of questionnaire survey, etc. It is akin to a 'what-if' analysis, and asks what damage would be caused if the flood waters were to reach a certain depth within a property. The database of absolute damage functions, developed at the Flood Hazard Research Centre in Middlesex is an example of a synthetically derived database (Penning-Rowsell *et al.* 2005). In Germany, the HOWAS database is a collection of empirical flood damage data (NaDiNe 2012).

Some authors have argued that empirical damage functions derived from real data are more accurate than synthetic data (Gissing and Blong 2004).The variability of the data within a category (such as residential) can be quantified. However, detailed damage data are rare, so that the functions may be based on limited data. The transferability of using data from one event or location to another also poses problems. The paucity of information may require the use of extrapolation techniques, which increases the uncertainty of the data. Synthetic data has the advantage that it provides a higher level of standardisation and therefore allows for a greater comparability of flood damage estimates. The data can be transferred more easily to different geographic areas. However, much effort is required to produce databases, and the analyses can be subjective, resulting in uncertain estimates. The lack of good quality damage data is the main bottleneck in the development of flood damage functions (Freni *et al.* 2010).

A simple example from Dhaka in Bangladesh will illustrate the most common technique used in flood impact assessment for direct tangible damage (Khan *et al.* 2012). Figure 2 shows the main steps that have been described in the preceding section.

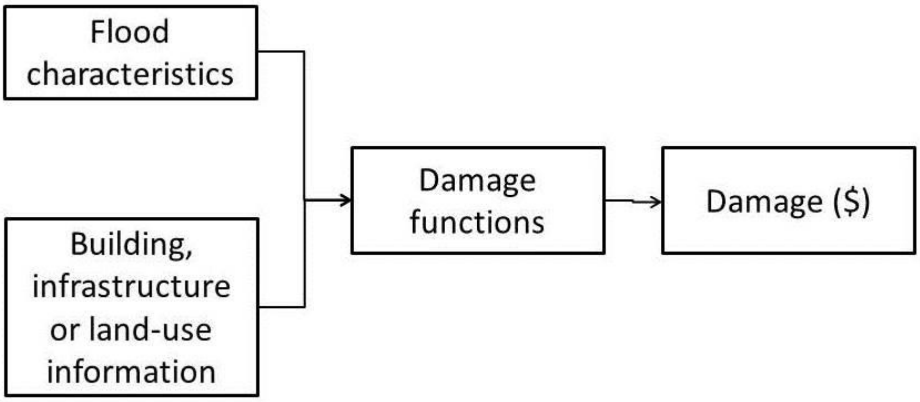

Figure 2 - Main steps in flood impact assessment

Building or land-use information is used to classify the building into homogeneous classes. In this Dhaka case study, 12 classes were identified, including commercial, government, and residential properties. These building classes are represented in Figure 3, combined with the flood characteristics.

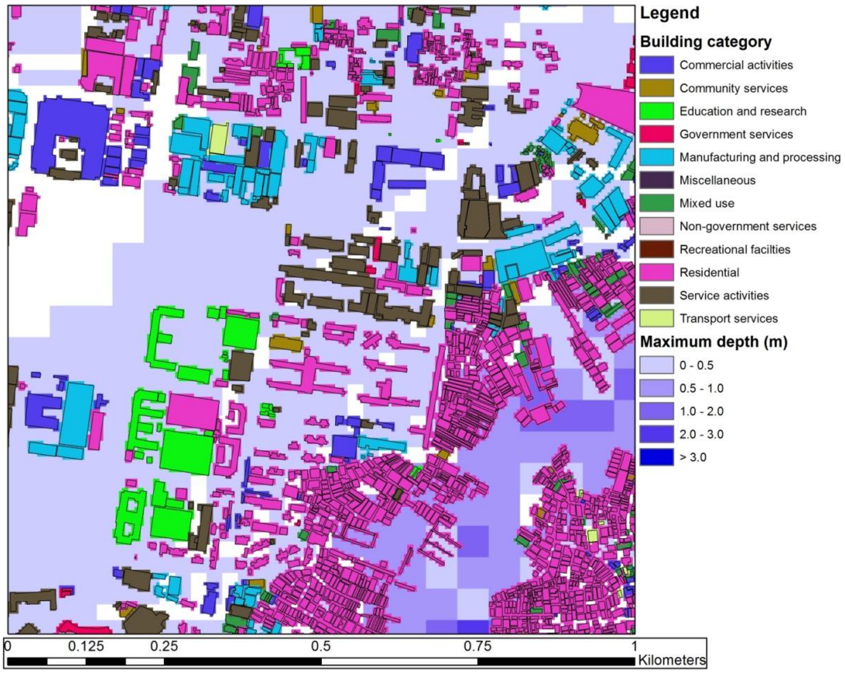

Figure 3 - Flood map of central Dhaka with building classifications

The flood characteristics of interest in this study are the flooded depth and extent. The flooded depth and flood extent are combined using flood depth-damage functions. The results of applying these damage functions are shown in Figure 4, which shows the total damage per building. These can then be summed over the model domain to calculate a total damage for a particular event.

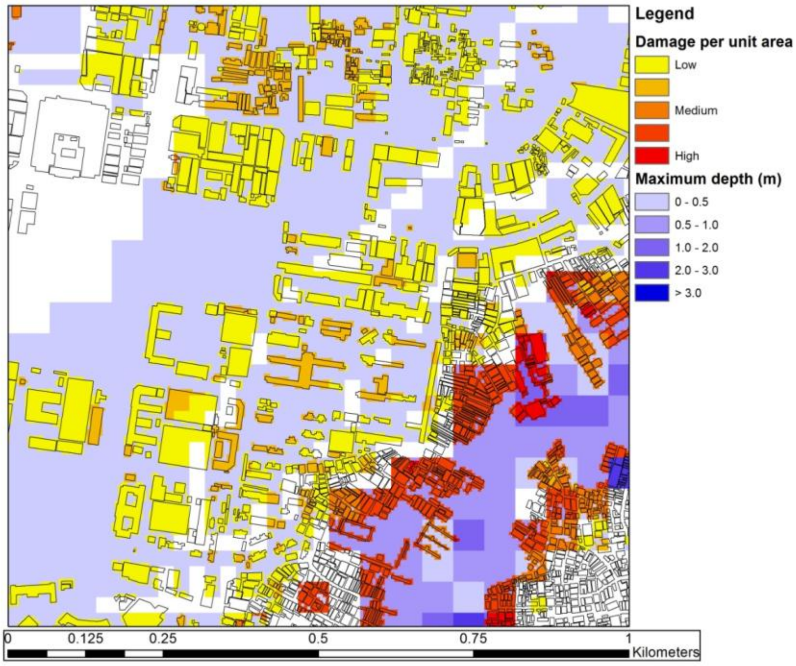

Figure 4 - Damage per unit building for Central Dhaka

Business interruption and indirect tangible impacts

Although some authors distinguish between business interruption and indirect tangible impacts, the literature is often unclear as to which costs are being assessed with a particular method (this review deals with these two categories together). To assess business interruption costs, there are two principal methods. The simplest technique is to apply a fixed percentage of the direct costs (James and Lee 1971). Penning-Rowsell and Parker (1987) empirically investigated the losses arising from flood events in the UK, and noted that the percentage of indirect losses with respect to the direct losses ranged from 21% for a study in Bristol, to 93% for a study in Chesil. This technique has also been applied in St Maarten in the Caribbean (Vojinovic et al., 2008), in Australia with the ANUFLOOD model developed by the Queensland Government (Natural Resources and Mines 2002) and in the Rapid Appraisal Method developed by the Victorian State Government (Victorian Department of Natural Resources and Environment 2000). The key advantage of such a technique is its simplicity; however the disadvantage is that the ratio that should be applied is highly variable not only between locations but also between events at the same location. A further disadvantage is that this technique does not take the duration of the disruption into account, which is a critical factor in calculating the total impact.

The second method is to apply a sector-specific unit loss value that represents the losses from added value, or wage losses. Booysen *et al.* (1999) estimated business interruption costs on a company level in a case study in South Africa by estimating the gross margin of individual companies per day, and multiplying that by the number of days of disruption. In an example from Nordrhein-Westfalen in Germany, figures for the gross value added per employee per day are multiplied by the number of employees and the number of days of disruption to estimate the total cost arising from business disruptions (MURL 2000). One challenge that arises from these methodologies is to assess the length of business interruption. Seifert *et al.* (2009) assessed flood loss data from flood events from 2002, 2005 and 2006 in Germany, and found that there were significant correlations between the length of business interruption, and the depth of water, the duration of the flood, the flow velocity, contamination, the size of the company, and an indicator that represented the precautionary steps taken by the company. Although this analysis was location specific and required good historical data, it could provide insights into the better understanding of business interruption losses.

Econometric models have also been used to assess the impacts of disasters. For example, Ellson *et al.* (1984) used such a model to investigate the potential losses from earthquakes in Charleston in South Carolina in the USA. However, there has been limited use of such models in the field of flood risk management.

Input-output (I-O) modelling is an economic technique developed by Wassily Leontief to understand economic linkages (Leontief 1936). I-O modelling rests upon the idea of an economy as a system, where industries receive inputs from other industries, and produce outputs for either other industries or final consumers. Their focus on production interdependencies makes them especially well suited to examining how damage in some sectors can ripple through the economy. There are several examples of such an application of I-O models to assess flood impacts (Van der Veen and Logtmeijer 2005, Jonkman *et al.* 2008a). I-O models are relatively easy to use, compared to more complex economic techniques. However, they are based on a microeconomic, consistent and closed framework, and so they can only lead to a limited impact analysis. They assume an entirely elastic supply-side in the economy, and in addition, they assume a constant return to scale (Kowalewski 2009).

Computable General Equilibrium (CGE) modelling is another economic technique which uses an equation system to represent the demand for goods by consumers and the supply of goods by producers. Equilibrium constraints are used to solve the supply and demand requirements simultaneously. CGE models have mainly been used to assess disaster impacts related to earthquakes, but the principles should be the same. Rose and Liao (2005) used such a model to study the resilience of the water supply system following an earthquake in Portland, USA. CGE models are not distinct from I-O analysis, but are rather a “more mature cousin or extension” and retain many of the advantages and overcomes some of their shortcomings (Rose, 2004). A major shortcoming is the assumption that decision-makers make optimal decisions, and that the economy is always in equilibrium. CGE models may be more suitable for long-term analysis, and can underestimate impacts in the short-term (Rose and Liao, 2005).

A hybrid model which attempts to bridge the gap between I-O and CGE models is the Adaptive Regional Input-Output model, which was used to assess the indirect impact of flooding following Hurricane Katrina in Louisiana (Hallegatte 2008). For this study, National Input-Output tables were obtained from the US Bureau of Economic Analysis for 15 sectors. These were then adjusted to produce regional input-output tables for the state of Louisiana. Parameters were required that describe overproduction, adaptation and for demand and price responses. These were calibrated with a combination of data from previous events (the Landfall of Hurricane Andrew in 1992, and the Northridge Earthquake of 1994, as well as other events from the 2004 hurricane season). The total economic damage was estimated to be 139% of the direct losses (an economic amplification ratio of 1.39). This model has also been applied to a case study in Copenhagen (Hallegatte *et al.* 2011) and in Mumbai (Ranger *et al*., 2011).

Barriers to the wider adoption of these models as a tool include the difficulty of obtaining the required data, and disaggregation of such data to the appropriate regional or even city scale. Green *et al.* (2011) have argued that such complex models are of limited use in flood impact assessment as they fail to meet the needs of stakeholders. Not only are the models are mostly applicable at scales larger than the city, (i.e. regional or national scales), they also require a high level of user skill and the results are highly uncertain. Alternatives for assessing the indirect costs at the city scale are therefore still lacking (Meyer *et al.* 2013).

An often overlooked indirect impact of flooding is the costs associated with traffic disruption. The fundamental method of estimating the cost of traffic disruption is to estimate the additional operating costs of vehicles, and the opportunity costs (Bureau of Transport Economics 2001). The additional operating costs will include the fuel used by the traffic network, and opportunity costs include the value of time. Dutta *et al.* (2003) used traffic data and standard values for the marginal costs of traffic and time costs for a case study in Japan. In that study, the time costs were significantly greater than the marginal operating costs, although the total costs were found to be minimal compared to other costs such as the direct tangible losses. This goes part way to explaining why the cost of traffic disruption is often ignored.

Transport planners have long used models to optimise road networks (Santos *et al.*, 2010). A few authors have attempted to link urban transportation models with hydrological or flood models to conduct an integrated assessment of these losses. Suarez *et al*. (2005) studied the impacts of flooding on the Boston transportation network. A transport model was used in combination with a flood model to estimate the number of cancelled trips and the lengths of delays during an extreme flood event. Chang *et al.* (2010) considered the impact of climate change on flood-induced travel disruptions in Portland, Oregon in the United States, using an integrated assessment technique. The results showed that the cost of delays and lost trips are relatively small compared with damage to the infrastructure and to other property.

There is clear scope for traffic models to be combined with flood models to improve these estimates, and the driver for this may come from sites where traffic disruption costs are thought to be more significant.

Infrastructure damage

Urban areas are served by a wide variety of infrastructures, which provide the services of modern life. These infrastructures include telecommunications, transport services, power, emergency services, water, agriculture and food, and health care, among others (Conrad *et al.* 2006). Damages to these infrastructures can be costly. In the 2007 summer floods in the UK, of the £4bn damage to the economy, approximately £670m was credited to damages to critical infrastructure (Chatterton *et al.* 2008).

The impacts of flooding on infrastructure can be particularly complicated to estimate, and this is a comparatively under-researched area. Infrastructure elements are often highly specialised, and how they are directly damaged by floodwaters can vary enormously. They typically form a part of a wider network of elements, such as the electricity or water supply networks, and flooding can lead to indirect effects that are geographically distant from the original flooding. Furthermore, infrastructures are highly interdependent; outages in the electricity supply can lead to interruptions to water supply and telecommunication networks. Identifying these linkages, and estimating costs associated with them, is especially difficult.

In the US HAZUS methodology for the assessment of the impacts of flooding, depth-damage functions for lifelines such as water, electric, roads and railroads are recommended, which can derive from expert opinion and historical data (Scawthorn *et al.* 2006). In the Netherlands, the standard methodology for flood-damage assessment uses depth-damage functions to represent damage to pumping stations, roads and railways, gas and water mains, and electricity and communication systems (Meyer and Messner 2005). However, these techniques for estimating the direct cost of flooding do not model the linkages that exist within infrastructure systems.

Techniques from a branch of economics, referred to as Input-Output economics (described in the previous section) have been extended to model the interdependencies between infrastructures, referred to as Interoperability Analysis (Haimes *et al.* 2005). This method has been applied to a US case study to model the threat to power infrastructure (Crowther and Haimes 2005). Cagno *et al.* (2011) adapted this methodology and used it to consider the vulnerability of underground infrastructure for a case study in Italy. To date, very few of these methodologies have been applied to assess the vulnerability of urban infrastructure to flooding.

Progress has been made on understanding and identifying the different interdependencies which exist between infrastructure networks. Rinaldi *et al*. (2001) identified four such classes: Physical, cyber, geographical, and logical interdependencies. Emanuelsson *et al*. (2013) adopted these concepts to develop a network analysis framework and applied it to the assets owned and operated by a privately owned water company, in the UK. This network consisted of sewage treatment works, sewage pumping stations, telecommunication assets and electric substations.

Eleutério *et al*. (2013) took an elementary approach by focusing on the individual assets in network infrastructures, and used interviews with experts to develop “damage-dysfunction matrices” that describe the linked vulnerability of the networks, and applied it to a case study in France, and included water supply, sewerage and drainage, power supply, gas distribution and public lighting networks, and were able to apply replacement and repair costs to these failures.

There is clearly much work to be done to understand how impacts of flooding go beyond the direct damage to individual assets and this presents a serious research challenge. A significant obstacle is again the lack of data, either through inadequate knowledge or through data that is sensitive and therefore not made available to researchers.

Intangible damage

Intangible impacts can include health impacts, as well as damage to the environment. The most prominent intangible impact is that of flooding on human health. There are two principal types of health impacts from flooding (Hajat *et al*., 2005):

- physical health effects sustained during the flood event itself or during the clean-up process, or from knock-on effects brought about by damage to major infrastructure including displacement of populations. These include injuries and the loss of life, as well as diseases linked to the flooding, such as waterborne diseases (e.g. diarrheoa), vector borne diseases (e.g. malaria and dengue fever) and rodent-borne diseases (e.g. leptospirosis)
- mental health effects, which occur as a direct consequence of the experience of being flooded, or indirectly during the restoration process, or by people proximate to the flooding

Ahern *et al.* (2005) reviewed epidemiological evidence on the global health impacts of flooding, and concluded that there is surprisingly little. There is therefore limited data upon which predictive models can be built. Of the few predictive models that do exist, most are related to the risk to life.

Studies on the risk to life from historical flood events have demonstrated that the risk is elevated when floods occur unexpectedly, and there is little warning, when there is little possibility for shelter, where the water is deep and fast flowing, and where vulnerable groups such as the elderly are exposed to flooding (Jonkman and Kelman 2005). This study showed striking geographical differences. In North America, 66% of those who drowned were in vehicles, compared to 18% in Europe.

These insights have been used to develop risk-to-life models. Jonkman *et al*. (2008b) developed a model which takes into account the characteristics of the flooding, an estimate of the number of people exposed, and an assessment of the mortality of those people exposed to the flooding. Figure 5 shows the general approach to the loss of life model.

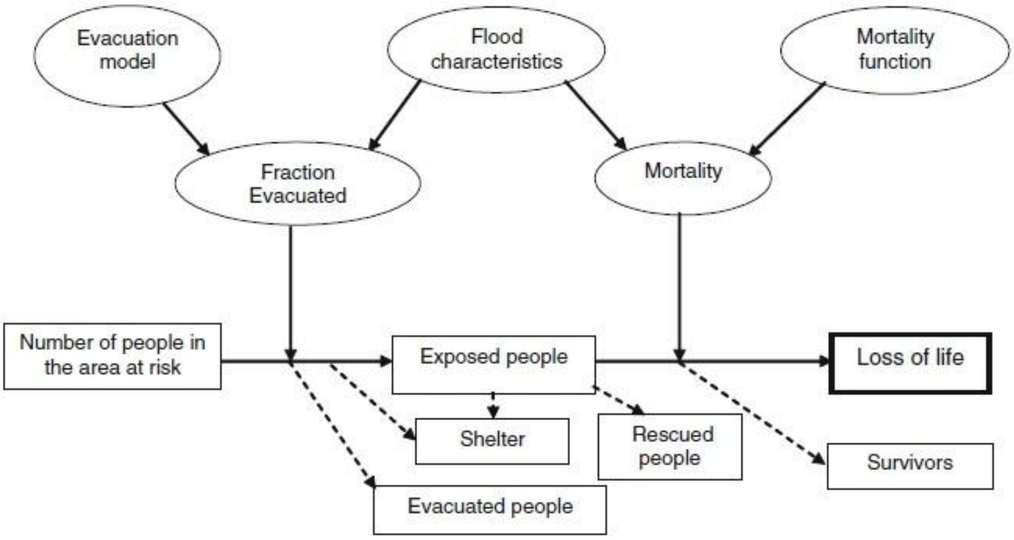

Figure 5 - General approach for the estimation of loss of life due to flooding (from Jonkman *et al*. (2008b))

Progress has been made in developing realistic simulations of the evacuation processes, using techniques such as agent-based modelling (Dawson *et al.* 2011) and probabilistic methods (Kolen *et al.* 2012).

Flooding is known to be linked to the outbreak of diseases (Ahern *et al*., 2005). These diseases range from bacterial outbreaks such as leptospirosis and diarrhoea through to vector-borne diseases such as malaria. Kay and Falconer (2008) have noted the growing international awareness of health risks associated with water, particularly in developing countries, and they noted that “more than half the world’s hospital beds are filled by people with water-related diseases”. There are many studies that investigate the risk factors associated with particular diseases and flooding. For example, several studies look at diarrhoeal epidemics in Dhaka, Bangladesh (Harris *et al.* 2008).

Schwartz *et al.* (2006) noted that patients showing diarrhoea during flood periods were older, more dehydrated, and of lower socio-economic status than the patients in non-flood periods. This information could lead to predictive models, but as of yet, only a few models have been developed.

Kazama *et al.* (2012) estimated the infection risks as a result of contact with coliform bacteria in the lower Mekong in Cambodia as a result of flood inundation. Their concentrations were simulated with a hydraulic model, and a dose-response model was used to estimate the risks from drinking contaminated groundwater. In another study, a quantitative microbial risk assessment (QMRA) was undertaken to estimate the infection risks in Utrecht in the Netherlands (ten Veldhuis *et al.* 2010). Concentrations were estimated from typical measured samples of cryptosporidium, giardia and campylobacter, and again, using dose-response models, annual risks of infections were calculated.

The relationship between vector-borne diseases and flooding is complex. In the short term, floods have been known to wash breeding sites away, reducing the cases of malaria (Sidley 2000). In contrast, following the 2005 floods in Mumbai, increased cases of malaria were reported (Gupta 2007).

Lau *et al.* (2010) considered the relationship between outbreaks of leptospirosis with flooding, and questioned whether the burden of the disease could be increased due to climate change and increased urbanisation. The areas most at risk from the increased burden would be those where multiple risk factors might coexist, such as increased flood risk, rising temperatures, overcrowding, poor sanitation, poor health care, poverty and an abundance of rats or other animal reservoirs. These factors often co-exist in urban slums, in cities such as Mumbai and Dhaka, and therefore may be at increased risk in the future. They argued that spatiotemporal modelling using Geographical Information Systems could potentially be useful to understand the disease burden.

The psychological impacts of flooding are complex and poorly understood. One major psychological impact of flooding is post-traumatic stress disorder (PTSD). A review of its epidemiology was conducted by Galea *et al.* (2005) using studies from 1980 to 2003. The prevalence of PTSD related to natural disasters was found to range between 5% and 60%, with most of the studies showing numbers towards the lower end of this range. The review demonstrated that the biggest risk factor for developing PTSD during a natural disaster was the extent of the exposure. Other risk factors included gender (women are shown to be more likely to suffer from PTSD), pre-existing psychological disorders and low social support (Brewin *et al.* 2000). More specifically related to flooding, studies quoted by Ahern *et al*. (2005) have shown a prevalence of 22% of PTSD during the 1993 Midwest floods, or 19% among flood victims of the 1997 Central Valley Floods in California. However, studies are limited by the fact that some of the results from these studies are self-reported.

Huang *et al.* (2010) studied post-traumatic stress disorder among people in flood-hit areas in the Hunan Province in China, and developed a predictive model of PTSD using a risk-score model among flood victims in a large population, using 25,500 respondents. The prediction model used 7 variables (age, gender, education level, flood type, flood severity, previous flood experience, and previous mental health status), and were used to create a risk score. The study limitations included the fact that recall bias could be a factor, and that diagnoses were not made by formally trained psychologists.

Beyond quantifying the intangible impacts in terms of the number of people affected (e.g. number of deaths, injuries, disease cases), two methods have been developed to quantify health impacts.

- Employ common metrics that amalgamate multiple health impacts. The two most prominent are the Disability Adjusted Life Year (DALY) and the Quality Adjusted Life Year (QALY);
- Calculate the health impacts in monetary terms, using economic tools to estimate the value of intangible benefits (or costs).

In health impact assessments, the DALY is perhaps the most commonly applied. It has been adopted by the World Health Organisation as a metric to assess the burden of diseases, injuries and risk factors on human populations (Murray and Acharya, 1997). The DALY is described as combining the "time lived with a disability and the time lost due to premature mortality". Years lost from premature mortality are estimated with respect to a standard expectation of life at each age. Years lived with disability are translated into an equivalent time loss by using weights which reflect the reduction in functional capacity (Anand and Hanson 1997). DALYs have been used to estimate the global health burden of poor water, sanitation and hygiene (Pruss *et al.* 2002).

The DALY has been used within the UK to assess the health risk from flooding (Fewtrell *et al.* 2008) This study categorised health impacts into three groups:

- Mortality and injuries
- Infection; and
- Mental health effects.

They used statistics from earlier studies to estimate the baseline incidences and the relative risk of some certain health-related problems linked to flooding. For example, following work by Reacher *et al*. (2004), psychological distress was estimated to have a baseline incidence of 15.5%, flooding increased this by over 400%, leading to an incidence rate of 64%. The study demonstrated that, in this case, the greatest impacts on human health were related to mental health problems. This may not be the case in developing countries where the risk of disease outbreak is known to be greater. However, Ahern *et al.* (2005) noted that the longer term impacts on mental well being are often underestimated and receive too little attention from health authorities.

A more controversial method is to place a monetary value on a particular health impact. There are a number of ways this can be achieved:

- Cost-of-illness approach
- Value of lost-production
- Willingness to pay methods

The cost-of-illness (COI) approach is a commonly used method that sets out to capture the economic impact of disease. It views the cost of diseases as the sum of several categories of direct and indirect costs. These include personal medical care costs for diagnosis, procedures, drugs and inpatient and outpatient care, non-medical costs, such as the costs of transportation for treatment and care, non-personal costs like those associated with information, education, communication and research, and finally income losses. Although not specifically related to flooding, an example of such a study was one that attempted to estimate the cost of childhood gastroenteritis in the UK (Lorgelly *et al.* 2008). Hutton *et al.* (2007) used a COI approach to estimate the benefits of sanitation improvements globally, looking at the cost of diarrhoea cases. These estimates could easily be applied in flood risk management. However, to date, no studies have attempted this.

The value of lost production is a method that attempts to model the loss of income (or added value) that accrues from being unable to work through ill-health. In one study, an “Anxiety-Productivity and Income Interrelationship Approach”, or API, approach was developed, which relates flood depth to anxiety, anxiety to productivity, and productivity to income. Finally, it is able to produce a relationship between flood depth and loss of income (Lekuthai and Vongvisessomjai 2001).

Willingness-to-pay (or accept) (WTP or WTA) methods are attempts to estimate the amount that a person is willing to pay to reduce the risk to their health by a certain amount (or willing to accept for an elevated risk). When valuing mortality, these values can be referred to as the Value of a Statistical Life (VSL). There have been some meta-analyses of the global estimates of the VSL (Viscusi and Aldy 2003). This study, which mainly focused on developed countries estimated a value of $6.7m in Year 2000 prices.

Values from WTP or WTA methods can be derived from Revealed or Expressed Preference studies. Expressed or stated preference studies rely on the idea of directly asking people how much they would be willing to pay, either in insurance premiums or indirectly for flood defences, for example, to reduce the risk of death or injury. These are often conducted through a methodology called *Contingent Valuation*. One study in the UK suggested a £200 value per household per year as representing the intangible benefits of a reduced risk of flooding (DEFRA and EA, 2004).

Expressed preference methods are contrasted with *Revealed Preference* techniques, where an individual’s valuation of their life and health is estimated by observing their decisions in relation to other markets. For example, several authors have studied the link between flood risk and house prices (Pryce *et al.* 2011, Chen *et al.* 2013). In a meta-study, Daniel *et al*. (2009) considered the difference in house prices to assess the value of flood risk. This is known as a *hedonic pricing* method. They concluded that the results were highly variable, but estimated that an increase in the probability of flood risk of 0.01 in a year is associated to a difference in transaction price of an otherwise similar house of –0.6%. This study does not explicitly estimate the health impacts of flooding however, but rather the value of being flood free.

Integrated approaches in practice

This review has described techniques for the assessment of specific flood impacts. This section will describe a few studies that integrate different methodologies into a single assessment. There are two methods that can be used to integrate the different methodologies. Either, a common metric can be applied (which is almost always in monetary terms), or the impacts can be combined using multicriteria techniques.

Where the common metric of money is used, intangible impacts are typically excluded. For example, Dutta *et al*. (2003) developed and applied a flood impact assessment methodology that included damage to residential and non-residential buildings, as well as infrastructure damage and traffic disruption. One of the few examples that does include intangible impacts with tangible impacts is for an urban case-study in St Maartens, that linked anxiety with productivity (Vojinovic *et al.* 2008). A further example comes from Denmark, where Arnbjerg-Nielsen and Fleischer (2009) attached a cost to the health impact of being exposed to sewage, and combined this with the total damage to roads, houses, and the cost of traffic delays.

The difficulty of combining intangible and tangible impacts together has fostered interest in multicriteria techniques. Kubal *et al.* (2009) used such a framework to assess the flood risks in Leipzig in Germany. The framework combined a hierarchy to prioritise the economic, social and ecological aspects of urban flood risk. Although such researches are promising, a greater understanding is needed of the social and ecological aspects of flood risk so that they can be combined with the much better understood economics risks. Some progress has been made in improving the integration of intangible losses (Dassanayake *et al.* 2012).

Integrating the results from multiple events is achieved through calculation of the Expected Annual Damage, and this is achieved through integrating the flood risk function (Arnell 1989, Arnbjerg-Nielsen and Fleischer 2009). By considering expected damages over longer time-frames, it is possible to estimate the cost-effectiveness of different adaptation measures (Zhou *et al.* 2012, 2013)

Discussion and conclusions

There are a number of conclusions that can be drawn from this review. Firstly, it is clear that there is a great emphasis in literature on direct tangible flood damage, particularly for damage to residential, commercial and industrial property. There are some shortcomings to the methods applied to estimate impacts, especially in reference to the impacts on infrastructure, as individual assets are highly specialised. The understanding of the vulnerability of critical infrastructure networks is limited, although progress is being made on understanding how failures within a system can cascade through a system. Some of this knowledge is limited by the lack of data, either on the grounds that it does not exist, or that the data on the functioning of networks is highly sensitive, and therefore protected either by industry or government agencies.

There is a less well developed understanding of the impacts of flooding on the wider economy, as indirect tangible damage. In the case of developing and applying complex models such as Input-output or Computable General Equilibrium models, some researchers question their value for small-scale flood impact assessment studies, in part due to the scale of the models, and also due to the skill needed to implement them (Green *et al*. 2011). Information on the duration of disruption on both businesses and infrastructure is often lacking, which arises both from the length of time that assets are inundated, as well a limited understanding of the time required to repair and restore services.

Health impacts are as significant, if not more significant than tangible flood impacts. Diseases are thought to be a more serious problem in the developing world. Mental health impacts are even more difficult to assess than the physical impacts. The understanding of the precise links between flooding and health is limited, and more research is needed to understand the epidemiology. An emerging research agenda has been identified, which has been termed hydro-epidemiology (Kay and Falconer 2008). The quantification of health impacts is difficult. The DALY appears to be a useful concept by which the impacts could be quantified. The monetising of health impacts is difficult and controversial and likely to remain so because of the need to attach a value to human life.

This review has shown that there is a range of methods used not only to assess flood impacts but also to quantify them. ten Veldhuis (2011) has demonstrated how quantifying impacts in terms of either the number of people affected or in monetary terms can have a significant effect on how flood impacts are prioritised. In a case study in the Netherlands, quantifying the effects in monetary terms gave more weighting to damage to buildings and property, whereas when the impacts were quantified in terms of the number of people affected, more weight was placed on roads and traffic disruption. The important point here is that the analyst should be aware of the biases and emphases that arise from using different metrics.

The assessment of all impacts is made more difficult by a lack of good quality flood impact data. This leads to problems with the validation and calibration of flood damage data. The collection of more data would be highly valuable to build upon as a research basis. Although some flood damage databases do exist (The Centre for Research on the Epidemiology of Disasters EM-DAT database is a good example), they often include summary data rather than individual data points, and therefore cannot be used in micro or meso-scale assessments.

It is important to highlight that no impact assessment can cover the full range of impacts, and the analyst needs to make choices as what to include and exclude. As a result, every flood impact assessment is incomplete, and the analyst should be aware of these biases and omissions that exist in any methodology.

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