Flood Damage Assessment: A Review of Flood Stage–Damage Function Curve

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Abstract Nowadays, flood control has been replaced by flood management concept in terms of living with flood, making benefit of it, and minimizing its losses. The success in flood management in any region depends on the evaluation of different types of flood losses. For the assessment of flood damages, this requires the use of stage–damage functions for different categories of land use. A review is presented of the methods used to construct stage–damage function curves for residential, commercial, agricultural, and industrial category. Two main approaches in constructing stage–damage functions are empirical approach, which is based on damage data of past floods, and synthetic approach, which uses damage data collected by interview survey or questionnaire. For a developing country like Malaysia which has limited history and actual flood damage data, the synthetic method is the preferred approach in constructing stage–damage function curve.

Keywords Flood management • Flood damage assessment • Stage–damage function • Land use • Synthetic approach

1 Introduction

Flood damage estimation is an essential element in water resources planning, mainly for the purpose of flood mitigation benefits' evaluation [1]. In conventional practice, the flood management approaches focus on the design standards and structural flood mitigation measures [2]. Normally, flood mitigation structures were designed in order to control up to a certain, predefined design flood, i.e. return period of the design rainfall. In recent years, this structural flood control approach has been changed to a new developed concept which is referred to as "flood risk management" [2]. The degree of protection is determined by broader

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considerations than some predefined design flood, while more attention is put on non-structural flood mitigation measures. A significant evolution that can be seen in this context is a dominant transformation from flood hazard to flood risk. In common practice, flood policies are focusing more on the regulation and reduction of flood hazard, i.e. decreasing the probability of occurrence and intensity of flood discharges and inundations [3]. In flood risk management, where flood risk is given more attention, risk is defined as damage that occurs or would be exceeded with a certain probability in a certain time period. Hence, damage aspects are important and need to be well considered on flood risk management [3].

In addition, unpredictable occurrences of disasters, such as flooding, are making people to take protection and prevention. In many countries, people can insure themselves against flooding. In developed countries such as the United States, the United Kingdom, and Australia, flood insurance has been adopted as a part of the tools for residual flood risk management to support and complement non-structural approach. As a result, flood insurance has been incorporated as part of a comprehensive integrated flood risk management. However, in Malaysia, having flood insurance is not a requirement. The awareness of taking flood insurance to protect their properties is still low, and furthermore, there is a lack of incentive from the government to promote flood insurance as an instrument for flood risk management in the country [4, 5]. Although it cannot prevent actual property damages or loss of life as structural measures would do, the advantages of having flood insurance are that it can significantly reduce the economic risk associated with flooding. An insured property damaged by the flood can be replaced quickly without depending on financial aid from the government [6]. As flood insurance has become a part of flood risk management, the flood hazard and the potential flood damage are of great interest to insurance companies [6]. Insurance companies need the information on flood risk data and damage curve to decide the customer prices for the flood insurance [7].

The generation and compilation of an adequate flood damage assessment concern many issues regarding the nature of damage caused by floods, such as

- Proper classification of damage categories considering nature of damage [8]
- Obtaining detailed flood parameters such as flow velocity, depth, and duration at any given location [8]
- Establishment of relationships between flood parameters and damage for different damage categories [8]

2 Flood Damage Assessment

The selection of approaches for flood damage assessment may depend on the types of damages. In undertaking a systematic flood damage assessment, it is important to recognize that flood damage consists of two main components, namely the tangible and intangible types of damage [9].

2.1 Types of Flood Damages

There are two main types of flood damages, i.e. tangible and intangible damage. The damage that can be readily measured in monetary value is the tangible damage, while the damage that cannot be directly measured in monetary terms is known as intangible damage [10]. Moreover, tangible damage is further divisible into two subtypes, i.e. direct and indirect damage. Direct damage is the damage caused to items (e.g. buildings and inventory items) by contact with or submersion in water. In contrast, indirect damage is the damage caused by the interruption of physical and economic networks, such as traffic flow disruption and individual income loss, as well as consequences of business cut-off [11].

In the other view, Merz et al. [3] define direct damages as damages which occur due to the physical contact of flood water with humans, property, or any other object, while indirect damages are the damages that are induced by the direct impacts and occur in space and time, outside the flood event. Both types of damages are further classified into tangible and intangible damages, depending on whether or not they can be assessed in monetary values [12, 13]. Tangible damages are damages that occur to man-made properties or resource flows which can be easily specified in monetary terms, whereas intangible damage is damage to assets which are not traded in a market and are difficult to transfer to monetary values [3].

Several fundamentally different types of flood damage have been discussed by Dutta et al. [8], Penning-Rowsell and Chatterton [14], and Lee and Mohamad [15]. Dutta et al. [8] further categorized the direct and indirect tangible damage into primary and secondary, as shown in Table 1, while a description of examples in Table 2 is given by Merz et al. [3].

2.2 Flood Parameters

The amount of damages resulting from a flood depends on variable flood parameters, such as flood water depth, flood water velocity, year of flooding, duration of flooding, sediment and effluent contents, flooded area covered, and flood warning system [1, 14]. These are also agreed by James and Hall [16] and McBean et al. [17], where they stated that flood damage is actually affected not only by water depth but also by many different factors associated with the local increase of

Table 1 Flood damages category and loss examples [8]

Category			Examples
Tangible	Direct	Primary	Structures, contents, and agriculture
		Secondary	Land and environment recovery
	Indirect	Primary	Business interruption
		Secondary	Impact on regional and national economy
Intangible			Health, psychological damage

Table 2 Examples for different types of damages [3]

	Tangible	Intangible
Direct	Damage to private building and contents; disruption of infrastructure such as roads; railroads; erosion of agricultural soil; destruction of harvest; damage to livestock; evacuation and rescue measures; business interruption inside the flooded area; clean up costs	Loss of life; injuries; loss of memorabilia; psychological distress, damage to cultural heritage; negative effects on ecosystems
Indirect	Disruption of public services outside the flooded area; induced production losses to companies outside the flooded area (e.g. suppliers of flooded companies); cost of traffic disruption; loss of tax revenue due to migration of companies in the aftermath of flood	Trauma; loss of trust in authorities

costs due to the occurrence of flood events. According to Dutta et al. [8], all the factors may be the significant flood parameters that influenced flood damages; however, most previous flood damage assessment studies have chosen water depth as the flood damage variable.

2.3 *Approaches of Flood Damages Assessment*

Two common flood damage estimation approaches are unit loss models and model applications. The unit loss approach is based on a property by property assessment, either actual or potential [8], while the model applications estimate the linkage effects, or inter-sectoral relationships, of floods within economy [18, 19].

From the literature, it can be summarized that most published information on damage collection and analysis come from the United States, the United Kingdom, Japan, and Australia, which have adopted a unit loss approach. The detailed methodologies for tangible loss estimation had been established by the United Kingdom and Australia [14, 20, 21], while for the United States, Japan, etc., detailed damage estimation methodology is limited to urban damage only [22, 23]. It has been noted that these countries adopt similar approach in damage estimation, i.e. unit loss approach [12, 24–26].

As mentioned earlier by Dutta et al. [8], the establishment of an adequate flood loss estimation model involves many issues due to the nature of the flood damages. Some of the most important issues in flood loss estimation are obtaining detailed flood parameters such as flow velocity, depth, and duration at any given location, proper classification of damage categories, and establishment of relationships between flood parameters and damage for different damage categories [8]. The relationship between flood parameters and flood damage can be represented by stage–damage function, which is developed based on historical flood damage information, questionnaire survey, laboratory experiences, etc. [26, 27].

3 Stage–Damage Function Curves

Stage–damage functions are important components in flood damage estimation model. Normally, stage–damage function curves were developed for estimating flood losses. Stage–damage curves are the first essential stage in flood loss assessment. They are combined with field surveys of property at risk and with hydrological information (probability and extent of flooding, velocity, and the like) to give predictions of event damages from which average annual damages can be calculated [26].

Stage–damage functions may be derived by using these two most commonly used methods, i.e. one is based on damage data of past floods, and the other one is from hypothetical analysis known as synthetic stage–damage functions based on land cover, land use patterns, type of objects, information of questionnaire survey, etc. [8].

3.1 Synthetic Stage–Damage Function Curves

The methodology of synthetic approach was first suggested by White [28]. Synthetic stage–damage curves are based on hypothetical analysis, where it doesn't depend on information from an actual flood event [2]. A detailed procedure of synthetic stage–damage curves for several land use types had been produced by Penning-Rowsell and Chatterton [14]. The procedure had been used to assess flood damage to both residential and commercial properties in the United Kingdom. It also provides an essential input into computer programs that are designed to evaluate the benefits of flood prevention measures.

Synthetic stage–damage curves are of two types, either depending on the existing databases, or by values and loss adjusters surveys, as shown in Fig. 1.

1. *Existing databases*: Estimates of the damage to building fabric were obtained using existing information on the possible effects of flooding on building material and the like. The losses inventory was based upon ownership rates obtained from marketing manuals and consumer research surveys [26].
2. *Valuation surveys*: The alternative approach to the inventory method is to undertake surveys of the different types of dwellings at risk in the flood-prone area. Valuation surveys select a sample of dwellings in each designated dwelling class, and a checklist of possible contents, usually by type of room (kitchen, bedrooms, etc.), is drawn up. For the selected properties, the surveyor (ideally a qualified loss adjuster or valuer) notes all items and their current value based on type, quality, and degree of wear. The survey can include information on the height above the floor of each item or the heights can be taken as standard from house to house. The information for the sample of each dwelling type is then averaged and stage–damage curves constructed [14].

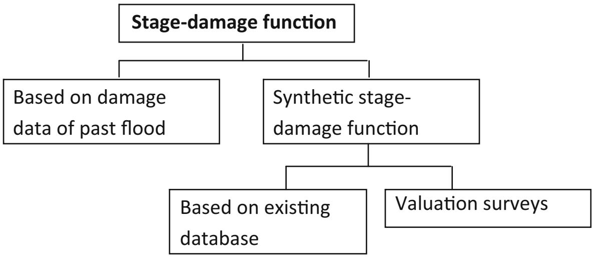

Fig. 1 Types of stage–damage function

3.2 *Categories of Stage–Damage Curves*

Stage–damage curves may be developed using two types of approaches: either depth–damage or depth–percent damage-based approaches. In depth–damage approach, stage–damage relationships are determined directly from prototype data, and normally, the curves are developed separately for many types of structures. Hence, it is time-consuming and costly [29]. Furthermore, the useful life of the relationship is short. The percent-damage approach defines the flood damage as percentage of the total value of the damaged property, depending on the water depth [29]. With the depth–percent damage approach, the percentages from a depth–percent damage function are multiplied by a replacement value in order to develop a stage–damage relationship [30].

A numbers of scientific articles discussing the development of stage–damage functions are referred to in this review. The articles classified the stage–damage functions into several categories as summarized below:

1. *Residential*: For residential category, building was classified into major categories such as detached, semi-detached, and terrace. These categories were also classified by age and then further subdivided by social class of the occupants [10]. The stage–damage information, following normal practice, was divided into "building fabric" and "inventory".

   A loss estimation model to describe urban flood damage in Japan used stage–damage functions that had been derived from the averaged and normalized data published by the Japanese Ministry of Construction. The respective data used are based on the site survey data accumulated since 1954 [18]. Five depth–percent damage curves had been formulated by Dutta et al. [8]: residential structure (wooden), residential structure (RCC concrete), residential content, non-residential property, and non-residential stocks. Figure 2 shows the stage–damage function curve produced by Dutta et al. [8] for residential structure (wooden) category.

   The determination of depth–percent damage relationship was also carried out by Oliveri and Sontoro [29], considering two building types with two and four storeys, respectively, having different average finishing levels and, consequently, different unit prices. The adopted technique is the same for both cases. The first phase of evaluations excluded the building contents, only analysing the structure. The damage begins when the water reaches a depth of 0.25 m; depth increments by steps of 0.25 m were considered. For each water depth, all component

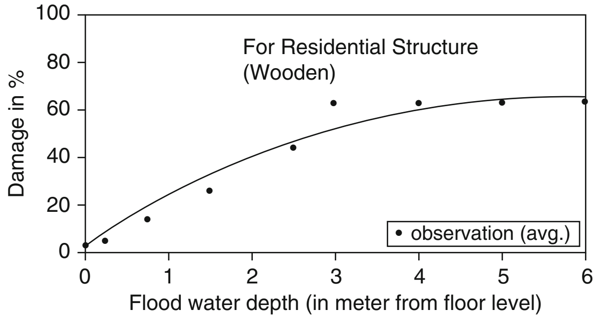

Fig. 2 Flood stage–damage function for residential structure (wooden) category [8]

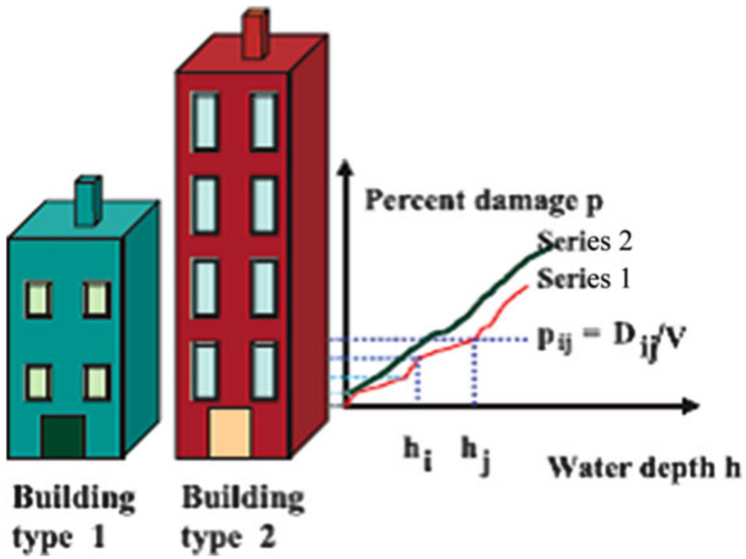

Fig. 3 Schematic of the local depth–percent damage relationships evaluation procedure [29]

categories damageable by water (the internal and external plaster, the textures, the paving tiles, the floors, and part of the electric appliances) were considered in order to compute the overall replacement costs. For each water depth, the percentages of damage were calculated by dividing the overall replacement cost with the estimated total replacement value of the building (structure plus contents) [29]. The procedure described is represented in Fig. 3.

2. *Commercial*: The Australian studies [31, 32] had produced stage–damage curves for commercial sectors. Commercial enterprises are classified by size and by value class. There are three sizes of classes: "Small" (<186 m^2) corresponds to the average high street shop, "medium" (186–650 m^2) to small supermarket, and for larger premises, the actual area (in m^2) was recorded. Each commercial

building was given a value class that indicates the susceptibility of the contents to flood damage. These are in the range of 1 (very low) to 5 (very high). The stage–damage curves form a matrix based on size and value class with average damages for each class given at five heights: 0.25, 0.75, 1.25, 1.75, and 2.00 m above floor level [26].

3. *Industrial*: According to Smith [26], loss assessment using stage–damage curves is inappropriate for industrial plants and they should be analysed using questionnaires. It is important to acknowledge that one single large industrial plant can be disposed to a direct flood damage that exceeds several hundred nearby dwellings subject to the same flood risk.

   A site questionnaire survey should be used to estimate damage to industrial and related properties [14]. The questionnaire method relies on the cooperation of local company management to provide information on the susceptibility of premises to physical damage and the likely magnitude of disruption to production. If information is incomplete or not forthcoming, estimates should be produced from either a similar type of premises within the area or from information previously collected. The example of depth–damage data curve of industry-related services for type 52 (vehicle services), 54 (contractors, merchants etc), and 55 (storage and wholesale establishment) is illustrated in Fig. 4.

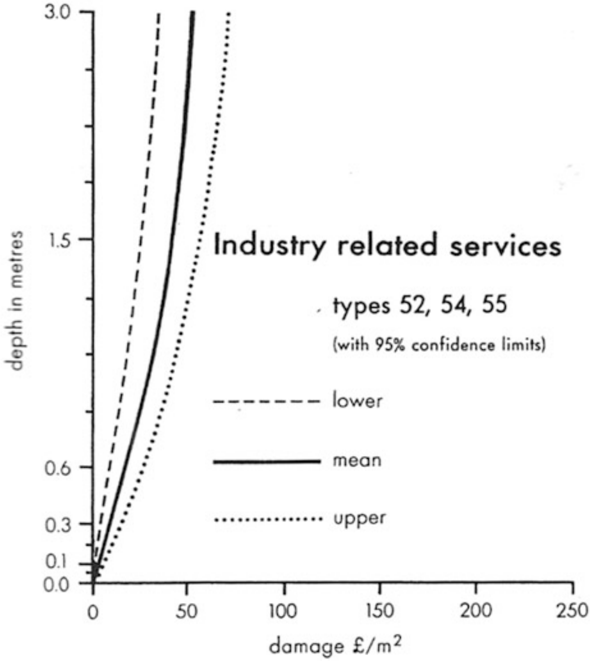

Fig. 4 Industry-related services depth/damage data [14]

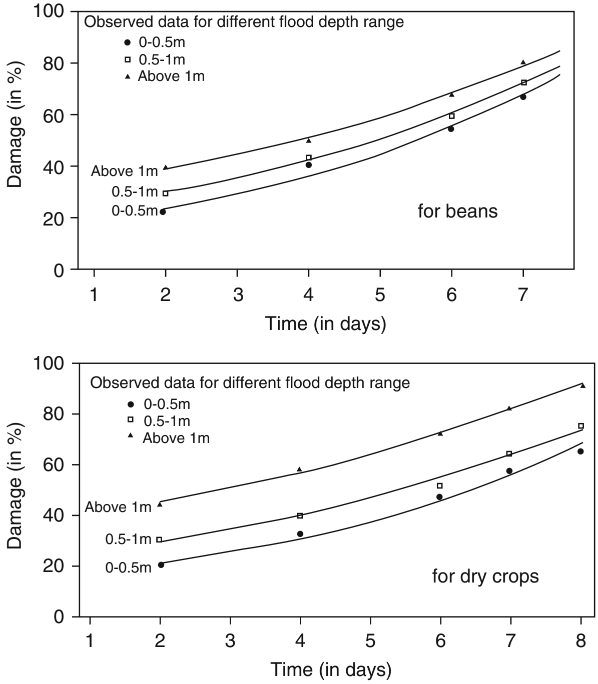

Fig. 5 Agricultural flood stage–damage function for beans and dry crops category [8]

4. *Agriculture*: Dutta et al. [8] formulated stage–damage functions for agriculture damage in Ichinomiya river basin, Japan. They considered two flood parameters: depth and floods duration. The agricultural stage–damage functions are categorized into eight categories, i.e. beans, Chinese cabbage, dry crops, melon, paddy, vegetable with root, sweet potato, and green leaf vegetables according to different flood depth range from 0 m to above 1 m. Example of stage–damage function curves formulated by [8] for agriculture product is shown in Fig. 5 for beans and dry crops category.

4 Development of Flood Stage–Damage Function Curve

In Malaysia, the pioneer study on flood damage estimation was conducted by Japan International Co-operation Agency (JICA), in the National Water Resources Study (NWRS) 1982 for Malaysia [33]. Later, in the year 2000, KTA Tenaga Sdn. Bhd., under the National Register of River Basin study commissioned by the Drainage and Irrigation Department (DID) Malaysia, carried out the updating of the flood damages that was completed by JICA in 1982. KTA Tenaga Sdn. Bhd. [29] proposed a two-tier approach, namely a rapid assessment method (RAM) and a detailed assessment method (DAM). The former is a first-level approximation which requires only basic information, whereas the latter requires extensive data collection and may be adopted for critical flood regions. However, the study by KTA Tenaga Sdn. Bhd. carried out exemplary detailed assessment following the methodology developed in Australia, which has limited applicability in the Malaysian context [15].

The fundamental steps in producing stage–damage curve were to collect damage data from actual flood events. However, the problem with this approach is that that kind of data is not available in Malaysia. Hence, synthetic stage–damage curves by the valuation surveys are the preferred option [26]. Synthetic approach develops standard flood damage information from a wide variety of sources, not necessarily related to specific flood events. This approach can be done by interview survey to gain flood damage information.

The development of questionnaire survey for different classes of building had been discussed by McBean et al. [17] and [26]. As stated by Smith [26], the development of questionnaire survey should include information on types of structure, description of room, household contents, location (either in basement, first floor, or second floor), the quality, and age of the structure and contents. The questionnaire survey also can include information on the height above the floor of each item and general information such as the household/commercial income, number of person in the houses/premises, and how often they experienced flooding.

Penning-Rowsell and Chatterton [14] conducted site survey for residential stage–damage data collection. The survey was divided into two parts: building fabric and inventory. The building fabric and inventory checklist for the site surveys is shown in Table 3. The details of type, total area or number, and quality

Table 3 Flood damage information required for stage–damage curve [14]

Category	Flood damage information required	
Residential	*Building fabric*: Plasterwork and wall finish Floors Joinery Decorations Path and paved areas Boundary/fence/garage/gates Main building	*Inventory*: Domestic appliances Heating appliances TV/hi-fi etc Furniture Personal effects Floor covering and curtains
Commercial	Damage to stock, damage to building fabric, equipment damage, clean-up coat, depth function	
Industrial	Name of company, type of business, total area of premises, total ground floor area of building only, height of floor level of buildings, plant and equipment, raw material and unfinished goods, finished goods (stocks if no processing is involved), total physical damage (estimate), average weekly turnover/output, ability to defer production/work, ability to transfer production/work	
Agricultural	Types of crops/land use, building fabric and clean-up cost, damage to stored crops, feedstuff, and fertilizers, damage to agricultural vehicles and movable equipment, damage to fixed equipment	

of building fabric and inventory had to be obtained during the surveys. The flood damage information required for the development of stage–damage function for commercial, industrial, and agricultural category as recommended by Penning-Rowsell and Chatterton [14] is illustrated in Table 3.

The questionnaires were sent to residents, companies, and farm and farm building owners according to their categories. A successfully completed questionnaire should yield answers which can be totalled to provide an overall damage figure.

Using the synthetic method, flood losses are calculated independently of a particular flood experience and independently of assumptions about damage averted by emergency actions. Although this method is preferable for a country with limited historical flood data, the disadvantages of the synthetic approach are the difficulty of incorporating every facet of flood damage into the standard data to allow for all flood event variables (velocity, effluent content, etc.). Also, the resulting data may not always be applicable to the area of concern, which might be particularly high quality or third rate. However, the advantages include not having to rely on the vagaries of historical data while still retaining the savings in resources arising from standard data rather than other approaches [14].

In this review, the assessment of flood damage is limited to considering only direct and indirect tangible damage, as the intangible damage assessment is very complicated and difficult to quantify due to its subjectivity [11]. The estimation of flood–damage function in previous study mostly concentrates on two variables, i.e. depth and duration of flood. Hence, it is suggested that other variables, such as velocity of flow, warning times and responses, and types, price, and different design of building, should also be taken into account in future research.

5 Conclusion

Assessment of flood damages is a fundamental step for the economic analysis of a flood control project. Moreover, the assessment of flood damage is gaining greater attention as nowadays flood risk management is becoming the dominant approach of flood control policies. One approach of flood damage assessment is to develop a flood–damage function, which relates flood damage to flood inundation parameters for different classes of assets. Synthetic method is the preferred method in constructing this for a developing country like Malaysia which has limited history/actual flood damage data. This presented review can be a starting point in producing Malaysia's very own flood loss estimation procedure that can be used as a tool for flood management practice.

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