



# Comparative analyses of flood damage models in three Asian countries: towards a regional flood risk modelling

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## Abstract

The use of different approaches in the development of flood damage models in various countries is expected to affect flood damage modelling at a regional or global scale. Since these models are often used as tools for disaster management and decision making, it is very needful to understand the comparative similarity and differences in countries' loss models; this can help in the overall integration for developing regional risk models and cross-country risk assessment. In this study, empirically generated generalised loss models in three Asian countries (Sri Lanka, Thailand and Japan) were compared and applied to estimate potential flood damages in two different urban river basins. For each case study, each model was normalised using cost prices and floor areas (as applied to each country) and were integrated within the Geographic Information Systems (GIS) to estimate damages for the flood events. Using the mean vulnerability index of corresponding building types for the selected countries, a single model for regional flood risk assessment was created. However, the study showed that there are variations in the vulnerability and the potential flood damage estimates of similar global building types from the three countries, despite being developed by the same approach. These are attributed to the country's specific conditions such as building regulations and codes, GDP per capita, cost price of building materials. Our results suggest that the average vulnerability index from the countries however reduced potential errors in the estimates. Moreover, it is proposed that the average regional vulnerability model derived with empirical data inputs from all the countries for regional risk assessment and cross-country comparison. Therefore, it can predict near accurate potential flood damages, which can serve as measures for regional flood disaster risk management plans.

**Keywords** Risk · GIS · Flood damage · Vulnerability

## 1 Introduction

Floods are the most frequently occurring environmental hazards in the world, which have been on the rise in the recent decade with the highest risk concentration in Asian countries (UNISDR 2009). Urban cities in Asia and Pacific regions are generally prone to flood due to geographical locations within the floodplains, climate change and land surface change. Cases of devastating floods hazards have been reported in recent years and have resulted in many casualties and damages (Ahmed and Suphachalasai 2014; Fahmida 2005; Richard 2014). These are often attributed to the increased population growth, development and wealth in the flood-prone areas (Carby 2014; Jongman et al. 2012; Richard 2014). UN DESA Population (2012) reported that half to two-thirds of Asia's cities with 1 million or more people are exposed to multiple hazards such as floods and cyclones. Cities like Tokyo in Japan, Delhi in India and Shanghai in China, etc.,

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are all located within floodplain and are prone to high risk of floods (Hijioka et al. 2014; UN DESA Population Division 2012). It is projected that by 2070s, more population of top Asian cities would be more exposed to coastal flooding due to increasing population and wealth creation (Hanson et al. 2010). Due to the prevailing disasters in this region, concerted efforts have been made towards regional cooperation in data sharing, disasters monitoring and damage assessments (Richard 2014). In order to proffer solution to the recurrent floods and the associated risks, the United Nations Office of Disaster Risk Reduction (UNISDR) proposed regional loss models for regional assessment of floods and the natural disasters' risk. This development informed the establishment of benchmark regional models by the regional risk experts during Global Risk Assessment Workshop in Australia, using expert approach (Masqsood et al. 2013). These models can serve as metrics for comparing risk from country to country within the region, which can form basis for common policy decision for adaptation and mitigation measures, and disaster risk reduction (Masqsood et al. 2013; UNISDR 2013b).

Flood damage model, otherwise known as loss function, vulnerability or stage-damage curve is a generally accepted tool for assessing both already occurred or potential flood damages at local and regional levels. It forms a focal point in flood damage modelling. Loss function explains the relationship between flood damage states of the exposed objects and flood inundation characteristics; a measure of how susceptible the element at risk (exposure) is to the flood hazards (Dutta et al. 2003; Herath et al. 1999; Herath and Wang 2009; Su et al. 2005; Tapia-Silva et al. 2011). Generally, loss functions are developed based on the influence of the inundation depths. Other rarely used flood characteristics are flow velocity, sediments load, warning time and awareness, winds and duration of inundation (Dutta and Herath 2001; Herath et al. 1999; Herath and Wang 2009). These factors are often neglected in damage modelling due to their heterogeneities both in space and time and as such, difficult to predict, hence the frequent use of flood water depths (Merz et al. 2010).

The unit loss model (damage function) was first developed in 1960s by the United States of America (White 1964) followed by the United Kingdom (Penning-Rowsell and Chatterton 1979), Australia (Smith and Greeaway 1988) and Japan (Dutta and Herath 2001; Dutta and Nakayama 2009; MOC 1996). Some other researchers have developed various methodologies for loss and damage estimation using different methods (Chormanski et al. 2011; Dutta et al. 2003; Herath and Wang 2009; James and Hall 1986; Jonkman et al. 2008; Salimi et al. 2008, Su et al. 2005; Tapia-Silva et al. 2011). Two main methods are usually adopted in the development of flood loss models: the empirical and synthetic method. The earlier is based on the use of damage data from

after flood events while the latter is dependent on the expert judgment via what-if-questions. Stage-damage functions are usually developed for various categories of the exposures using different statistical fitting models (e.g. polynomial, linear, square root) (Freni et al. 2010; Notaro et al. 2014).

Many countries, research agencies and insurance companies have developed loss models for various purposes such as flood insurance, estimation of future (potential) flood damages, land-use planning and calculation of cost–benefit analysis for investments in risk prevention (Jongman et al. 2012). Due to the variations of loss functions from country to country, especially in the classification of damage categories and methodological approaches (Jongman et al. 2012), which cannot be used for the assessing and comparing risk globally, there is the need for unified loss model from the same approach (UNISDR 2013b). A unified loss function would enable common parameters flood risk assessment general procedure, which then allow comparison between countries. This is a need to produce general classifications and ranking between countries, comparing the level of disaster risk for clear understanding of needed measures for risk reduction and preparation for disaster (CIMNE et al. 2013). However, the current procedure of flood risk evaluation (GIS, field survey, flood model, damage function) will remain similar. The main contribution of the unified loss function lies in the unified damage function estimation. Currently, loss function are country specific (i.e. costly to produce, complex to compare between countries) therefore a unified loss function will allow comparison as well as function transfer with a minimal parameter modification. According to UNISDR (2013a), the global risk model would provide comparable disaster risk metric for all countries in the world. Assessing global disaster impact of flood hazards using common methods of evaluation would help international organisations such as World Bank, United Nations-UNISDR and World Meteorological Organization (WMO) to assess the risk level of each country equally for risk reduction processes and analyses, and for adaptation and mitigation measures.

Defining flood loss functions at regional or global level is a huge and difficult task as it requires data input from various countries either through both expert-based approach and administration of questionnaires to the flood-affected basins. Most studies on flood damage estimation made use of aggregated loss functions for classified group of damage categories (e.g. residential, commercial or non-residential structures) (Dutta et al. 2003; Herath et al. 1999; Islam and Ado 2000; Tang et al. 1992); but, for regional or global comparison, a more detailed categories would be required. Generally, for similar building structures, the damage or loss to flood would depend on the construction methods, materials and strength, which varies from country to country, hence the need for inputs from

various countries for the development of such regional model (Jaiswal et al. 2011). It is expected that classified flood loss curve by material construction categories can lead to unify loss model function that can present cross-country characteristics. Nevertheless, the new unified function may result in wrong results, due to the non-captured of damage or non-damage that are not related to the building material. For example, the use of flood counter-measure such as pillow elevation is not captured by the current loss function parameters. However, we should bear in mind that detailed category such as building construction material presents strong physical-based assumption, such as material resistance to collapse and capability to support water; therefore, it should be one of the primary parameters related to loss function. In addition, construction style will most likely present larger variability in wood than concrete because concrete construction presents higher construction constrain. Moreover, specific country-based loss functions are too specific for comparability between countries therefore, there is no tool available currently. The incorporation of different countries will therefore lead to a list or a collection of comparable and physically based parameters.

This study presents a comparative analyses of empirically established generalised loss models from the three selected river basins in Asia Pacific region (Ichinomiya, Japan; Chao Phraya, Thailand and Kelani, Sri Lanka), with a view to understand their various susceptibilities to flood hazards and for possible integration for a common loss model, and for regional flood risk assessment. Due to data limitation, only three countries were considered. The research questions to be addressed in this study are as follows:

- How comparable are structural loss functions from different countries?
- How much differences are expected by transferring loss functions from one country to another?
- Can near accurate estimates be achieved by integrating similar structural loss functions from different countries for regional flood damage modelling?

The research objective is to address the previous questions such as comparing similar structural functions from different countries. Moreover, we investigate potential of transferring of loss function in basin that belong to different countries assuming that the building classification (wood–concrete) is a most determinant parameter. This research benefits from two primary datasets collected from intensive field survey by the authors during field campaign. Therefore, new damage curves based on specific basin were elaborated. Finally, multiple damage curves generated from different river basins allow their comparison.

## 2 Methodology

This study made use of the established loss models from Sri Lanka, Thailand and Japan. The methodology followed general framework for the flood damage estimation, which makes use of GIS approach to integrate potential flood hazard's characteristics (flood water depths), the vulnerability (loss functions) and exposure (land use) attributes. The following steps are followed for each river basin:

1. GIS system development of each basin
2. Data collection through survey
3. Cost function computation
4. Transferred loss model normalisation

Existing global building classifications as specified by the World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR), which have been adopted by UNISDR, were used. Spatial distributions of the exposures in the study areas were mapped with remote sensing image classification method. Event-based flood inundation for both Kelani river basin, Sri Lanka and Ichinomiya river basin, Japan were predicted using hydrological (SHER) and GIS grid-based (Flo 2D) models. Based on the flood inundation prediction, flood damage survey was done in Sri Lanka and Thailand using questionnaire survey in the basins. Questionnaires were designed to capture economic impacts of previous floods to the classified global residential building exposures and the experienced water depths in the study area. Using regression modelling, the data collected were processed to establish loss functions based on the relationship between global building structural damage ratio and water depths. The established damage models for global building types in the three study areas were quantitatively compared, integrated and applied to two of the three locations: Sri Lanka and Japan. Similar structures common to each country were compared by (i) using their damage index at the same water depths, (ii) applying the loss models to estimate damages in other country and (iii) averaging the structural damage ratio for the combined structural damage models and compare with the individual country models.

### 2.1 Case studies and loss models

In order to compare loss models from the selected countries, similar structural loss models were developed using empirical approach through questionnaire surveys in the three river basins: Kelani, Sri Lanka; Chao Phraya, Thailand and Ichinomiya, Japan. Table 1 summarised the household sampling (i.e. interview) use for the field data collection.

**Table 1** Surveyed households versus basin population

River basin	Survey household number	Total basin population (in millions)	References
Kelani (Sri Lanka)	297	5.602 (2015)	Mahagamage and Manage (2015)
Chao Phraya (Thailand)	120	23 (1996)	UNESCO (2003)
Ichinomiya (Japan)	<sup>a</sup>	0.144 (1995)	Dutta et al. (2003)

<sup>a</sup>Japanese loss function was developed from the accumulated averaged and normalised data published by the Japanese Ministry of Construction (Dutta et al. 2003)

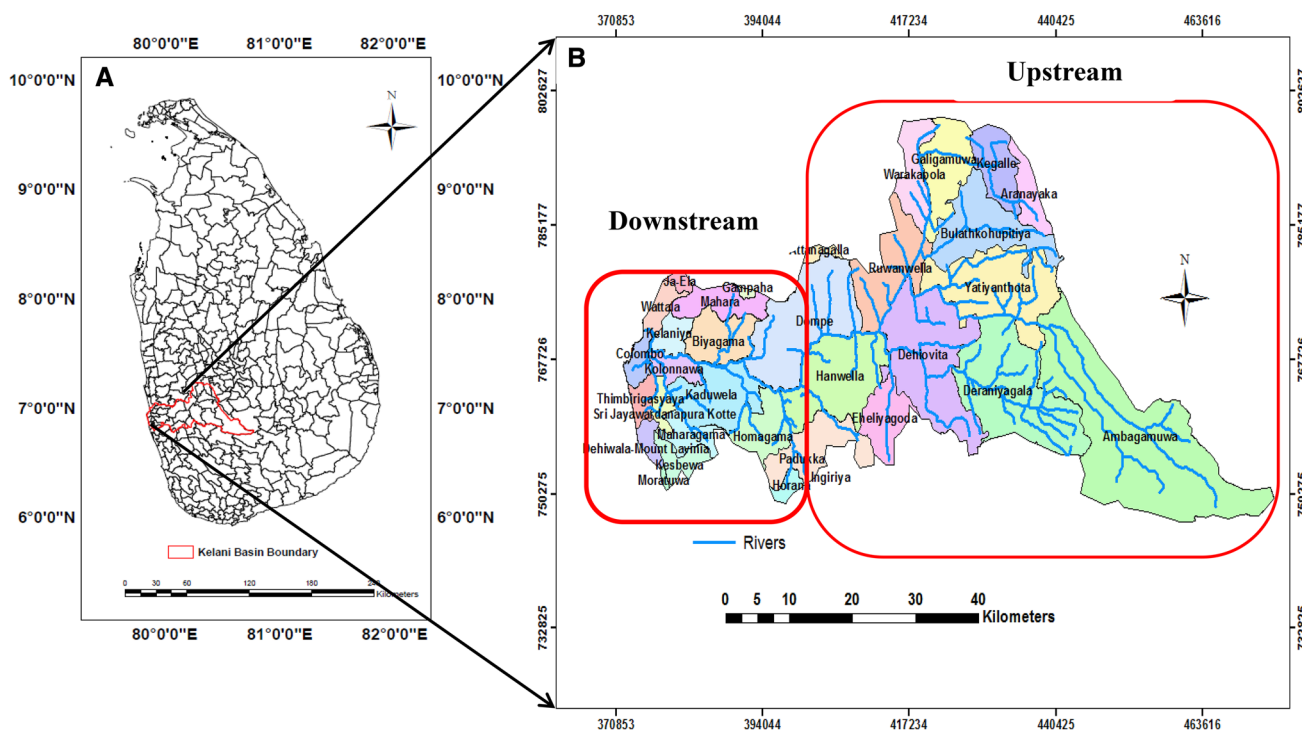
**2.1.1 Sri Lanka**

The cases studies and applications were done in Kelani river basin, Sri Lanka (Fig. 1). The river basin has experienced various degrees of flooding in the past. Historical events in 1989, 1992, 2005, 2008 and 2010 left an indelible destruction to properties in the basin. The May 2010 flood event was documented extensively by the Ministry of Disaster Management, in collaboration with the World Bank (DMC 2010). Flood impacts in the form of damages and losses during this period were estimated at LKR 5059 million (about US\$ 46 million). These recorded flood damages make it straightforward to validate the established loss models, and provide opportunity references. In Kelani river basin, Sri Lanka, detailed loss functions were developed for global exposures by the authors using empirical approach through questionnaire survey, with the aim of providing tools for

estimating differentiated detailed flood damages to structural elements at risk and also for cross-country risk comparison.

A total of 297 flood damage data were collected in the study area on the economic loss impacts on the most recent floods. Table 2 shows the basic questions included in the questionnaires used for the field survey. The data include different building classes, repair and replacement costs of the building structures, with their corresponding flood water heights, water duration and building floor areas. The existing structures in the study area were recorded with their corresponding flood water depths and damage variables. From this, damage to structures was calculated based on structural damage ratio, which is the ratio of the repair cost of the structure after the flood event to the replacement (actual) cost of the structure as expressed in Eq. (1). (Komolafe et al. 2018a, b).

$$\text{Structure damage ratio (\%)} = \frac{\text{Repair cost}}{\text{Replacement cost}} * 100. \tag{1}$$



**Fig. 1** a Sri Lanka boundaries map. b Kelani River Basin

**Table 2** Sample questionnaire survey

<b>Interviewer Information</b>			
1. Interview Date.....			
2. Name:.....			
3. Interview number.....			
4. Location Coordinates: Northing..... Easting.....			
<b>SECTION A: Interviewee Information</b>			
<b>Please tick one : Residential Building ( ) Commercial Building ( )</b>			
<i>For Residential Building</i>			
5. Name .....			
6. No of family members.....			
7. Age.....			
8. Sex: Male (M) ( ) Female (F) ( )			
9. Educational Level: No education.....Primary..... High School..... Graduate.....			
10. City.....			
11. Primary occupation/work ( tick as applied): Farming ( ); Hired Labour ( ) Civil Servant ( ); Business ( ); Private company ( ); Trading ( ); Fishing ( )			
12. Secondary occupation/work: Farming ( ); Hired Labour ( ) Civil Servant ( ); Business ( ); Private company ( ); Trading ( ); Fishing ( )			
<i>For Commercial Building</i>			
13. Contact Person's Full Name: .....			
14. Contact Person's Title.....			
15. Company name .....			
16. No of employees, if applicable.....			
17. Type of business (e.g. Store, services, computer accessory etc.).....			
18. City: .....			
19. Year of business establishment in this location .....			
<b>SECTION B: Exposure Characteristics</b>			
20. Building types: Single ( ), Attached house ( ), Flat ( ), Duplets ( ), Town House ( ), Row House/line rooms ( ), Hut/ shanty ( ), others.....			
21. Building Materials: Wooden ( ), Steel ( ), Concrete ( ), Bamboo and Thatch ( ) Adobe ( ), Brick ( ), Mixed Structure ( ); others, please specify.....			
22. Building classifications based on Global building construction types. Please tick the appropriate category the building falls below.			
No.	Category	Description	Please tick
1	Wood	Wood	
2	All Steel structures	Steel Light Frame	
3	All Concrete frames	Concrete Frame with Unreinforced Masonry Infill Walls	
4		Reinforced Concrete Moment frame	
5		Reinforced Concrete frames and concrete Shear	
6	All Masonry	Unreinforced Masonry Bearing Walls	
7		Reinforced Masonry Bearing walls	
8	Adobe	Adobe (made of sand, water, clay etc.)	
9	Slab	Flat Slab Structure	
23. Age of building: .....			

Loss functions were developed for three global residential building exposures (wooden, unreinforced masonry walls (URM) and concrete frame with unreinforced masonry walls

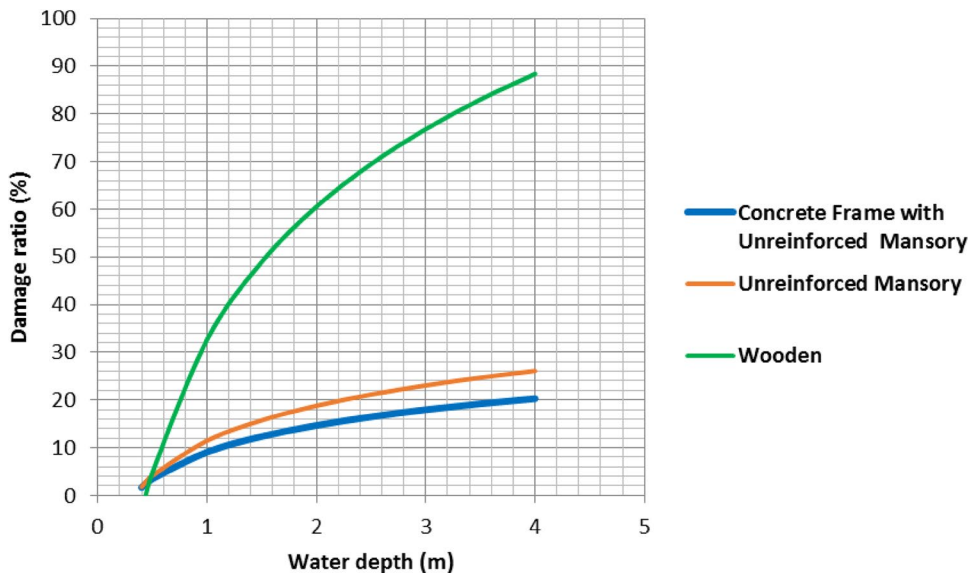
(CFURM)) based on the relationship between flood water depths and the structural damage ratio (Fig. 2) (Komolafe et al. 2018a, b). In this study, the established loss models in



**Table 2** (continued)

24. No. of stories .....	
25. Floor Heights: First floor.....(m) Second floor.....(m)	
26. Building floor area: .....	(sq.m)
27. Plinth height, if any.....m	
<b>SECTION D: Memories of Past Flood Events (Damages and Economic Losses)</b>	
28. Date of flood event: Day..... Month..... Year.....	
29. How many times did you experienced flood in the past?.....	
30. Maximum Water Heights: i. Ankle..... (m); ii. Knee.....(m); Hip.....(m); Breast.....(m); Head.....(m); First floor flooded.....(m); Second floor flooded.....(m)	
31. Maximum flood duration .....	(hours)
<b>Damage to Building Structure</b>	
32. Repair cost of the building structure .....	(LKR)
33. Replacement cost of building structure.....	(LKR)
34. Degree of Damage to building structure (please circle): No Damage (0%); b. Very low (< 10%), c. low (10%–20%), d. Moderate (20–50%), high (50–70%), e. Very high (70–80%), d. extremely high, irreparable (90–100%)	
35. Insurance payment received for the building structure, if any.....(LKR)	
Stereo Equipment	
Desk	
Fan	
Air Conditioner	
Bed/Mattress	
Drapes/Curtains/Blind	
Clothes	
Others (specify please)	

**Fig. 2** Depth-damage functions developed for the Kelani river basin in Sri Lanka



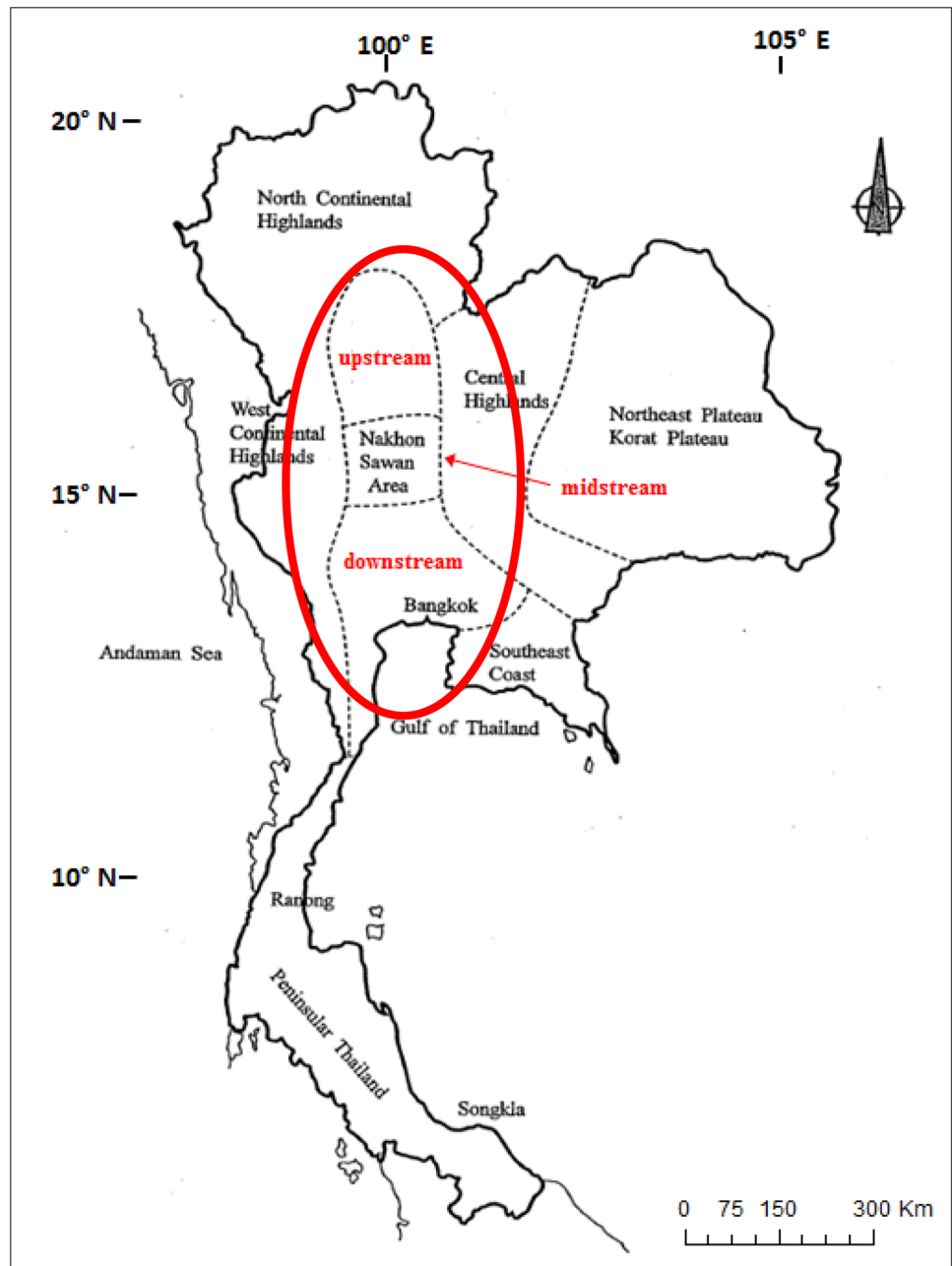
the basin will be quantitatively compared with other similar loss models from the three countries and integrated for possible regional flood damage modelling.

**2.1.2 Thailand**

Location considered in Thailand is in Chao Phraya river basin (Fig. 3). This basin, which is very prone to flooding, has witnessed previous flood events. The most recent of these flood events was in 2011 with devastating damages estimated at about US\$ 46 Billion Thailand Ministry

of Finance (2012). Loss functions for three global building types (wood, reinforced concrete moment frame and concrete frame with unreinforced concrete (CFURM)) were developed in this basin by the authors through a detailed field survey (Fig. 4). A detailed questionnaire survey was designed to gather data on recent impacts of flood on urban residential buildings in the study area. The questionnaire captured the economic impact of floods, flood parameters (water depths and duration), exposure characteristics (floor area, plinth heights, building heights) and external flood disaster prevention factors (flood experiences). Damage survey

**Fig. 3** Study location of the Chao Phraya river basin in Thailand



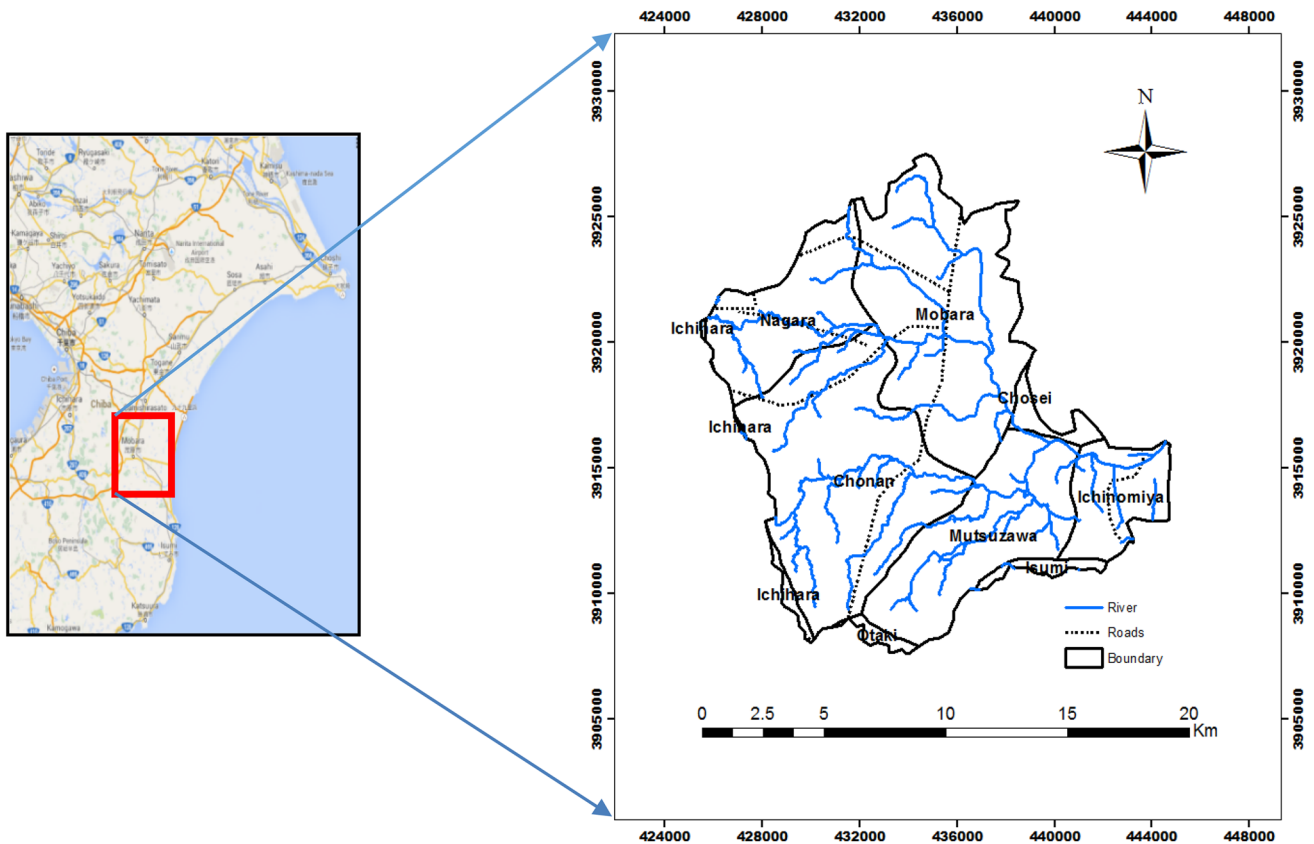
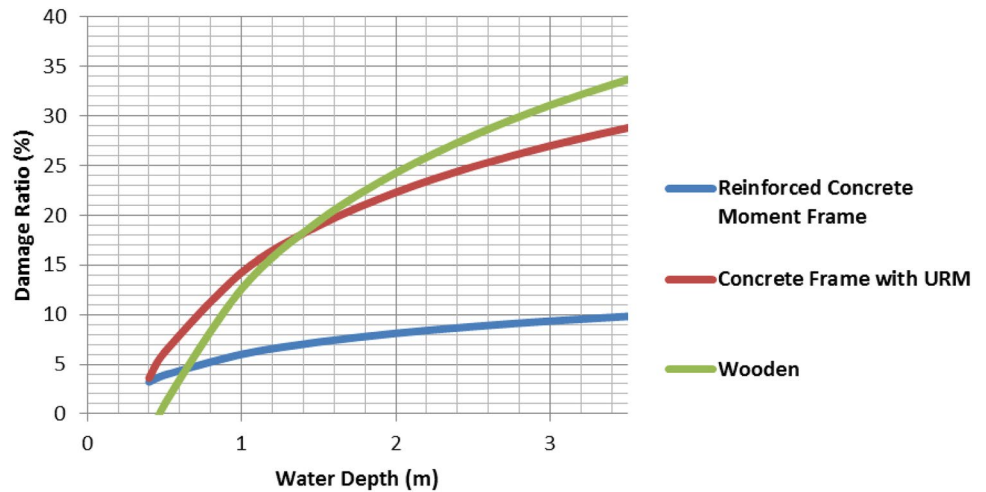
was done with the aim of establishing relationships between flood damages and the potential damages parameters, and the construction of stage-damage curves (loss functions) for global residential building types.

A total of 120 residential houses were surveyed with three global building structural types identified. Identified building structures and their corresponding numbers surveyed are (i) Concrete frame with unreinforced masonry infill (77), (ii) Reinforced concrete moment frame (39) and (iii) Wood (4). The economic losses to the structures with their corresponding water depths were measured, recorded and plotted (Fig. 4).

### 2.1.3 Japan

Ichinomiya basin in Chiba prefecture was used for the application in Japan (Fig. 5). Like other river basins in this study, Ichinomiya river basin has previously experienced floods. In 1996, the basin witnessed a huge disaster resulting from a heavy typhoon, which resulted in many damages as reported by the Japan ministry of construction (MOC) (MOC 1996). In Japan, over the years, the Ministry of Construction in Japan, based on standard procedure, publishes economic damage estimate for each flood event (Dutta and Herath 2001; Dutta et al. 2003; MOC 1996). These regularly

**Fig. 4** Depth-damage functions developed for Chao Phraya river basin, Thailand



**Fig. 5** Location and map of the case study area in Japan

updated damage data are used for establishing loss curves for flood damage forecast throughout Japan and form key element in flood disaster risk reduction planning.

Flood damages in Japan are categorised as (i) General Assets, including residential and commercial structures and content, farmhouses and fisherman houses structure and content damage; (ii) Damage to crops and (iii)

Public infrastructure, which include rivers, streets, roads, railways, bridges, infrastructure of farms, telecommunications and power supply (Dutta and Herath 2001; Dutta et al. 2003). Residential structures are classified into two types: wooden and non-wooden. The non-wooden are made up of steel frame with reinforced concrete, steel frame and reinforced concrete structures, others (e.g. masonry, brick,



plain concrete, plain concrete block) (MLITT 2001). Dutta et al. (2003) developed various functions for Japanese flood damage categories, based on the averaged and normalised data retrieved from the Japanese Ministry of Construction (MOC), acquired from flood damage surveys. In their research, loss curves were developed for two categorised residential structural damages: residential (wooden) and residential (non-wooden) (Fig. 6).

Due to the original/initial aggregated nature of the latter data (non-wooden), it is practically impossible to incorporate into regional risk modelling, cross-country risk comparison and detailed structural vulnerability analysis since there are variations in buildings’ structural components from country to country and susceptibility of structures to flood water. This informed the need to simplify the loss function of the non-wooden structure to global structures available in the country. The non-wooden structure was disaggregated into three prominent non-wooden structures in Japan: steel frame with reinforced concrete, steel frame and reinforced concrete using spatial based approach, incorporating the building distribution ratios. In addition to the disaggregated functions, existing wooden loss function was included in the comparative analyses in this study.

## 2.2 Data analysis

The established damage models for global building types in the three study areas were quantitatively compared, integrated and applied to two of the three locations: Sri Lanka and Japan. Similar structures common to each country were compared, firstly, using their structural damage ratio at the same water depths; secondly, applied the loss models using Geographic Information Systems (GIS) to estimate damages in other country by normalising with

the floor area and the country’s cost price and thirdly, calculation of the average structural damage ratio for the combined structural damage models and comparison with the individual country models. In this study, only common structures that are applicable in two or three countries were utilised for the risk comparison and integration (Table 3). Therefore, loss functions for wooden, concrete frame with unreinforced masonry walls (CFURM) and reinforced concrete only were considered. Damage models were not applied to Thailand due the lack of basin characteristics data for flood simulation.

### 2.2.1 Structural damage ratio

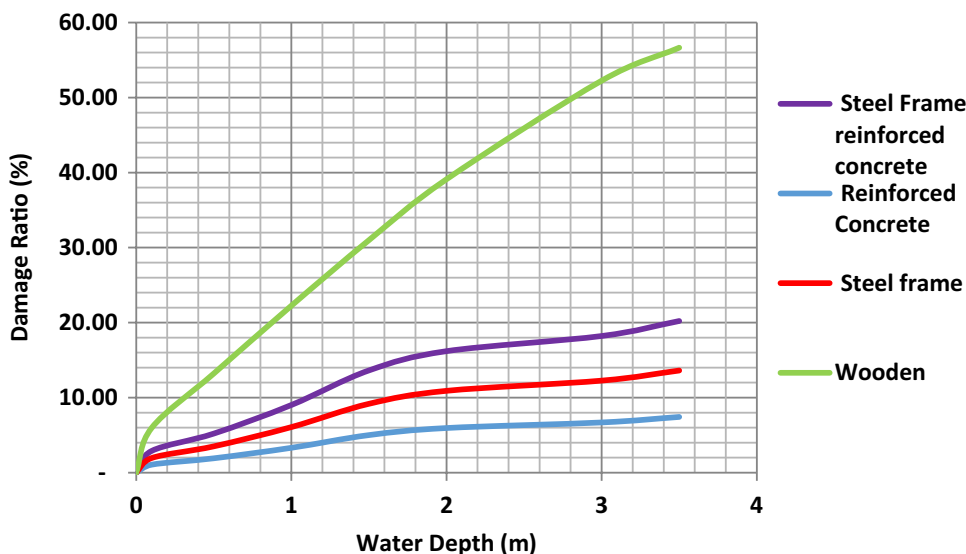
Structural damage ratio at different water depths are determined by dividing the structural damage ratio by 100. The values range from 0 to 1 and show the damage characteristics or vulnerability of each structure from the selected country to flood water.

**Table 3** Structural loss functions and their selected countries for risk comparison

Country	Wooden	Concrete frame with unreinforced masonry walls (CFURM)	Reinforced concrete
Sri Lanka	Yes	Yes	No
Thailand	Yes	Yes	Yes
Japan	Yes	No	Yes

“Yes” means loss functions—the global building types are applicable in the country, whereas “no” means they are not applicable

**Fig. 6** Disaggregated depth-damage functions and wooden function for Japan after Dutta et al. (2003)



## 2.2.2 Transferability and application of loss models to other countries

The transferability and applicability of the three global exposures' loss functions considered in this study was demonstrated by using specific function to estimate flood damages in another country where such global structure exists. Kelani river basin in Sri Lanka and Ichinomiya river basin in Japan were used for the loss models application and transfer.

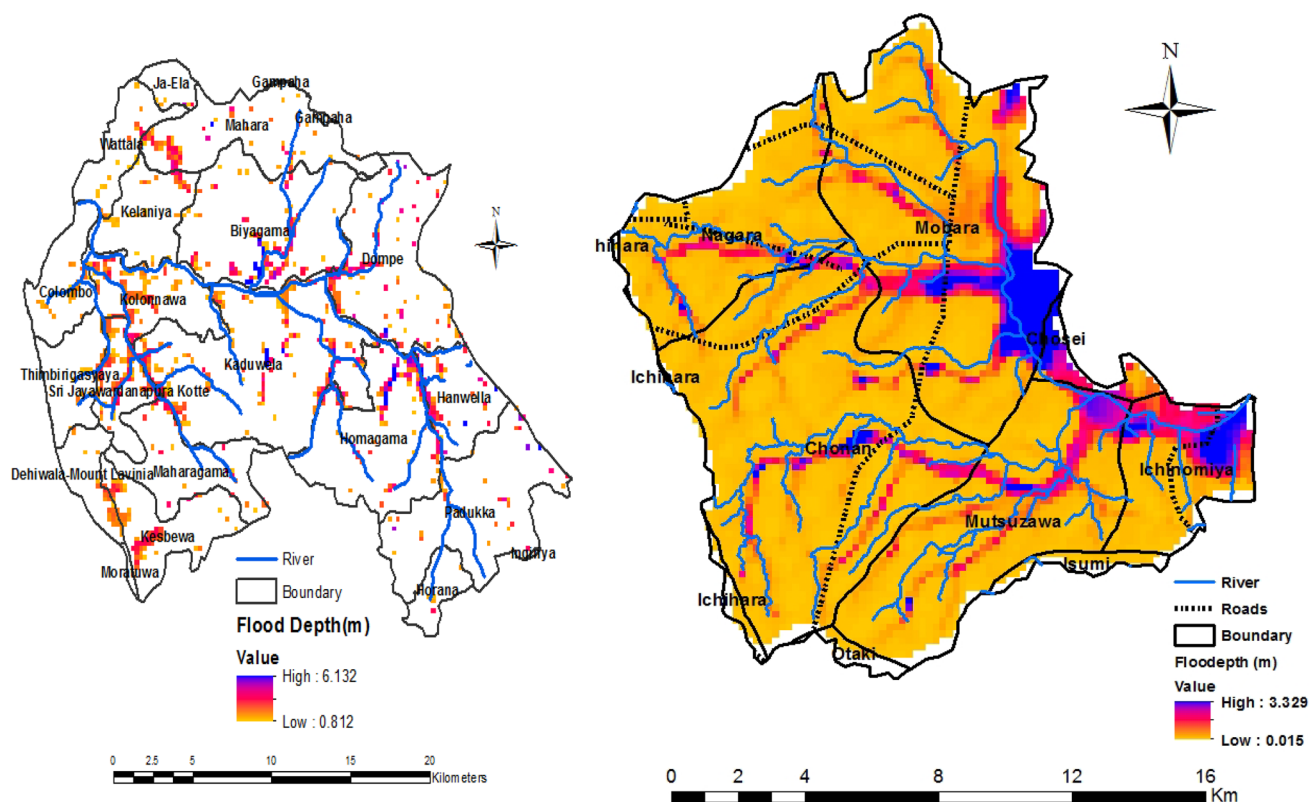
## 2.2.3 Inundation data

Event-based flood simulation was adopted for validation purposes. May 2010 and September 1996 flood events were simulated for Kelani river basin, Sri Lanka, and Ichinomiya river basin, Japan, respectively. Flood simulations for both case studies were done in FLO-2D model, an integrated GIS and hydrological and a volume conservation flood routing model that can be used to simulate overland and channel flow over a complex topography. It is a physical process model that routes rainfall-runoff and flood hydrographs over unconfined flow surfaces or in channels using the dynamic wave approximation to the momentum equation (Flo-2D 2009). In Sri Lanka, the downstream of the river basin, which consists of most the urban areas and is often flooded, was simulated, while the upstream

acts as the inflow to it (see Fig. 1b). The inflow hydrology to the downstream was validated with the observed discharges of 2010 event. Model calibration was done by tuning the simulation parameters to fit the observed data. The simulated flood inundation extent was validated by the observed flood map of the study area from ALOS PALSAR 1.5 data product, by Japanese Aerospace Exploration Agency (JAXA) Resolution at 6.3 m ground resolution, on 18 May 2010. For the Japan case, the hydrology data input to the model was basically rainfall data of the flood events. The historical rainfall data within the period of the September 20–23, 1996 flood events, were simulated over the selected basins terrain using FLO-2D Flood model. Figure 7a, b shows the simulated flood hazards for Kelani river basin and Ichinomiya river basin, respectively.

## 2.2.4 Land use

The land use in this study was extracted using earth observation data (Landsat-8-OLI and the Advanced Visible and Near Radiometer type 2 (AVNIR-2)). Landsat-8 OLI (30 m resolution) was used in Sri Lanka and AVNIR (10 m resolution) in Japan. The land cover analysis was carried out using Maximum Likelihood (ML) Supervised Classification in ArcGIS classification tool. ML is the most powerful and commonly used algorithm for image classification (Nicholas, 2005); it



**Fig. 7** Simulated flood hazards in **a** Kelani river basin, Sri Lanka and **b** Ichinomiya river basin, Japan

makes use of both variances and covariance of the class signatures to assign each cell to classes in the signature file. Training classes were generated from the existing land-use datasets by Japan Aerospace Exploration Agency (JAXA) (JAXA 2014) and Google Earth, and classification was done interactively in ArcGIS by ensuring accurate picking of the right pixels for classification. The Interactive Supervised Classification tool gives opportunity to carry out supervised classification without explicitly creating a signature file. In Sri Lanka, due to inhomogeneity of the urban land covers and lack of high image resolution, three basic land cover indices—water, built-up and vegetation, were integrated using principal component analysis to extract the built-up areas of the basin (Fig. 8a). Generally, in Japan, the basin consists of urban area, vegetation, grass, water bodies and agricultural lands. The urban area is largely situated downstream (lowlands) with flat topography; these areas are most vulnerable to flooding in the past, with severe damages. The forest areas, which constitute highest proportion of the entire coverage, serve as watershed and are distributed mostly upstream of the study area (Fig. 8b).

### 2.2.5 Damage models

Three loss models for wooden, reinforced concrete and concrete frame with unreinforced masonry walls (see Figs. 2, 4, 6) were transferred and applied to Sri Lanka and Japan. The Japan and Thailand wooden loss functions were applied to Sri Lanka. The Japan wooden loss function was extracted from the work done by Dutta et al. (2003). In case of reinforced concrete, Thailand loss function was transferred and applied to Japan; the concrete frame with unreinforced concrete frame (CFURM)’s loss function for Thailand was applied to Sri Lanka.

### 2.2.6 Transfer of loss models and damage modelling

Damage estimation was carried out using GIS-based mathematical model, linking the loss models, inundation depths and the land use. The transferred loss models were normalised by the prevailing cost price in each country and the floor area using the following equation:

$$D_{s(i,j)} = \sum_{k=1}^n [BD(i,j,k) * BR(i,j,k) * FA(i,j,k) * EC_s(i,j,k) * C_s(i,j,k)], \tag{2}$$

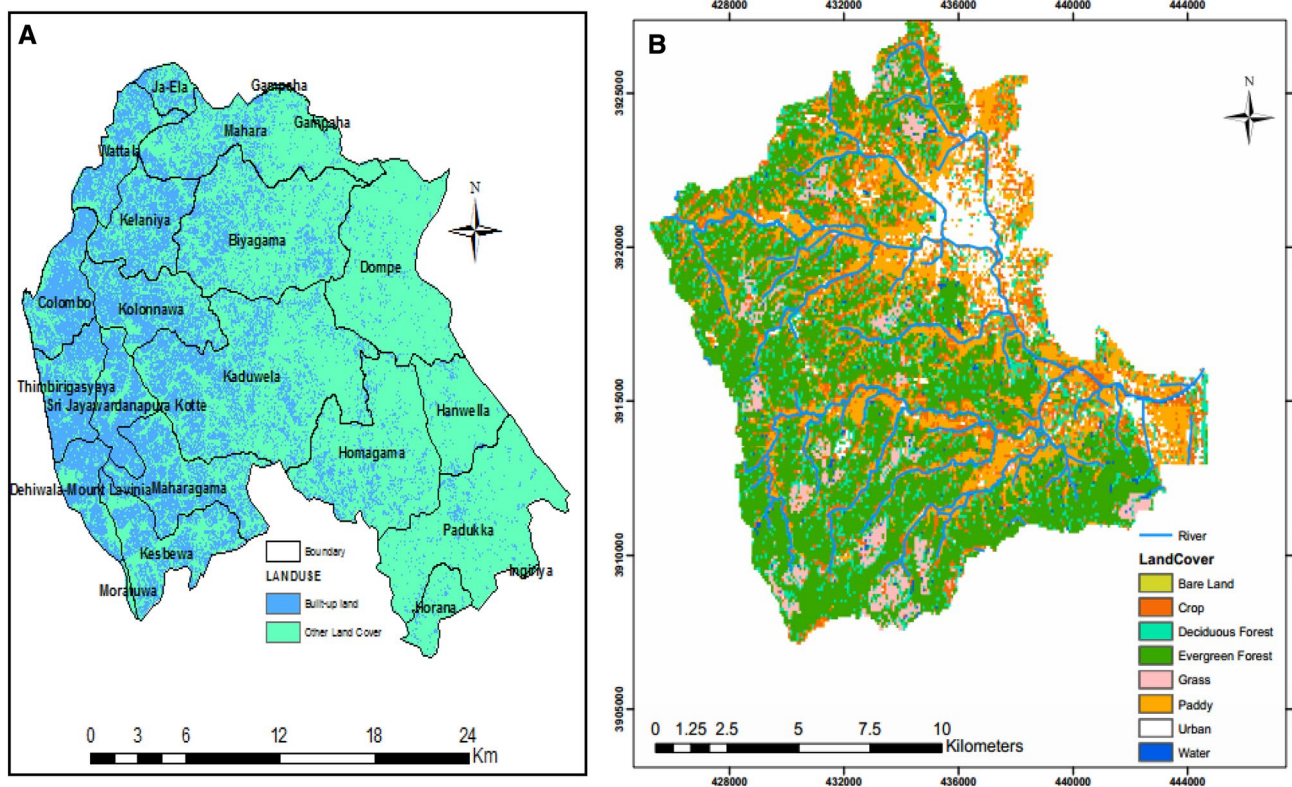


Fig. 8 Land cover in a Kelani river basin, Sri Lanka, b Ichinomiya river basin, Japan

where for any grid  $(i, j)$ ;  $D_s(i, j)$  = total damage to structure,  $n$  = total number of types of building structure,  $BD(i, j, k)$  = building density (building units/km<sup>2</sup>),  $BR(i, j, k)$  = ratio of building type  $k$ ,  $FA$  = average floor area per building unit of structure type  $k$ ,  $EC_s$  = estimated cost of a building of structure type  $k$  per unit area,  $C_s$  = depth-damage function for building structure type  $k$ . In Sri Lanka, we simulated flood damages based on the price of \$165 per square metre for CFURM, and \$50 per square metre for wooden structures according to building construction associations. We used the average floor area of 500 square feet (46 m<sup>2</sup>) as reported by the Census and Statistics Department (2012). Damages were simulated using 30 \* 30 m<sup>2</sup> and 50 \* 50 m<sup>2</sup> grid resolution for Sri Lanka and Japan, respectively. In Japan, the economic cost value per unit floor area of residential building obtainable from the study area as at the time of the flood event is about 0.169 million yen (\$1690) (Dutta et al. 2003). Building density (BD) is the number of building units in any given occupied area. Landsat 8 remote sensing data were used to map urban densities in the study area. The Landsat image was classified into five areas: High Dense Urban, Medium Dense Urban, Low Dense Urban, Water Bodies and Vegetation. Building densities were derived by dividing the number of buildings within each number of classes by the total area covered.

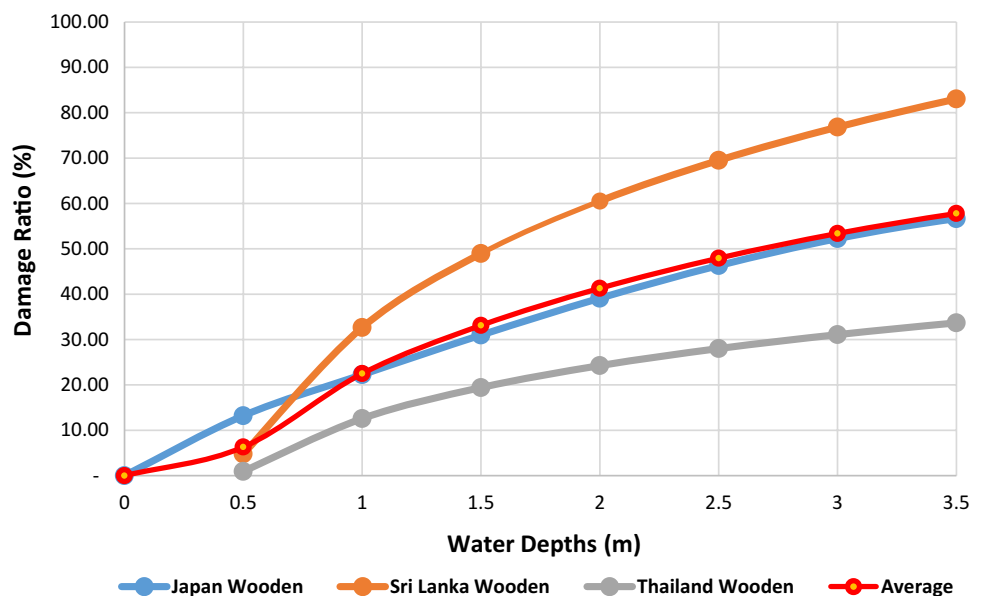
Two approaches were utilised in damage modelling by (i) transferring and applying similar structural loss functions to other country where such structures exists and (ii) using the average damage index derived from the countries to simulate damages in the applicable country. These were compared with damages estimated from the individual country's loss function and the surveyed damages.

### 3 Results and discussion

#### 3.1 Comparative analyses of structural damage indices

Wooden structures showed high vulnerability to flood hazards in the three countries (Fig. 9). At maximum water depths or 3.5 m, Sri Lanka's wooden showed higher structural damage ratio (0.83) compared to the other two countries: Japan (0.58) and Thailand (0.34). Damage rate of this structure is largely dependent on the (i) the quality of the wood materials for the walls and (ii) the elevation above ground surface. In Sri Lanka, wooden structures are rarely used as they are classified as partly semi-permanent or improved housing types, which are situated mainly in the rural areas without supporting the walls with any other building materials such as concrete or steel. These attributes could have resulted in more vulnerability index to flood hazards. Wooden structures constitute about 36% of residential structures in Japan (MLITT 2001). For many years, Japan due to the prevalent of seismic hazards in the country has engaged in constructing wooden structures that are very resistant to earthquakes and are designed and constructed using both Japanese traditional and some special engineering methods. Wooden structures that are well supported with seismic reinforcement are considered the best materials in earthquakes prone zones. Contrary to earthquakes requirement, flood hazards does have great effects on wooden structures and such would result in more damages. That informs the higher degree of damage (58%) in wooden structures in Japan. In Thailand, however, a lower vulnerability index is experienced. Two reasons for this could be (i) the lack of

**Fig. 9** Established stage-damage curves for the wooden structural types in (i) Kelani river basin, Sri Lanka, (ii) Chao Phraya river basin, Thailand and (iii) Ichinomiya river basin, Japan



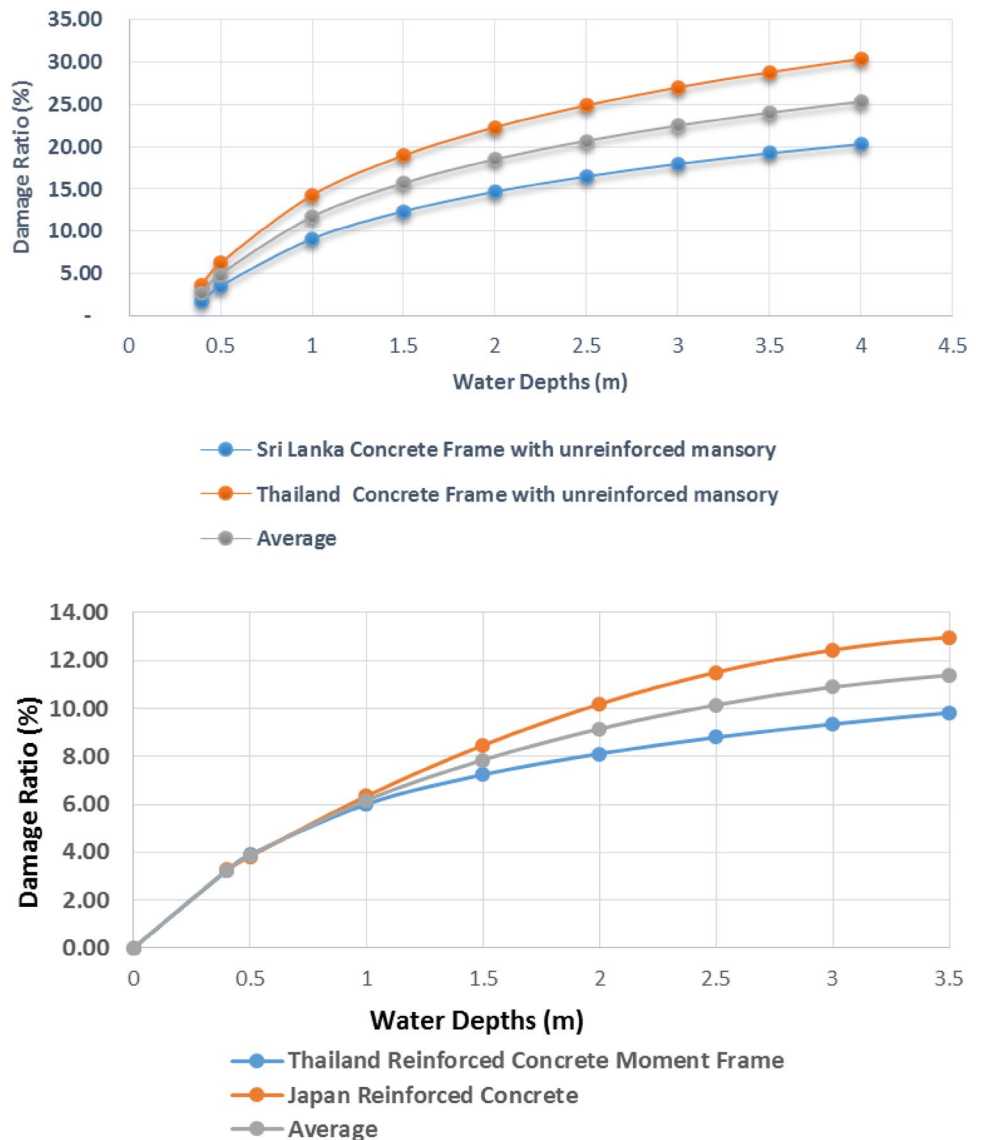


adequate and representative empirical data in the wooden category during the field survey. Only four (4) data points were used to develop the wooden structure loss model; and (ii) Thailand wooden structures are often constructed above the ground or constructed on an elevated concrete, thereby preventing immediate flood water interaction when during a heavy typhoon.

Concrete Frame with Unreinforced Masonry Walls (CFURM) structures are common to Thailand and Sri Lanka. Comparatively, the CFURM in Thailand shows higher damage/vulnerability index at each water depth than that of Sri Lanka (Fig. 10a). The significant difference in the damage indices can be attributed to the quality of building material, the level of compliance to the building codes and design and the cost of buildings materials. The Reinforced Concrete in Japan and Thailand shows almost equal vulnerability index at water depths less than 1 m

with a little disparities above 1 m. These little disparities can only be attributed to the higher cost of building in Japan compared to Thailand (Fig. 10b). In this study, it can be inferred that the wooden structures with highest vulnerability index (in all the countries) are more prone to damages due to flood hazards when compared with other two structures (Concrete frame with URM and reinforced concrete). The implication is that construction of more wooden structures within the floodplain can result in more damages and losses at any given flood events. It is, however, obvious that in some countries, building structures are erected to specified construction and engineering standards based on the prevalence hazards. In Japan, for instance, wooden structures are prominent because of its capability to resist and absorb seismic shock/tremor and thus are able to prevent damages whenever earthquake occurs. In this case, however, efforts are needed to ensure

**Fig. 10** Established stage-damage curves for **a** concrete frame with URM; **b** reinforced concrete structural types and **c** regional average in Kelani river basin, Sri Lanka; Chao Phraya river basin, Thailand and Ichi-nomiya river basin, Japan





that wooden structures within the floodplains are reinforced to reduce possible damage during flood.

### 3.2 Empirical comparison of damage estimates from country-based and transferred loss models in the selected two river basins

In an attempt to provide insight to the possibility of transferring similar regional/global structural loss models from one country to the other, simulated damages for the country-based functions and the transferred functions were compared. Using the damage function in Eq. 2, the transferred loss models were normalised in the applied country by the prevailing country’s unit cost price and the building floor area. In view of regional loss modelling, which would perhaps require a unique single regional structural loss model, the mean structural damage ratio of the selected countries’ structural models was used to estimate damages in the selected river basins.

#### 3.2.1 Kelani river basin, Sri Lanka

Sri Lanka’s wooden loss model as applied to Kelani river basin estimated damage to wooden to about US\$ 64,065, whereas the transferred wooden loss models from Japan and Thailand, applied to the same river basin returned estimates of US\$ 41,901 and 25,269, respectively (Fig. 11). The transferred Japan and Thailand models underestimated the Sri Lanka’s loss model estimates by 60% and 34%, respectively. Simulated damage from the average structural damage ratio for wooden loss models in the three countries is about US\$ 47,253. This is about 26% difference compared to Sri Lanka’s model. Damage estimated from the Sri Lankan concrete frame with unreinforced masonry walls (CFURM) loss model is about US\$ 248,096 while the transferred

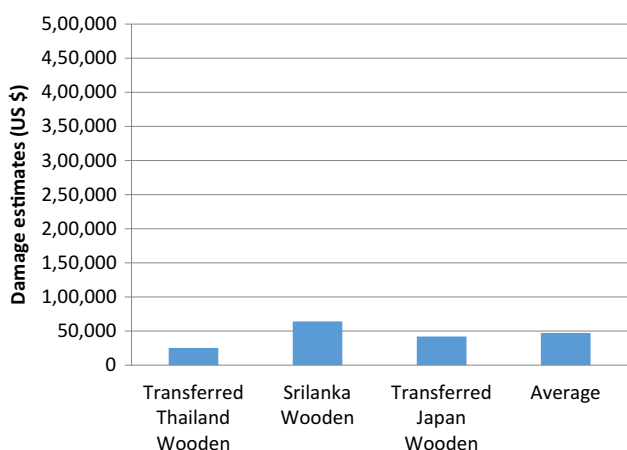


Fig. 11 Comparison between the estimated damages derived from country-based, the transferred and the average wooden loss models

CFURM model from Thailand yielded estimates of about US\$ 381,932. CFURM loss model from Thailand overestimated the Sri Lanka’s CFURM model by 54% (Fig. 11). The average structural damage ratio from the two countries predicts US\$ 315,020 damages, about 26% higher than the Sri Lanka’s CFURM model. Given the fact that the loss models in Sri Lanka were able to predict about 70% of the actual surveyed damages, the transferred wooden loss model damage estimate is by far a large deviation, whereas the CFURM would be overestimating the potential damages in the river basin with about 24% above the surveyed damages, a closer estimate than the country-based loss model. The derived average stage-damage functions for the two structural damage categories show some level of agreement with the country-based model and reduce damage estimate errors relative to the observed flood damages. For example, the concrete frame with unreinforced concrete drastically reduced error and can predict about 96% of surveyed damages in Sri Lanka (Fig. 12). However, further validation criteria should be used to improve the validation method rather than simply the damage value. First, the inaccuracy should be estimated in term of flood depth data that will first validate the hydrological model itself and then loss function could be validated in a second step. The inaccuracy comes most likely from large water depth because the depth scares. Improvement of the loss function can be done by increasing the survey size in particular with area with the lower water depth frequency sampling.

#### 3.2.2 Ichinomiya river basin, Japan

Reinforced concrete loss models from Thailand and Japan were applied in the basin. Japan loss function predicted flood damages at US\$ 445,801 while the transferred Thailand

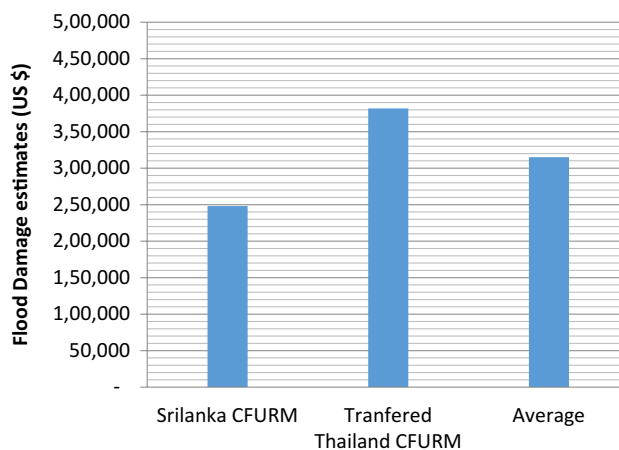


Fig. 12 Comparison between the estimated damages derived from country-based, the transferred and the average concrete frame with URM loss models

function is at US\$ 221,763; this estimate is about 50% lower than the country’s loss model. The average of the two-loss models estimated damages at US\$ 268,649 (Fig. 13). Although the vulnerability index of the two countries matches, especially at flood depth less or equal to 1 m, the greater disparity as revealed in the estimates can be attributed to the differences in the structural damage ratio above 1 m water level. As mentioned aforetime, this difference can be credited to the cost of building construction, which is likely to be higher in Japan than in Thailand. Average vulnerability index from the two countries reduced the relative errors in the transferred loss model by 10% (from 50 to 60% at 268,649\$ cost) when compared with the Japan loss model.

### 3.3 Regional flood damage modelling: associated uncertainties and possibilities

Based on the above simple loss functions’ transfer and comparative analyses, it can be alleged that estimation of flood damages at regional scale would be accompanied by some uncertainties, especially the loss models, which varies from country to country, and the resolution or scale of flood modelling.

It is true that regional risk comparison and modelling would require loss models for detailed classified global exposures applicable in all countries, but their comparability are largely affected by inevitable local factors. As demonstrated in this study, all the loss models, though similar in terms of structural characteristics and developed using the same methods, vary significantly from country to country. These variations are largely dependent on the cost of buildings, adherence to the building design codes and level of exposure to flood hazards. From the loss models transfer example, we can achieve near accurate results if country’s factors such as cost price and building floor area are

incorporated in damage modelling. Since the aim of regional risk modelling is to compare risk from country to country for regional flood risk adaptation and resilience planning, and provide metrics for accessing common adaptation sources by all countries, it is important to know as analysed in the study that the accuracy of the estimates may be undermined by the individual loss models if local factors are not incorporated. Two approaches in regional risk comparison would be to:

- i. Estimate flood damages in each country with individual country’s detailed global structural loss models. With this, damage estimates from the same categories calculated from each country’s loss model can be compared. This approach is probably the best as it reveals flood risk associated with each country, and as such reduces errors arising from loss model transfer.
- ii. Create a single regional loss model for each classified global residential building structure from the empirical damage data from all the countries within the region. As indicated in this study, the average/mean structural damage ratio from selected countries reduced the level of errors in the flood damage estimates when compared with the surveyed damage data. In order to create regional single model for each structure, therefore, concerted efforts would be required to gather empirical flood damage data from all the countries in the region.

Flood modelling at a regional scale is no reservation going to be at large spatial extent, coarse resolution and obviously less detailed information. The damage modelling components such as flood inundation depths and land use have to be presented at a coarse resolution, which can affect the results of the damage estimates and also affects the regional decision making for potential adaptation measures and risk prevention. Proposed regional modelling by UNISDR, Asia region, according to Masqsood et al. (2013) is expected to be estimated at a grid resolution of 30\*30 km<sup>2</sup>. This is a very coarse resolution with possible potential errors in the estimates. Investigation by Komolafe et al. (2018c) thus affirmed that, apart from the errors arising from spatial inputs components, spatial resolutions used in the estimation significantly affect the results of flood damage estimation. Their results indicated that accurate flood damage estimates can be achieved at a higher resolution of both flood inundation depths and land use. But, as explained earlier, regional flood modelling is at a large spatial extent and it is obvious that coarse resolution would be needed. Using a coarse resolution of flood hazards and property in flood damage estimation can lead to over and under estimation of flood damages depending on data integration approach. Therefore, as proposed by Komolafe et al. (2018c), in order to ensure near accurate estimation in modelling, land use (property layer)

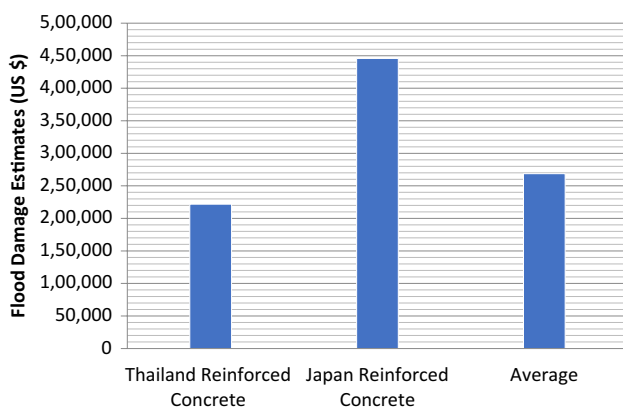


Fig. 13 Comparison between the estimated damages derived from country-based, the transferred and the average reinforced concrete loss models

must be estimated at high resolution while flood inundation is simulated at coarse resolution. This is absolutely the obvious because nowadays, it is possible to generate detailed land-use land cover maps from very high-resolution remote sensing image for a very large spatial extent, but, simulating flood depths at a high resolution is practically unfeasible due to computing resources.

In terms of monetary damage as emphasised in this study, the role of velocity is rather secondary compared to the water depths, but plays a vital role when considering dam- and levee-break floods, tsunami and storm surge inundation (Gallegos et al. 2012). However, it should be noted that the study areas considered in this research are mostly alluvial floodplain with less steepness and the account of dyke breaches were not recorded during the flood events. The flood inundations are often a result of river overflow, which may not result in much high flow velocity. In this case, the influence of velocity is insignificant as revealed by Kreibich et al. (2009). Apart from inundation depths, flood characteristic such as flow velocity can make important contribution to the structural flood damages, due to physical pressure on the building in steep terrain or aftermath of dyke breaches (Walliman et al. 2012). While it is easier to accurately measure the water level on the field for the inclusion in loss model and simulation in hydraulic model, empirical measurement of velocity and modelling can be a lot complex, which might affect significantly the final damage output (Dransch et al. 2013). It is, therefore, reasonable to adopt water depths as structural damage contributing factor in the study areas. Despite the insignificance of the velocity in the established models in the study areas considering the above background, future inclusion of flow velocity can improve the model, especially in the case of dyke breaches.

The study focused on only three out of nine building material categories in the development of loss function, both in Sri Lanka and Thailand due to strong assumption in the material construction of the countries. Indeed, the three building categories were used because they are the predominant structures in the study areas. Moreover, Bamboo and Thatch, Adobe, Brick account for a minority of construction. The Mixed Structure was not used by the survey participant; therefore, it was not investigated. Loss models in this study focused only on the direct economic damage to buildings structure, resulting from the impact of flood water depths. The impacts of velocity and viscosity were not taken into consideration.

The loss models were developed mainly as broader simplified tools or instruments for policy decision, planning and resources mobilisation towards future flood disaster risk reduction rather than exact measures of actual damage. The potential variability in flood characteristics and accuracies of their estimation in the future, and the possibilities of change in future structural responses of buildings to flood

hazards were considered in the selection of loss model's variables and categories. The generalised building characterisation was based on the international standard by the World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) as adopted by the UNISDR for global risk assessment. These categories account for various building types that are applicable in all countries and are therefore comparable. With these unified loss models, potential detailed categorised structural damage estimates can be approximated, which can be utilised to support the flood risk prevention's decision making processes. The models are very useful tools for land-use planning and building regulations, as it helps to differentiate land-use types and their degree of vulnerabilities to flood water. They are very useful tools in flood disaster risk reduction for identifying vulnerable structures in the floodplain while ensuring less vulnerable buildings are utilised within the flood zone. This is also necessary to improve the insurance system in the study areas. With these models, risk associated with different building types can be quantified and approximately estimated and can aid the flood insurance schemes before, during and after flood disasters. These are necessary for risk management, especially in (i) the financing of residual risks, which can support climate change adaptation, (ii) quick restoration and renewal of livelihood activity for the communities and individual, (iii) land-use planning, especially in the relocation of the affected people and communities to a safe location in case of future flood and (iv) the provision of coping capacity against the financial impacts of the climate- and weather-related hazards (IGES Research Report 2015).

In principle, the models can be transferred to countries with similar structural damage categories, provided they are normalised with countries' cost prices and floor area. However, as stated earlier, the performance of the transferability and adaptability of the loss models are undermined by some local factors such as predominant building style, building code design and regulations, household income and flood insurance practice, which influences the local vulnerability and the exposure. Incorporating this local variability can ensure a good performance of the models outside countries or regions where they were developed. When applying these models, efforts are needed to disaggregate the land use within the grid as done in the cases of Kelani and Ichinomiya river basins in this study. The ratio of land-use (building) types and densities approach used in this study can be adopted in any country and flood damages to different building structural types can be estimated. Finally, it is worthy of note that there has been increasing consideration for both Regional and Global scale flood damage modelling in the recent years, which would allow for risk comparison and assessments across countries. In this regard, the established unified models are very much applicable and can be incorporated into regional or global risk assessment framework.

## 4 Conclusion

This study has reported the results of the empirically established unified loss models in three countries, their comparison and integration for regional risk modelling. A total of three flood damage models were compared based on their damage indices and their performances in two case studies. This risk comparison provides understanding of the possibility of developing regional loss models for regional damage modelling in the South Asia and Pacific region. From the study, it can be concluded that similar countries' loss models, though developed from the same approach will exhibit different damage characteristics, which are dependent on country's specific factors such as the cost of building construction, level of exposure to flood hazards, country's GDP per capita (Jongman et al. 2012) and strict adherence to building construction codes and regulations. Transferability of loss models from country to country is possible by normalising with country cost price and building floor area, but it is associated with errors in the estimates. More accurate damage results can be achieved by using average loss model derived from the empirical damage of all the countries in the region. Risk comparison across countries can be done by estimating damages in each country separately using each country's loss model or by creating single average loss model and normalised with country-specific parameters such as floor area and cost price. In order to develop regional models for regional flood risk assessment, therefore, the study proposes detailed flood damage surveys to gather empirical damage data associated with global building exposures in the flood-prone river basins within all the countries in the region. With the availability of these data, which represent the degree of vulnerability of each exposure to water depths from each country, the mean structural damage ratio can be derived for regional damage modelling.

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