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Analysis of flood damage and influencing factors in urban catchments: case studies in Manila, Philippines, and Jakarta, Indonesia

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Abstract

The sustainability and efficiency of flood risk management depends on the assessment of flood hazards and on the quantification of flood damage. Under the conditions of climate change and rapid urbanization, the evaluation of flood risk can lead to the success of adaptation strategies. The main objectives of this study are the estimation of future direct flood damage in two urban watersheds: The Pasig–Marikina–San Juan River in Metro Manila, Philippines, and the Ciliwung River in Jakarta, Indonesia, as well as the determination of the relation between factors that drive floods and flood damage. A spatial analysis approach based on the integration of several parameters, such as flood hazard, climate, and property value, was applied using a Geographic Information System (GIS). The flood depth-damage function generated from the field surveys was employed for the analysis to identify the spatial distribution of flood loss. The findings showed that, under future scenarios (target year: 2030), the total flood damage will increase by 212% and 80% in the target areas of Manila and Jakarta, respectively, compared to the current scenarios. This growth is due to the higher level of extreme rainfall events and to the degree of urbanization in the future. A comparative analysis of the two study areas highlighted the significant effects of the level of water depth and the inundated areas on flood damage, depending on the sites. This study is useful for local decision makers to implement suitable strategies for urban planning and flood control.

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1 Introduction

Due to its severe impact on society, climate change has become a major interest of scholars, researchers, and decision makers. It is projected that climate change may increase the frequency and intensity of extreme weather and climatic events and, consequently, to rise disaster risk (IPCC 2012). The number of climate-related disasters, such as hydrometeorological and climatological disasters, has increased and become more recurrent (ADB 2015). Climate-related disasters are divided into four groups: hydrological disasters that account for 52%, followed by meteorological (28%), climatological (11%), and geophysical disasters (9%) (Guha-Sapir et al. 2016).

Climate-related disasters cause serious economic losses and damages that require appropriate and innovative mitigation and adaptation programs (Stabinsky et al. 2012). Damage from hydrological disasters, which includes floods, landslides and wave actions, represents 38% of the total damage, and the number in 2015 has increased by 24.6% compared to 2006 (Guha-Sapir et al. 2016). Disaster risk management is based on the understanding of damage from past disasters that reflect the vulnerabilities of communities, regions and institutions (Chiba et al. 2017). The economic evaluation of damage from disasters, such as flooding, can provide scientific evidence to enhance decision makers' awareness and let them implement strategies to reduce the damage. In addition, flood hazard assessment is also essential for flood mitigation and it is also important for the implementation of sustainable urban planning strategies (Bathrellos et al. 2016).

Flood damage can be categorized as direct/indirect damage and tangible/intangible damage (Jonkman et al. 2008). Several methodologies have been developed to assess and to quantify economic damage by flooding considering the types, the hazard characteristics, or the scale of application (Jongman et al. 2012; Messner et al. 2007; Dutta et al. 2003). Direct tangible damage, which mainly represents physical damage due to contact with water, is, in many cases, estimated in flood damage assessments (Komolafe et al. 2018; Pistrika et al. 2014; De Moel and Aerts 2011) compared to the intangible damage or non-economic loss that includes loss of life, health, home, human mobility, territory, cultural heritage, indigenous/local knowledge, biodiversity, and ecosystem services (Fankhauser et al. 2014). Although the concept of intangible damage has been integrated in the negotiation of United Nations Framework Convention on Climate Change (UNFCCC), its assessment for planning purposes remains uncertain (Serdeczny et al. 2018).

Asian countries are the most severely affected regions in the world by natural disasters, including flooding. Due to the climate conditions in Asia, such as monsoons that are characterized by heavy rainfall, flooding was very frequent in the region and has caused severe damage. It was reported that during the period between 2000 and 2016, 40% of the flood events occurred in Asia and represented approximately 60% of the overall flood damage (Centre for Research on the Epidemiology of Disasters 2018). In addition, Asian countries are experiencing rapid economic growth, which enhances the migration of rural populations to urban areas. It was projected that the population of the urban areas will be approximately 60% in Asia in 2030 (UNDESA 2015). Due to the rapid urbanization and inappropriate infrastructure, millions of people have been forced to live in marginal lands, which are, in many cases, flood-prone areas along rivers and canals (ADB 2013). Indeed, hydrometeorological disasters are positively correlated with rising exposed populations, in

addition to the rainfall anomalies (ADB 2015). For this reason, adaptation measures should be adopted to reduce risk and to attenuate the effects of driver factors.

Many researches focused on the evaluation of flood damages either by using appropriate models or with the application of GIS tools (Glas et al. 2017; Kundzewicz et al. 2014; Te Linde et al. 2011; Afifi et al. 2019). Additionally, determination and knowledge of driving factors influencing flood damage may guarantee the efficiency of disaster risk management (Thieken et al. 2005; Pathirage et al. 2014; Lechowska 2018).

Therefore, the main objectives of this work were to assess the future direct and tangible flood damage in two urban river watersheds in Asian megacities, namely the Pasig–Marikina–San Juan River system in Metro Manila, the Philippines, and Ciliwung River in Jakarta, Indonesia, and to estimate the effect of main driving factors on the flood damage. In this study, urban flood hazard and flood damages were performed in GIS environment. A flood depth-damage function was established to evaluate flood damage through data collected from the field survey. The assessment and the quantification of urban flood damage will help local decision makers to cope with flood risks at watershed scale. Moreover, the identification of main factors influencing flood damage is a relevant outcome for the implementation of sustainable strategies.

2 Materials and methods

2.1 Research framework

The flood damage was evaluated considering three components, namely flood hazard, exposure and vulnerability using spatial analysis method (Kefi et al. 2018; Foudi et al. 2015). The GIS-based approach applied is principally composed of the three components of Eq. (1)

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \tag{1}$$

Water depth was used as the main parameter in assessing the flood hazard. Land cover in inundated areas as the exposure component factor was also useful for the assessment of elements at risk. Flood damage-depth function is used for the vulnerability component. The flowchart in Fig. 1 provides an overview of the datasets used and a description of the applied approach. Maps of each parameter were established to assess flood damage. This method was applied in two urban watersheds, namely "the Pasig–Marikina–San Juan River" in Metro Manila, the Philippines, and the "Ciliwung River" in Jakarta, Indonesia. As introduced in Fig. 1, the analysis is required to collect and process several data and information related to the study areas. The main data used for the assessment are topographic data, soil characteristics, land cover, property prices, and flood damage rates considering the concept of flood depth-damage function. In order to calibrate and to validate the models, flood of 2009 in Metro Manila and flood of 2007 in Jakarta were used as reference flood events. All data used were georeferenced to WGS1984 UTM Zone 48S (Jakarta) and WGS1984 UTM Zone 51N (Metro Manila) and were converted to raster format at a grid cell scale. In this study, ArcGIS 10.4.1 was applied for the data processing and analysis. The parameters of the three components were integrated in GIS to estimate the tangible and direct flood damage with a grid size of 90×90 m and of 100×100 m in Metro Manila and Jakarta, respectively, and to determine the projected flood conditions in 2015 as current situation and 2030 as future situation at watershed scale.
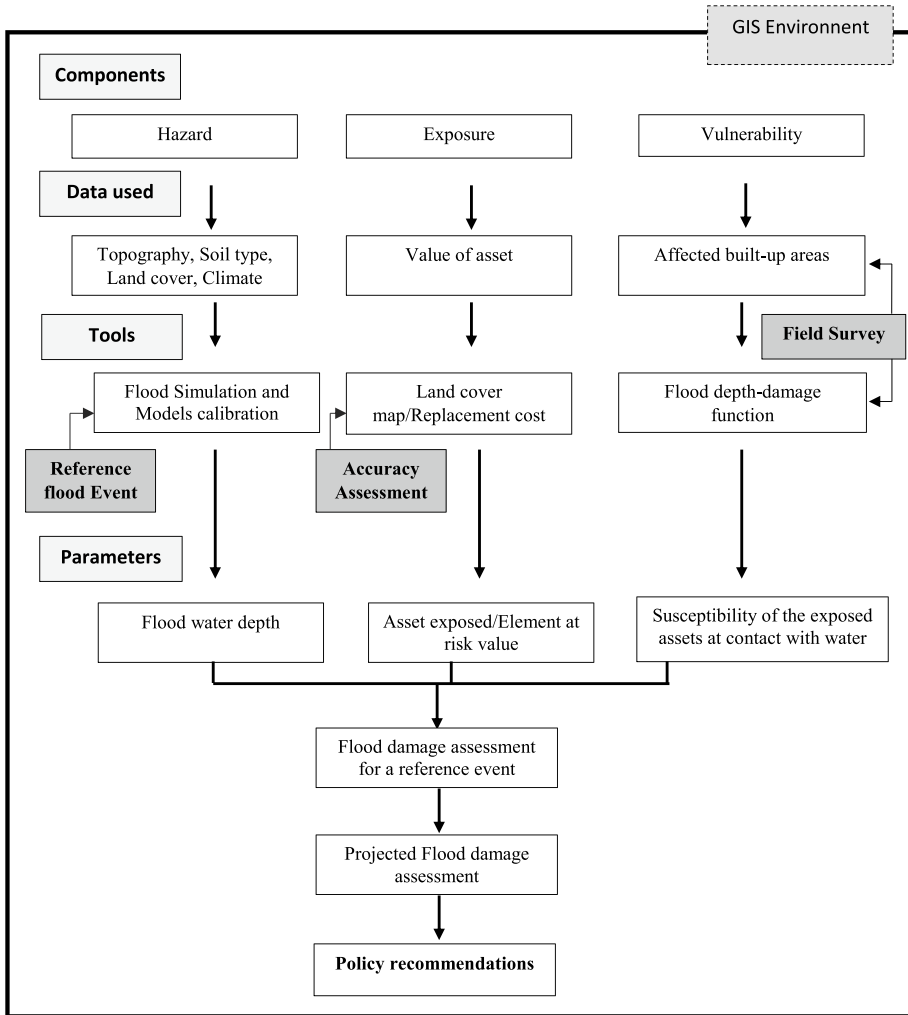
Fig. 1 Flowchart of the assessment of flood damage in this study

2.2 Description of study sites

The Pasig–Marikina–San Juan River in Metro Manila, the Philippines, and the Ciliwung River in Jakarta, Indonesia, were selected for our analysis (Fig. 2). These two study areas were chosen because both are experiencing rapid urbanization and frequent flood events. The two countries, Indonesia, and the Philippines, were historically affected by exceptional floods that caused profound economic losses and fatal incidents. In addition, these two countries presented significant progress in Disaster Risk Reduction (DRR) strategies and policies. The Philippines approved in May 2010 after Typhoon Ondoy the Disaster Risk Reduction and Management Act (Republic Act No. 10121). This law aims to make disaster risk reduction and management (DRRM) a proactive approach considering climate change adaptation, and to put DRRM as the mainstream of development
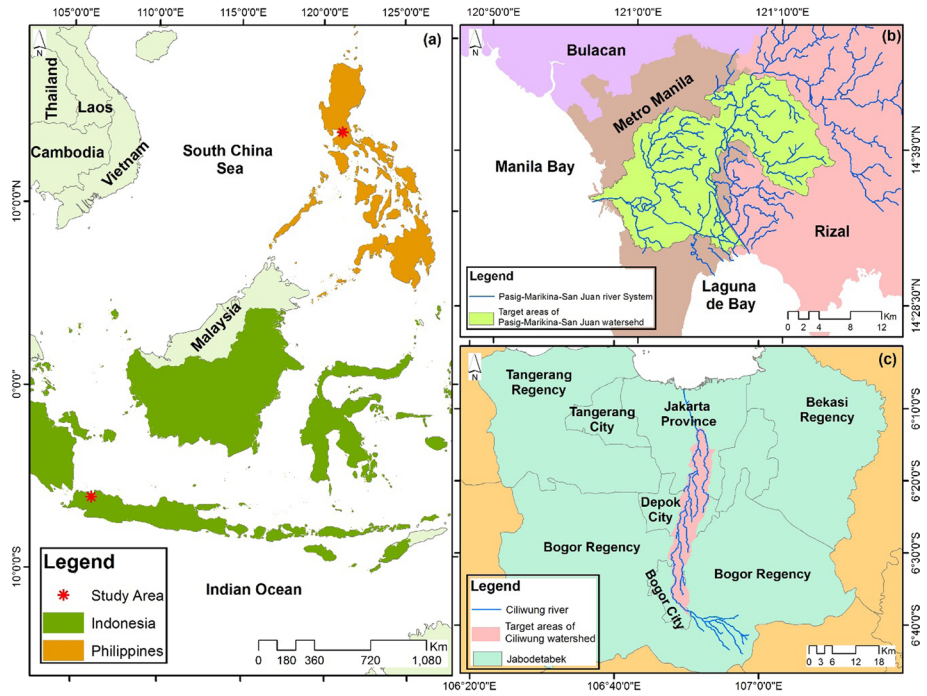
Fig. 2 Study areas

plans from the national to local level. Within this law, National Disaster Risk Reduction and Management Council (NDRRMC) has been set up. Moreover, Local Government Units (LGUs) have established their Disaster Risk Reduction and Management Offices (DRRMO) for provinces, cities and municipalities. The Barangay Development councils have the responsibility for DRRM at Barangay level. In June 2011, the National Disaster Risk Reduction and Management Framework was issued which is composed of 4 components: (1) Prevention and Mitigation, (2) Preparedness, (3) Response, and (4) Rehabilitation and Recovery (CTI and WCI 2013).

For the case of Indonesia, regulatory and institutional frameworks for DRR were established and several relevant laws related to DRR were adopted such as the Law 24/2007 on disaster management. In order to improve the efficiency of DRR strategies, national and local Disaster Management Agencies were also implemented (Mardiah et al. 2017).

The National Capital Region, called Metro Manila, is located between Manila Bay and Laguna de Bay at 14° 40′ N latitude and 121° 03′ E longitude. The total area of Metro Manila is 636 km^2. The climate is characterized by relatively high temperatures and abundant rainfall. The annual average rainfall is 2400 mm. The temperature ranges from 21 to 39 °C. The Marikina River Basin is the main catchment of Metro Manila, which consists of the Marikina, Pasig, San Juan and Tullahan Rivers (Lagmay et al. 2017). As reported in the 2015 census, Metro Manila is the most populated region in the country, with 12,877,253 inhabitants (population density: 20,785 persons/km^2) (PSA 2015). Indeed, the Philippines is one of the fastest urbanizing Asian countries. In 2010, the level of urbanization was 45.3% (PSA 2010). The inundation modeling area delimited for the analysis was 401 km^2.

Jakarta is the most densely populated area in Indonesia, and is located in the lower part of Ciliwung River and other smaller rivers (Mishra et al. 2017). The study area for the Jakarta case study was in the middle of the Ciliwung River basin. The Ciliwung River starts upstream at Tugu Puncak in Bogor Province, flows northward through the cities of Bogor, Depok and Jakarta, and finally ends at Jakarta Bay. The Ciliwung River basin is located between 106° 45′ E and 107° 00′ E and 6° 05′ S and 6° 50′ S. The average annual rainfall is 3125 mm, and the average annual temperature is 29 °C. The watershed is mainly covered by forest, agriculture (e.g., paddy fields), urban land, and water. The inundation areas applied for the assessment were located between Katulampa and Mangarrai sections, and the total area was 238 km^2.

2.3 Components of flood damage

In this study, specific approaches and data were used to assess each component.

2.3.1 Hazard

Flood simulation mainly included hydrologic simulation of high flow discharge from upstream region and hydraulic simulation of water depth over the inundation modeling area. The models applied for this study consisted of HEC-HMS as hydrologic model and FLO-2D as hydraulic routing model. These models require major inputs as extreme rainfall values, DEM, land cover, and flood control measures. The hydrologic model enabled to generate flood hydrographs at the inlet point of the inundation area, which were integrated into the FLO-2D model to generate flood inundation over the lower regions. The calibration and validation approach used for the hydrologic-hydraulic model is based on comparison of simulated and observation data. Simulation of climate change impacts impact were carried out using bias-corrected rainfall data for multiple global climate models (GCMs) and representative concentration pathways (RCPs) output.

2.3.1.1 Rainfall bias correction GCM output is used for climate predictions and to study climate variability and change. Most of the GCMs are characterized by coarse grid resolution resulting greater uncertainty. The accuracy of GCMs can be improved with progressively finer spatial and temporal scales (Srinivasa Raju and Nagesh Kumar 2018). Downscaling enables to improve the accuracy of GCM output. Several downscaling techniques, popularly classified as dynamical or statistical methods, are available to convert GCM outputs into locally applicable climate data (Mishra and Herath 2011). Climate change impact assessment based on GCMs is simulated by the integration of future emission paths (socioeconomic scenarios) called as representative concentration pathways (RCP) (Moss et al. 2010).

In this study, multiple GCMs and scenarios (RCP) were applied to reflect the uncertainty associated climate change. Quantile bias correction technique was applied to minimize the biases in the GCM data (Mishra et al. 2017). This technique applies simulated deviations in the daily frequency distribution of GCM rainfall to the observed rainfall. Bias corrections of rainfall frequency were performed to convert days with scant to dry days so that the number of wet days from the GCM predictions and actual observations were approximately equal. In this study, an empirical frequency analysis was conducted to estimate the long-term probability of dry (zero rainfall values) days in the observation data series. Accordingly, a threshold (GCM rainfall value) corresponding to the non-exceedance probability of observed zero rainfall was determined. GCM rainfall intensities above the

threshold value were corrected using inverse of cumulative distribution function (CDF) of GCM data with observation distribution parameters. An average of two GCMs and two RCPs was used in Pasig–Marikina–San Juan watershed. On the other hand, an average of 3 GCMs and 1 RCP was applied for the case of Ciliwung River basin (Table 1).

2.3.1.2 Hydrologic modeling Hydrologic modeling was primarily performed to generate flood hydrographs at the inlet location of the inundation modeling area (Mishra et al. 2017; Rafiei Emam et al. 2016). The discharge from the upper region to the lower region was simulated using HEC-HMS model. The HEC-HMS model was developed by the US Army Corps of Engineers (Feldman 2000). It is capable of analyzing runoff based on sub-hourly to daily rainfall. Use of this model can be found for different geographic settings, including large river basins to small urban areas. In this study, Watershed Modeling System (WMS) program was used for preparing the initial parameters of the HEC-HMS. The US Natural Resource Conservation Service (NRCS) (formerly the Soil Conservation Service (SCS)) runoff curve number (SCS-CN) method was used for loss estimation and excess rainfall. The runoff curve number (CN) quantifies the infiltration capacity, which theoretically ranges from 0 to 100. Correct estimations of CN values are crucial for the accuracy of the modeling results. SCS unit hydrograph method, which requires few input data, was used to transform rainfall into runoff. Muskingum-Cunge method was used as streamflow routing. A series of model parameter sets can be estimated using the optimization tools of the HEC-HMS model. The Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) and root mean square error (R^2) methods were selected because of their widespread use in hydrological modeling.

For the case of Manila ("Pasig–Marikina–San Juan" watershed), hydrologic/hydraulic model was performed to generate flood hydrographs at the inlet (Montalban) of the inundation modeling area. The soil data were obtained from the FAO soil database, and a DEM map with 1-m resolution from Light detection and ranging (LiDAR) and a land cover map (30-m resolution) from Landsat Imagery were used. Typhoon Ondoy of September 2009 was used for the hydrologic–hydraulic model set up.

For Jakarta case (Ciliwung watershed), a DEM was developed from Shuttle Radar Topography Mission (SRTM) with a 90-m resolution. HEC-HMS was used for hydrologic modeling to generate flood hydrographs at Katulampa section. By using high river flows at this section as inflows in the hydraulic model, inundation depths were determined up to the Manggari gate. The HEC-HMS model was set up using flood event of February 2007. The HEC-HMS model set up was finalized by adjusting the model parameters until the simulated results matched the historical data.

2.3.1.3 Flood inundation simulation FLO-2D, a two-dimensional flood routing model, was used to simulate runoff over a system of square grid elements. The model is capable of numerically routing a flood hydrograph while predicting the area of inundation and simulating flood wave attenuation. The model simulates the progression of the flood hydrograph,

Table 1 GCMs and RCPs used for the evaluation of climate change

Case study	GCM	RCP
Pasig–Marikina–San Juan	MRI-CGCM3 MIROC5	RCP 4.5/RCP 8.5
Ciliwung	MRI-CGCM3 MIROC5 HadGEM2-ES	RCP 4.5

conserving flow volume, over a system of square grid elements representing topography and flow roughness. FLO-2D project dataset requires representation of the potential flow surface topography in a square grid format. Although grid elements of any size can be used by the model, the time step is governed by the wave celerity and small grid elements will require small time steps. FLO-2D inundation modeling was calibrated considering the comparison of observations with the simulation flood characteristics. Based on real situation and the estimation of daily rainfall during the flood event, the flood hazard was evaluated for a 100-year return period in both case studies. The observed flood in study cities during recent century, with roughly 100-year return period, enabled us to select extreme scenario in the analysis.

2.3.2 Exposure

2.3.2.1 Data used and data processing Land cover and the identification of the element at risk are the main parameters of the exposure component. In fact, land use/cover data are applied to describe exposure in terms of affected sectors or economic activities (Merz et al. 2010). In this study, exposed built-up areas are extracted by intersecting land use/cover data with inundation data by GIS tools. As the main target is also to estimate the future effects of floods, a projected land cover of 2030 was utilized in the analysis. In order to avoid high uncertainty related to projection of future, official data of future land cover derived from local master plan were the first priority for the analysis. Unfortunately, only future land cover of Jakarta was available. In fact, the land covers in 2009 and 2030 were used for the assessment and they were provided by Lembaga Ilmu Pengetahuan Indonesia (LIPI) (Mishra et al. 2017). However, future land cover of "Pasig–Marikina–San Juan" watershed was generated using remote sensing techniques in a GIS environment. In this context, land cover map of 2030 was developed using two past land covers and using the application of the Land Change Modeler (LCM) for ArcGIS as presented in Fig. 3. The LCM was used to predict the land cover pattern based on the previous change trend. During the analysis, Markov Chain was applied to identify appropriate land cover prediction considering a combination of driver factors (DEM, slope) which were applied to influence change allocation. In this case study, the Landsat 7 of 2002 and the Landsat 8 of 2014 were employed to assess the land cover in 2030, as indicated in Table 2. Level-1 Landsat images were downloaded from the USGS website (https://earthexplorer.usgs.gov/). Image preprocessing, including image stacking and band combination, is required to establish accurate land cover map and to reduce uncertainty. Landsat sensors have a moderate spatial resolution (30 m), which can be difficult to identify in the details of buildings or houses or to establish a detailed land cover. However, it is easy to distinguish urban growth for a regional coverage. Therefore, only four (04) aggregated classes were selected, namely the built-up, water bodies, forest, and green land considering specific land occupation as indicated in Table 3. All categories were classified based on a supervised classification method using the maximum likelihood algorithm.

2.3.2.2 Accuracy assessment Classified image or thematic map derived from remote sensing data requires to assess the accuracy of the classification. Indeed, this technique of accuracy is determined empirically by selecting a sample of pixels from thematic map and checking them from reference data/ground truth (Richards and Jia 2006). Moreover, accuracy defines correctness. It measures the agreement between a reference assumed to be correct and a classified image (Campbell 2007). In order to evaluate the accuracy, confu-
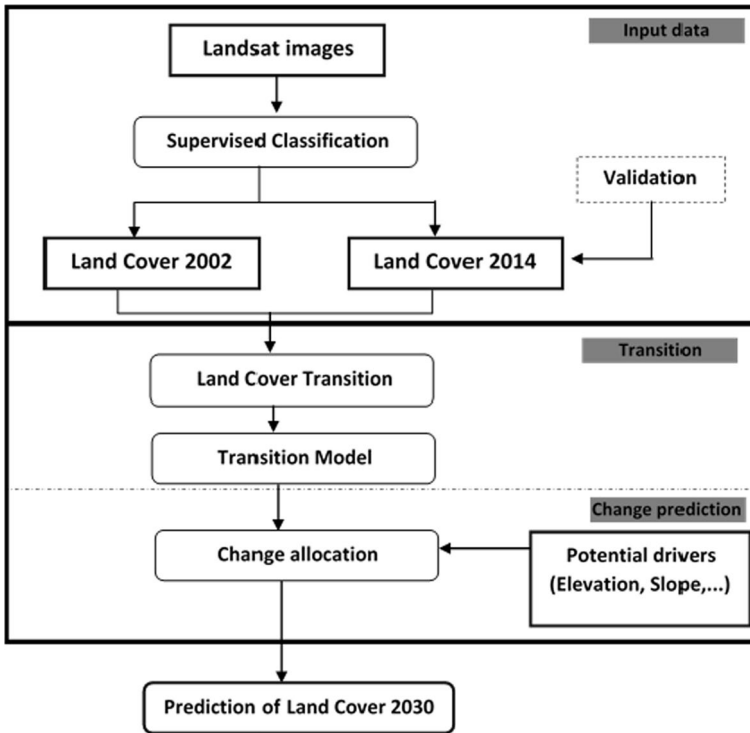
Fig. 3 Land cover establishment using Land Change Modeler (LCM)

Table 2 Satellite images applied

No.	Path/row	Data set	Acquisition data	Scene cloud cover (%)
1	116/050	Landsat 7 ETM+C1 Level 1	03/04/2002	1
2	116/050	Landsat 8 OLI/TIRS C1 Level 1	07/02/2014	3.06

Table 3 Land cover categories

Land cover type	Description
Built-up area	Residential, commercial and industrial areas, settlement and infrastructure
Water body	Rivers, lakes, ponds, reservoirs
Green land	Gardens, grasslands, croplands
Forest	Deciduous and evergreen forest

sion or error matrix was applied. Overall accuracy indicator including user's accuracy and producer's accuracy and Kappa statistic are estimated (Richards and Jia 2006). As land cover map of Ciliwung watershed was obtained and approved by local government, accu-

racy assessment was only established for land cover of Pasig–Marikina–San Juan watershed case. Indeed, land cover of this watershed was generated and validated using a comparison approach. For accuracy assessment, ground point combined with Google earth source was used as reference data to check the classified image. About 150 pixel points were selected and assigned to one of 04 land cover identified in Table 3. Then, the classified image was compared pixel by pixel with truth data obtained from field and Google Earth.

2.3.2.3 Value of asset To measure the flood damage in monetary terms, data concerning the value of assets at risk were integrated into the analysis. In this study, the values of the built-up class were expressed as the replacement costs of residential and non-residential buildings. The value of assets can be indicated as the replacement cost or the depreciated/repair cost (Albano et al. 2015; Komolafe et al. 2015). This value was estimated based on the assumption that damaged assets have to be replaced by a similar object (Messner et al. 2007; Kefi et al. 2018). The average unit property by district from the residential and non-residential sectors was based on the 2015 constant price (property value). To have a homogenous analysis of flood damage, the property prices were converted into comparable units. In fact, all costs changed from the local currency Philippine Peso (PHP) and Indonesian Rupiah (IDR) to the US Dollar (USD).

2.3.3 Vulnerability

2.3.3.1 Flood depth-damage function The flood depth-damage function is considered the main indicator of vulnerability and is useful for direct flood damage (Handmer 2002; Smith 1994). This function is based on the susceptibility of the exposed assets to contact with water. Due to the lack of information about detailed types of land cover, only one function was generated for the entire catchment. Moreover, this function is established for an aggregated built-up class, which included the residential and non-residential sectors as well as all types of construction materials. A regression analysis was applied to obtain the functions. The dependent variable was the direct flood damage percentage, and the independent variable was the flood depth. In this work, the flood damage depth was constructed as a logistic function, which was developed using XLSTAT software. For both case studies, the flood depth-damage function was generated based on the data collected through field survey in both areas.

2.3.3.2 Field survey The survey was organized at barangay level in Metro Manila and village level in Jakarta. In order to get information from exact location of selected areas, a global positioning system (GPS) unit and Survey123 for ArcGIS were used by local partners. In Jakarta, the survey was done between May and June of 2017 in collaboration with the Center of Environmental Research; Research and Community Services Institute; and Bogor Agricultural University, Indonesia (PPLH–IPB). However, for the case of Metro Manila, field surveys were conducted in February and March of 2017 in collaboration with a local NGO. The survey was based on face-to-face approach. Data were collected about the flood event in 2009 in Metro Manila and in 2007 in Jakarta. In total, responses of 398 people were collected in the Pasig–Marikina–San Juan watershed, and 401 in the Ciliwung River Basin. The location of the survey of each study area is presented in Table 4. The field survey was conducted with local people in the affected residential and non-residential areas using specific questionnaires in some locations in the target basins. An example of the question-

Table 4 Location of the survey

No	Location	District/city	Respondents
Ciliwung watershed, Indonesia			
1	East Jakarta	Cipayung, Jatinegara, Kramat Jati, Matraman, Pasar Rebo	110
2	South Jakarta	Jagakarsa, Pancoran, Pasar Minggu, Tebet	80
3	Depok City	Beji, Cimanggis, Pancoran Mas, Sukmajaya	130
4	Bogor Regency	Bojong gede, Sukaraja	12
5	Bogor City	Bogor Selatan, Bogor Utara, Bogor Timur	69
Pasig–Marikina–San Juan watershed, Philippines			
1	Metro Manila	City of Manila	85
2		Makati	27
3		Marikina	49
4		Pasig	62
5		San Juan	45
6	Rizal	Cainta	29
7		Taytay	101

naire is presented in the Online Appendix section. During the survey, a representative population was carefully chosen from the flood hazard map established from the flood event of each study area. Additionally, the exact location of each respondent was recorded, and then potential respondents were interviewed randomly. As presented in Fig. 4, it was determined that female respondents represents the majority of the interviewees in both study areas with about 60% and 72% in Ciliwung watershed and Pasig–Marikina–San Juan watershed, respectively. It was also revealed that the survey is mainly composed of young and middle aged people (between 25 and 60 years). It was also found that most of the interviewed people were well educated. Moreover, the questionnaire was designed to get information related to household characteristics and flood characteristics/damage. With this survey, data about the flood history, such as flood depth and damage, were collected. As the main target was to assess the direct flood damage and to develop flood damage function, some questions were related to housing information, such as areas or construction materials. Moreover, some information about flood emergency responses and preparedness was also gathered. The last part of the questionnaire is related to people perception following disaster risk reduction.

2.4 Factors influencing flood damage

Several factors have potential impact on flood damage such as water depth, flow velocity, flood duration, frequency, contamination and affected areas (Smith 1994; Kreibich and Thieken 2008; Dutta et al. 2011). However, in this study, only inundated areas and flood depth were considered for analysis. Additionally, an average of inundated and flood depth values were estimated at city level using GIS tools. In order to detect the potential impact of each factor to flood damage, a statistical analysis was performed. A correlation matrix was established and Pearson correlation coefficient was applied to estimate the effect of flood-related factors and damages. Pearson coefficient is used to identify the strength and
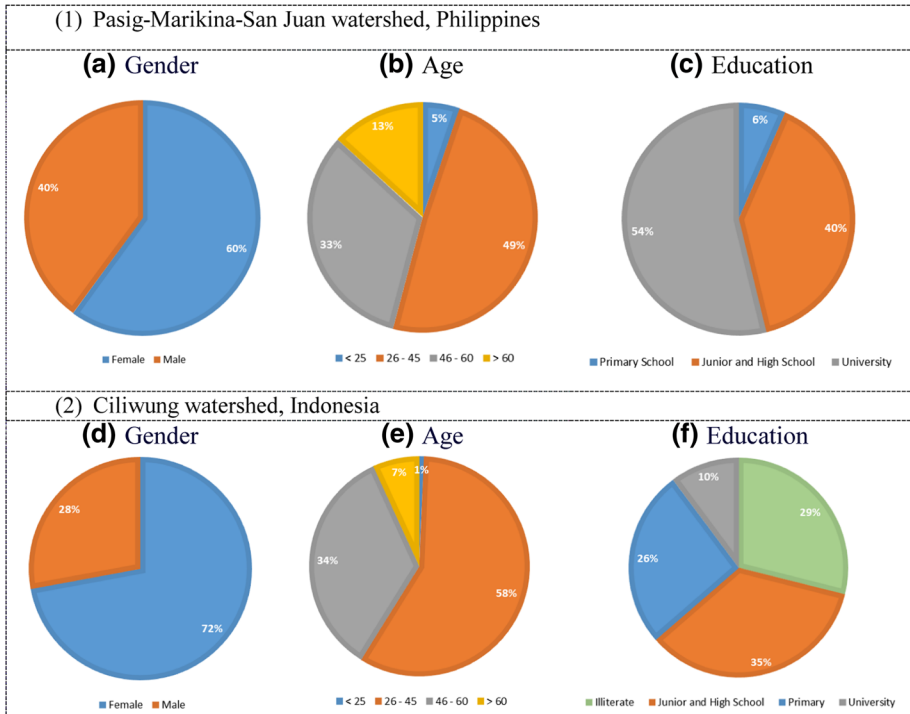
Fig. 4 Sample characteristics in both study area (1) Pasig–Marikina–San Juan watershed, Philippines, (2) Ciliwung watershed, Indonesia

direction of relationships between two variables in linear regression. XLSTAT software was used to assess the correlation. In this statistical context, the analysis was done based on flood damage in both situation "Current: 2015" and "Future: 2030".

3 Results and discussion

The tangible direct damage was estimated using the spatial analysis approach and was applied in two urban watersheds, Pasig–Marikina–San Juan watershed and Ciliwung watershed. In this section, the impact of the driving factors to the flood damage was also determined.

3.1 Hazard

The findings about flood depth assessment as indicated in Fig. 5 revealed a significant increase in inundated areas in both case studies between the current and future situation. An increase of 26% and 8.7% was detected in areas with flood depths greater than 0.5 m in Metro Manila and Jakarta, respectively. The future increase in inundated areas is mainly due to climate change impacts characterized by the intensification of rainfall (Jalilov et al. 2018). As it is indicated in Table 5, many GCMs and RCPs were applied to detect future daily rainfall. Indeed, the evaluation based on the future average of GCMs considering also RCPs showed an increase in
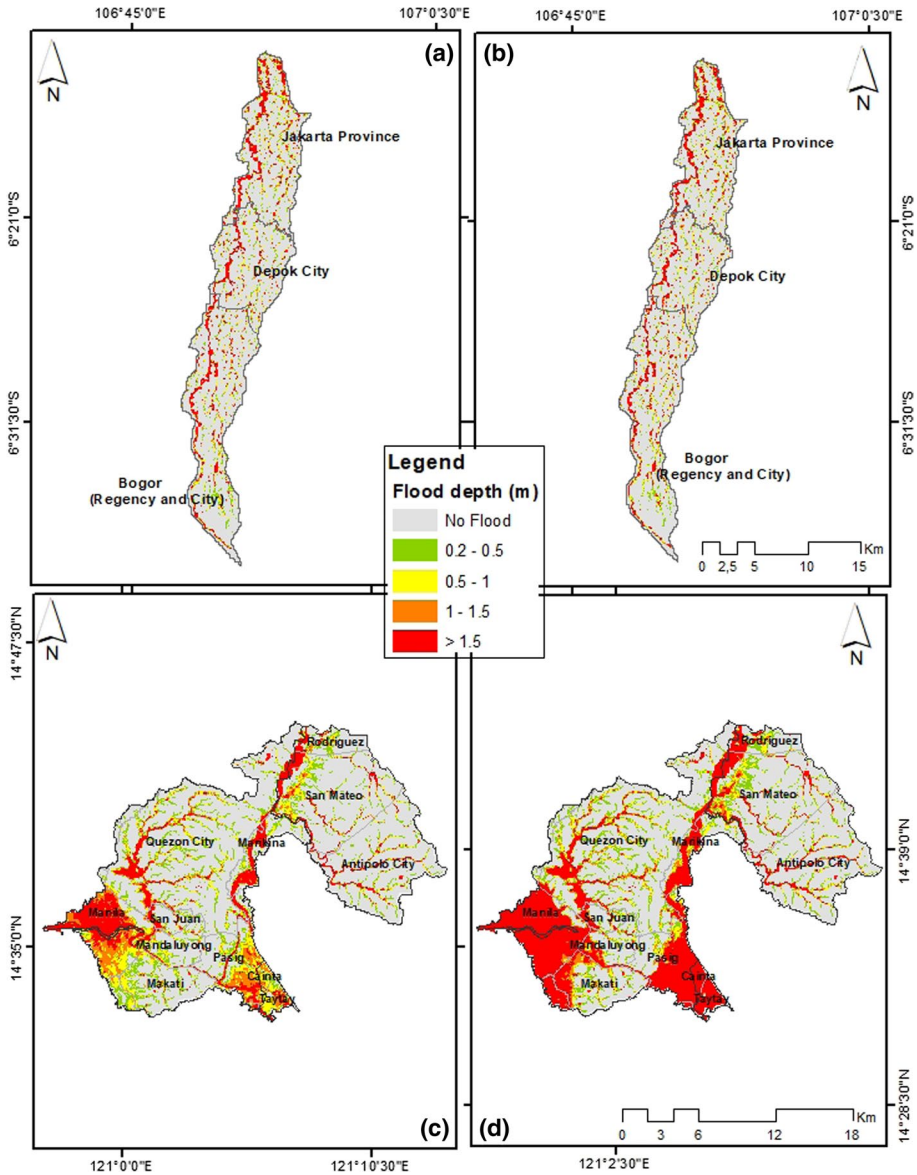
Fig. 5 Spatial distribution of the flood depth. **a** Ciliwung current, **b** Ciliwung future, **c** "Pasig–Marikina–San Juan River" current, **d** "Pasig–Marikina–San Juan River" future

rainfall in the future, as indicated in Table 6. Heavy rainfall and extreme rainfall represented by an exceedance of the average rainfall level can result in flooding (Komori et al. 2012). The spatial distribution of the water depth and the inundated areas conducted to identify the most vulnerable cities to floods and to detect safe and unsafe areas. Manila City and a portion of Jakarta Province are the most at-risk areas in the two watersheds. These two cities are located in the downstream part of the watershed. They are characterized by lowland morphology,

Table 5 GCMs and RCPs assessment

| | Watershed | | |
| | Pasig–Marikina–San Juan | | Ciliwung |
	RCP4.5	RCP8.5	RCP4.5
MRI-CGCM3	411.6	449.6	365
MIROC5	425.9	516.5	158
HadGEM-ES			223
Average	451	249	

Table 6 Comparison of rainfall change

| Study area | Average rainfall (mm) | | Increase (%) |
	Current	Future	
Pasig–Marikina–San Juan watershed	360	451	25
Ciliwung watershed	228	249	9

Table 7 Confusion matrix

| | Category | Ground truth classes | | | | Total | UA (%) |
		Forest	Green land	Built-up	Water		
Image to be evaluated	Forest	26		1		27	96
	Green land	3	23	1		27	85
	Built-up		10	69	1	80	86
	Water				16	16	100
	Total	29	33	71	17	150	
	PC	90%	70%	97%	94%		
Overall accuracy	89%						
Kappa statistic	0.84						

UC: User's accuracy/PC: producer's accuracy

moderate slope, high population density and intensive urban growth. In fact, heavy or persistent rains in the catchment area or the upper regions of the river system can lead to an excess of water in a river and can create floods downstream (Mall and Srivastava 2012). In addition, the growth of inundated areas will lead to an increase in the risk of the exposed built-up areas to flood. Indeed, Lagmay et al. (2017) confirmed the assessment for the case of Manila. Asdak et al. (2018) corroborated the estimation of Jakarta analysis.

3.2 Exposure

3.2.1 Accuracy assessment results

As explain in methodology section, accuracy assessment was applied to check the correctness of image generated from remote sensing data. The accuracy of the derived image of Pasig–Marikina–San Juan watershed was established. Table 7 summarizes the results of the accuracy assessment.

The results show a high accuracy of the classification. It was estimated that the overall accuracy of thematic map is 89% and the kappa statistic was 0.84. These indicators show high agreement between the images generated and reference map. Indeed, high accuracy will reflect the reliability of the analysis and it will be useful for future assessment. Moreover, the classified images were used to generate projected land cover, which will be used to identify future exposure component and consequently flood damage assessment.

3.2.2 Spatial distribution of built-up change

The comparison between spatial distribution of built-up areas in both urban watershed showed that urbanization of the study areas will be more significant in 2030 (Fig. 6). The built-up areas will increase by 11% and 42% in 2030 in Pasig–Marikina–San Juan watershed and Ciliwung watershed, respectively (Fig. 7). The increase in built-up areas will lead to an enhanced exposure of assets to flood water. The flood damage was estimated considering the exposed built-up layers to flood water depth at the grid cell scale. For the case of the Pasig–Marikina–San Juan watershed, a major change was detected in the north part of the area in the cities of Rizal Province. Similarly, for the Ciliwung watershed, the expansion of the built-up areas will be significant in the upper part of the river basin. It was noticed that the built-up areas will increase by 85% in Bogor (Regency and City). Indeed, the conversion of forest areas and ponds to housing areas have aggravated the risk of flood in the urban areas (Asdak et al. 2018).

3.3 Vulnerability

The flood depth-damage function is used as an indicator of vulnerability, and it was applied to estimate the damage rate and the flood depth-damage function was constructed as a logistic function, with two parameters for the case of Metro Manila and three parameters for Jakarta, as indicated in Eqs. (2) and (3) in Fig. 8, respectively. In spite of the high correlation coefficient in both cases, the damage curves depended on the local conditions, such as building materials (Huizinga et al. 2017). The comparison between the two cities showed that the maximum damage rate in the Jakarta case was lower than in Metro Manila, mainly due to the selected samples during the survey. In fact, it was observed that approximately 66% and 93% of the buildings from the samples were constructed with concrete and brick in Metro Manila and Jakarta, respectively. These types of materials are more water resistant. This result is corroborated with the finding of Komolafe et al. (2018). In their research, the authors revealed that the damage ratio for the building categories fluctuates, and the concrete frame with unreinforced masonry walls showed the lowest damage rate.
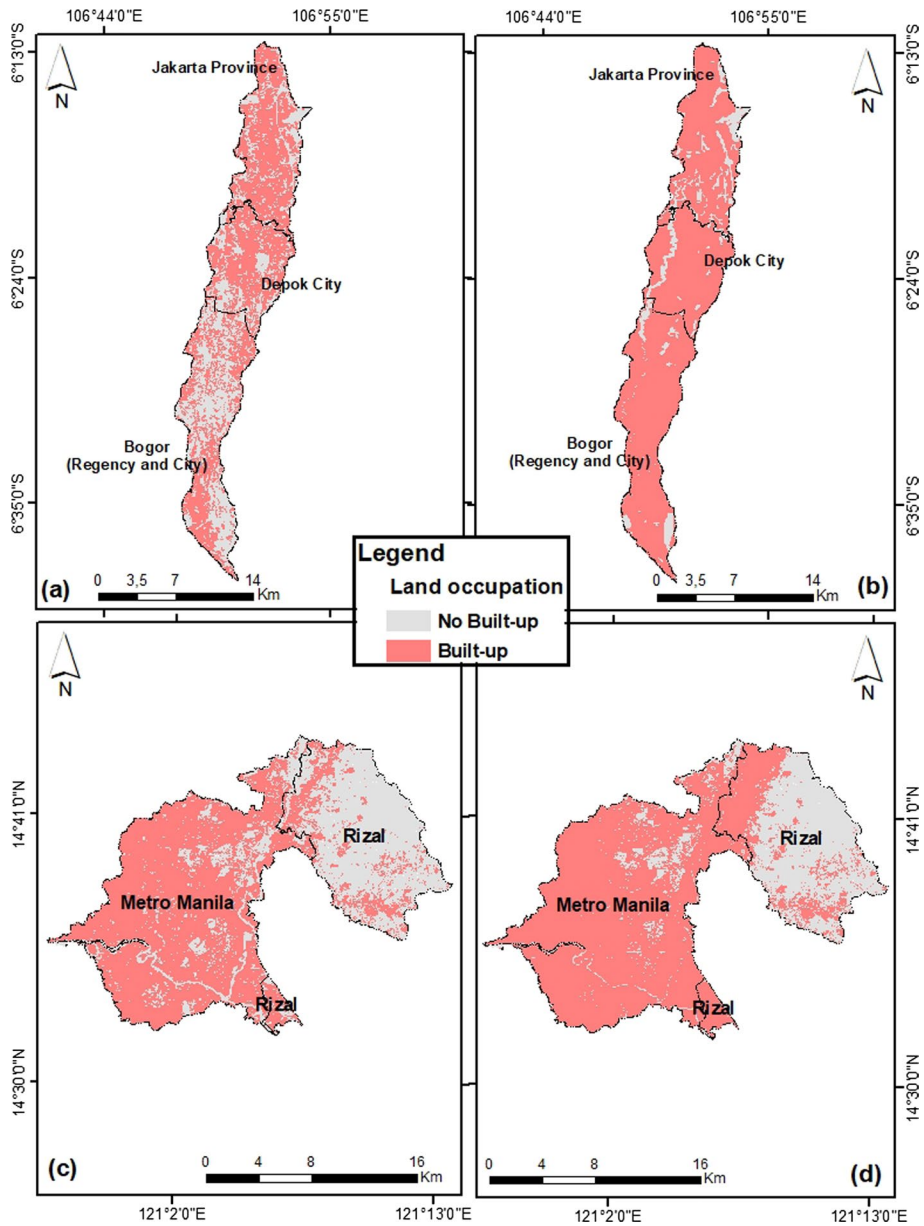
Fig. 6 Built-up change in two watersheds. **a** Ciliwung current situation, **b** Ciliwung future, **c** "Pasig–Marikina–San Juan River" current, **d** "Pasig–Marikina–San Juan River" future

3.4 Direct flood damage

Based on GIS approach, the spatial distribution of flood damage was established for both watersheds and considering current and future scenarios. The finding of the analysis is illustrated in Fig. 9. The assessment of total flood damage revealed a significant increase
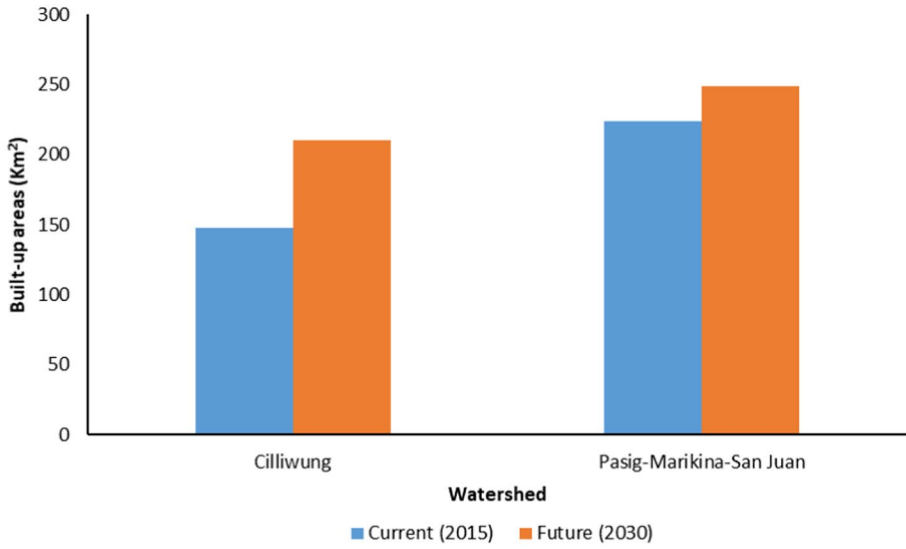
Fig. 7 Built-up areas change

$$\text{Damage rate} = \frac{1}{(1 + Exp(4.894 - 1.735depth))} \quad \text{eq.2}$$

$$R^2 = 0.980$$

$$\text{Damage rate} = \frac{0.803}{(1 + Exp(4.138 - 2.928depth))} \quad \text{eq.3}$$
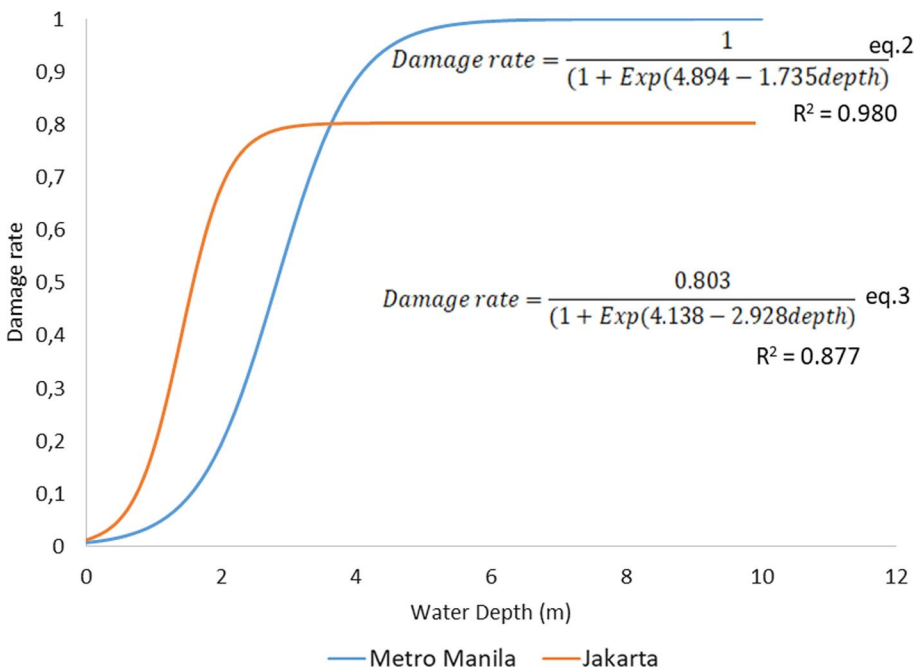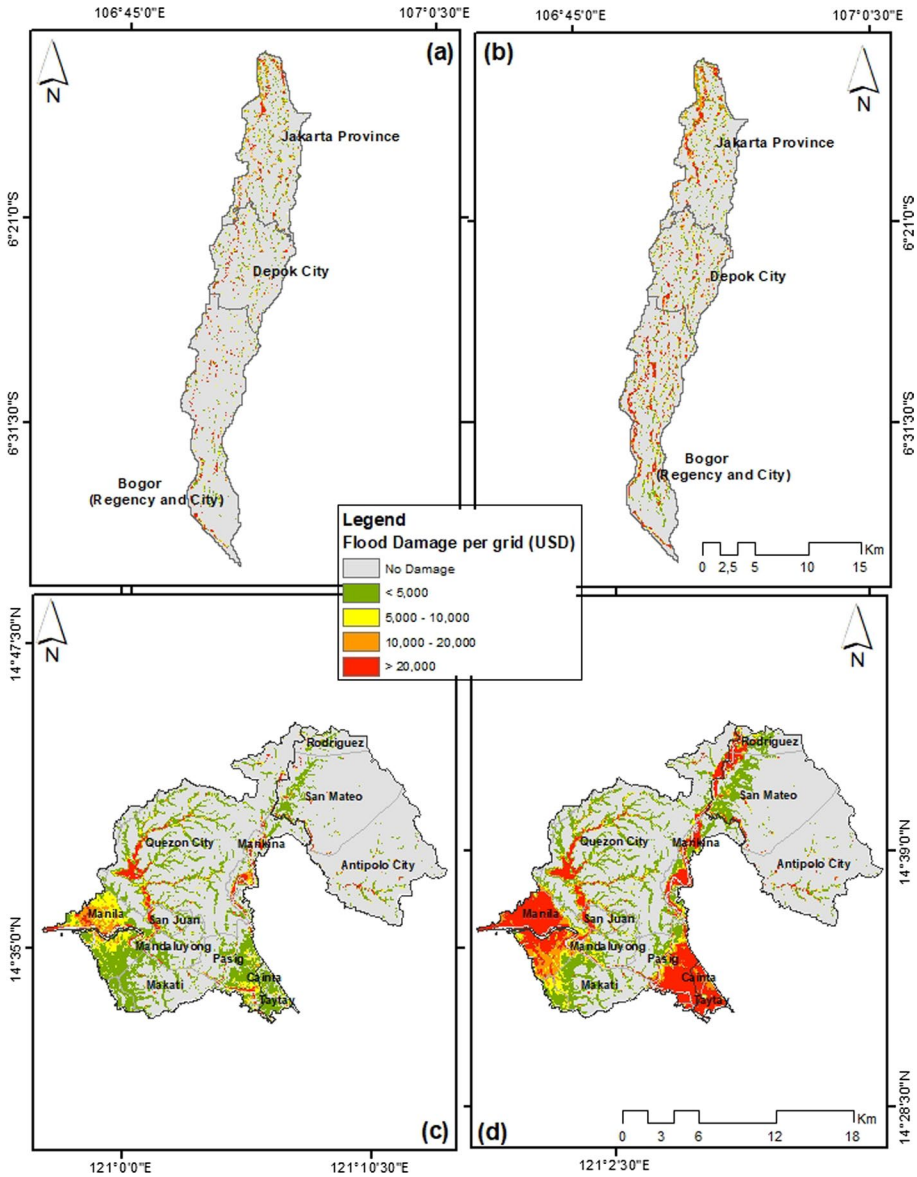
$$R^2 = 0.877$$

Fig. 8 Flood depth-damage function for the built-up areas in the study areas

in the future scenario (year: 2030) in both study cases. Moreover, the comparison between current and future situations shows that direct damage will increase by 212% and 80% in the Pasig–Marikina–San Juan Basin and the Ciliwung Basin, respectively. As presented

Fig. 9 Spatial distribution of the flood damage. **a** Ciliwung current situation, **b** Ciliwung future, **c** "Pasig–Marikina–San Juan River" current, **d** "Pasig–Marikina–San Juan River" future

in Fig. 9, the spatial distribution is characterized by four classes of damage considering pixel basis from less than 5000 USD to more than 20,000 USD. The comparison by classes between the current and future situation revealed that in 2030, a significant growth will be observed in the class of more than 20,000 USD, with 79% and 376% in Jakarta and Metro Manila, respectively. The rise is due to the intensification of rainfall and the expansion of urban areas and, consequently, to the increase in the inundated urban areas. The detailed
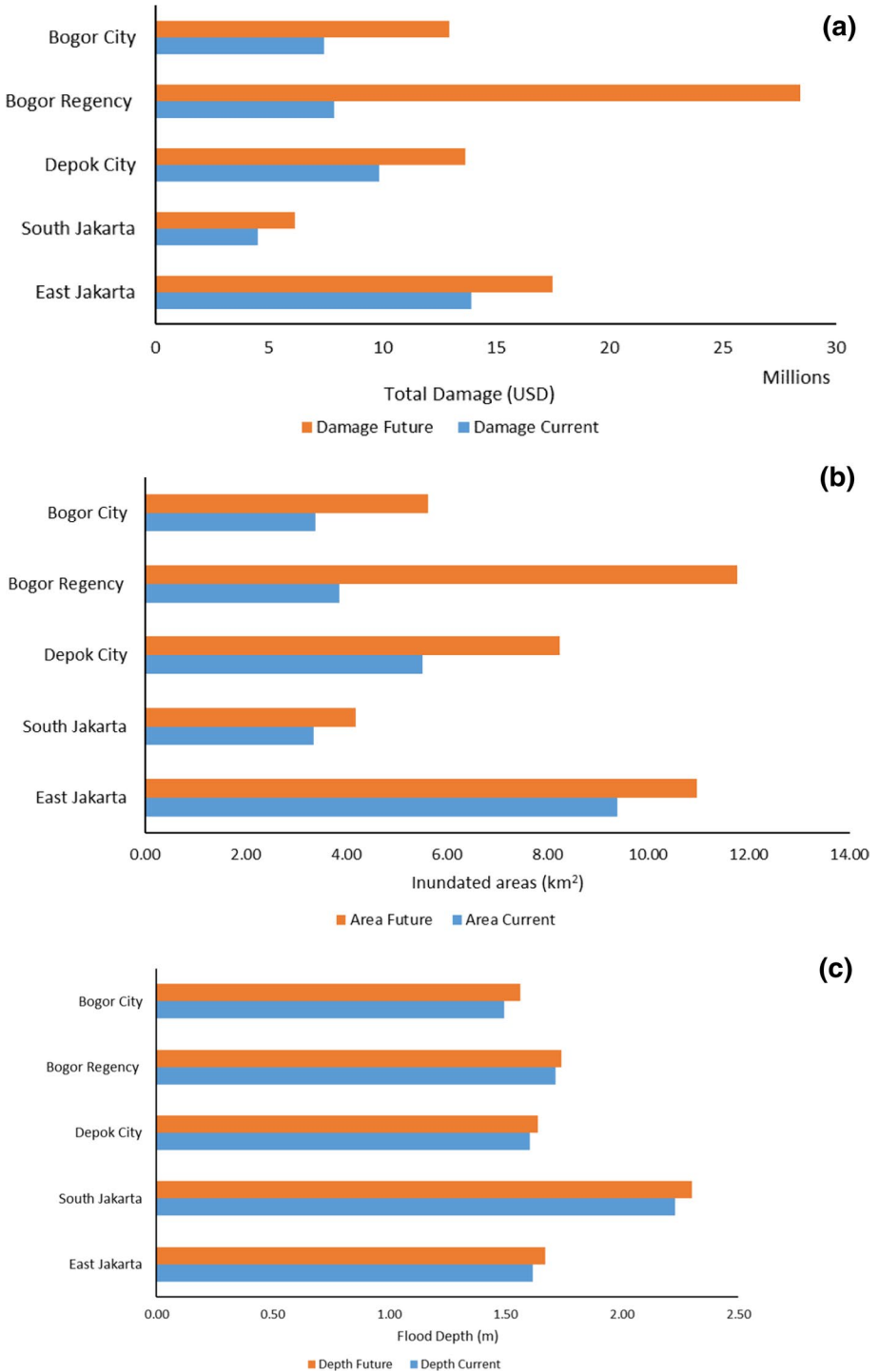
Fig. 10 Impact of driver factors on flood damage by districts in the Ciliwung Basin: **a** flood damage, **b** inundated areas, **c** flood depth

analysis of the study areas showed that the spatial distribution of the flood damage depends on several factors, such as water depth and property value as well as the rate of built-up areas. Indeed, due to the value of the assets at risk, the economic impacts of floods in urban areas are more serious (Neal et al. 2009). Moreover, water depth is a principal factor in flood hazards but flood duration and velocity can also contribute to flood risk (Dang et al. 2011). In the current situation in Jakarta, the findings showed that damage is very important in Jakarta Province (East and South). However, it was noticed that in the future scenario, the risk will increase in all the regions, and Bogor (Regency and City) is expected to be more affected than the other regions. In fact, in Bogor, the flood depth will increase, and the urbanization will be more significant, at 85%. In addition, it was observed in Fig. 10c that the level of the water depth is quite similar in the current and future situations. However, the total damage will increase in all locations (Fig. 10a). In contrast, the variation of inundated areas is important (Fig. 10b). The most important increase in flood damage was detected in Bogor Regency. In this area, it is estimated that the total damage will increase by 260%, and the inundated areas will increase by 205%, but the variation of the water depth will only increase by 2%.

However, in the case of the Pasig–Marikina–San Juan River system, the results showed that the cities of Manila, Pasig, Taytay, Cainta and Marikina, as well as some parts of Rodriguez and San Mateo, are the most susceptible cities in the study area. Additionally, serious damage was detected in cities located along the Pasig–Marikina-San Juan River system, such as Marikina city. Moreover, cities located in low-lying areas are also vulnerable to flooding such as Manila. As shown in Fig. 11a, c, flood damage is high in some cities, such as Pasig, Manila or Taytay, because it was due to the increased water depth in 2030. Moreover, it was detected that the total damage and average flood depth in Pasig City will increase by 525% and 116%, respectively, but the inundated areas will increase by only 38%. The trend was more significant in Taytay, where severe damage was observed in the future, with an increase of 1468%, which is mainly due to the increase in flood depth (223%) rather than that in the inundated areas (37%). In contrast, in some cities, such as San Mateo and Rodriguez, urbanization can be a relevant factor for the increase in flood damage. In San Mateo, the total damage will increase by 252%, and the increase in flood depth and inundated areas will be 41% and 105%, respectively, which suggests higher impacts by the latter. Due to urbanization, permeable soil will be replaced by impervious land that will lead to diminished infiltration and to increased runoff. Consequently, the occurrence of more severe flooding is increasing (Rafiei Emam et al. 2016). Additionally, anthropogenic activities can contribute to an increase in the happening of flood events such as deforestation (Fohrer et al. 2001).

Climate change, combined with the expansion of built-up areas, increases the vulnerability of urban areas to flooding and therefore to economic damage. Indeed, the separated analysis of the two study areas was conducted to determine that water depth and land cover are major factors in flood damage assessments. For this reason, in the following section, a comparative statistical analysis between Jakarta and Metro Manila case studies was done to assess the interaction effects between driver factors and flood damage estimations.

3.5 Interaction effects of driver factors

Identifying parameters affecting flood hazard leads to a more precise evaluation of flood damage and subsequently to the implementation of more efficient flood control strategies. As the flood depth-damage function was built based on the maximum water depth,
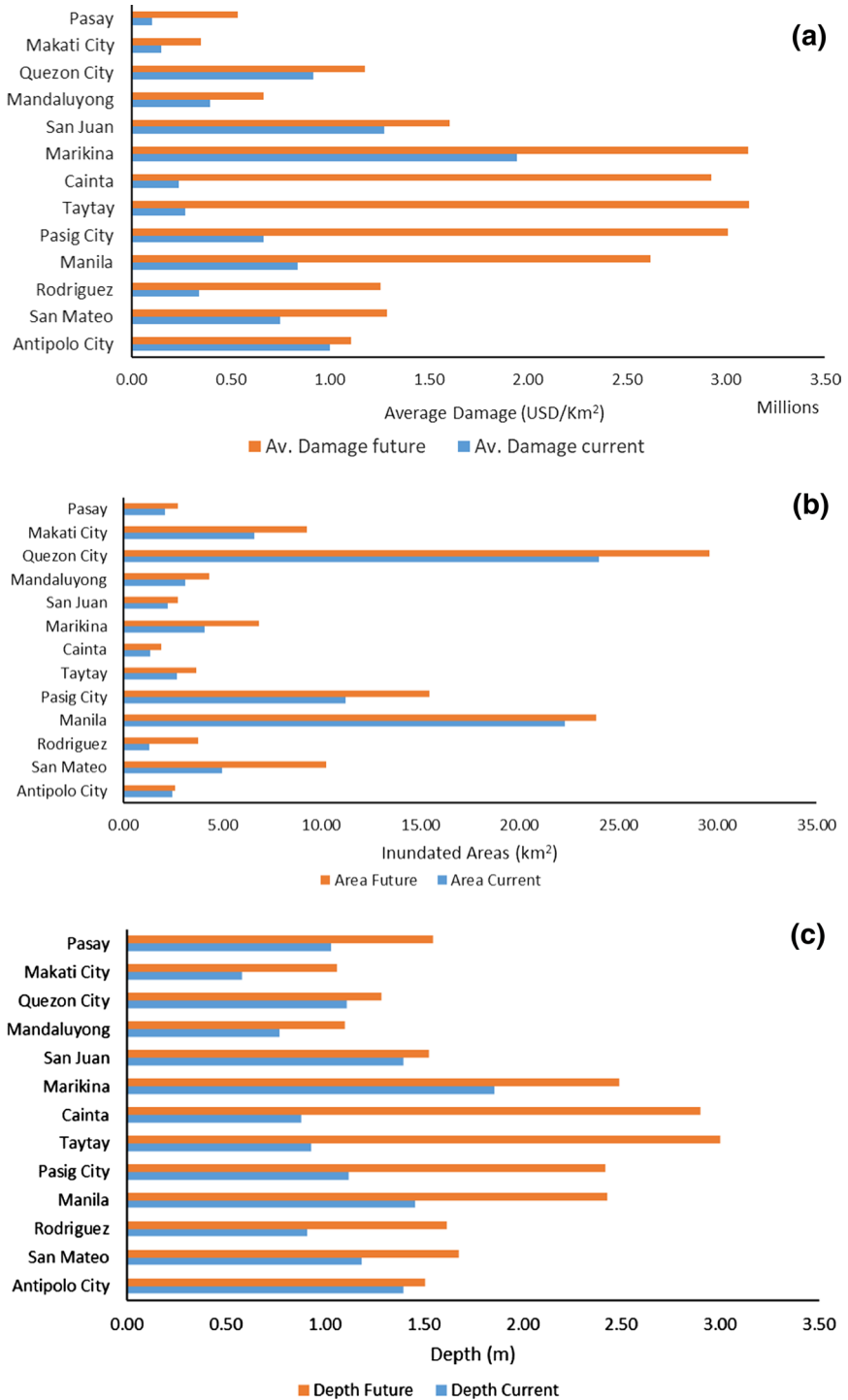
Fig. 11 Impact of driver factors on flood damage by district in "Pasig–Marikina–San Juan" watershed: **a** flood damage, **b** inundated areas, **c** flood depth
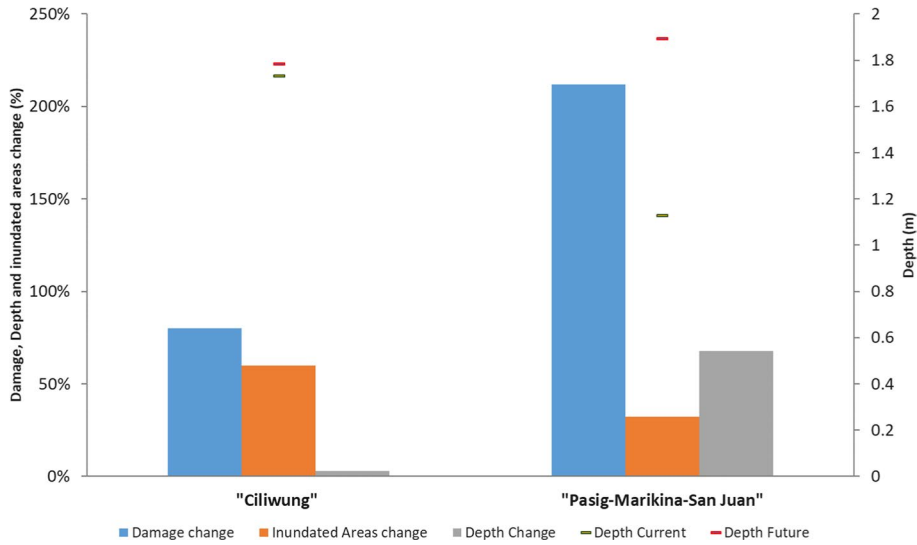
Fig. 12 Interaction between driver factors and flood damage in both study areas

this parameter was applied as the main factor for flood hazard assessment and damage in urban areas. Although flood damage will be more severe in the future in both case studies (Fig. 12), the parameters affecting the flood damage were different. Water depth was the main driver in the Pasig–Marikina–San Juan watershed, while the change in built-up areas increased the flood damage in the Ciliwung watershed. This result in Ciliwung watershed was corroborated by Asdak et al. (2018). Indeed, the authors found that anthropogenic factors such as uncontrolled land-based activities caused by rapid population growth combined with an inappropriate spatial planning may conduct to increase flood damage. To determine the effect of each driving factors on flood damage,

Table 8 Correlation matrix of main factors and flood damage in (a) current situation and (b) future situation

	Damage current	Depth current	Inundated areas current
(a)			
Damage current	1		
Depth current	0.367	1	
Inundated areas current	0.887*	0.017	1
	Damage future	Depth future	Inundated areas future
(b)			
Damage future	1		
Depth future	0.311	1	
Inundated areas future	0.832*	− 0.073	1

*Denotes that a significant difference was observed at the 1% level

Table 9 Correlation matrix of effect of flood factors changes and flood damage

Variables	% Damage change	% Depth change	% Inundated areas change
% Damage change	1		
% Depth change	0.929*	1	
% Inundated areas Change	0.160	− 0.078	1

*Denotes that a significant difference was observed at the 1% level

a correlation analysis was designed based on the Pearson correlation coefficient, considering the observation of 18 cities (Tables 8a, b, 9). Table 8a, b is related to the correlation between factors for current and future analysis. However, Table 9 is mainly linked to the effect of factor changes between two periods.

The results showed a significant correlation between the inundated areas and flood damage in both situation current and future. This finding corroborates the results of Zischg et al. (2018), who stated that the flood risk changed because of the growth of settlements. These authors emphasized the implementation of land cover regulations to reduce flood exposure. In addition, the analysis based on change of flood factors between current and future situation indicated a high correlation between the variation of flood depth and flood damage (Table 9). In addition, the size and value of affected properties may also increase flood damages (Thieken et al. 2005). However, some authors considered flood depth as key variable in determining flood damage (Win et al. 2018; Messner et al. 2007).

Finally, the results showed that inundated areas combined with the magnitude of the flood (i.e., water depth) should be considered to implement suitable flood mitigation strategies for sustainable urban development. Moreover, the detection of flood-prone areas will let planners adopt appropriate strategies on urban planning and flood risk reduction, such as in Bogor or Manila City. In these regions, suitable urban resilience strategies should be adopted to avoid the risk of floods and, consequently, to reduce exposure to floods. Moreover, the prediction of future flood situations will be useful for planning and designing structural and non-structural measures. The implementation of blue–green infrastructures can also help to minimize the effects of floods and can help to protect the environment.

Table 10 Disaster risk reduction

No.	Measures	Metro Manila (%)	Jakarta (%)
1	Structural/hard measures	18	53
2	Improvement of drainage system	26	5
3	Updated flood information	16	21
4	Evacuation plan	14	0.2
5	NGO/people contributions	5	2
6	Disaster training/education	7	0.2
7	Disaster insurance	6	5
8	Mixed measures	0	13
9	No answers	9	0

3.6 Risk perception

During the survey, it was requested from interviewees to provide their perception about flood risk and risk management based on their own experiences. The collected information is useful to determine people awareness of the risk of flood. Moreover, understanding flood risk based on past experiences widely influences risk management and the implementation of national strategies. The result is presented in Table 10.

Based on the survey analysis, it was noticed that engineering actions such as dams and improvement drainage system are highly requested and it should be the main priority of the government. In fact, 44% and about 58% of respondents, respectively, in Metro Manila and the surrounding areas and Jakarta strongly agreed about the necessity to implement structural measures. In addition, the improvement of early warning system is also required to reduce the impact of flood. However, the measures related to disaster insurance and training are still low.

According to the respondents in both study areas, the strategy of flood reduction will be more relevant with the implementation of soft and hard measures. In fact, considering the importance of historical knowledge and past experiences of extreme events may contribute to implement effective measure. In conclusion, the respondents are aware of the risk flood but they believe that the responsibility of the government to implement strategies should be essential.

4 Conclusion

The spatial distribution and quantification of flood damage in two urban watersheds in Southeast Asian countries are suitable for regional assessments. The application of the spatial analysis approach is useful to determine susceptible areas to floods and can be appropriate for local decision makers to prioritize their strategies and to implement sustainable flood risk reduction. The flood depth-damage function constructed for the two cities enabled us to quantify the direct tangible flood damage in the flooded areas. Integrating other inundation characteristics such as velocity or duration in this model would enhance the evaluation of flood damage. The evaluation of future flood damage shows that it will be more significant under the effects of the increase in rainfall and urbanization. The analysis of the relation of the drivers affecting floods and flood damage indicated that the inundated areas combined with the magnitude of water depth are both important, depending on the sites. For this reason, water depth and urban resilience should be considered in adaptation strategies. Furthermore, appropriate and sustainable flood control measures should be designed, taking into account potential future conditions, such as climate and land cover. Consequently, the protection against floods will be more efficient and less costly. Moreover, the perception of local people, which is based on their own experiences related to flood event, will be useful to improve the disaster risk reduction strategy.

The evaluation of flood damage provides relevant information to cope with flood problems. This assessment might help to launch insurance programs for affected local communities. However, the findings can be more accurate by reducing the degree of uncertainty related to data availability or by reducing the scale of application and the establishment of flood depth-damage function to several land use categories.

The integration of all costs (tangible and intangible) can provide more details about flood impacts, and it can lead to enhancing people's perceptions and decision makers' awareness.

Data availability The data collected and used in this study are strictly anonymous and are used for research purposes only.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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