

Flood risk assessment for delta mega-cities: a case study of Jakarta

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Received: 25 October 2013 / Accepted: 13 July 2014 / Published online: 20 July 2014
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Abstract Jakarta has suffered major floods in 2002, 2007, and 2013. To cope with and adapt to both the current and future flood problem, the city requires quantitative assessments of flood risk. In this study, we develop a flood risk assessment model for Jakarta. The model is based on the Damagescanner model, adapted for Jakarta using local information on hazard, exposure, and vulnerability. The model was first set up using existing estimates of economic exposure of different land use classes to represent exposure and depth-damage functions (vulnerability curves) from several existing studies in south-east Asia to represent vulnerability. Using these data to simulate damage led to an overestimation by several orders of magnitude. Hence, we held a series of expert meetings and workshops with local stakeholders to develop specific estimates of economic exposure per land use class and to derive vulnerability curves specific for Jakarta. We compare the resulting simulated damages to reported damages and found them to be in good agreement, giving confidence in the use of the model for flood risk assessment. Under current conditions, we found the annual expected damage due to river flooding in Jakarta to be approximately USD 321 million per year. We also examined the sensitivity of flood risk assessments to the use of different vulnerability curves. The sensitivity is high: using the six curves described in this study to simulate risk led to a factor eight difference between

Electronic supplementary material The online version of this article (doi:[10.1007/s11069-014-1327-9](https://doi.org/10.1007/s11069-014-1327-9)) contains supplementary material, which is available to authorized users.

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the lowest and highest values. Our findings demonstrate that flood risk assessments need to pay close attention to the selection, development, and testing of vulnerability curves.

Keywords Flood risk assessment · Damagescanner model · Flood risk model · Depth-damage function · Vulnerability curve · Synthetic vulnerability · Jakarta

1 Introduction

Floods are the most commonly occurring natural disasters in Asia. Recent studies on flood risk at the global scale show many regions of Asia to be amongst the most high-risk regions in terms of potential damages and affected population, both in terms of river flooding (e.g. Hirabayashi et al. 2013; UNISDR 2011; Ward et al. 2011a, b), and coastal flooding (Hanson et al. 2011).

One of the countries in Asia with the highest impacts from flooding is Indonesia, and in particular its capital city Jakarta. Indeed, Jakarta has already suffered several devastating floods in the twenty-first century, with major floods in 2002, 2007, and 2013. For the 2002 and 2007 events, the government issued formal estimates and documentation on the flood damages, through The National Development Planning Agency (Bappenas). An overview of these findings is shown in Table 1. Moreover, the indirect impacts of the floods to the society and regional economy may have been even greater than those reported below, since these investigations do not include aspects such as transformational losses by individuals, and the period of investigation was only 10 days between 5 and 14 February 2007, whilst indirect losses may have been felt over a longer time span (Bappenas 2007). The floods of 2007 caused the displacement of over half a million people, the closure of many roads and rail lines, including the main highway to the international airport, and telephone lines were cut-off (Ward et al. 2011a, b). Whilst the social and economic impacts of the flood in January 2013 are still being assessed, initial reports suggest that the flood was one of the most severe on record, along with those of 2002 and 2007 (Sagala et al. 2013).

Historical records show that flooding per se is not a new problem in Jakarta. Floods have occurred since the era of the Tarumanegara kingdom in the fifth century, as documented in the Prasasti Tugu (Noorduyn and Verstappen 1972). However, the impacts of flooding have increased in recent decades as a result of a large number of drivers, both physical and socioeconomic in nature. Examples of physical drivers include land subsidence due to the extraction of groundwater (Abidin et al. 2008), and low drainage, and/or storage capacity in the city's waterways, partly due to them being clogged up by solid waste and by sediments eroded from upstream (Steinberg 2007). At the same time, socioeconomic development has caused rapid changes in Jakarta. Over the last half century, Jakarta's population has risen from 2.7 million in 1960 to 9 million in 2007 (BPS 2012), accompanied by a rapid growth in GDP. These changes in population and wealth have also led to rapid changes in land use (Verburg et al. 1999), which can affect flood disasters in Jakarta in two main ways: (a) due to increased discharge and sediment delivery of the rivers running through Jakarta as a result of reduced soil water holding capacity and infiltration rates in the watersheds above Jakarta (Poerbandono et al. 2009) and (b) due to changes in the value of assets and number of people potentially exposed to floods if they do occur (Ward et al. 2011a, b).

Table 1 Comparison of Jakarta flood damage during 2002 and 2007 flood (Bappenas 2007)

Description	2002	2007
Precipitation	361,7 mm (mean Jakarta in 10 days)	327 mm (mean Greater Jakarta in 6 days)
Inundated area	331 km ² in Jakarta	454,8 km ² in Jakarta
Loss of life	80 persons	79 persons (status of 12 February 2007)
Refugee	381 persons	590.407 persons (status of 6 February 2007)
Direct losses	IDR 5.4 trillion (2002 values) USD 1,510 million (2012 values) ^a	IDR 5.2 trillion (2007 values) USD 890 million(2012 values) ^a
Indirect losses	IDR 4.5 trillion (2002 values) USD 1,260 million(2012 values) ^a	IDR 3.6 trillion (2007 values) USD 620 million (2012 values) ^a

^a Values in Rupiah (IDR) are original values in year of event. These were converted into USD values for the year of the event using exchange rates from the World Bank (<http://data.worldbank.org/data-catalog/world-development-indicators>), and then adjusted to 2012 values using GDP deflators from the International Monetary Fund (<http://www.imf.org/external/pubs/ft/weo/2013/01/weodata/index.aspx>)

Moreover, the flood problems in Jakarta may become more severe in the future as a result of climate change. For example, observations based on altimetry satellite detection for selected Indonesian coasts, including Jakarta, show a mean sea-level rise in the Bay of Jakarta of ca. 3–4 mm per year over the period 1993–2009 (Nurmaulia et al. 2010). Moreover, most climate studies in south-east Asia suggest that extreme rainfall events may increase in severity and frequency within the twenty-first century (e.g. IPCC 2008), which could lead to increased extreme river discharges.

Hence, there is a clear need for coordinated efforts to reduce flood risk in the city, both under current and future conditions. Indeed, Jakarta has a long history of dealing with floods. To date, Jakarta has conducted three main master plans on coping with floods (Caljouw et al. 2005; Kooy and Bakker 2008; Gunawan 2010; Sutyoso 2007). A similar aspect of all of these past plans has been the traditional approach to flood management, i.e. using infrastructural measures to reduce the chance of flooding (Sagala et al. 2013).

However, there is a growing recognition amongst practitioners and researchers that due to the ongoing and large physical and socio-economic changes outlined above, it will become increasingly expensive to defend against floods. Moreover, the chance of flooding can never be completely removed. Hence, long-term adaptation plans are required that reduce both the chance of flooding and the consequences should a flood occur. This is facilitated by a flood risk approach, whereby flood risk is the product of hazard, exposure, and vulnerability (e.g. UNISDR 2011). Hazard refers to the physical flood event, including its characteristics and probability of occurrence; exposure refers to the location of economic assets or people in a hazard-prone area; and vulnerability refers to the susceptibility of those assets or people to suffer damage and loss. Throughout this paper, we have used the same terminology as UNISDR (2011). Whilst risk assessment and risk management are already encapsulated in several Indonesian regulations (such as the regulation related to risk assessment in Law No. 24/2007 and its descriptives in the Regulation of the Government of Indonesia No. 21/2008), no detailed flood risk assessment method is currently available for the city. Bappenas, together with the National Office for Disaster Management (BNPB), have produced a document called National Action Plan for Disaster Risk Reduction (NAP-DRR 2010–2012) that contains a rough risk map for the entire country, showing areas of low, medium, and high risk at the country scale.

City-scale flood risk assessments are important since they allow planners to identify the most at risk areas, to assess how risk may change in the future, and to assess the

effectiveness (in terms of reduced flood risk) of various adaptation measures (Ward et al. 2011a, b).

For coastal flooding, several efforts have already been carried out to assess both current and future flood exposure and risk in Jakarta. In a study of the exposure of people and assets to coastal flooding in 136 port cities worldwide, Hanson et al. (Hanson et al. 2011) projected that Jakarta will be ranked in 20th place by 2070, in terms of exposed population. Similarly, Hallegatte et al. (2013) projected that Jakarta will be the 11th ranked city worldwide by 2050 in terms of annual expected loss, considering socio-economic change, land subsidence, sea-level rise, and adaptation to maintain flood probability. Ward et al. (2011a, b) also simulated the potential impacts of future sea-level rise and land subsidence on the exposure to flooding in northern Jakarta. They found that the economic exposure to flooding may increase by a factor of 4–5 between 2010 and 2100, predominantly as a result of land subsidence.

However, to date, there have been no studies of river flood risk in Jakarta, despite that fact that many of the recent major flood events have resulted from riverine flooding. In this paper, we develop a first river flood risk assessment tool for Jakarta and use it to calculate risk under current conditions. To do this, data are needed on all of the components of risk, i.e. hazard, exposure, and vulnerability. Whilst in many cities information on flood hazard (i.e. inundation maps) and exposure (i.e. land use and/or population maps) may be available, data on vulnerability are limited. As a result, some studies attempt to only assess exposure to flood hazard, ignoring vulnerability. For example, Ward et al. (2011a, b) carried out an assessment of the economic exposure to coastal flooding for the northern part of Jakarta. Other studies often apply generic depth-damage functions, or curves from studies in other cities, to represent vulnerability (e.g. Beckers et al. 2013; Messner et al. 2007; Muto et al. 2010; Pillai et al. 2010; Te Linde et al. 2011; Ward et al. 2011a, b). Both of these approaches may be problematic for flood risk assessments, since vulnerability is known to be highly heterogeneous (Jongman et al. 2012; UNISDR 2013). However, little is known on the sensitivity of flood risk assessments to the use of different vulnerability curves transferred from elsewhere.

To respond to these issues, the main aims of this paper are therefore to:

- develop a flood risk assessment model for the mega delta city of Jakarta;
- use the model to estimate riverine flood risk under current conditions; and
- assess the sensitivity of flood risk assessments to the use of different vulnerability curves transferred from other cities.

This paper extends the work of Ward et al. (2011), in which economic exposure to coastal flooding was carried out for northern Jakarta. The paper extends this work by investigating risk (rather than economic exposure), producing a coverage for the entire city, and focusing on riverine flooding rather than coastal flooding. Riverine flooding is examined due to the lack of existing studies.

2 Methods

In this study, we developed a damage model for Jakarta, based on the Damagescanner model (Klijn et al. 2007; Aerts et al. 2008). We used this model to estimate the direct economic damage as a result of floods of different return periods (2–100 years). We then calculated flood risk (in terms of expected annual damage) by plotting these damages and their associated exceedance probabilities on an exceedance probability-loss (risk) curve,

whereby the risk is approximated by the area under the curve (Meyer et al. 2009a). In this section, we first describe the flood damage model (Damagescanner) and then describe the input data used to run the model in this study.

2.1 Damagescanner

We calculated the direct economic damage for floods of different return periods using an adapted version of the Damagescanner model (Aerts et al. 2008; Klijn et al. 2007). The model considers flood risk as a function of hazard, exposure, and vulnerability; the basic framework is presented in Fig. 1. Damagescanner, and its application in several European basins, has been described in several studies (e.g. Aerts and Botzen 2011; Aerts et al. 2008; Bouwer et al. 2010; de Moel and Aerts 2011; Klijn et al. 2007; Te Linde et al. 2011; Ward et al. 2011a, b, 2013a, b, c), so we only provide a brief overview here.

Damagescanner needs three inputs, namely: (a) a map showing inundation extent and depth to represent the hazard; (b) a land use map, with associated economic values of each land use class, to represent the exposure; and (c) depth-damage functions to represent the vulnerability. Depth-damage functions estimate the expected damage for a given inundation depth and a given land use for each grid cell. In this study, a new version of Damagescanner was developed in Python. The resolution of the model used in this study is 50 m × 50 m. Hence, all input data were first resampled to this spatial resolution. In the following section, we describe the specific data used in this study to represent hazard, exposure, and vulnerability.

2.2 Input data

2.2.1 Hazard data

Flood hazard is represented by maps showing inundation depth and extent for several return periods (1, 2, 5, 10, 25, 50, and 100 years). These inundation maps for Jakarta were produced by the Flood Hazard Mapping (FHM) framework by Deltares in 2007 and Deltares 2009, as well as the Flood Management Information System (FMIS) projects by Deltares in 2012 together with the Research and Development Center For Water Resources (Pusair) and the National Office for Climate (BMKG) for the province of DKI Jakarta (Special Capital Region of Jakarta) administration and the national government of Indonesia (Deltares et al. 2012). The FHM framework includes a hydrological and hydraulic model of the Ciliwung River integrated with an overland flow model of DKI Jakarta. The framework is used by and updated in close communication with stakeholders in Jakarta [i.e. local office of Public Works (PU DKI) and the office for Ciliwung Cisadane river management (BBWSCC)].

The hydrological and hydraulic processes are computed using the SOBEK model; a full description of SOBEK has been developed by Deltares (2014) and is accessible online. SOBEK is a modelling framework for flood forecasting, optimisation of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt intrusion, and surface water quality. The components within the SOBEK modelling framework simulate the complex flows and the water-related processes in almost any system. The coupled one- and two-dimensional (1D/2D) hydrodynamic system over horizontal plane engine operates with complete Saint–Venant equations including transient flow phenomena and backwater profiles (Stelling and Verwey 2006). The hydrodynamic engine has an automatic drying and flooding procedure that is 100 % mass conservative. The engine can deal with steep

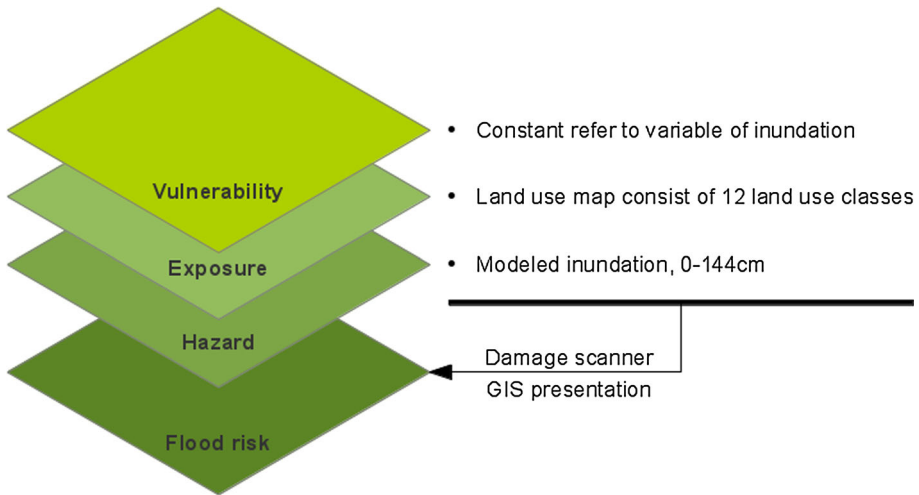


Fig. 1 Flow diagram representation of Damagescanner

canals with supercritical flows, moving hydraulic jumps and complex interloped water systems.

In the FHM framework (Tollenaar et al. 2013), all major rivers discharging to Jakarta Bay are included in a 1D network for the computation of water levels and discharges. A 2D grid is included for the computation of overland flow in case 1D embankments are overtopped. The overland flow model uses grid cells of 50×50 m at the Ciliwung floodplain and 100×100 m for the rest of the Jakarta province. To force the 1D model, a library of rainfall run-off (RR) models is available in SOBEK. In the Ciliwung catchment, the Sacramento model (Burnash 1995) is used to generate run-off for 449 sub-catchments from rainfall and evaporation records. Sacramento discriminates an upper zone and lower zone for the computation of quick (e.g. surface run-off) and slow (e.g. base flow) run-off components. Incorporation of both quick and slow run-off components is important for a proper simulation of major flood events. Such events are characterised by days or weeks of wet conditions increasing baseflow and an extreme rainfall event at which river and canal embankments are overtopped.

As an example, the hazard map for a 50-year return period flood is shown in Fig. 2. The spatial resolution of the original hazard map is $50 \text{ m} \times 50 \text{ m}$, and the depths are given for increments of 1 cm.

2.2.2 Exposure data

Exposure is represented by a map showing the economic exposure per grid cell, which is in turn based on a land use map. In this study, we used the land use map available for the year 2002, supplied by the office of city planning in Jakarta (DTR DKI 2003). The map shown in Fig. 3 shows land use at a horizontal resolution of $50 \text{ m} \times 50 \text{ m}$, for 12 land use classes, namely: agriculture and open space; low-density urban kampung (self-made houses or residential areas with no site plan); swamp, river, and pond; industry and warehouse; commercial and business; planned house; education and public facility; government facility; high-density urban kampung; transportation facility; and park and cemetery. The

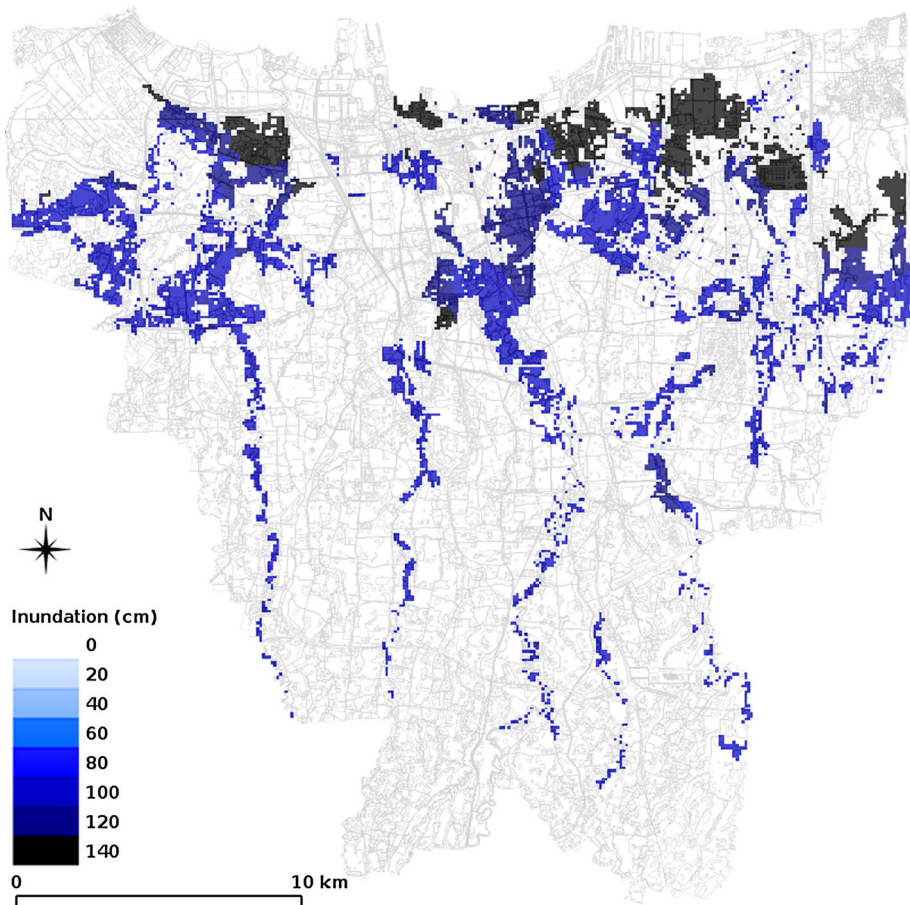


Fig. 2 Map of Jakarta showing the modelled hazard for a 50-year flood return period using the SOBEK hydrology suite

map is harmonious in terms of land use classes with land use maps for 1980 and 1995, thus allowing for extrapolations to the future in subsequent studies.

In the Damagescanner model, a value for economic exposure is applied to each land use class. In this study, we used two approaches to assign these values. Firstly, we carried out a literature review of past studies in Jakarta in which the economic value of different land use classes has been estimated. This review was based on available studies in Jakarta using different approaches. The first is a study of flood exposure in northern Jakarta (2010), in which market valuations were assigned based on interviews (for two land use categories, namely uniform and non-uniform settlements) and on existing literature and statistics for the other land use types. The second is a study carried out in the Kampung Melayu area of East Jakarta (Marschiavelli 2008), based on a limited number of household surveys. This resulted in the maximum value estimates shown in Table 2.

However, the aforementioned studies note that these values are very rough and uncertain. Hence, for this study, we also developed new estimates of economic exposure values based on a series of expert meetings and workshops described in Sect. 2.2.3.

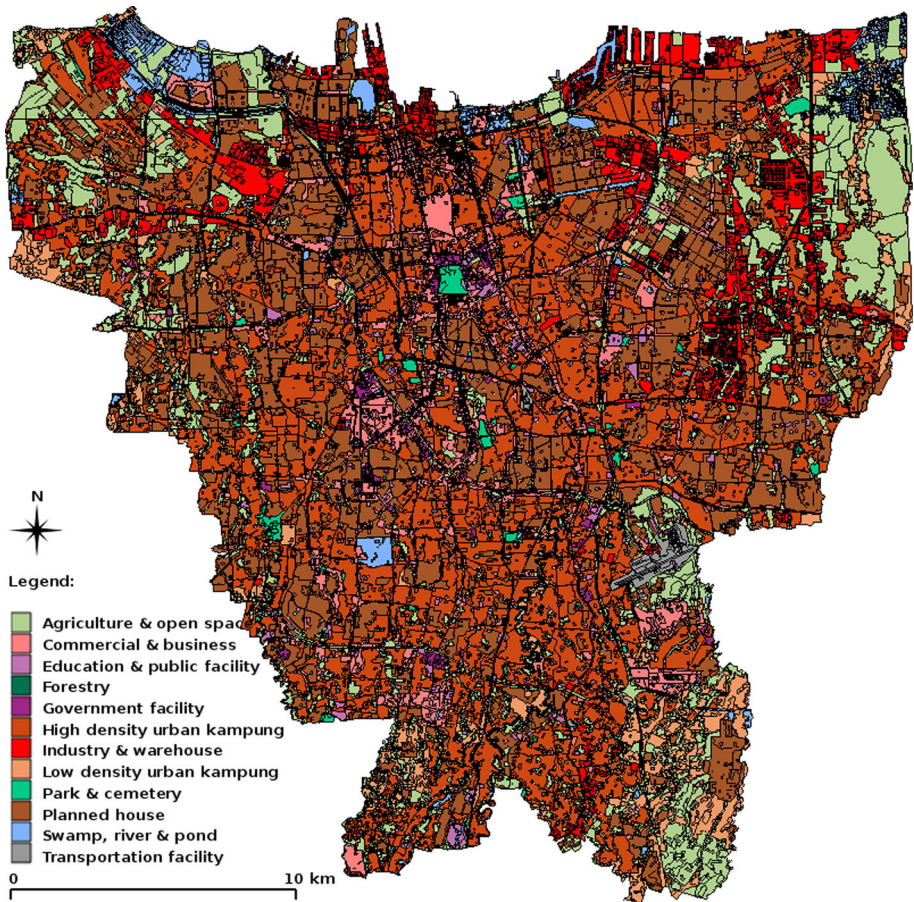


Fig. 3 Jakarta land use map for 2002 from the office of city planning, showing twelve land use classes (DTR-DKI 2007)

2.2.3 Vulnerability data

In Damagescanner, vulnerability is represented by depth-damage functions, hereafter referred to as vulnerability curves. These curves show the percentage of the economic exposure values that would actually suffer damage for different flood depths per land use class (e.g. Merz et al. 2010a). For Jakarta, no officially recognised vulnerability curves are currently available. Hence, in this study, we first calculated risk based on vulnerability curves derived from flood risk studies in large cities in the south-east Asia region. We then held a series of expert meetings and workshops to derive new vulnerability curves specific to the Jakarta region and recalculated risk based on these curves. Finally, we compared the risk results obtained through using the different vulnerability curves, in order to assess the sensitivity of the final risk results to the choice of vulnerability curve.

For the existing vulnerability curves, we used the following: curves for specific localities in the Kampung Melayu village of East Jakarta (Marschiavelli 2008); curves for Bangkok (World Bank 2009); curves for Ho Chi Minh City (HCMC) (Dickens 2011); and

Table 2 Economic exposure values per land use class according to literature review of past studies in Jakarta

Land use name	Economic exposure (thousand USD per hectare)
Industry and warehouse	2,500
Commercial and business	2,500
Government facility	2,500
Planned house	1,200
Transportation facility	Not available
Education and public facility	1,000
High-density urban kampung	1,000
Low-density urban kampung	1,000
Forestry	1.7
Swamp, river, and pond	1.7
Park and cemetery	1.7
Agriculture and open space	80

curves for Manila (Muto et al. 2010; Pillai et al. 2010). The methods used to derive these curves are only documented in summary, and therefore, it is difficult to know the assumptions made in their development and hence the impacts of those assumptions on the risk calculations. In brief, the curves for Kampung Melayu in Jakarta, Bangkok, and HCMC were based on surveys in those localities, whilst the curves for Manila are in fact simply the standard vulnerability curves for Japan.

In order to derive the new economic exposure values and synthetic vulnerability curves (Penning-Rowsell and Chatterton 1977), specific to the case of Jakarta, a series of expert meetings and workshops was held in 2012 in Jakarta. Essentially, this process followed a Fuzzy Cognitive Mapping (FCM) approach (Groumpos 2010; Stach et al. 2010), as previously employed by Murungweni et al. (2011) to estimate livelihood vulnerability. The process consisted of two main rounds. In the first round, a series of four expert meetings was held with nine stakeholders in order to derive preliminary economic exposure values and vulnerability curves. In a second round, a one-day workshop was held with a larger group of different stakeholders in order to validate, and where necessary improve, these initial values and curves. The two rounds are described briefly below.

In the first round, BPPT (Agency for the Assessment and Application of Technology) hosted a series of four one-day expert meetings, as part of the project ‘SMS based flood early warning system to decrease flood risk in Jakarta’. This project was funded by Ministry of Research and Technology, Indonesia (PKPP fund FI.129/2012) and had the purpose of assessing the potential effectiveness of an early warning system to reduce flood risk in Jakarta. The meeting was attended by nine experts from different stakeholder groups involved in the project, namely stakeholders from the fields of: agriculture, education, infrastructure, machinery, ecosystem modelling, hydrology, forestry, environmental science, and administration. The meetings addressed three main aspects. Firstly, for each of the land use classes listed in Table 3, the meetings were used to identify ‘fuzzy elements’, i.e. the elements potentially exposed to flooding in each land use class, both in terms of fixed elements (e.g. houses, offices, and infrastructure) as well as their contained assets. For example, for the land use class ‘low-density urban kampung’, the experts identified the buildings that could be affected, as well as fixed elements of those buildings that could be

affected (e.g. houses, being made of fixed elements such as walls, roofs, doors, and windows), as well as the assets contained in a standard unit (e.g. furniture, books, television, and motorcycles). Secondly, each of these fuzzy elements was assigned an economic exposure values equal to its market price. Finally, the experts were asked to estimate the percentage damage to each fuzzy element that would occur for inundation depths of the following increments: 25, 50, 75, 100, 125, 150, and 200 cm. All of these meetings were carried out in plenary sessions.

In the second round, a one-day workshop was held in Jakarta on ‘*Vulnerability synthesis for flood risk assessment*’, with representatives from outside the project from local governments, and private and public organisations, as listed in Table 3. In the first part of the workshop, the theory and practice of flood risk assessment were explained, so that the attendants understood the reason for developing the values and vulnerability curves. As part of this presentation, the flood risk that would occur in Jakarta assuming the existing economic exposure values and vulnerability curves was shown in the form of maps and tables. For each land use class, the representatives were then asked to discuss the economic exposure values and forms of the vulnerability curves in order to reach a consensus on each. Carrying out the analyses in two rounds aims to give a better focus to the workshop.

3 Results

We first show the new values for economic exposure values and the new vulnerability curves derived from our workshop. We then show the results of our damage modelling exercise when only the economic exposure values and vulnerability curves from the literature study are used, followed by the results based on the new economic exposure values and vulnerability curves. Next, we show how the economic risk (expressed as annual expected damages) is distributed over different land use classes, as well as a spatial representation of the risk.

3.1 Vulnerability curves and economic exposure values

3.1.1 *Economic exposure values*

In Table 4, we show the economic exposure values per hectare for each land use class. The values in the left-hand columns are derived from the literature on past studies in specific parts of Jakarta, as described in the Methodology section. For some of these past studies, it is not always clearly documented how these estimates were derived. Hence, we also derived economic exposure values specific for Jakarta during our workshops with stakeholders. These values are shown in the right-hand column. The first thing to note is that the values derived from the workshop are, in general, significantly lower than the values derived from the literature review. The only classes where this is not the case are ‘swamp, river, and pond’, ‘park and cemetery’, and ‘forestry’, all of which only contribute minimally to flood damage in Jakarta. For the main damage-causing categories (i.e. ‘industry and warehouse’, ‘commercial and business’, ‘planned house’, and ‘high-density urban kampung’), the difference between the values from the past studies and our workshop is about a factor of four to six.

Table 3 List of experts attending workshop to develop economic exposure values and synthetic vulnerability curves specific for Jakarta

Land use class	Representatives		
	Government	Public	Private
Agriculture and open space	Office of marine issues and agriculture	Association of farmers (HKTI)	Bureau of logistics (Bulog)
Low-density urban kampung	The national office for disaster management (BNPB)	STEI Tazkia University, PKPU Zakat charity	Takaful microinsurance
Swamp, river, and pond	Office of marine issues and aquaculture	Ciliwung National Park, HKTI	Takaful microinsurance
Industry and warehouse	DKI Jakarta (special capital region of Jakarta) administration	AAUI	Axa insurance
Commercial and business	DKI Jakarta (special capital region of Jakarta) administration	AAUI	Axa insurance
Planned house	DKI Jakarta (special capital region of Jakarta) administration	Association of building developers	Bintaro residence, Axa Insurance
Education and public facility	DKI Jakarta (special capital region of Jakarta) administration	Association of teachers (PGRI)	Takaful microinsurance
Government facility	DKI Jakarta (special capital region of Jakarta) administration	Association of building developers	Takaful microinsurance
High-density urban kampung	The national office for disaster management (BNPB)	STEI Tazkia University, PKPU Zakat charity	Takaful microinsurance
Transportation facility	Jakarta office of public works	AAUI	Axa insurance
Park and cemetery	DKI Jakarta (special capital region of Jakarta) administration	PKPU Zakat charity	Takaful microinsurance
Forestry	DKI Jakarta (Special Capital Region of Jakarta) administration	PKPU Zakat charity	Takaful microinsurance

3.1.2 Vulnerability curves

In Fig. 4, we show the vulnerability curves for the four land use classes that generate the highest flood damages, namely: (a) ‘industry and warehouse’; (b) ‘commercial and business’; (c) ‘planned house’; and (d) ‘high-density urban kampung’. Whilst the curves from different studies described in the literature are very different from each other, there are clear similarities in the curves of each individual study between the classes ‘industry and warehouse’ and ‘commercial and business’, and between the classes ‘planned house’ and ‘high-density urban kampung’.

For ‘industry and warehouse’ and ‘commercial and business’, the curves based on the studies on Bangkok and Manila clearly show much lower damages (as a percentage of economic exposure values) for a given inundation depth than those derived for HCMC, past studies focusing on specific parts of Jakarta, and those developed in our workshop. The curves developed during our workshop show the highest damages of all curves for these classes; though for inundation depths above 125 cm, they show the same fractional damage as those for HCMC and the other two studies in parts of Jakarta. For ‘planned house’ and ‘high-density urban kampung’, again the curves from the Bangkok study show

Table 4 Economic exposure values per land use class according to literature review of past studies in Jakarta and according to results of our workshop

Land use class	Economic exposure (thousand USD per hectare)	
	Past studies	Workshop ^a
Industry and warehouse	2,500.0	517.9
Commercial and business	2,500.0	517.9
Government facility	2,500.0	517.9
Planned house	1,200.0	341.8
Transportation facility	Not available	331.5
Education and public facility	1,000.0	259.0
High-density urban kampung	1,000.0	155.4
Low-density urban kampung	1,000.0	129.5
Forestry	1.7	10.4
Swamp, river, and pond	1.7	3.8
Park and cemetery	1.7	3.1
Agriculture and open space	80.0	2.0

^a Original values were derived in the workshop in Indonesian Rupiah (IDR) and converted to USD using exchange rate of 9,654 IDR to 1 USD

very low fractional damages at all inundation depths, though the curves for HCMC show even lower damages. The curves derived from our workshop appear to give damage fractions corresponding to around the average of the other curves.

Given the large spread of the vulnerability curves, we can expect that the flood risk estimates based on the different curves will also show a large range.

3.2 Economic damage and risk based on existing economic exposure values and vulnerability curves

In Table 5, we show the damages for floods of different return periods, as well as the risk (expressed as annual expected damages), based on calculations carried out with the vulnerability curves and economic exposure values taken from the past literature. There is a large variation in the damage estimates depending on which vulnerability curve is used. This is to be expected, since the vulnerability curves vary significantly between each other, as shown in Sect. 3.1. In terms of annual expected damages, there is a factor seven difference between the lowest value of USD 250 million per year and the highest value of USD 1,825 million per year.

A comparison of the modelled flood damages with reported damages based on past events is provided in Sect. 4.1. However, here, we already note that in general the modelled damages based on these existing economic exposure values and vulnerability curves appear to be significantly higher than the losses reported by Bappenas and displayed in Table 1. The floods of 2002 and 2007 are estimated to have had a return period of somewhere between 25 and 50 years. Comparing the reported direct damages for 2002 and 2007 from Bappenas (USD 1,510 million and USD 890 million, respectively) with the modelled values for 25- and 50-year flood return periods shows the modelled values to be much higher.

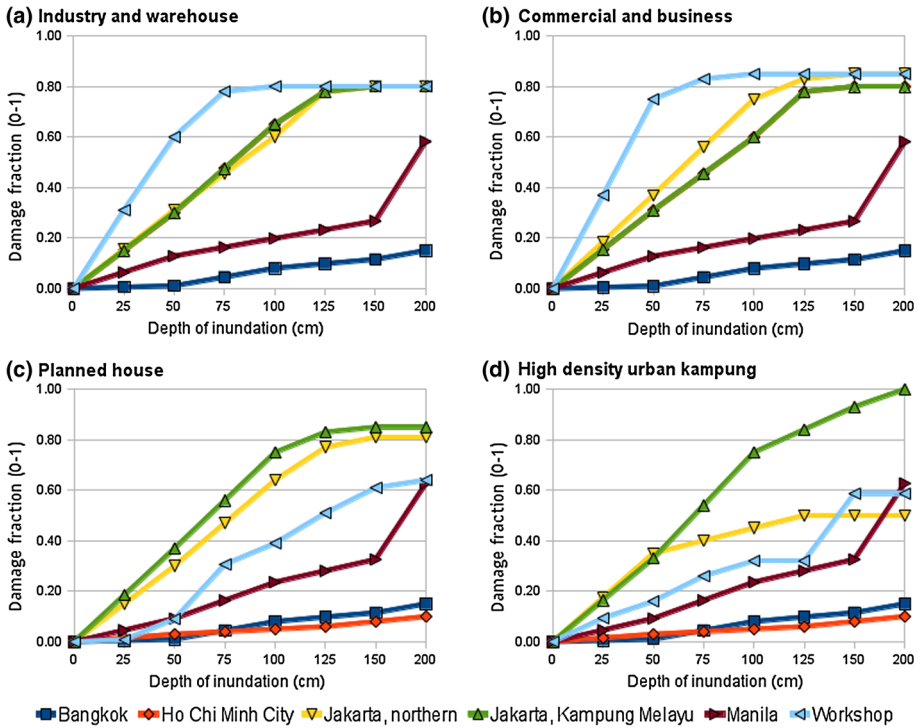


Fig. 4 Vulnerability curves for the four land cover classes that cause the highest economic damage, namely: **a** ‘Industry and warehouse’; **b** ‘Commercial and Business’; **c** ‘Planned house’; and **d** ‘High-density urban kampung’. For each land cover, the curves show the fraction of the economic exposure values that is damaged at given inundation depths

Table 5 Flood damage (USD millions) and flood risk (USD millions/year) based on vulnerability curves and maximum values from previous research in south-east Asian countries

Flood return period	Bangkok	Ho Chi Minh City	Jakarta, northern	Jakarta, Kampung Melayu	Manila
Flood damage (USD millions)					
1	0	0	0	0	0
2	165	616	1,032	1,213	390
5	399	1,531	2,509	2,904	930
10	592	2,334	3,718	4,289	1,373
25	875	3,522	5,603	6,408	2,039
50	1,078	4,228	6,877	7,898	2,503
100	1,297	5,014	8,287	9,495	3,008
Flood risk (USD millions/year)					
	250	965	1,576	1,825	584

The damage values are show for different return periods (1–100 years), and the risk is shown in terms of annual expected damage

3.3 Economic damage and risk based on new economic exposure values and all vulnerability curves

Based on the results described in Sect. 3.2, it appears that using the estimates of economic exposure values taken from existing literature in Jakarta may lead to an overestimation of damage. As explained earlier, given the large uncertainty in using these estimates, as part of our workshop with local stakeholders, we also derived new estimates of economic exposure values for the different land use classes. The new values are shown in Table 4.

In Table 6, we show the damages for the different return periods and the annual expected damages, based on these new estimates, and in combination with both the vulnerability curves from past literature, as well as the new curves derived from our workshop. The resulting values are about a factor 5 lower than those shown in Table 5, which is logical since the economic exposure values derived from the workshop are about 4–6 times lower (depending on the land use class) than those based on the literature review.

The results using the new vulnerability curves for Jakarta derived from our workshop are very similar to the results using the vulnerability curves based on past studies in specific parts of Jakarta. The results based on all three sets of vulnerability curves for Jakarta are significantly higher than the results based on the vulnerability curves derived from studies in Bangkok, Ho Chi Minh City, and Manila.

3.4 Economic damage per land use class

In Fig. 5, we show the percentage distribution of annual expected damage per land use class, based on the vulnerability curves taken from the literature as well as those derived from our workshop. The results are shown for the four most damaging land use classes (using the workshop vulnerability curves), with other land uses being classed as ‘others’. The figure clearly shows that the majority of the damage occurs within these four land use classes. Broadly speaking, these four land use classes can be split into two categories: (a) commercial, represented by ‘Industry and warehouse’ and ‘Commercial and business’ and (b) residential, represented by ‘Planned house’ and ‘High-density urban kampung’.

The figure also shows that the distribution of annual expected damages between these two broad categories (commercial and residential) is rather similar between the results based on the vulnerability curves for Bangkok, Jakarta (northern and Kampung Melayu, and Manila). In these cases, these categories account for ca. 90 % of the total annual expected damages, with about half in the commercial category and half in the residential category. For the results based on the vulnerability curves from our workshop, damages in the commercial category account for a greater proportion of the overall damages (57 %) than residential damages (29 %). However, the most anomalous results (in terms of distribution of damages between land use categories) are for the Ho Chi Minh City vulnerability curves. In this case, commercial damages are by far the largest (83 % of the total), with residential damages accounting for 7 % of the total.

4 Discussion

4.1 Comparison with reported damages and past modelling studies

In this section, we compare the modelled flood damages with reported flood damages based on past events in Jakarta. The main estimate of the costs of the flood events in 2002 and

Table 6 Flood damage and risk (USD millions) and flood risk (USD millions/year) based on (1) economic exposure values plus new curves from the stakeholder workshop (column to the right) and based on vulnerability curves from previous research and economic exposure values from the workshop (column 2–6)

Flood return period	Bangkok	Ho Chi Minh City	Jakarta, northern	Jakarta, Kampung Melayu	Manila	Workshop
Flood damage (USD millions)						
1	0	0	0	0	0	0
2	29	121	218	247	76	208
5	71	302	530	592	181	511
10	106	461	785	874	267	764
25	160	698	1,190	1,318	401	1,151
50	197	838	1,465	1,629	494	1,415
100	237	994	1,768	1,963	595	1,702
Flood risk (USD millions/year)						
	45	191	333	373	114	321

The damage values are show for different return periods (1–100), and the risk is shown in terms of annual expected damage

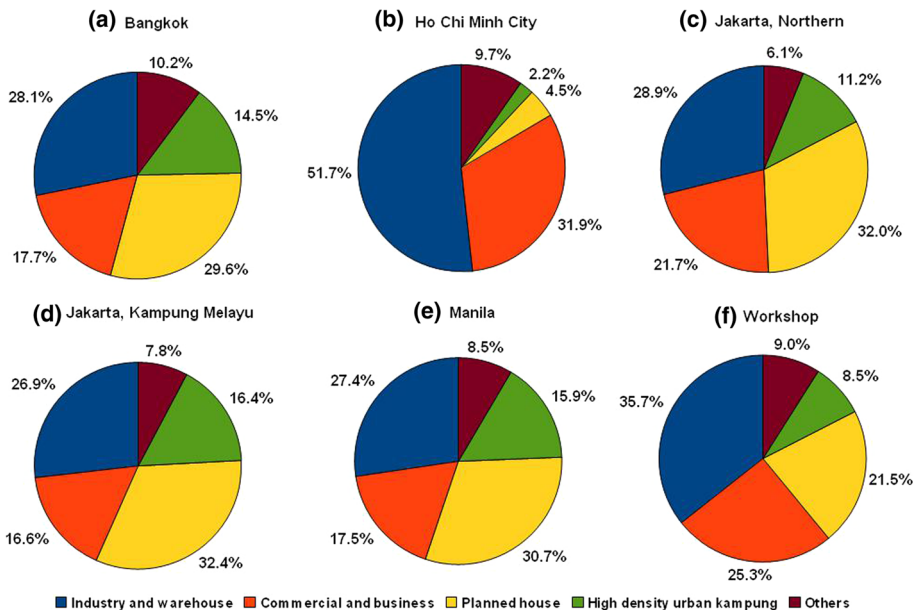


Fig. 5 Pie charts showing the percentage of total annual expected damage, resulting from each land use class. The pie charts are shown for the new maximum damage based on the workshop and for the vulnerability curves for: **a** Bangkok; **b** Ho Chi Minh City; **c** northern Jakarta; **d** Kampung Melayu, Jakarta; **e** Manila; and **f** Workshop

2007 has been carried out by Bappenas (see Table 1), who estimated the direct economic damages for these events at USD 1,510 million and USD 890 million, respectively. Bappenas (2007) estimated these damages based on the *quick damage and loss assessment*

approach described by the United Nations Economic Commission for Latin America and Caribbean (ECLAC) (ECLAC 2003). The approach has previously been implemented following other large disasters in Indonesia, such as the Indian Ocean tsunami in 2004 and the Yogyakarta earthquake in 2006. Bappenas (2007) report the sum of damages for five categories, namely: housing, infrastructure, productive economy, social infrastructure, and other losses. Damage to housing is sub-divided into three damages categories, namely medium, heavy, and total loss. Each category is assigned a damage value (USD 850 per house for medium loss, USD 1,700 for heavy loss, and USD 3,400 for total loss; all values in 2012 values). These values are then multiplied by the number of houses suffering from medium, heavy, and total loss. Note that these values are relatively low, since they are considered to occur on non-permanently constructed houses. In addition, the quick scan assessment for housing generally focuses mainly on places that require government recovery, such as in the high-density urban kampung areas. Infrastructure damage covers transportation, energy, post and telecommunication, water supply, and agriculture. Damage in the productive economy covers industry and merchants, but does not include damage to modern supermarkets. Damage to social infrastructure covers schools, hospitals, worship houses, and other social infrastructure. Other damage covers government buildings, security infrastructure, and banking. The carrying out of the calculation is supported by government institutions under the administration of BNPB, as well NGOs (e.g. the Indonesia Employers Association; Apindo), the General Insurance Association of Indonesia (AAUI); and the United Nations Development Programme (UNDP). Since the approach mainly focuses on houses that require government recovery, not all damages are included, and therefore, the approach may represent a lower total damage than that which actually occurs on the ground.

The flood event of 2007 is estimated to have had a return period of about 50 years (Van der Most et al. 2009); in terms of precipitation intensity, the 2002 event was a little more severe, whilst in terms of inundated area, it was a little less severe. Hence, we compare our modelled results for a 50-year return period with the reported losses of Bappenas (USD 1,510 million and USD 890 million for 2002 and 2007, respectively). Using the economic exposure values taken from the literature and used in past studies, the simulated damages are much higher than these reported values, except for when using the vulnerability curves for Bangkok, for which modelled damage is USD 1,077 million. For all of the other vulnerability curves, the modelled damages are in excess of even the higher damages reported for 2002, by a factor ranging from 1.7 (Manila curves) to 5.2 (Jakarta Kampung Melayu curves). However, the economic exposure values from the former study are known to be very rough estimates. Hence, the series of expert meetings and workshops described in this paper was used to develop updated economic exposure values specific to Jakarta, based on local expert knowledge. Applying these values in Damagescanner led to the improved estimates of damages displayed in Table 6. Here, we see that the modelled damages for a 50-year return period flood are more similar to the reported values and are of a similar order of magnitude to the reported losses either in 2002 or 2007 (except for the estimates using the vulnerability curves from Bangkok, for which the damages are a factor 4.5 lower than the reported value for the event of 2007).

The results based on all three sets of vulnerability curves for Jakarta (based on our workshop and based on past surveys in Kampung Melayu and northern Jakarta) give damages for a 50-year return period flood slightly higher than the reported damages in 2002. The results are of the same order of magnitude, and as stated earlier, it is to be expected that the reported losses based on the ECLAC approach are somewhat lower than observed damages on the ground, since in the category 'houses', this approach mainly

focuses on those houses that require government recovery and do not all include damages. The modelled damages using the curves from Ho Chi Minh City are also similar to the reported damages.

The reported damages of Bappenas for 2007 also give some information on the distribution of damage between different land use categories, which can also be used to further verify the model outputs. Bappenas (2007) estimate that for the 2007 flood, approximately 56 % of damages occurred in ‘commercial’ activities, whilst about 25 % occurred in ‘housing’. Reference to the pie charts in Fig. 5 shows that this distribution of damages is most similar to the modelled distribution of risk based on the vulnerability curves developed in our workshop. Using these curves, commercial activities accounted for ca. 57 % of total damages, and residential for 29 %. Whilst the overall modelled damage estimate for a 50-year return period flood using the vulnerability curves from Ho Chi Minh City fell between the reported damages for the 2002 and 2007 events, the distribution of the damage between categories is very different for the modelled data (83 % commercial and 7 % residential). The same is true for the damage results using the vulnerability curves from northern Jakarta and Kampung Melayu, though the difference in the distribution between categories is less severe than for the Ho Chi Minh City curves.

In summary, the results based on the Jakarta-specific economic exposure values and vulnerability curves appear to produce the most reliable damage estimates, since they have both a similar order of magnitude to reported losses and a similar distribution of those losses over the categories commercial and residential. None of the other combinations of economic exposure values and curves provide damage estimates satisfying both of these criteria.

4.2 Sensitivity of flood risk assessment to the use of different vulnerability curves transferred from elsewhere

As stated earlier, our results are highly sensitive to the vulnerability curves used in the calculation of damages and risk. The difference in annual expected damage between the curves with the lowest values (Bangkok) and highest values (Kampung Melayu) is a factor greater than eight. Moreover, whilst the total annual expected damages are very similar using all three sets of curves based on studies in Jakarta (USD 321 million using the workshop curves; USD 333 million using the northern Jakarta curves, and USD 373 million using the Kampung Melayu curves), our analysis of the distribution of damages between different categories reveals that there is an equifinality problem here. Whilst they all produce similar estimates in this case, only the values based on the workshop curves show a distribution across damage categories similar to the reported damages. Whilst the validation of flood damage and flood risk models is notoriously difficult (e.g. Merz et al. 2010b) due to the lack of reported data, we show here the added value of also using information on the reported distribution of damages across damage categories (where available).

The findings above have important implications for flood risk assessments around the world. Flood risk assessments in various parts of the world are often carried out by transferring vulnerability curves from other countries (e.g. Beckers et al. 2013; Muto et al. 2010; Pillai et al. 2010; Te Linde et al. 2011; Ward et al. 2011a, b). Indeed, Messner et al. (2007) state that relative vulnerability functions (i.e. those in which the damage for different inundation depths is expressed as a percentage of the maximum potential damage, such as those used in this study) are easier to transfer to other regions than absolute damage functions. Whilst this is true, our results show that great care is still needed to assess

whether the relative damage relationships are transferable from the region in which they are developed to the target region in which they are to be applied.

Until recently, few flood risk studies assessed the uncertainty in flood damage estimates, resulting specifically from the use of vulnerability curves. In the last decade, however, several such studies have shown that they form a large source of uncertainty. For example, Merz et al. (2004) evaluated empirical relationships between inundation depths and reported flood damages to buildings in Germany and found large uncertainty in the data used to derive damage functions. Other studies have examined uncertainty in flood damage assessment values based on different factors (e.g. inundation depth, elements at risk, and/or vulnerability curves) (e.g. Apel et al. 2008; Egorova et al. 2008; Merz and Thieken 2009; Meyer et al. 2009b; De Moel and Aerts 2011; Jongman et al. 2012). De Moel and Aerts (2011) systematically assessed the relative contribution of four components to overall uncertainty, namely: inundation depth, land use; the value of elements at risk; and depth-damage curves, for a case study region in the Netherlands. For this region, they found that the elements at risk and the depth-damage curves were the most important sources of uncertainty. Jongman et al. (2012) assessed the sensitivity of modelled flood damage for two case study regions (in the UK and Germany) to the use of eight different vulnerability curves; the resulting damages differed from each other by a factor of 4–11. In this study, the use of different vulnerability curves leads to results differing by a factor ranging from 2.5 to 8.3. The previous research also found that the uncertainty associated with different vulnerability curves was greatest for floods with relatively low inundation depths (>2 m), since the vulnerability curves show the largest differences between each other at these depths. This finding is also relevant in the case of Jakarta, since the simulated inundation depths have a maximum depth of 1.44 m.

Clearly, flood risk assessments need to pay close attention to the selection, development, and testing of vulnerability curves. Whilst much research tends to focus on the correct simulation of the flood hazard, the vulnerability assessment part has traditionally been rather simplified and neglected. By holding just one workshop with key local stakeholders who can provide expert knowledge on flood damage in Jakarta, and a series of meetings with experts, we were able to improve our overall damage estimates, highlighting the need to carry out such activities.

4.3 Implications

Given the serious nature of the flood problem in Jakarta, there is a clear need for risk-based information in order to adapt to both current and future climatic and socio-economic conditions (Firman et al. 2011). Since quantitative risk-based assessments, especially in terms of flood damages, are relatively new in Indonesia, our study provides useful information for stakeholders involved in disaster risk reduction in Jakarta, such as BNPB and DKI Jakarta. We found that we were able to develop a flood risk model capable of producing flood damage estimates of a similar order of magnitude to reported events, by using a simple series of expert meetings and a workshop to develop synthetic vulnerability curves specific to the Jakarta situation based on local expert knowledge.

Examples of uses of such risk-based information can be for targeting areas for prioritising risk reduction measures, including spatial planning measures (e.g. not building in the most flood-prone areas and relocation of people in high-risk areas) and building codes (e.g. assigning building use dependent on the risk characteristics of the region, building houses with second storeys so that valuable items are not damaged during regular inundation). The flood risk data and maps are also of interest for the insurance industry, since they could be

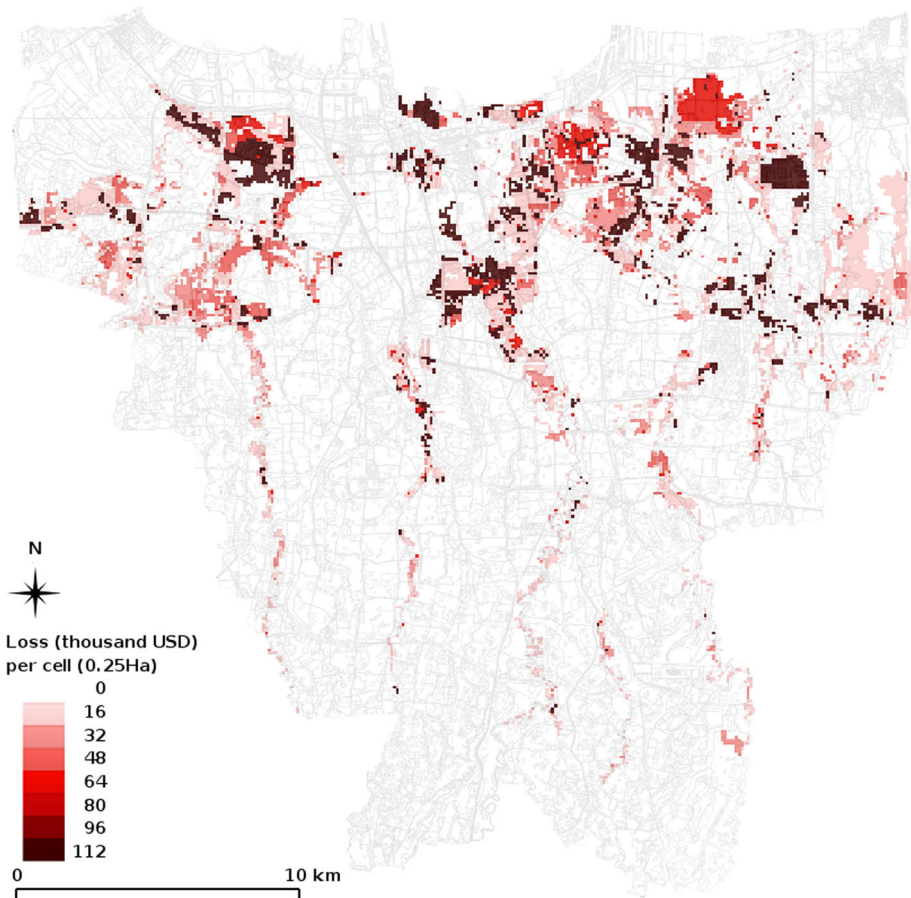


Fig. 6 Maps of Jakarta showing damages in USD (thousands) for a 50-year return period flood

used as a basis for developing a flood insurance market; at present, flood insurance is merged with fire insurance in Jakarta. Moreover, flood risk mapping can be used as a tool for increasing awareness on flooding in communities, which may lead to increased interaction between communities and authorities in discussing and designing possible adaptation measures (Fuchs et al. 2009; Van Alphen et al. 2009).

For these purposes, flood risk mapping is particular useful, since it gives a clear idea of areas where flood risk is highest. For example, Fig. 6 shows the geographical distribution of flood damage for a 50-year return period flood, as simulated using the Damagescanner approach. The digital version of this map, as well as the damage maps for the other return periods, can be found in the supplementary material. The figure clearly shows that most damage is concentrated in northern Jakarta. This part of the city includes the historical centre, which has become a commercial area over time. In turn, this has led to a shift in residential areas to more southern areas and to the northern reclamation area. This also explains why a large proportion (57 %) of the simulated damages in Jakarta are in areas with a predominantly commercial land use type. Maps similar to those shown in Fig. 6 can also be developed for each individual land use class. Compared with existing inundation

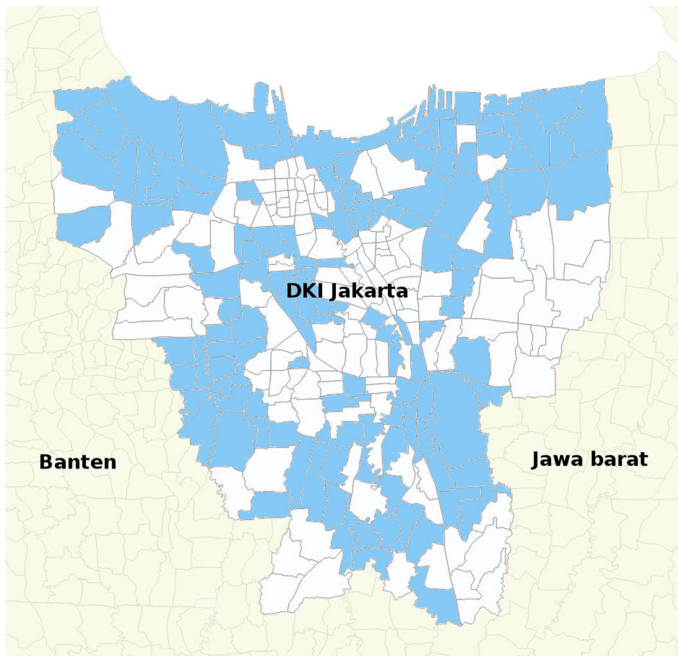


Fig. 7 Map of Jakarta showing districts reported as being inundated (in blue) by village managers. Map translated from Bakornas PB-UNDP report, 14 February 2007 (Bappenas 2007)

maps available in Jakarta, maps such as the one displayed in Fig. 6 provide a large step-forward in terms of their potential for both awareness raising and adaptation planning. An example of an existing inundation map is shown in Fig. 7. The map shows inundated areas (in blue) during the 2007 flood event, based on reports from village managers. The delineation of the inundated areas is based on district boundary information. Hence, if a flood was reported in any part of the district, it is displayed in the map as inundated. The flood hazard and risk maps produced in this study provide more geographically specific information, as well as a greater detail of data (for example, flood depths instead of just inundated or not; flood extents and depths for different magnitude events; and expected damages related to different flood hazards).

4.4 Limitations and future research

One of the main aims of this paper was to assess the sensitivity of river flood risk assessments in Jakarta to the used of different vulnerability curves transferred from other cities. Whilst we have done this, we have not carried out a full assessment of the uncertainty in the overall risk estimates to all input and model parameters. Generally, uncertainties in absolute flood risk estimates are large (Apel et al. 2008; Merz et al. 2010a; De Moel and Aerts 2011). However, we have shown here that the results of the Damages-canner model do compare well with reported damages, both in terms of total damage and the distribution of that damage across different damage categories. This validation lends support to the use of the model in future studies on flood risk in Jakarta, in which more thorough uncertainty assessments would be useful.

One of the planned applications of the model is to assess the relative change in flood damages and risk in the future (compared to present) under scenarios of changes in both physical and socio-economic conditions (for example, climate change, land subsidence, land use change, population increase, and increase in asset values). Bubeck et al. (2011) have shown that estimates of relative changes in risk under different scenarios are more robust than absolute flood risk estimates.

In the current work, we have not used the model to assess the effectiveness of adaptation measures in terms of reducing flood risk. However, this has been one of the main reasons for developing such a modelling framework, and this will be addressed, together with stakeholders, in our future research. The Damagescanner approach provides a useful tool in this regards, since it allows the user to assess the influence on risk of changes in any one (or combination) of the three elements contributing to risk, namely hazard, exposure, and vulnerability. For example, Poussin et al. (2012) used Damagescanner in the Netherlands to assess the effectiveness in terms of flood risk reduction in: (a) spatial zoning measures, by adapting the land use maps used to represent exposure and (b) measures taken at the household level to prevent water from entering houses in the event of a flood, by adapting the shape of the vulnerability curves. Moreover, the model can be used to assess the potential reduction in risk due to changes in the probability of flooding, i.e. the hazard (e.g. Aerts and Botzen 2012), for example, due to a theoretical implementation of higher flood protection standards (such as dikes or water retention areas).

The vulnerability curves developed for this paper assume that individuals do not take private adaptation measures to deal with floods or reduce the damages associated with floods. However, it is known that such measures are in fact taken at the household level in many communities, such as building small concrete retaining walls in front of houses to prevent inundation from relatively shallow floods and moving valuable goods to the second storey of houses to avoid damages during floods (Ward et al. 2010; Marfai et al. 2013). Therefore, research is required to examine how such soft measures taken at the individual and community level affect the relationship between flood depth and damage (and therefore the shape of the vulnerability curve). Once these relationships are known, surveys could be carried out within the communities to ascertain the percentage of households in which such measures are taken. Including this information in the risk modelling approach would further improve the representation of vulnerability. Also related to the vulnerability curves, whilst the validation performed in his study showed that the development of synthetic vulnerability curves for Jakarta led to simulated damages of the same order of magnitude as reported damages, we also plan to compare the vulnerability curves derived using this approach with new curves that are currently being developed in Jakarta based on extensive surveys in several areas.

The current paper only assesses flood risk due to river flooding. In practice, Jakarta is also subject to coastal flooding and flash flooding due to intense rainfall within the city. Ward et al. (2011a, b) have assessed the economic exposure due to coastal flooding in northern Jakarta. Future research would benefit from examining the risk from river and coastal flooding, both separately and where they occur simultaneously.

5 Conclusions

In response to the demand for risk-based information on flooding in Jakarta, we have developed a river flood risk assessment model, based on the principles of the Damagescanner model, but adapted with local information on hazard, exposure, and vulnerability.

The model was first used to assess flood damage and risk using economic exposure values and vulnerability curves taken from a literature review of past studies in Jakarta. We found that the use of these values to represent exposure led to simulated damage several orders of magnitude larger than reported damages during the 2002 and 2007 floods. Hence, workshop series of expert meetings and a workshop was held to derive new estimates of economic exposure values for different land use classes. For the land use classes that have the highest contribution to flood damage, these were between four to six times lower than the values taken from the past studies. Using these new estimates of economic exposure values in the risk model led to simulated damages of the same order of magnitude as reported damages.

We then assessed the sensitivity of flood risk estimates to the use of different vulnerability curves transferred from other cities. To do this, we took five sets of vulnerability curves from studies in cities in south-east Asia, namely: Bangkok, Manila, Ho Chi Minh City, northern Jakarta, and Kampung Melayu (Jakarta). Next to these, we used our series of expert meetings and a workshop to derive a new set of synthetic vulnerability curves generic for the entire city of Jakarta. We found that flood risk is highly sensitivity to the choice of vulnerability curve. The difference in annual expected damage between the curves with the lowest values (Bangkok) and highest values (Kampung Melayu) is a factor greater than eight.

We found that the damage estimates based on the workshop-derived values of economic exposure values and vulnerability curves were closest to the damages reported during the floods of 2002 and 2007. Whilst the vulnerability curves for Ho Chi Minh City, northern Jakarta, and Kampung Melayu also led to total modelled damages similar to the reported values, only the modelled values using the new workshop-derived vulnerability curves led to a similar distribution of damages across different land uses, compared with the reported data.

These findings give confidence in the use of the model for flood risk assessment in Jakarta. Using the workshop-derived vulnerability curves and values for economic exposure values, we estimated the present day annual expected damage as a result of river flooding in Jakarta to be ca. USD 321 million. In our future work, the model will be used to assess the relative change in risk in the future due to changes in physical and socio-economic conditions (e.g. climate change, land subsidence, and population growth) and to assess the effectiveness of different adaptation measures in terms of their potential to reduce, or limit the growth of, that risk.

Our findings demonstrate that flood risk assessments need to pay close attention to the selection, development, and testing of vulnerability curves. Whilst much research tends to focus on the correct simulation of the flood hazard, the vulnerability assessment part has traditionally been rather simplified and neglected. Even the simple approach used here to develop synthetic vulnerability curves led to improved estimates of flood damages (in terms of the agreement with reported damages) when compared to the simple adoption of vulnerability curves from other cities in south-east Asia.

Acknowledgments This research was funded by the Dutch research programme *Knowledge for Climate* and *Delta Alliance* research project HSINT02a (*Jakarta Climate Adaptation Tools*).

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