Index-based flood risk assessment for Metro Manila

C. J. Rubio, I. S. Yu, H. Y. Kim and S. M. Jeong

ABSTRACT

This study focuses on index-based flood risk assessment in Metro Manila, the capital region of the Philippines and most densely populated region in the country. Its objective is to properly address urban characteristics in flood risk assessment by introducing a specific urban-type set of physical, social, economic and ecological indicators. Analytical hierarchy process (AHP) was used to quantify the optimal selection weights for each of the selected 14 indicators. Five levels of flood risk will be presented in spatial maps using geographic information system (GIS) ranging from *Very Low Risk* to *Very High Risk*. Results of this study are expected to aid in understanding flood hazard and risk in Metro Manila. Moreover, the resulting flood risk information can be used as a decision tool in policy making, land-use planning, developing guidelines and countermeasures and flood disaster insurance.

Key words | analytical hierarchy process, flood risk assessment, GIS, Metro Manila

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INTRODUCTION

Flood is one of the most destructive natural disasters in the Philippines (EM-DAT 2018), including Metro Manila, the National Capital Region, which is home to 12 million people. To reduce losses due to flooding, there is a need to know the extent of areas that are affected by floods and how vulnerable the people of these areas have become, thus spatial assessment of risk and identification of areas affected by floods would be effective.

Traditionally, flood risk is expressed in terms of expected damage and likelihood of occurrence. The flood damage is combined with information on the probability of the flood event and then plotted as a return period–damage curve (Apel *et al.* 2004; Meyer *et al.* 2009). However, the results obtained using this method provide neither sufficient information nor the required level of detail for input into flood risk reduction strategies. In addition, the use of damage to assess flood risk suffers from data scarcity, particularly in developing countries (Birkmann 2007; Gall 2007). According to Birkmann (2007), highly exposed regions, with high poverty levels and subject to repeated and catastrophic floods, may not necessarily register significant deaths and damage, although these factors make such places highly risky. Moreover, since mortality and damage figures are obtained from actual events, the use of damage assesses actual vulnerability, but potential vulnerability is ignored (Gall 2007).

Flood management cannot become technically controllable without a proper assessment of flood hazard mapping and flood hazard (Gigović *et al.* 2017). However, flood hazard itself only assesses the extent and depth of flood; it does not assess the consequences on the population, economy and environment, as flood risk assessment does (Rincón *et al.* 2018). In general, risk refers to the expected losses (in terms of fatalities, or in economic terms as damage to property) of a specific hazard to a specific element (e.g., evacuation center) at risk in a particular future time period or future scenarios (Albano *et al.* 2017).

In recent years, studies pertaining to flood risk assessment in the Philippines have been increasing. Pornasdoro *et al.* (2014) examined the flood-prone areas within Metro Manila to find out their degrees of disaster risk. Although the study was limited to population data and physical characteristics of barangays, the findings can be useful to urban and regional planners and government agencies involved in disaster risk reduction and mitigation management.

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Siddayao *et al.* (2014) combined analytical hierarchy process (AHP) and geographic information system (GIS) to come up with a tool for evaluating flood risks in all areas in the municipality of Enrile, located in the province of Cagayan, northern Philippines. Three disaster criteria were considered in their estimation of flood risk: population density (F1), distance from the riverbank (F2) and site elevation (F3). Their study revealed that F2 is assessed by experts to be the largest contributing factor for disaster at 63.33% followed by F3 at 26.05% and F1 at 10.62%. Their developed tool is expected to be a very valuable resource for consulting, planning agencies and local governments in managing risk, land-use zoning, damage estimates, land tax valuation, life, and property insurance claim validation, good governance, lifeline emergency services and remediation efforts to mitigate risk.

Another study by Siddayao *et al.* (2015) incorporated the combination of AHP and GIS to evaluate flood risk in the Central Business District areas of Tuguegarao City, Philippines. They included four disaster criteria, namely population density (F1), distance from the riverbank (F2), site elevation (F3) and distance from ponds and creeks (F4).

In our study, AHP was used as the multi-criteria decision technique within a GIS mapping environment. A multi-criteria analysis method such as AHP provides a framework which can handle different views on the identification of the elements of a complex decision problem, organize the elements into a hierarchical structure, and study the relationships among components of the problem (Boroushaki & Malczewski 2010). Moreover, multi-criteria decision analysis within GIS may be used to develop and evaluate alternative plans that may facilitate compromise among interested parties (Malczewski 1999).

The objective of this study is to provide flood risk information considering urban characteristics by introducing physical, social, economic, and environmental indicators. The resulting different levels of flood risk will be presented in spatial maps using GIS.

METHODOLOGY

Study area

The National Capital Region (NCR) of the Philippines, more widely known as Metro Manila, has 17 local government units (LGUs). It is composed of 16 independent cities, classified as highly urbanized cities, and one independent municipality. NCR, with an area of 619.57 km^2, has a population of 12,877,253, making it the second most populous region in the Philippines.

One of the most devastating flood disasters happened on September 2009 when Typhoon Ondoy (Typhoon Ketsana) struck southwest Luzon in the Philippines. Flood disasters caused by the continuous heavy rainfall affected 872,097 people throughout the entire Metro Manila region, causing 241 fatalities, 394 injuries and damaging 65,521 buildings (of which 12,562 were completely destroyed) (Sato & Nakasu 2011).

Conceptual framework

There are several conceptual frameworks for assessing the structure of flood risk. This study follows that of Davidson (1997), adopted by Bollin *et al.* (2003). This conceptual framework views risk as the sum of hazard, exposure, and vulnerability minus capacity measures as shown in Equation (1). This framework is very flexible and can be easily adapted to specific limitations of research such as data availability. This framework can also be easily updated whenever updated data are available.

$$\text{Risk} = H + E + V - C \tag{1}$$

The formulae used for defining the components of flood risk, namely hazard, exposure, vulnerability and coping capacity, are listed in Equations (2)–(5), where $H =$ hazard index, $E =$ exposure index, $V =$ vulnerability index, $C =$ coping capacity index; α, β, γ, $\delta =$ global weight for hazard, exposure, vulnerability and coping capacity, respectively; and a_i, b_i, c_i, $d_i =$ local weights for hazard, exposure, vulnerability and coping capacity, respectively.

$$H = \alpha(a_1H_1 + a_2H_2) \tag{2}$$

$$E = \beta(b_1E_1 + b_2E_2 + b_3E_3) \tag{3}$$

$$V = \gamma(c_1V_1 + c_2V_2 + c_3V_3 + c_4V_4 + c_5V_5) \tag{4}$$

$$C = \delta(d_1C_1 + d_2C_2 + d_3C_3 + d_4C_4) \tag{5}$$

A set of indicators (H_i, E_i, V_i, and C_i) was selected based on availability of data and review of previous studies (Bollin *et al.* 2003; Siddayao *et al.* 2014, 2015) and these indicators are listed in Table 1. The global, local and indicator weights were calculated using the AHP by Saaty (1980).

Data collection

For the values of indicators, most of the data were gathered and collected from government agencies such as the Philippine Statistical Authority (PSA), Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), Department of Education (DepEd), Commission of Higher Education (CHED) and Bureau of Local Government Finance (BLGF). Several available spatial data from the LiDAR Portal for Archiving and Distribution (LiPAD), PhilGIS and Humanitarian Data Exchange (HDX) were also used.

As for the data needed for the calculation of the global, local and indicator weights, a survey questionnaire was distributed to 12 respondents comprising engineers, municipal risk reduction officers, academics, government employees and medical personnel. In order to integrate their individual responses, a geometric mean was calculated for each indicator.

AHP analysis

Analytical hierarchy process was used to calculate the weights for the different indicators that were considered in this study. In order to perform the AHP analysis, a total of 12 respondents were selected from different fields including academics, engineering, government employees, local disaster risk reduction officers, rescue personnel and doctors. The survey was launched using both printed questionnaires and online survey forms.

In AHP, a pairwise comparison method (PCM) is used to obtain the weight or priority vector of the criteria. Saaty (1980) employed a numerical scale from 1 to 9 in order to evaluate the relative importance between two criteria. The respondents' judgment is then transferred to a pairwise comparison matrix A. Each numerical value r_{ij} of A represents the relative importance of the ith indicator in comparison with the jth indicator. The numerical values satisfy the condition given by Equation (6):

$$r_{ij} * r_{ji} = 1 \tag{6}$$

After building the matrix A, a normalized pairwise comparison matrix was derived by dividing each value of r_{ij} by

Table 1 | List of indicators and their corresponding descriptions

Criteria	Indicator	Description
Hazard	Flood depth (*m*) [H_1]	Depth of flood for a 25-yr return period rainfall
	Total precipitation (*mm*) [H_2]	Total precipitation calculated from the rainfall intensity duration frequency for a 25-yr return period
Exposure	Number of housing (*unitless*) [E_1]	Number of housing units per municipality
	Locally sourced revenue (LSR) (*PHP*) [E_2]	Real property tax + tax on business + other taxes + regulatory fees + service/user charges + receipts from economic enterprises
	Population density (*person/km*^{2}) [E_3]	Measurement of population per unit area of land
Vulnerability	Elevation (*m*) [V_1]	Elevation in metres derived from the digital elevation model
	Poverty index (%) [V_2]	Proportion of families with per capita income/expenditure less than the per capita poverty threshold to the total number of families
	Percentage of vulnerable population (%) [V_3]	Ratio between vulnerable population (children aged 0–6, persons with disability, senior citizen, etc.) and the total population
	LSR dependency (%) [V_4]	Locally sourced revenue/annual regular income
	Percentage of impermeable area (%) [V_5]	Proportion of the total area with impermeable (paved) surface
Coping capacity	Literacy rate (%) [C_1]	Percentage of the population ten years old and over, who can read, write and understand simple messages in any language or dialect
	Number of medical personnel (*unitless*) [C_2]	Number of medical personnel per municipality
	Annual regular income (*PHP*) [C_3]	Locally sourced revenue + internal revenue allotment (current year) + other shares from National Tax
	Disaster preparedness rating (%) [C_4]	Disaster preparedness rating from the Government Assessment Report

the sum of all values of that column. Finally, the relative weights (w_{AHP}) vector was estimated by calculating the average values on each row of the normalized pairwise comparison matrix.

The AHP method makes it possible to check the consistency of the estimated weights. This is done with the consistency ratio (CR) shown in Equation (7):

$$CR = \frac{CI}{RI} \quad (7)$$

where CI is the consistency index and is calculated using Equation (8):

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (8)$$

where $\lambda_{\max}$ is the largest eigenvalue (Malczewski 1999) of the matrix and n is the number of indicators. RI is a constant that depends on n as shown in Table 2. When $CR < 0.1$, the evaluation is consistent, and reliable results can be expected from the AHP model.

Spatial mapping of flood risk

The calculated indicator weights from the AHP analysis is then used to spatially distribute the flood risk. Since the selected indicators have different units of measurement, an initial standardization is performed using the z-score method. This pre-processing method for the raw indicator values thus made the range of mean and standard deviation within 0 to 1.

After calculating the flood risk using Equation (1), the different levels of flood risk were spatially mapped in GIS using the raster calculator and overlay function.

RESULTS AND DISCUSSION

Computation AHP pairwise matrix and consistency ratio

Table 3 shows the calculated global, local and indicator weights from the AHP analysis. Based on the survey responses, exposure has the highest global weight with a value of 0.37. It is followed by vulnerability, hazard and

Table 2 | Random index (*RI*) adapted from Saaty (1980)

n	1	2	3	4	5	6	7	8	9	10
Random Index (RI)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3 | Resulting global, local and indicator weights from the AHP analysis

Criteria	Indicator	Global weight	Local weight	Indicator weight	Consistency check
Hazard	H_1	$\alpha = 0.21$	$a_1 = 0.67$	0.1407	*Not applicable*
	H_2		$a_2 = 0.33$	0.0693	
Exposure	E_1	$\beta = 0.37$	$b_1 = 0.54$	0.1998	$\lambda_{\max} = 3.0036$
	E_2		$b_2 = 0.28$	0.1036	$CI = 0.0018$
	E_3		$b_3 = 0.18$	0.0666	$CR = 0.0031$
Vulnerability	V_1	$\gamma = 0.26$	$c_1 = 0.42$	0.1092	$\lambda_{\max} = 5.2681$
	V_2		$c_2 = 0.13$	0.0338	$CI = 0.0670$
	V_3		$c_3 = 0.22$	0.0572	$CR = 0.0599$
	V_4		$c_4 = 0.13$	0.0338	
	V_5		$c_5 = 0.10$	0.0260	
Coping capacity	C_1	$\delta = 0.16$	$d_1 = 0.37$	0.0592	$\lambda_{\max} = 4.1458$
	C_2		$d_2 = 0.20$	0.0320	$CI = 0.0486$
	C_3		$d_3 = 0.27$	0.0432	$CR = 0.0540$
	C_4		$d_4 = 0.16$	0.0256	

coping capacity with values of 0.26, 0.21 and 0.16, respectively. For the local weights, the value is in the range 0.10–0.67. The indicator weight was calculated by multiplying the local weights with their corresponding global weights. The resulting indicator weights are in the range 0.0256–0.1998.

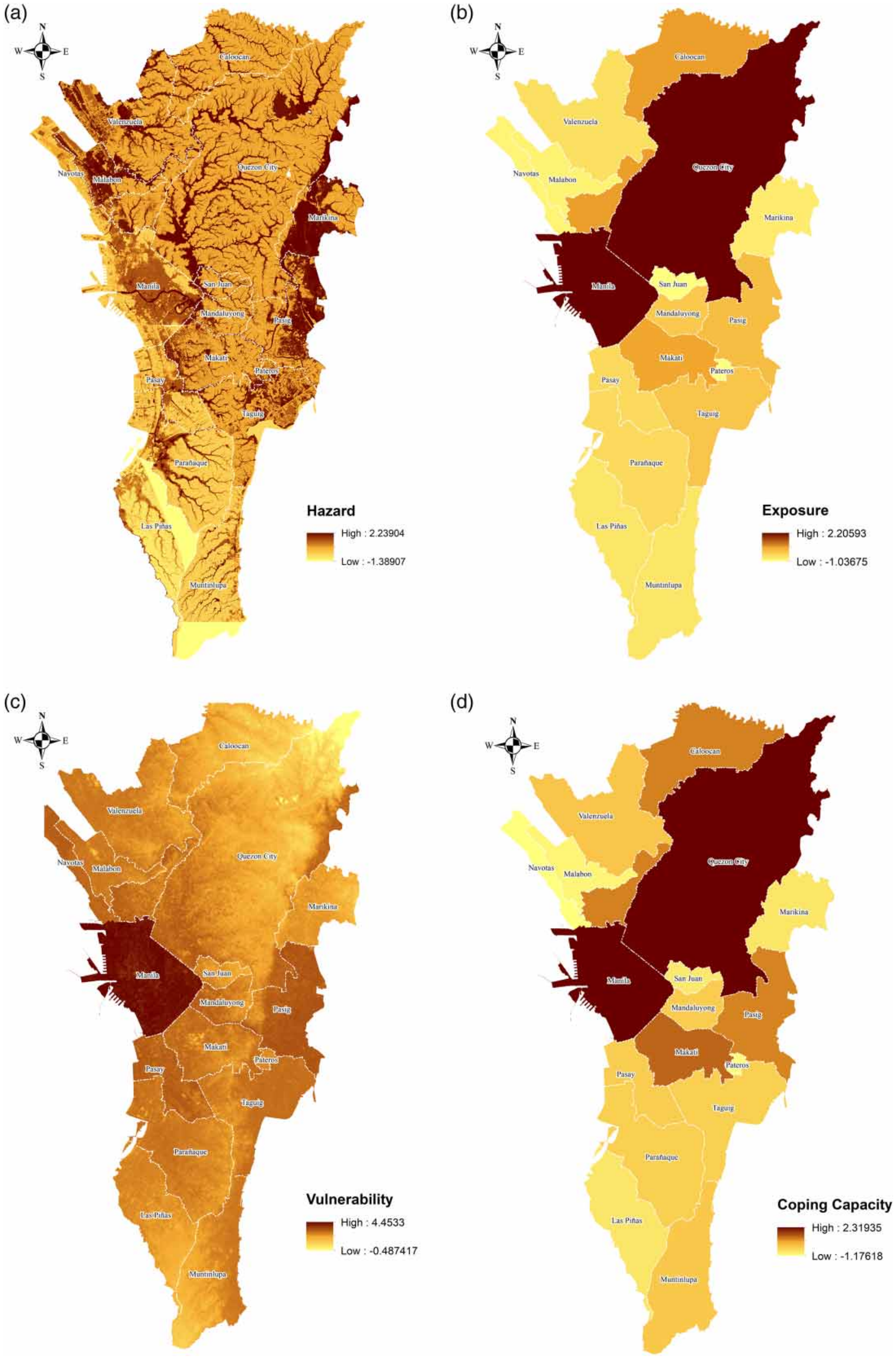

Figure 1 | Spatial map of Metro Manila: (a) hazard, (b) exposure, (c) vulnerability and (d) coping capacity.

The consistency ratios listed in the last column of Table 3 indicate that the integrated respondent's judgment is very consistent since the *CR* values are all less than 0.10. Since there are only two indicators for hazard, the consistency check is not applicable. This is because, as seen in Table 2, the RI for $n = 2$ indicators is equal to zero (0). With zero as a denominator, the value of CR will be undefined or undetermined. This only emphasizes that since there are only two choices, the responses will automatically be consistent.

Flood risk mapping

The calculated indicator weights were used to spatially lay out the components of flood risk using linear combination. Figure 1 shows the spatial maps of flood hazard, exposure, vulnerability and coping capacity of Metro Manila. Figure 1(a) shows that the areas near the rivers and some areas in Marikina and Pasig have the highest flood hazard. This map is very similar to the flood maps developed by Lagmay *et al.* (2017) since the values for the flood depth indicator have been derived from their results. In terms of flood exposure, Manila and Quezon City have the highest values while Pateros, Mandaluyong, Malabon and Navotas have the lowest exposure (Figure 1(b)). For flood vulnerability, most areas in Manila and Quezon City score the highest values as implied in Figure 1(c). As for the coping capacity, Figure 1(d) illustrates that Manila and Quezon City have the highest value. This can be attributed to the fact that these cities both have high annual regular income and a sufficient number of medical personnel.

Table 4 shows the average value of the calculated hazard, exposure, vulnerability, coping capacity and flood risk for each LGU. Values highlighted in bold are the maximum values for each column. It can be observed that Marikina has the highest value of hazard among the LGUs while Manila has the highest exposure. For vulnerability and coping capacity, Quezon City has the highest value. Due to the extremely high value of exposure for Manila, it is also the municipality with the highest risk. It can also be noted that although Marikina has the highest hazard, it has low value of flood risk since its exposure and

Table 4 | Mean values of criteria and flood risk per LGU

LGU name	Hazard	Exposure	Vulnerability	Coping capacity	Flood risk
Manila	0.1018	**0.6538**	0.1623	0.1610	**1.5552**
Mandaluyong	0.1196	0.1143	−0.0374	−0.0253	0.0027
Marikina	**0.2728**	−0.1432	−0.1306	−0.0648	−0.4456
Pasig	0.2127	−0.0095	−0.0146	0.0558	−0.2418
Quezon City	0.1282	0.5873	**0.1962**	**0.3711**	0.9184
San Juan	0.1429	−0.1667	−0.1117	−0.0719	−0.8209
Caloocan	0.1012	0.1807	0.1462	0.0595	0.4302
Malabon	0.2379	−0.2249	−0.1091	−0.0882	−0.6497
Navotas	0.0402	−0.2110	−0.0941	−0.0989	−1.1159
Valenzuela	0.1540	−0.1122	−0.1047	−0.0171	−0.7813
Las Piñas	−0.1134	−0.1453	−0.0856	−0.0670	−1.4405
Makati	0.1319	0.0802	−0.0308	0.0791	−0.3430
Muntinlupa	−0.0535	−0.1206	−0.0421	−0.0181	−1.2176
Parañaque	0.0065	−0.0550	−0.0961	−0.0314	−0.9654
Pasay	0.0324	−0.0007	−0.0858	−0.0303	−0.7071
Pateros	0.1534	−0.4421	−0.1323	−0.1882	−1.3088
Taguig	0.1239	0.0150	−0.0883	−0.0321	0.3759
TOTAL	**0.1013**	**0.1805**	**0.0323**	**0.1039**	**−0.0250**

Note: Values highlighted in bold are the maximum values for each column.

vulnerability are also low. These findings suggest that although Marikina has the highest hazard, it is the municipality of Manila which has the highest possible flood risk, which was calculated considering physical, social, economic and ecological indicators.

Figure 2 shows the spatial map for the flood risk index of Metro Manila. The resulting flood risk index was standardized using the *z*-score method and was divided into five classifications, namely *Very Low Risk*, *Low Risk*, *Moderate Risk*, *High Risk* and *Very High Risk*. The range of values for this index was classified as shown in Table 5.

The percentage area of the LGUs under each flood risk classification are presented in Table 6. Values that are highlighted in bold indicate the highest percentage area, which identifies the flood risk classification of the greater area of the LGU. Only Manila is classified under *Very High Risk* and only Quezon City is under *High Risk*. Mandaluyong, Marikina, Pasig, Caloocan, Malabon, and Makati are under *Moderate Risk*. *Low Risk* was observed in the greater areas of San Juan, Navotas, Valenzuela, Las Piñas, Muntinlupa, Parañaque, Pasay, Pateros and Taguig. As a region, 42.69% of Metro Manila is under *Moderate Risk*.

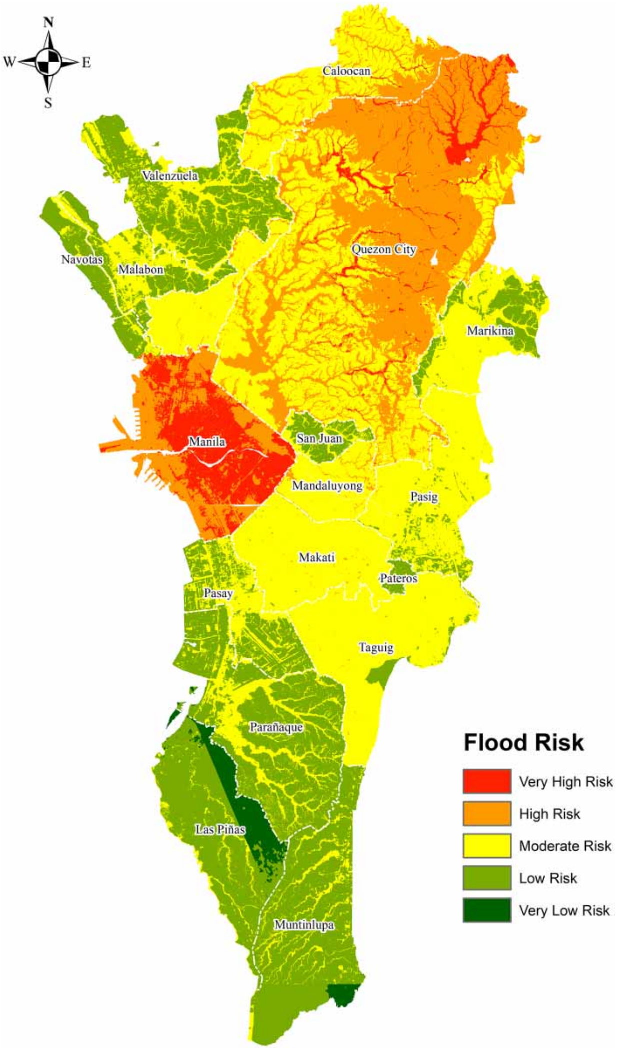

Figure 2 | Index-based flood risk map for Metro Manila.

Table 5 | Flood risk index classification

Range of flood risk index	Classification
>1.75	Very High Risk
0.75 to 1.75	High Risk
−0.75 to 0.75	Moderate Risk
−1.75 to −0.75	Low Risk
<− 1.75	Very Low Risk

Table 6 | Percentage area of LGUs under each flood risk classification

LGU name	Very Low Risk	Low Risk	Moderate Risk	High Risk	Very High Risk
Manila	0.00	0.00	0.03	44.09	**50.13**
Mandaluyong	0.00	0.03	**94.47**	5.08	0.05
Marikina	0.00	31.06	**62.65**	0.03	0.00
Pasig	0.00	15.19	**78.53**	0.09	0.00
Quezon City	0.00	0.01	41.63	**49.93**	4.21
San Juan	0.00	**69.20**	30.64	0.12	0.05
Caloocan	0.00	0.04	**65.06**	13.53	0.29
Malabon	0.00	43.99	**46.32**	0.00	0.00
Navotas	0.20	**58.20**	17.27	0.02	0.01
Valenzuela	0.00	**49.08**	23.90	0.02	0.00
Las Piñas	24.35	**69.34**	5.95	0.00	0.00
Makati	0.00	1.18	**98.48**	0.26	0.01
Muntinlupa	2.92	**84.32**	9.35	0.00	0.00
Parañaque	0.42	**73.62**	25.14	0.00	0.00
Pasay	0.00	**51.05**	48.36	0.01	0.00
Pateros	0.00	**98.60**	1.40	0.00	0.00
Taguig	0.00	**88.40**	6.19	0.08	0.00
NCR	1.56	25.69	**42.69**	17.96	4.68

Note: Values that are highlighted in bold indicate the highest percentage area, which identifies the flood risk classification of the greater area of the LGU.

This flood risk map can be used to assist decision makers in policy making, land-use planning, developing guidelines and countermeasures and flood disaster insurance. One concrete example would be to assess the adequacy of the available numbers of evacuation centers in each LGU. Areas classified under *Very High Risk* must have enough evacuation centers to accommodate affected residents. However, these evacuation centers must not be located in low-lying areas, which could also be verified using the resulting flood risk map. Otherwise, evacuation centers will forfeit their main purpose. Another possible application of the developed risk map will be to identify impacts of flooding on several sectors such as the education sector (Cadag *et al.* 2017), medical sectors and private sectors. Additionally, the developed flood risk map can also be used to appropriately assist stakeholders of the government in prioritizing budget and type of countermeasure, either structural or non-structural. Badilla *et al.* (2014) emphasized that understanding large-scale patterns in flood hazard and food risk in Metro Manila should be done with appreciation of the limitations of the underlying datasets, methods and models used.

CONCLUSION

This study used the combination of multi-criteria decision making (MCDM) with geographical information system (GIS) which allows the integrating of the four components of risk assessment (hazard, exposure, vulnerability, and coping capacity), wherein the physical, social, economic, and/or environmental factors can be considered. This comprehensive flood risk assessment was performed for the local government units of Metro Manila. A total of 14 indicators considering urban characteristics including physical, social, economic, and environmental factors were selected and the AHP method was applied to calculate the weights of each indicator. Among the four criteria weights, exposure was the highest with a value of 0.37, followed by vulnerability, hazard and coping capacity with values of 0.26, 0.21 and 0.16, respectively. Although the greater area of Metro Manila is under *Moderate Risk*, about 42.69%, there were areas under *Very High Risk* and *High Risk*. The results of this study are expected to aid in understanding flood hazard and risk in Metro Manila. Moreover, the resulting flood risk information can be used as a decision tool in policy making, land-use planning, developing guidelines and countermeasures and flood disaster insurance.

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