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Fuzzy based multi-criteria M&E of the integrated flood risk management performance using priority ranking methodology: A case study in Metro Manila, Philippines

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ABSTRACT

This study proposes an approach in conducting an overall performance evaluation of the integrated flood risk management (IFRM). The proposed approach is a monitoring & evaluation (M&E) framework for IFRM suitable in data-poor areas. The proposed framework has two main tasks: 1) to monitor the measures of the four IFRM strategies (prevention, preparedness, response, and recovery/rehabilitation) by asking experts for qualitative appraisals and 2) to evaluate the monitored measures using fuzzy based multi-criteria evaluation based on priority ranking methodology (FME-PRM). The M&E framework is applied for Metro Manila, Philippines, as a case study, where it enabled the quantification of qualitative data and provided a systematic solution for the weight assignment on the IFRM strategies and measures in Metro Manila. The results successfully show the IFRM performance level at the 13 cities and Metro Manila as a region. The results reveal that Metro Manila is at the "Good" performance level, which indicates that IFRM implementation had already progressed, but the achievements are not yet substantial.

1. Introduction

According to a recent report [1], about 47% of the world's natural disasters from 1995 to 2015 are due to flooding. Flood disasters are expected to increase and intensify in the future due to climate change [2,3] and non-climatic changes such as alteration of the land, river, etc. [4,5]. Thus, many countries shifted to the integrated flood risk management (IFRM) approach from the traditional flood management approach using structural measures (e.g., dams, levees, and floodwalls) because these measures failed to cope with residual risks from extreme weather events [6]. The IFRM includes non-structural measures (e.g., land use regulations; flood forecasting and warning; floodproofing) to complement structural measures proactively [6,7]. Moreover, IFRM considers all disaster risk reduction management (DRRM) cycle (prevention, preparedness, response, and recovery/rehabilitation) [8–10], and it necessitates multiple actors' involvement across various sectors and levels in policymaking and practice [11].

The plans for IFRM vary with each country to permit the tailoring of responses to local flood risk situations (including flooding type, severity, and extent) and to recognize political priorities and legal requirements [12,13]. Consequently, adapting to IFRM can be diverse but the outcome from this is universal, i.e., to reduce flood risks [13]. Fully implemented IFRM plans have not yet been achieved in most countries because the implementation is still in its infancy [9], and several recognized barriers hinder the adaptation to IFRM [6,7,14]. Nevertheless, outstanding achievements have already been attained for IFRM implementation, particularly on flood risk assessments, inundation analysis, flood forecasting and warning, etc., which are part of IFRM's preparedness strategy [13,15,16]. For example, Lyu et al. [17–20] have conducted inundation analysis in the metro systems in urban megacities using GIS coupled with multi-criteria decision-making methods (MCDM) technique, and the current authors have also conducted GIS-based inundation analysis with Tokyo as the target area [21,22]. Aside from flood risk assessments and inundation analysis, assessments on stakeholder's perception [23], collaborative planning and public participation [24–26], flood resilience [27], and governance, legal and policy analysis

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[5,12,28] towards IFRM implementation are also widely explored research that supports adaptation and sustainable flood risk management. Despite this extensive research, the overall performance evaluation of IFRM implementation has not yet been conducted, as far as the authors know.

Monitoring & evaluation (M&E) is a suitable method to assess and review the implementation performance, progress, and impact of developmental plans, projects, or programs [29]. However, M&E for IFRM typically revolves around the prevention and preparedness strategies of the DRRM cycle which are specific only to detailed risk assessments and inundation analysis as mentioned above. There is still a gap in research that evaluates the overall performance of IFRM that considers all four DDRM cycle strategies since M&Es that include response and recovery/rehabilitation strategies are rare. Therefore, this study attempts to present an M&E framework for IFRM that incorporates all four DRRM cycle strategies instead of limiting the assessment to only one DRRM strategy. The proposed M&E framework utilizes qualitative appraisals, and these are evaluated using fuzzy based multi-criteria evaluation based on priority ranking methodology (FME-PRM). This framework is simple, systematic, and suitable to data-poor areas such as developing countries, so we applied it in Metro Manila, Philippines as a case study. Metro Manila is considered the most at risk to climate impacts mainly due to its exposure to tropical cyclones among the megacities in Asia [30]. In fact, a supertyphoon struck Metro Manila in 2009, which led to disastrous flooding and the formulation of an IFRM Masterplan for this megacity. Its IFRM Masterplan includes prevention, preparedness, response, recovery/rehabilitation strategies, and several specific measures within these strategies, but their implementation has not yet been assessed due to the lack of M&E activity.

There are two mains tasks in the proposed M&E framework for IFRM: 1) monitoring and 2) evaluation. For the monitoring, indicators are necessary, which are ideally measurable and quantifiable. However, data for such indicators are often unavailable in developing countries because they inherently lack data and technological capabilities [14]. In fact, there are no prescribed measurable indicators in the IFRM for Metro Manila. To cope with this, an M&E framework for IFRM suitable for data-poor areas is proposed in this study, in which data are qualitative appraisals. For this study, the criteria for monitoring are the four strategies of the IFRM, while the sub-criteria are the specific measures in every four strategies. To obtain the data for the specific measures in this study, we conducted interviews and surveys with the practitioners from each city in Metro Manila. We asked them to qualitatively appraise each measure based on their subjective evaluation to capture the IFRM implementation since its inception in 2012. The interview and survey with the practitioners is a laborious and time-consuming process in a developing country, because a special endorsement or connection with the government offices is needed for them to cooperate willingly, and the selection of the respondents with overarching knowledge on the IFRM Masterplan is also challenging. For the evaluation, FME-PRM is employed to aggregate the qualitative appraisals for each measure to evaluate the overall IFRM performance.

Fuzzy set theory using fuzzy numbers is a suitable method for this study because the IFRM measures' data are qualitative appraisals. This method enables the quantification of such qualitative information through a membership function that cannot be arbitrarily represented with two-valued logic (true or false), probabilistic, or probability values [31,32]. These membership functions can then be evaluated using fuzzy logic or fuzzy operations. Fuzzy set theory has been extensively applied to MCDM problems related to science, management and business, engineering, and technology that required qualitative judgments or preferences from the users [33,34]. For DRRM-related problems, fuzzy sets have been applied for risk assessments and evaluations [35,36], selection of risk management strategies [37], and decision support frameworks [38]. On the other hand, the priority ranking methodology (PRM) by the current authors' previous work [39,40] is used to decide the ranking of the strategies and measures to determine their weights. In this study, we coupled PRM with fuzzy set theory, which results in the proposed approach we call FME-PRM. The FME-PRM provides a systematic solution in the weight assignment of M&E IFRM strategies and measures. The weights are based on the ranking according to priority activities where pre-disaster activities are more critical than during and after disaster activities; thus, pre-disaster activities have higher priority rankings. The FME-PRM has not yet been applied to any M&E frameworks for DRRM or IFRM, as far as the authors know.

The specific objectives of this study are 1) to propose an M&E framework for IFRM, 2) to apply the FME-PRM as the evaluation method for M&E for the first time, and 3) to determine the IFRM performance of Metro Manila and its cities. The following sections introduce Metro Manila and its IFRM; elaborate and demonstrate the proposed M&E framework; analyze and discuss the IFRM performance of Metro Manila and its cities; present the conclusions.

2. Study area and its IFRM

Metro Manila is the Philippines' capital region, as it is the center of economic, political, and educational activities in the country. This region encompasses 619.57 km^2, located on an isthmus between Manila Bay and Laguna Lake, and it is composed of 16 cities and 1 municipality, as shown in Fig. 1. Flooding is a perennial problem in Metro Manila as it is situated in one of the country's widest floodplains. Flood occurrences are intense and frequent during the typhoon season (from June to October), when the Philippines typically receives 80% of its annual rainfall. There are about three to four incidences of significant flooding in Metro Manila annually, and these are usually caused by typhoons, monsoon rains, and even torrential rains [41].

In the last two decades, the worst flooding in Metro Manila was brought by Typhoon Ondoy (internationally known as Typhoon Ketsana) in September 2009. This typhoon poured about 450 mm of rainfall in just 12 h, which was equivalent to almost one-fourth of Metro Manila's annual rainfall. This unexpected massive downpour inundated more the one-third of Metro Manila, in which the flood depths were nearly 7 m in some parts. Consequently, this led to an imminent disaster that had affected 4,901,234 people with 464 fatalities, 529 injuries, and 37 missings, and this resulted in damages amounting to almost Php 4.2 Billion (PHP 1: USD 0.0216 in 2009) [42]. The estimated direct damages and the percentage inundated area for 13 selected cities are shown in Table 1. Thus, this disaster catalyzed the inception of the IFRM Masterplan for Metro Manila to manage the flooding in the region proactively.

The IFRM Masterplan for Metro Manila was formulated by the Department of Public Works and Highways (DPWH) in 2012, and it is based on the DRRM cycle that has four main strategies: prevention, preparedness, response, and recovery/rehabilitation [45]. For each strategy, several proposed measures aim 1) to reduce risk by proposing systems to resist, absorb, accommodate floodwaters for prevention 2) to build the capacities of the communities to anticipate, cope and recover from flooding for preparedness, 3) to provide life preservation on the event of the flood disaster for the response, and 4) to suggest strategies to recover from and improve well-being in the face of flood disasters for recovery/rehabilitation. The specific measures in Table 2 are not new, but they are specifically proposed by DPWH to fit the contextual needs in Metro Manila.

Despite the inception of the IFRM Masterplan for Metro Manila, flooding has been perennially persistent, in which two monsoon rains in 2012 and 2016 were as damaging as Typhoon Ondoy. There is also no information on the IFRM implementation status, and it is uncertain if the measures are being adopted accordingly. The lack of M&E activities for IFRM is attributed to the lack of agency-in-charge of its regional implementation [14]. Thus, there are no quantifiable indicators and baseline information for M&E and flood management in Metro Manila, except the authors' study on the gap analysis in flood DRRM during Typhoon Ondoy [39,40]. Therefore, it is timely to evaluate the

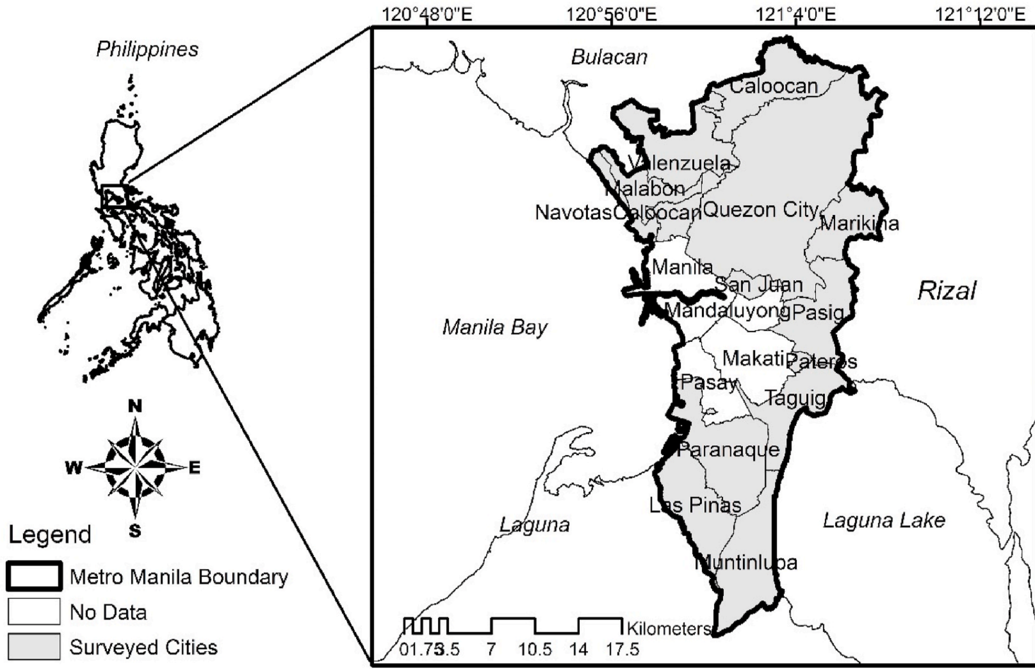

Fig. 1. Location map of Metro Manila, Philippines.

Table 1
Profile of the 13 surveyed cities in Metro Manila.

m	Municipality	Area (km^2)	Population as of 2015 Census[a]	2018 Revenue[b] (10^3 USD[c])	Damage from Typhoon Ondoy[d]	
					Inundated area (%)	Direct Damage (10^6 USD[e])
1	Caloocan City	53.33	1,583,978	108,457	21.3	98
2	Las Piñas City	32.02	588,894	56,804	33.6	29
3	Malabon City	15.96	365,525	32,539	86.3	62
4	Marikina City	22.64	450,741	108,314	73.8	80
5	Muntinlupa City	41.67	504,509	126,593	6.0	13
6	Navotas City	11.51	249,463	128,315	44.6	14
7	Parañaque City	47.28	665,822	127,212	35.9	45
8	Pasig City	31.46	755,300	652,101	78.1	94
9	Pateros City	1.76	63,840	4465	54.0	17
10	Quezon City	165.33	2,936,116	1,312,683	20.6	158
11	San Juan City	5.87	122,180	58,572	37.1	13
12	Taguig City	45.18	804,915	227,507	38.1	55
13	Valenzuela City	45.75	620,422	91,248	47.5	46

[a] [43].
[b] [44].
[c] PHP 1: USD 0.0191 in 2018.
[d] [45].
[e] PHP 1: USD 0.0216 in 2009.

Table 2
Strategies and measures in the IFRM Masterplan for Metro Manila [45].

Prevention	• Structural flood mitigation measures • Urban Drainage Facilities • Land use management and resettlement • Watershed conservation management
Preparedness	• Flood information and warning system (FIWS) • Evacuation system • Community-based flood risk management • Two-way communication mechanism • Information, education, and communication program • Vulnerability Assessment • Management Information System
Response	• Rescue operation • Relief activities • Evacuation Response
Recover/ Rehabilitation	• Rehabilitate affected houses, infrastructure, and damaged land

implementation of the IFRM by determining the performance levels of Metro Manila and its cities.

3. Methodology

The flowchart of the proposed M&E framework for IFRM is shown in Fig. 2, and the elaboration of this is presented in the succeeding subsections.

3.1. Monitoring scheme for the IFRM

There are no specified indicators for the M&E of the IFRM in Metro Manila, so we utilized the 15 specific measures in Table 2 as sub-criteria in monitoring the progress for IFRM performance in this region as a first attempt. These specific measures are proposed by DPWH in the IFRM Masterplan, which fit the contextual needs of Metro Manila. There are a

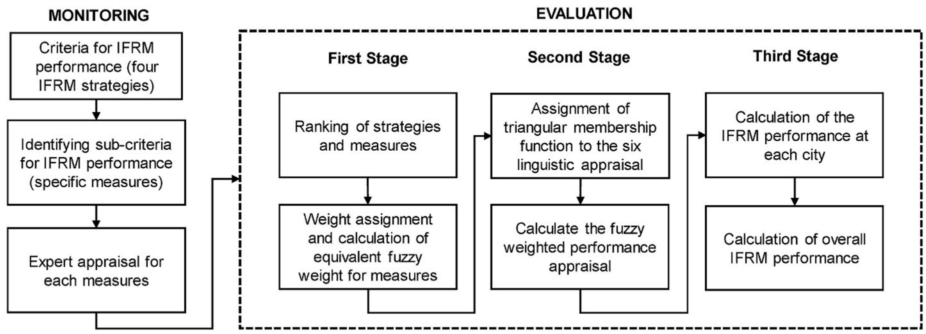

Fig. 2. Flow chart of the M&E activity for the IFRM.

total of 15 measures in the IFRM for Metro Manila, in which four, seven, three, and one measure are under the prevention, preparedness, response, and recovery/rehabilitation strategies, respectively, as shown in Table 2.

The 15 measures are to be appraised subjectively by practitioners of the implementing local government units (LGUs) in Metro Manila. To collect the appraisals for each measure, the authors organized a team of researchers to conduct interviews and surveys at each city in Metro Manila from December 2019 to February 2020. The target respondents were the LGUs in Metro Manila, particularly the practitioners or the officers-in-charge of the: City Disaster Risk Reduction Management Office, Engineering Office, and City Environment and Natural Resources Office. These practitioners are chosen specifically because their offices are mandated to be in charge of the DRRM activities for their respective LGU. Out of the 17 cities in Metro Manila, the 13 cities shaded in Fig. 1 have completed the interviews and surveys during the mentioned time frame of investigation.

During the interviews and surveys, the practitioners were asked to appraise only each measure according to their degree of implementation to reflect their respective city's current performance for IFRM. We utilized six linguistic terms or performance appraisals to describe the IFRM performance, as shown in Table 3, and the practitioners were requested to select only one out of the six linguistic performance appraisals. In contrast to studies that utilized five linguistic terms to rate items, e.g., groundwater sustainability assessment [46] and fuzzy analysis [47,48], we have added one more linguistic term (Bad) to denote "almost no improvement", which was not considered in the previous studies. Aside from this, we explicitly described the six linguistic terms in Table 3, which aim to help practitioners select the most appropriate appraisal for each IFRM measure since the linguistic terms alone can be arbitrary. These descriptions were formulated after numerous consultations with experts from DPWH. So, the descriptions are intended to capture the degree of implementation of the IFRM compared to when there was no IFRM Masterplan for Metro Manila. For example, "Bad" denotes almost no improvement since the IFRM's inception; "Poor" denotes as having minor improvement but with few signs of forwarding action in plans or policy; and so on. In addition to the appraisals, we asked the practitioners additional queries that served as evidence of the measures' actual implementation.

Table 3
Linguistic performance appraisals of the current flood management with the IFRM compared to when there was no IFRM.

Linguistic Performance Appraisal	Description
Bad (B)	Almost no improvement
Poor (P)	Minor improvement with few signs of forwarding action in plans or policy
Fair (F)	Some progress, but without systematic policy and/or local government commitment
Good (G)	Institutional commitment attained, but achievements are neither excellent nor substantial
Very Good (VG)	Substantial achievement but with recognized limitations in capabilities and resources (human or financial)
Excellent (E)	Excellent achievement with sustained commitment in capacities at the local government level

3.2. Fuzzy based multi-criteria evaluation based on the priority ranking methodology (FME-PRM)

Decision-makers often encounter multiple objectives and conflicting requirements when solving a problem. Similarly, the M&E of the IFRM has multiple conflicting strategies and specific measures (IFRM strategies and measures) with the ultimate goal of evaluating the IFRM performance in Metro Manila, as illustrated in Fig. 3.

The proposed FME-PRM method may provide transparent and reasonable means to aggregate the monitored measures, especially when the data is qualitative or preferential information. Zadeh [31] developed the fuzzy set theory to describe modes of reasoning as approximate rather than exact. This method is effective for decision-making problems where available data is imprecise because such data can be represented using a linguistic variable. The values of these linguistic variables can be generated from a possibility distribution through the use of attributed grammar techniques [38], i.e., the use of "Bad", "Poor", "Fair", "Good", "Very Good", and "Excellent" to describe the IFRM performance.

This study utilized a fuzzy set with a triangular membership function to quantify the linguistic terms and the strategies and measures' weight. The triangular membership function is defined as follows [49]:

Definition 1. A fuzzy set A in a universe of discourse X is characterized by a membership function $\mu_A(x)$ that assigns each element in x in X real number in the interval [0, 1]. The numerical value of $\mu_A(x)$ stands for a grade membership function of x in A.

Definition 2. The fuzzy elements of A having a triangular membership function is parameterized by a triplet (a, b, c) as follows:

$$\mu_A(x) = \begin{cases} \frac{(x-a)}{(b-a)}, & a \le x \le b \\ \frac{c-x}{(c-b)}, & b \le x \le c \\ 0, & otherwise \end{cases} \quad (1)$$

Definition 3. For triangular fuzzy numbers, the fuzzy addition operations and fuzzy multiplication operations are expressed as follows [40, 49]:

$$Addition : A \oplus B = (a_1, b_1, c_1) \oplus (a_2, b_2, c_2) = (a_1 + a_2, b_1 + b_2, c_1 + c_2) \quad (2)$$

$$Multiplication : A \otimes B = (a_1, b_1, c_1) \otimes (a_2, b_2, c_2) = (a_1 \times a_2,\ b_1 \times b_2,\ c_1 \times c_2) \quad (3)$$

The operators $\oplus$ and $\otimes$ denotes fuzzy addition and fuzzy

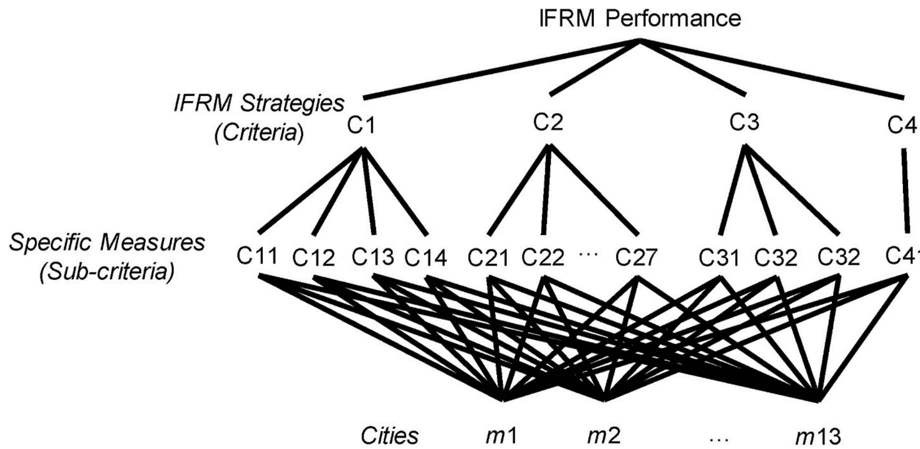

Fig. 3. Performance hierarchy of the IFRM for Metro Manila.

multiplication operations. Triangular fuzzy numbers can also be expressed to a singular value or crisp number, Υ, as follows [49]:

$$\Upsilon = (a\_2b+c)/4 \quad (4)$$

There are three stages in the FME-PRM for the IFRM performance. The first stage is to assign fuzzy weights to the four strategies and 15 measures of the IFRM by ranking them using PRM. The conventional way of determining the weights is by asking the experts, but this is a very tedious task due to: (i) finding the appropriate experts, (2) waiting for them to make large series of comparisons, and (3) repeatedly asking the experts until acceptably consistent weights are obtained [46]. For developing countries like the Philippines, this task is too challenging without any financial support. To cope with this, we adopted a systematic approach for the strategies and measures' triangular fuzzy weights using FME-PRM instead of involving the experts in the weight assignment. Priority ranking of the strategies and measures was not considered when the IFRM Masterplan for Metro Manila was formulated by the DPWH in 2012, even though this was crucial in prioritizing activities to prevent and reduce flood risks. Thus, this study attempts to decide the priority ranking of the strategies and measures for the IFRM.

The rank, r, is a positive value from 1 to n_R, where n_R is the number of the strategies or measures within the strategy. In this case, $r = 1$ has the highest relative importance, while $r = n_R$ has the lowest. The ranking of the strategies and measures is decided based on relative importance. In our previous study on the gap analysis of the flood DRRM [39,40], the relative importance was determined based on 1) order of need prior to a disaster and 2) prerequisite activities, i.e., when a measure is a prerequisite activity of succeeding measure. Based on these criteria, we can also decide the priority ranking for the IFRM strategies and measures, as

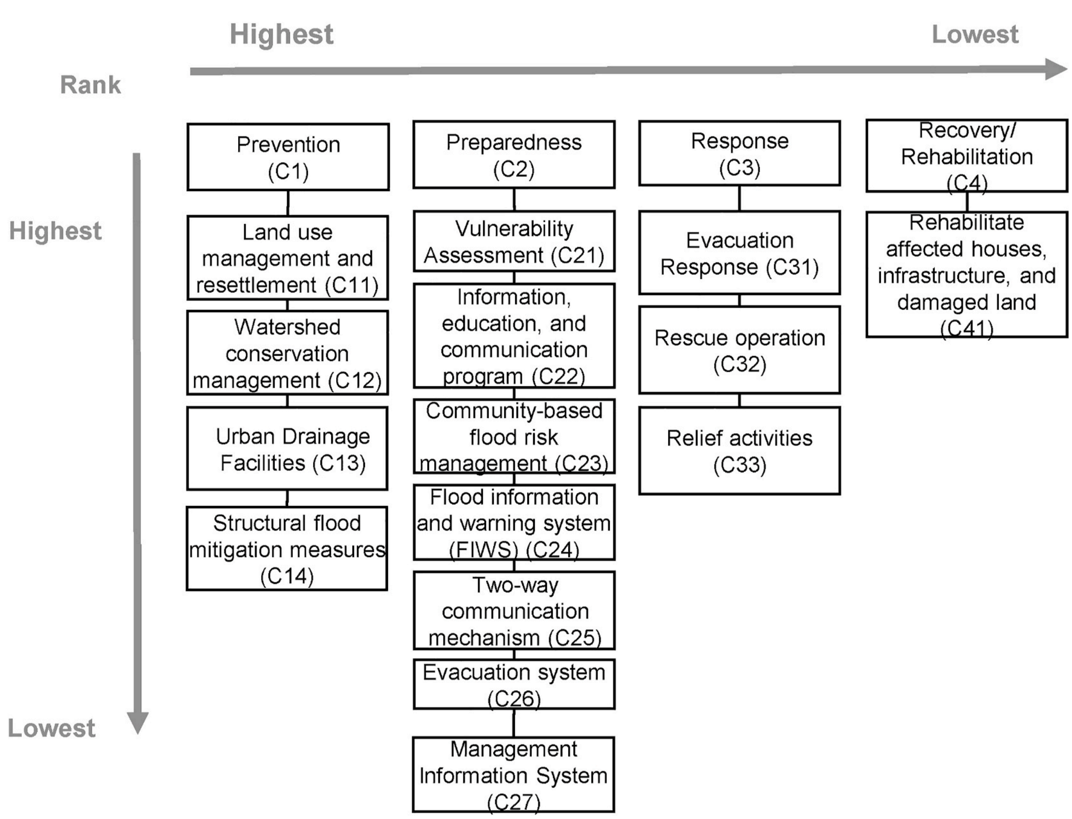

Fig. 4. Ranking of the strategies and measures of the IFRM for Metro Manila.

shown in Fig. 4.

Then, rank r is used to determine the fuzzy weights of the strategies W_i (i = 1,2,3,4) and the fuzzy weight of the measure W_{ij} of the jth measure (j = 1,2,3,4 if i = 1; j = 1,2, …7 if i = 2; j = 1,2,3 if i = 3, and j = 1 if i = 4) by the equation below:

$$W_i, W_{ij} = (a, b, c) = \left(\frac{2(n_R - r)}{n_R(n_R + 1)}, \frac{2(n_R + 1 - r)}{n_R(n_R + 1)}, \frac{2(n_R + 2 - r)}{n_R(n_R + 1)}\right) \tag{5}$$

This equation is based on our previous study [39,40], in which fuzzy weights have values equally divided by the number of the attribute (strategies and measures) from 0 to 1. In Eq. (5), the weight is further divided by $n_R/2$ to provide more reasonable and standardized fuzzy weights independent of the attribute's number because our previous approach is not standardized, i.e., the fuzzy number b is not equivalent to 1 when summed. Figs. 5 and 6 show the triangular membership function of the fuzzy weights W_i and W_{ij}, respectively, derived from Eq. (5). Then, the equivalent fuzzy.

weight for each measure $W_{eq,ij}$ is then calculated using the following equation:

$$W_{eq,ij} = W_i \otimes W_{ij} \tag{6}$$

The second stage is the calculation of the fuzzy weighted performance appraisal $WP_{m,ij}$ for city m. Firstly, the six linguistic performance appraisals $P_{m,ij}$ are given triangular membership functions. As a first attempt to conduct M&E for IFRM in Metro Manila, we made the triangular membership functions uniform in Fig. 7. These triangular membership functions were explained to the practitioners before conducting the interviews and surveys to explain the linguistic performance appraisals' fuzziness and descriptions. Then, the $P_{m,ij}$ appraised by the practitioner of the m city for jth measure in ith strategy is multiplied to the $W_{eq,ij}$ of the same measure to determine $WP_{m,ij}$, as expressed by the following equation:

$$WP_{m,ij} = W_{eq,ij} \otimes P_{m,ij} \tag{7}$$

The third stage is the calculation of the fuzzy performance of city m, F_m. The F_m is the aggregation of $WP_{m,ij}$, in which the $WP_{m,ij}$ can also be aggregated according to strategies $F_{m,i}$ as expressed by the equations below:

$$F_{m,i} = \sum_{j=1}^{n_j}{}^{\oplus}\, WP_{m,ij} \tag{8}$$

$$F_m = \sum_{i=1}^{n}{}^{\oplus}\, F_{m,i} \tag{9}$$

where n_j is the number of measures within each ith strategy, and n is the number of strategies. The $\Sigma\oplus$ symbol is the fuzzy summation based on the fuzzy addition operation in Eq. (2). These $F_{m,i}$ and F_m fuzzy numbers can also be transformed to crisp values using the following equations that were based on Eq. (4):

$$\gamma_{m,i} = f(F_{m,i}) = (a_{m,i} + 2b_{m,i} + c_{m,i})/4 \tag{10}$$

$$\gamma_m = f(F_m) = (a_m + 2b_m + c_m)/4 \tag{11}$$

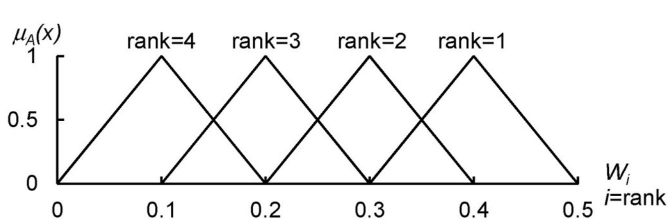

Fig. 5. Membership functions for the fuzzy weights of strategies (W_i).

with respect to the overall IFRM performance of Metro Manila ($F_{M,i}$, F_M) the fuzzy performance is calculated by Eqs. (12) and (13), and the crisp values for these is calculated by Eqs. (14) and (15) as follows:

$$F_{M,i} = \frac{1}{N}\sum_m{}^{\oplus} F_{m,i} = \left(\frac{\sum_{m=1}^{N} a_{m,i}}{N}, \frac{\sum_{m=1}^{N} b_{m,i}}{N}, \frac{\sum_{m=1}^{N} c_{m,i}}{N}\right) = (\overline{a_{m,i}}, \overline{b_{m,i}}, \overline{c_{m,i}}) \tag{12}$$

$$F_M = \frac{1}{N}\sum_m{}^{\oplus} F_m = \left(\frac{\sum_{m=1}^{N} a_m}{N}, \frac{\sum_{m=1}^{N} b_m}{N}, \frac{\sum_{m=1}^{N} c_m}{N}\right) = (\overline{a_m}, \overline{b_m}, \overline{c_m}) \tag{13}$$

$$\gamma_{M,i} = \frac{1}{N}\sum \gamma_{M,i} = \left(\overline{a_{m,i}} + 2\overline{b_{m,i}} + \overline{c_{m,i}}\right) \Big/ 4 \tag{14}$$

$$\gamma_M = \frac{1}{N}\sum_m \gamma_M = \left(\overline{a_{m,i}} + 2\overline{b_{m,i}} + \overline{c_{m,i}}\right) \Big/ 4 \tag{15}$$

where N is the total number of surveyed cities in Metro Manila.

4. Results and discussions

The summary of the linguistic performance appraisal for the 15 IFRM measures in Metro Manila is shown in Table 4. Each measures' performance is presented in our study [50], where we carefully discussed the best and worst-performing measures of the IFRM. The linguistic performance appraisals were evaluated by employing the FME-PRM that has three stages, as explained in the Methodology. The first stage's result is two-fold: the priority ranking and the fuzzy weights of the strategies and measures. In Fig. 4, the strategy's ranking (highest to lowest) is arranged from left to right, while the measures within the same strategy are arranged from top to bottom. The prevention and preparedness strategies were given a higher ranking because these strategies are pre-event disaster activities that lessen or limit the adverse impact of flooding, whereas the other two strategies provide life preservation of the affected population on the onset, during, and after a flood disaster. Similarly, the measures within the same strategy are ranked using the criteria specified in the Methodology. As an example, "land use management and resettlement" (C11) ranks higher than "structural flood mitigation measures" (C14) because the IFRM conceptually prioritizes "keeping the people away from water" rather than "keeping the water away from the people". Subsequently, the decided ranking is used to determine the fuzzy weight for the strategy (W_i) and measure (W_{ij}) and the equivalent weight of the measures ($W_{eq,ij}$.). Table 5 shows the fuzzy weight values in the W_i, W_{ij}, and $W_{eq,ij}$ columns.

The result of the second stage is the weighted fuzzy performance appraisal $WP_{m,ij}$, which was calculated by Eq. (7). As an example, the fuzzy linguistic performance appraisal $P_{m,ij}$ and $WP_{m,ij}$.values for Caloocan City (m = 1) are shown in Table 5. Then, these values are aggregated to determine the fuzzy performance of each strategy $F_{m,i}$ and fuzzy performance F_m for city m = 1, as shown in the last column and row of Table 5, respectively.

Fig. 8 shows the summary of each strategy's fuzzy performance at the 13 surveyed cities, and these are plotted against the fuzzy performance level threshold (Excellent~Bad). The thresholds are illustrated in the figure as broken lines, which are derived by assigning one linguistic appraisal for all measures, e.g., all measures are appraised as "Excellent" to derive the Excellent threshold. The results show that most cities perform between the Fair-Very Good level for prevention, Good-Very Good level for preparedness, Good-Excellent level for response, and Poor-Very Good level for recovery/rehabilitation strategies. Averaging the 13 cities' fuzzy performance by Eqs. (12) and (13) reflects each strategy's overall fuzzy performance for Metro Manila shown in Fig. 9. The boundaries of the fuzzy performances in Fig. 9 provide a range that best illustrates each city's actual performance, which copes with the uncertainty in quantifying qualitative information. The results reveal

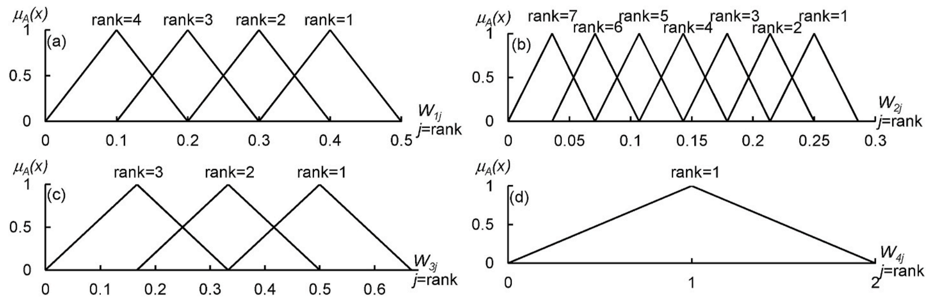

Fig. 6. Membership functions for the fuzzy weights of measures (W_{ij}) that have (a) 4 attributes, (b) 7 attributes, (c) 3 attributes, (d) 1 attribute.

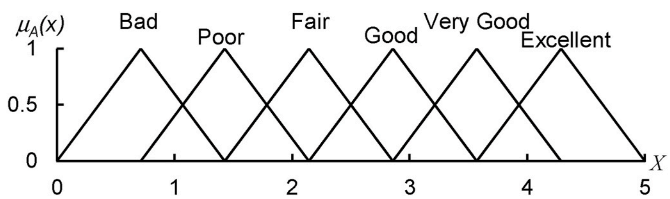

Fig. 7. Membership functions for the linguistic performance appraisals.

that the prevention strategy is the lowest among all strategies for IFRM, while the response strategy is the highest performing strategy in Metro Manila.

The fuzzy performance in Figs. 8 and 9 can be further transformed into crisp values by Eqs. (10) and (11) and Eqs. (14) and (15), respectively. Fig. 10 shows the crisp performance Υ_m of all 13 cities and the crisp overall performance of Metro Manila. The maximum and minimum $\Upsilon_{m,i}$ values are also depicted in this figure on the right side, while the crisp performance thresholds are also plotted using horizontal broken lines. The Υ_m and $\Upsilon_{m,i}$ allows rapid comparison between IFRM performance of the cities and strategies, and these enable the cognizance of cities and strategies that needed more work and improvement.

The results reveal that most cities have surpassed the Good level threshold in which one city, Las Piñas City ($m = 2$), even surpasses the Very Good level threshold. The $\Upsilon_{m,i}$ for the prevention strategy for city $m = 2$ is highest among the 13 cities, almost reaching the maximum value.

Table 4
Summary of the linguistic performance appraisal for the 15 measures of the IFRM.

m	IFRM Measures														
	C11	C12	C13	C14	C21	C22	C23	C24	C25	C26	C27	C31	C32	C33	C41
1	G	P	F	F	G	VG	G	VG	VG	G	G	G	G	G	P
2	E	E	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
3	VG	B	G	VG	G	G	VG	VG	G	G	G	G	G	VG	G
4	VG	G	G	VG	VG	VG	VG	E	VG	VG	VG	VG	E	VG	VG
5	E	B	G	VG	G	G	G	G	G	G	G	G	VG	E	VG
6	VG	G	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG
7	VG	B	VG	VG	VG	VG	G	VG	G	VG	VG	VG	VG	VG	VG
8	G	G	G	VG	G	G	G	VG	G	G	G	G	G	G	G
9	G	B	VG	VG	G	VG	B	VG	G	G	G	G	G	G	G
10	VG	G	G	G	VG	G	VG	VG	E	E	E	VG	E	E	VG
11	G	G	VG	VG	VG	E	G	VG	E	F	VG	E	E	E	VG
12	G	G	G	G	G	G	G	G	G	G	VG	G	G	E	G
13	G	G	G	G	G	VG	VG	VG	VG	VG	VG	VG	VG	VG	VG

Table 5
Fuzzy values of the strategy, measure, and equivalent weights and sample fuzzy performance values for city $m = 1$.

Ranked strategy	Fuzzy weight of Strategy (W_i)	Ranked measures	Fuzzy weight of measure (W_{ij})	Equivalent fuzzy weight ($W_{eq,ij}$)	$m = 1$		
					Fuzzy Linguistic Performance Appraisal ($P_{m,ij}$)	Fuzzy Weighted Performance Appraisal ($WP_{m,ij}$)	Fuzzy Performance of each Strategy ($F_{m,i}$)
C1	(0.300,0.400,0.500)	C11	(0.300,0.400,0.500)	(0.090,0.160,0.250)	(2.143,2.857,3.571)	(0.193,0.458,0.893)	(0.279,0.886,2.037)
		C12	(0.200,0.300,0.400)	(0.060,0.120,0.200)	(0.714,1.423,2.143)	(0.043,0.171,0.429)	
		C13	(0.100,0.200,0.300)	(0.030,0.080,0.150)	(1.423,2.143,2.857)	(0.043,0.171,0.429)	
		C14	(0.000,0.100,0.200)	(0.000,0.040,0.100)	(1.423,2.143,2.857)	(0.000,0.086,0.286)	
C2	(0.200,0.300,0.400)	C21	(0.214,0.250,0.286)	(0.043,0.075,0.114)	(2.143,2.857,3.571)	(0.092,0.2142,0.408)	(0.372,0.957,1.949)
		C22	(0.179,0.214,0.250)	(0.036,0.064,0.100)	(2.857,3.571,4.286)	(0.102,0.230,0.429)	
		C23	(0.143,0.179,0.214)	(0.030,0.053,0.086)	(2.143,2.857,3.571)	(0.061,0.153,0.306)	
		C24	(0.107,0.143,0.179)	(0.021,0.043,0.071)	(2.857,3.571,4.286)	(0.061,0.153,0.306)	
		C25	(0.071,0.1071,0.143)	(0.014,0.032,0.057)	(2.857,3.571,4.286)	(0.041,0.115,0.245)	
		C26	(0.036,0.0714,0.107)	(0.007,0.021,0.043)	(2.143,2.857,3.571)	(0.015,0.061,0.153)	
		C27	(0.000,0.036,0.071)	(0.000,0.011,0.029)	(2.143,2.857,3.571)	(0.000,0.031,0.102)	
C3	(0.100,0.200,0.300)	C31	(0.333,0.500,0.667)	(0.033,0.100,0.200)	(2.143,2.857,3.571)	(0.071,0.286,0.714)	(0.107,0.571,1.607)
		C32	(0.167,0.333,0.500)	(0.017,0.067,0.150)	(2.143,2.857,3.571)	(0.036,0.190,0.536)	
		C33	(0.000,0.167,0.333)	(0.000,0.033,0.100)	(2.143,2.857,3.571)	(0.000,0.095,0.357)	
C4	(0.000,0.100,0.200)	C41	(0.000, 1.000,2.000)	(0.000,0.100,0.400)	(0.714,1.423,2.14)	(0.000,0.143,0.857)	(0.000,0.143,0.857)
Fuzzy performance (F_m)							(0.758,2.557,6.449)

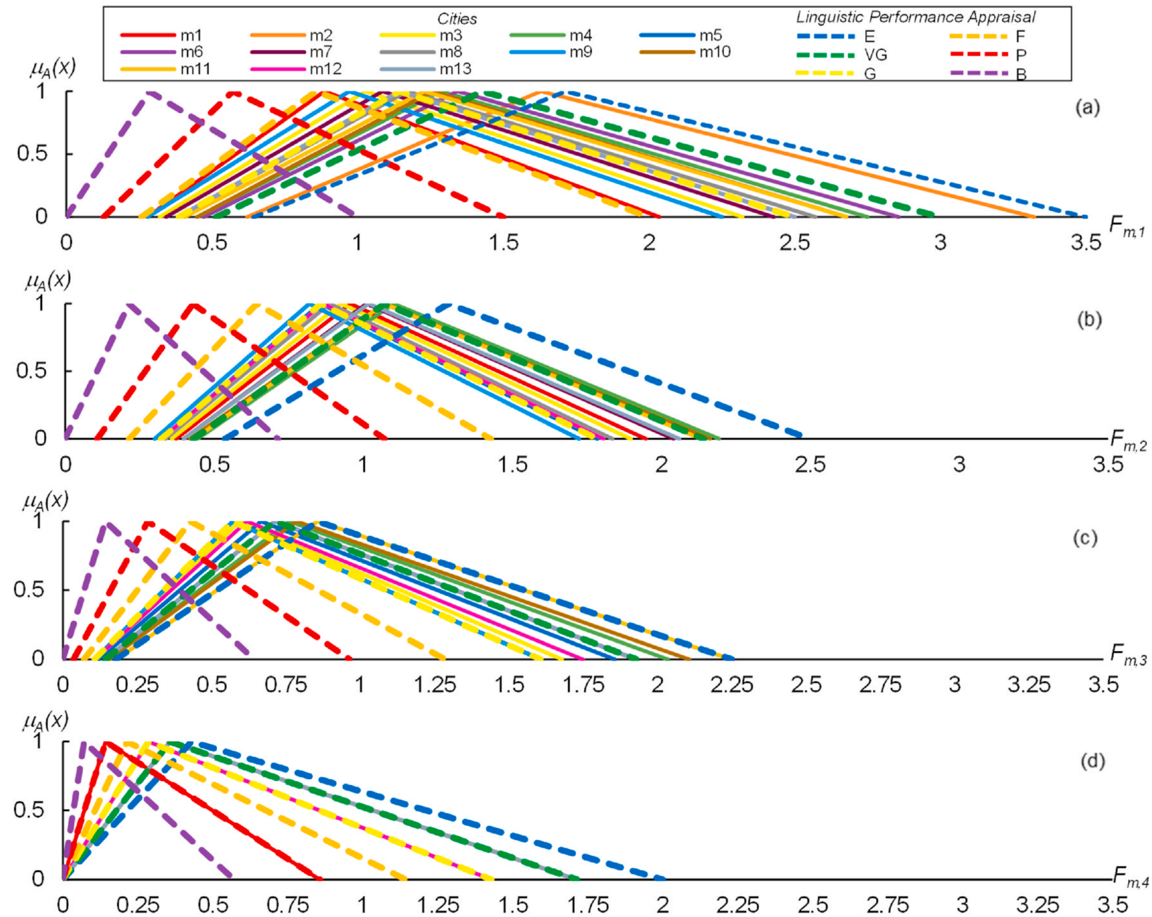

Fig. 8. Fuzzy performance of a) prevention, b) preparedness, c) response, and d) recovery/rehabilitation strategies of the IFRM at the 13 cities in Metro Manila.

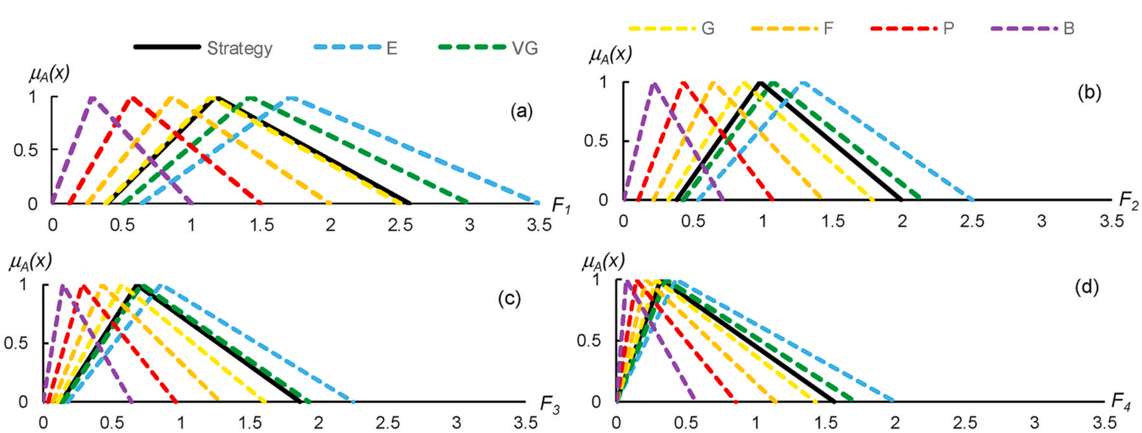

Fig. 9. Fuzzy performance of a) prevention, b) preparedness, c) response, and d) recovery/rehabilitation strategies of the IFRM for Metro Manila.

However, the $\Upsilon_{m,i}$ for its other strategies are relatively similar to the other cities, which are much lower than the maximum values. According to the practitioners, a comprehensive drainage masterplan was formulated for this city, strengthening its prevention measures. Even though city $m = 2$ has surpassed the Very Good level, this level indicates that there are still recognized limitations "in capabilities and resources (human and financial)", as we have defined in Table 3. The practitioners of city $m = 2$ have emphasized their constraints on the limited workforce, equipment, and capacity training reflecting on the low-performance appraisals for the preparedness, response, and recovery/rehabilitation strategies.

Meanwhile, four cities, Marikina City ($m = 4$), Navotas City ($m = 6$), Quezon City ($m = 10$), and San Juan City ($m = 11$), almost reached the Very Good level threshold. The $\Upsilon_{m,i}$ in these cities are relatively close, but the prevention strategy is much lower than city $m = 2$ or the maximum value, as seen in Fig. 10. The practitioners of these cities have contended that the IFRM is still in progress, so the achievements are currently not yet substantial. On the other hand, Pasig City (m = 8) and Taguig City (m = 12) barely surpassed the Good level threshold. These cities have considerably lower $\Upsilon_{m,i}$ for all strategies but their $\Upsilon_{m,i}$ are still above the minimum value. Despite surpassing the Good level threshold, these cites' IFRM performance still indicate that achievements for IFRM

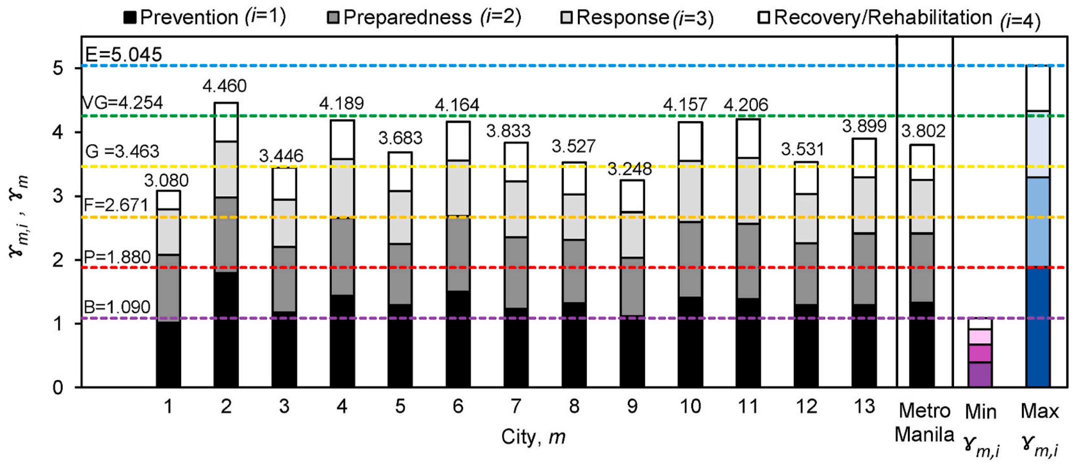

Fig. 10. Crisp performance of IFRM (Υ_m) and its strategies ($\Upsilon_{m,i}$) at each city in Metro Manila.

are "neither excellent nor substantial", as we have defined in Table 3.

The results in Fig. 10 further reveal three cities, Caloocan City ($m = 1$), Malabon City ($m = 3$), and Pateros City ($m = 9$), that did not reach the Good level but surpassed the Fair level. City $m = 1$ has the lowest $\Upsilon_{m,i}$, in which the $\Upsilon_{m,i}$ for prevention and recovery/rehabilitation are the lowest among the 13 surveyed cities. The practitioners of city $m = 1$ recognize the lack of political will among their high officials for prevention and recovery/rehabilitation strategies, which resulted in the non-recognition of flooding as a severe issue in their city. Cities $m = 3$ and $m = 9$ also have low $\Upsilon_{m,i}$ for prevention due to the "Bad" appraisal on the watershed conservation management measure (C12), as seen in Table 4. These two cities have identified C12 measure as not applicable, so no programs, activities, or policies promote this measure. According to the practitioners of city $m = 3$, the lack of political will is the main factor for the low IFRM performance, especially for the prevention strategy, while the lack of city funding and income is the most significant limitation towards the IFRM adaptation for city $m = 9$.

Overall, the IFRM performance of Metro Manila as a region is within the Good level threshold since majority of the cities surpassed the Good level threshold even though there are three cities below this threshold. The least performing IFRM strategy is revealed to be prevention, yet this has the highest relative importance among the four IFRM strategies. According to the practitioners, the implementation of prevention measures necessitates substantial financial requirements and political will from the local government and the national government, but these are also their current limiting issues. The lack of funding and other governance-related issues are the critical barriers to the IFRM adaptation in Metro Manila [50], which are evident in the implementing LGUs in Metro Manila.

On the other hand, the response strategy's performance is the highest in Metro Manila, which may be attributed to establishing the local DRRM offices in all the cities, according to the practitioners. The results suggest that Metro Manila is still "reactive" rather than "proactive" in managing flood risks. The results further indicate that IFRM adaptation in Metro Manila is still underway, and the achievements are not yet excellent or substantial. Therefore, the efforts for IFRM in this region need to focus on the cities that have the lowest performance and on pre-disaster strategies, especially on the prevention strategy.

Overall, the proposed M&E framework for IFRM provides a systematic, rapid, and reasonable evaluation of the IFRM measures' qualitative appraisals. The approach, however, is highly dependent on the experts' knowledge of the IFRM implementation, so uncertainty is inherent in this assessment. Nevertheless, the fuzzy set theory has mitigated the uncertainty [17], and it enabled the qualitative appraisals' aggregation. As a first attempt to evaluate the overall performance of the IFRM that includes all four strategies (prevention, preparedness, response, and recovery/rehabilitation), the proposed framework provided valuable insights into the current IFRM implementation even though there are no specific quantitative data on IFRM measures in Metro Manila. The strongest and weakest IFRM strategy and the most improved and least improved cities in Metro Manila are identified systematically through the FME-PRM. The approach can be applied in other areas, even in developed countries, at various scales (local, regional, or national). The proposed framework can also be flexible wherein the measures can be replaced with the ones applicable in the study area, and measurable indicators can also be added later once they are available. For the developed countries with benchmarked quantitative data, it is recommended to modify the framework to integrate the quantitative data with fuzzy assessment results.

5. Conclusions

The M&E of the IFRM implementation has not yet been explored, especially for developing countries. To address this gap in research, this study presents an M&E framework for the IFRM performance by focusing on the prevention, preparedness, response, and recovery/rehabilitation strategies, which are the general activities in the IFRM and DRRM cycle. An M&E of the IFRM was conducted in Metro Manila for the first time as a case study. The monitoring activity was done by conducting a series of laborious interviews and surveys in 13 cities, and the collected data were heavily dependent on the qualitative appraisals from the practitioners. These qualitative appraisals need to be aggregated to determine the IFRM performance; thus, we employed the FME-PRM for this task. This proposed evaluation approach provided a two-fold solution for the M&E: 1) the weight assignment on the IFRM strategies and measures, and 2) the quantification and aggregation of the qualitative appraisal for each measure.

Through the FME-PRM, the highly subjective appraisals from the practitioners were aggregated quantitatively and reasonably. The results revealed that most cities had surpassed the Good level threshold, in which one city even surpassed the threshold for Very Good. However, the Very Good level still suggests that there may be factors that limit the city's capacities for IFRM. The results further revealed that three cities were performing below the Good level threshold. In terms of the IFRM strategies, the performance for prevention has the weakest performance, while the response is the strongest for all 13 surveyed cities. The findings imply that Metro Manila has already refined its response efforts for a flood disaster, but its prevention capacities have not yet substantially improved.

The approach used in this study has enabled systematic, rapid, and quantitative comparisons of the strategies and overall performance for IFRM. This approach had also enabled the cognizance of the priority cities and IFRM strategies that needs more attention and resources to improve the performance for IFRM. This study's approach is aimed at data-poor areas, which are predominantly in developing countries. Once the qualitative data becomes available, the approach proposed in this study is useful and straightforward for the M&E of the IFRM. The approach can be applied in other areas, even in developed countries, at various scales (local, regional, or national), and the specific measures can be replaced with the ones applicable in the study area. Measurable indicators can also be added for each specific measure once they become available. In addition, we may improve the approach by accounting for the expert's input on the fuzzy linguistic function and their feedback on the results to determine whether the aggregated results support their implementation on the IFRM.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] UNISDR, CRED, The Human Cost of Weather-Related Disasters 1995-2015 vol. 30, UNISDR Publ., 2015, https://doi.org/10.1017/CBO9781107415324.004, 1.
[2] A.K. Jha, R. Bloch, J. Lamond, Cities and Flooding: a Guide to Integrated Urban Flood Risk Management for the 21st Century, The World Bank, 2012, https://doi.org/10.1596/978-0-8213-8866-2.
[3] M. Hurlbert, J. Gupta, Adaptive governance, uncertainty, and risk: policy framing and responses to climate change, drought, and flood, Risk Anal. 36 (2016) 339–356, https://doi.org/10.1111/risa.12510.
[4] P.C.D. Milly, R.T. Wetherald, K.A. Dunne, T.L. Delworth, Increasing risk of great floods in a changing climate, Nature 415 (2002) 514–517, https://doi.org/10.1038/415514a.
[5] J. Vinke-de Kruijf, S.M.M. Kuks, D.C.M. Augustijn, Governance in support of integrated flood risk management? The case of Romania,, Environ. Dev. 16 (2015) 104–118, https://doi.org/10.1016/j.envdev.2015.04.003.
[6] S. van Herk, J. Rijke, C. Zevenbergen, R. Ashley, Understanding the transition to integrated flood risk management in The Netherlands, Environ. Innov. Soc. Transitions 15 (2015) 84–100, https://doi.org/10.1016/j.eist.2013.11.001.
[7] P. Samuels, F. Klijn, J. Dijkman, An analysis of the current practice of policies on river flood risk management in different countries, Irrigat. Drain. 55 (2006) S141–S150, https://doi.org/10.1002/ird.257.
[8] C. Dieperink, D.L.T. Hegger, M.H.N. Bakker, Z.W. Kundzewicz, C. Green, P.P. J. Driessen, Recurrent governance challenges in the implementation and alignment of flood risk management strategies: a review, Water Resour. Manag. 30 (2016) 4467–4481, https://doi.org/10.1007/s11269-016-1491-7.
[9] S. van Herk, C. Zevenbergen, B. Gersonius, H. Waals, E. Kelder, Process design and management for integrated flood risk management: exploring the multi-layer safety approach for Dordrecht, The Netherlands, J. Water Clim. Chang 5 (2014) 100–115, https://doi.org/10.2166/wcc.2013.171.
[10] C. Luu, J. Von Meding, S. Kanjanabootra, Flood risk management activities in Vietnam: a study of local practice in Quang Nam province, Int. J. Disaster Risk Reduct 28 (2018) 776–787, https://doi.org/10.1016/j.ijdrr.2018.02.006.
[11] L. Cumiskey, S.J. Priest, F. Klijn, M. Juntti, A framework to assess integration in flood risk management: implications for governance, policy, and practice, Ecol. Soc. 24 (2019), https://doi.org/10.5751/ES-11298-240417.
[12] S.J. Priest, C. Suykens, H.F.M.W. van Rijswick, T. Schellenberger, S. Goytia, Z. W. Kundzewicz, W.J. van Doorn-Hoekveld, J.C. Beyers, S. Homewood, The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods Directive in six European countries, Ecol. Soc. 21 (2016), https://doi.org/10.5751/ES-08913-210450.
[13] T. Hartmann, T. Spit, Implementing the European flood risk management plan, J. Environ. Plann. Manag. 59 (2016) 360–377, https://doi.org/10.1080/09640568.2015.1012581.
[14] J.M.R. Mercado, A. Kawamura, H. Amaguchi, Interrelationships of the barriers to integrated flood risk management adaptation in Metro Manila, Philippines, Int. J. Disaster Risk Reduct 49 (2020), https://doi.org/10.1016/j.ijdrr.2020.101683.
[15] W. Grabs, Benchmarking flood risk reduction in the Elbe River, J. Flood Risk Manag 9 (2016) 335–342, https://doi.org/10.1111/jfr3.12217.
[16] U. Müller, Implementation of the flood risk management directive in selected European countries, Int. J. Disaster Risk Sci 4 (2013) 115–125, https://doi.org/10.1007/s13753-013-0013-y.
[17] H.M. Lyu, W.H. Zhou, S.L. Shen, A.N. Zhou, Inundation risk assessment of metro system using AHP and TFN-AHP in Shenzhen, Sustain. Cities Soc. 56 (2020) 102103, https://doi.org/10.1016/j.scs.2020.102103.
[18] H.M. Lyu, S.L. Shen, J. Yang, Z.Y. Yin, Inundation analysis of metro systems with the storm water management model incorporated into a geographical information system: a case study in Shanghai, Hydrol. Earth Syst. Sci. 23 (2019) 4293–4307, https://doi.org/10.5194/hess-23-4293-2019.
[19] H.M. Lyu, S.L. Shen, A.N. Zhou, W.H. Zhou, Flood risk assessment of metro systems in a subsiding environment using the interval FAHP-FCA approach, Sustain. Cities Soc, 50 Plus 101682 (2019), https://doi.org/10.1016/j.scs.2019.101682.
[20] H.M. Lyu, W.J. Sun, S.L. Shen, A. Arulrajah, Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach, Sci. Total Environ. 626 (2018) 1012–1025, https://doi.org/10.1016/j.scitotenv.2018.01.138.
[21] H. Amaguchi, A. Kawamura, J. Olsson, T. Takasaki, Development and testing of a distributed urban storm runoff event model with a vector-based catchment delineation, J. Hydrol 420–421 (2012) 205–215, https://doi.org/10.1016/j.jhydrol.2011.12.003.
[22] H. Amaguchi, A. Kawamura, Development of a storm runoff model considering process of individual building inundation, Int. J. Saf. Secur. Eng 6 (2016) 570–581, https://doi.org/10.2495/SAFE-V6-N3-570-581.
[23] M. Buchecker, G. Salvini, G. Di Baldassarre, E. Semenzin, E. Maidl, A. Marcomini, The role of risk perception in making flood risk management more effective, Nat, Hazards Earth Syst. Sci. 13 (2013) 3013–3030, https://doi.org/10.5194/nhess-13-3013-2013.
[24] S. van Herk, C. Zevenbergen, J. Rijke, R. Ashley, S. Van Herk, C. Zevenbergen, J. Rijke, R. Ashley, Collaborative research to support transition towards integrating flood risk management in urban development, J. Flood Risk Manag 4 (2011) 306–317, https://doi.org/10.1111/j.1753-318X.2011.01113.x.
[25] S. van Herk, Delivering integrated flood risk management: governance for collaboration, learning and adaptation (2014). www.crcpress.com. www.taylorandfrancis.com.
[26] U. Wehn, M. Rusca, J. Evers, V. Lanfranchi, Participation in flood risk management and the potential of citizen observatories: a governance analysis,, Environ. Sci. Pol. 48 (2015) 225–236, https://doi.org/10.1016/j.envsci.2014.12.017.
[27] K. Schelfaut, B. Pannemans, I. van der Craats, J. Krywkow, J. Mysiak, J. Cools, Bringing flood resilience into practice: the FREEMAN project,, Environ. Sci. Pol. 14 (2011) 825–833, https://doi.org/10.1016/j.envsci.2011.02.009.
[28] S. Koop, F.M. Gomes, L. Schoot, C. Dieperink, P. Driessen, K. Van Leeuwen, Assessing the capacity to govern flood risk in cities and the role of contextual factors, Sustain. Times 10 (2018) 1–21, https://doi.org/10.3390/su10082869.
[29] United Nations Office for Disaster Risk Reduction (UNISDR), Technical Guidance for Monitoring and Reporting on Progress in Achieving the Global Targets of the Sendai Framework for Disaster Risk Reduction Collection of Technical Notes on Data and Methodology, 2017. http://www.preventionweb.net/drr-framework/open-ended-working-group.
[30] World Wide Fund for Nature, Mega-Stress for Mega Cities, A Climate Vulnerability Ranking of Major Coastal Cities in Asia, 2009. https://www.wwf.org.uk/sites/default/files/2009-13/mega_stress_cities_report.pdf.
[31] L.A. Zadeh, Fuzzy logic and approximate reasoning, Synthese 30 (1975) 407–428, https://doi.org/10.1007/BF02389711.
[32] L.A. Zadeh, Fuzzy logic, Computer (Long. Beach. Calif) 21 (1988) 83–93, https://doi.org/10.1109/2.53.
[33] A. Mardani, A. Jusoh, K. Nor, Z. Khalifah, A. Valipour, Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014, Econ. Res. Istraživanja 28 (2015) 516–571, https://doi.org/10.1080/1331677X.2015.1075139.
[34] C. Kahraman, S.C. Onar, B. Oztaysi, Fuzzy multicriteria decision-making: a literature review, int, J. Comput. Intell. Syst 8 (2015) 637–666, https://doi.org/10.1080/18756891.2015.1046325.
[35] E. Guo, J. Zhang, X. Ren, Q. Zhang, Z. Sun, Integrated risk assessment of flood disaster based on improved set pair analysis and the variable fuzzy set theory in central Liaoning Province, China, Nat, Hazards 74 (2014) 947–965, https://doi.org/10.1007/s11069-014-1238-9.
[36] Q. Zou, J. Zhou, C. Zhou, Comprehensive Flood Risk Assessment Based on Set Pair Analysis-Variable Fuzzy Sets Model and Fuzzy AHP, 2013, pp. 525–546, https://doi.org/10.1007/s00477-012-0598-5.
[37] A. Azarnivand, A. Malekian, Analysis of flood risk management strategies based on a group decision making process via interval-valued intuitionistic fuzzy numbers, Water Resour. Manag. 30 (2016) 1903–1921, https://doi.org/10.1007/s11269-016-1259-0.
[38] L.S. Iliadis, S.I. Spartalis, Fundamental fuzzy relation concepts of a D.S.S. for the estimation of natural disasters' risk (the case of a trapezoidal membership function), Math. Comput. Model. 42 (2005) 747–758, https://doi.org/10.1016/j.mcm.2005.09.004.
[39] R. Gilbuena, A. Kawamura, R. Medina, H. Amaguchi, N. Nakagawa, Multi-criteria gap analysis of flood disaster risk reduction management in Metro Manila, Philippines, Annu. J. Hydraul. Eng. JSCE. 56(2012). https://www.jstage.jst.go.jp/article/jscejhe/68/4/68_19/_pdf (accessed May 22, 2018).

[40] R. Gilbuena, A. Kawamura, R. Medina, H. Amaguchi, Fuzzy-based gaps assessment of flood disaster risk reduction management systems in Metro Manila, Philippines, Water Environ. J. 33 (2019) 443–458, https://doi.org/10.1111/wej.12416.
[41] DPWH, The study on flood control project implementation system for principal rivers, Metro Manila, Philippines (2004).
[42] World Bank, Tyhpoons Ondoy and Pepeng: Post-Disaster Needs Assessment, 2010. Manila, Philippines.
[43] Philippines Statistics Authority (PSA), Highlights of the Philippine Population 2015 Census of Population | Philippine Statistics Authority, (n.d.). https://psa.gov.ph/content/highlights-philippine-population-2015-census-population (accessed November 17, 2020).
[44] Commission on Audit (COA), Annual Financial Report Local Government, vol. I, 2019. Quezon City.
[45] Master DPWH, Plan for flood management in metro Manila and surrounding areas, Metro Manila, Philippines (2013).
[46] N.T. Bui, A. Kawamura, D. Du Bui, H. Amaguchi, D.D. Bui, N.T. Truong, H.H.T. Do, C.T. Nguyen, Groundwater sustainability assessment framework: a demonstration of environmental sustainability index for Hanoi, Vietnam,, J. Environ. Manag. 241 (2019) 479–487, https://doi.org/10.1016/j.jenvman.2019.02.117.
[47] H.Y. Wu, G.H. Tzeng, Y.H. Chen, A fuzzy MCDM approach for evaluating banking performance based on Balanced Scorecard,, Expert Syst. Appl. 36 (2009) 10135–10147, https://doi.org/10.1016/j.eswa.2009.01.005.
[48] A. Rabbani, M. Zamani, A. Yazdani-Chamzini, E.K. Zavadskas, Proposing a new integrated model based on sustainability balanced scorecard (SBSC) and MCDM approaches by using linguistic variables for the performance evaluation of oil producing companies, Expert Syst. Appl. 41 (2014) 7316–7327, https://doi.org/10.1016/j.eswa.2014.05.023.
[49] S.M. Chen, Evaluating weapon systems using fuzzy arithmetic operations, Fuzzy Set Syst. 77 (1996) 265–276, https://doi.org/10.1016/0165-0114(95)00096-8.
[50] J.M.R. Mercado, A. Kawamura, H. Amaguchi, C.J.C. Prudencio-Rubio, Multi-criteria monitoring & evaluation analysis of integrated flood risk management in metro Manila, J. Japan Soc. Civ. Eng. Ser.G (Environmental Res. 76 (2020). I_269-I_276.