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Evaluating the vulnerability of buildings to urban flooding using the fuzzy inferences method

Kiyong Park[a], Insang Yu[b,*]

[a]*Department of Disaster Prevention, Chungbuk National University, Chungdae-ro 1, Seowon-gu, Cheongju, Chungbuk, 28644, Republic of Korea, email: pky3489@chungbuk.ac.kr*
[b]*Korea Environment Institute, KACCC 232, Gareum-ro, Sejong, 30121, Republic of Korea, email: isyu@kei.re.kr*

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ABSTRACT

The scale of urban flooding has grown recently in size and frequency because of climate change, but it remains difficult even to predict at-risk areas due to various uncertainties including local downpours. Thus, the vulnerability of each building was analyzed to minimize flood damage by classifying the vulnerability of each building to flood damage during flooding events in urban areas. The buildings that need to develop anti-flood measures were identified with priority scoring. To prepare measures for land use and building, non-structural measures, characteristic land use indicators, and buildings were selected. The vulnerability of each building towards flooding was analyzed using the fuzzy model and categorized into five grades. Urban flooding vulnerability analysis of 108,256 buildings in Ulsan City showed that Red Buildings 2,156 (occupied 1.99%), Orange Buildings 927 (occupied 0.86%), Yellow Buildings 97,296 (occupied 89.88%), Yellowish-green Buildings 2,092 (occupied 1.93%) and Green Buildings 5,785 (occupied 5.34%). The analysis indicated that industrial complexes with basements in new towns and slack old sections of the city exhibited high vulnerability. Buildings and areas with higher asset values and higher building densities, in particular, had high vulnerability, and buildings with basements and aged buildings were also potentially vulnerable. The vulnerability analysis of each building to urban flooding can be used to determine the urban spatial appropriateness of each building. Buildings with high vulnerability are significant, as it may provide a sense of direction for preparing preferential measures, enabling improved efficiency and systematic management.

Keywords: Climate change; Urban flood; Building characteristics; Vulnerability; Fuzzy

1. Introduction

Flood damage prediction has become increasingly important due to extreme climate events. In 1989, the International Decade for Natural Disaster Reduction (IDNDR) was declared to reduce the damage caused by natural disasters. Since the IDNDR, the international community has continued to work to mitigate flood damage by developing the Hyogo Framework for Action and the post-2015 framework for disaster risk reduction as part of the International Strategy for Disaster Reduction (UNISDR) [1].

In terms of the relationship between land use and flood damage, the major cause of flood damage can be examined in three major aspects. The increased amount of impervious area and artificial ground in urban areas, short travel times, and increased surface run-off rate may significantly impact rain run-off characteristics and cause flood damage by exceeding the draining and detention system capacities [2].

Lundgren [3] showed that the land use has changed due to indiscreet development during urbanization, increasing the number of impervious areas, deteriorating penetration and natural draining during rain events, and increasing the

* Corresponding author.

flow rate. Eventually, city development changes the character of the land and increased amounts of impervious areas are the major factor that increases run-off coefficient.

Fig. 1 shows changes in the run-off coefficient before and after urban development due to the increased number of impervious areas. The solid line represents the changes in the run-off coefficient before urban development and the dotted line is the changes in the run-off coefficient after development. Before development, the changes in the run-off coefficient increased slightly and the run-off rate declined even when rainfall increased. In contrast, changes in the run-off coefficient were significant due to the increased impervious areas due to development. In other words, the run-off coefficient increased during heavy rain events over a short period in the impervious areas in developed land, which creates an enormous strain on the rainwater drainpipe.

Considering that damages due to recent localized downpour have mainly caused damages by inland flooding compared to those caused by river flood, and the changes in the run-off coefficient caused by impervious areas have great implications.

However, land-use measures have potential advantages in terms of response to natural disasters. First, land-use measures are very effective for reducing long-term loss of life and property damage. Secondly, substantial long-term cost savings can be achieved compared to other measures. Third, the value of natural environments and ecosystems can be preserved. Fourth, eco-friendly, sustainable housing, and urban development can be achieved [5]. Disaster experts in the United States have recently focused on land-use planning approaches that restrict the location of buildings in hazardous areas, rather than crisis-oriented approaches including emergency recovery after disasters [6].

From this perspective, in terms of rehabilitation and recovery efforts, it is important to consider the principle of building back better or building back safer, which is a primary focus of many disaster recovery frameworks, with the most notable being the Sendai Framework for Disaster Risk Reduction (SFDRR) [7,8]. SFDRR emphasizes the rebuilding of structures, systems, and communities to a higher standard than previously enforced. In other words, buildings that are stronger, safer, and more resilient than what previously existed should be built after a disaster.

Building back better includes the development of a resilient post-disaster building stock [9], that is, buildings that are reconstructed to a higher structural performance standard than those before the disaster event. To achieve this goal, building performance must be fully understood when exposed to a particular hazard. At the outset of every disaster, a plethora of useful information is available, so it is essential to carefully record and analyze data during post-disaster assessments [8,10,11].

Herein, the vulnerability of each building type was analyzed for flood risk analysis. Specifically, the research aims to identify resilient building types and construction vulnerabilities, as evidenced by the flood damage caused by hazard and exposure. This analysis is pertinent to flood damage reduction for prioritizing building types that should be upgraded.

2. Methods

2.1. Study scope

Using data from the Ministry of Public Administration and Security regarding natural disasters (Disaster Yearbook, 2018), damage to facilities over the past 10 years (2008–2017) were examined and are shown in Table 1. The damages caused by natural disasters in Korea over the past 10 years, including typhoons (KRW 158,773 M), heavy rain (KRW 149,402 M), heavy snowfall (KRW 22,623 M), earthquake (KRW 9,642 M), wind waves (KRW 4,272), and strong wind (KRW 3,929 M) were compiled. The damage from typhoons includes the sum of the damage from floods and winds, while the heavy rain is the amount of damage from floods. The damage from typhoons was determined to be mostly flood damage because it was difficult to classify the damage into separate categories of flood and wind damage. The damage caused by flooding was the highest at 88.39%, making water damage the disaster category that inflicted the most damage. In addition, the damages by facilities were as follows: KRW 2,418,588M (69.37%) for public facilities, KRW 171,402M (4.92%) for other buildings, KRW 78,712M (2.26%) for farmland, and KRW 11,123 M (0.32%) for vessels. Although the damage to the public facilities was the most expensive, public facilities are managed by the state, while buildings in the

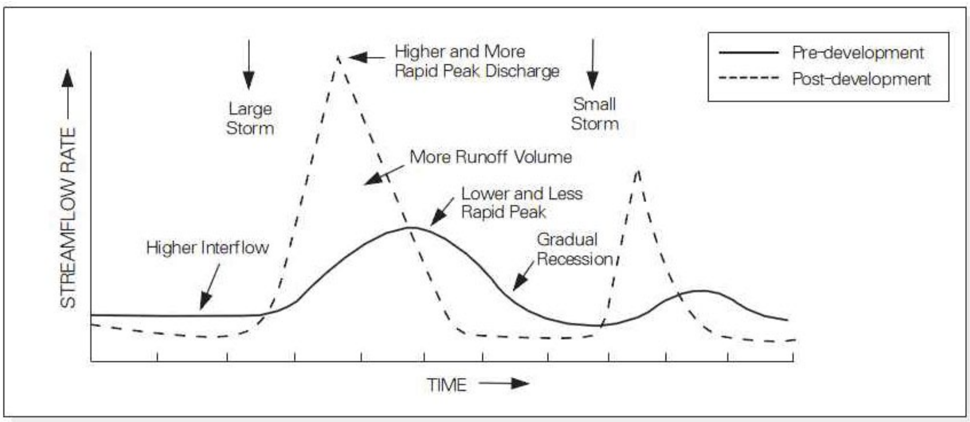


Fig. 1. Changes in runoff coefficients due to increased impermeable area [4].

Table 1
Damage caused and facilities by natural disasters (2008–2017) in Korea [12] (unit: in million KRW)

	Building		Vessel		Farmland		Public facilities		etc.		Total	
	Damage	%	Damage	%	Damage	%	Damage	%	Damage	%	Damage	%
Heavy rain	61,280	4.10	724	0.05	57,196	3.83	1,330,702	89.07	44,127	2.95	149,402	42.85
Heavy snowfall	1,397	0.61	282	0.12	–	0.00	14,538	6.42	210,018	92.83	22,623	6.49
Wind wave	477	1.10	810	1.87	267	0.61	7,717	18.05	33,450	78.30	4,272	1.23
Strong wind	459	1.15	413	1.04	54	0.13	3,242	8.25	35,125	89.39	3,929	1.13
Typhoon	45,294	2.85	8,894	0.56	21,195	1.33	1,028,570	64.78	483,779	30.47	158,773	45.54
Earthquake	62,495	64.81	–	0.00	–	0.00	33,819	35.07	109	0.10	9,642	2.77
Total	171,402	4.92	11,123	0.32	78,712	2.26	2,418,588	69.37	806,608	23.14	348,641	100.00

other category must be insured and managed by the private sector. In addition, although public facilities include roads, parks, as well as water and sewage facilities, assessment units focused only on buildings because many health and welfare buildings including schools, hospitals, and libraries, were included.

2.2. Urban flooding measures

Flood damage was divided into consequences including loss of life, loss of property, and damage to urban functions. Depending on the damage subject, loss of property and damage to urban functions accounted for more damage than loss of life because most flood damage is caused by weather conditions such as heavy rain or storms and involves a certain degree of predictability [13].

Table 2 provides an overview of the structural and non-structural measures that can be used to cope with floods. In the long run, preparedness and non-structural adaptations are more efficient and sustainable solutions to flood-related problems to reduce the vulnerability of citizens and goods exposed to flood risk [14].

General measures can be used to minimize damage from urban flooding, including structural measures, but recently because of the uncertainty of torrential rains, defense capacity has been limited. Because structural measures in the form of temporary responses are limited, the problem must be approached spatially and systematically by analyzing land use and building measures, which are largely unstructured measures.

America has made significant efforts to alleviate disasters through land-use plans. White (1936) first raised the issue in the Planners Journal, arguing that fundamental countermeasures against disasters are related to land use. Disaster experts have also stressed that prevention of development in the disaster areas is an effective method to mitigate disasters [16]. Land use plans are the most powerful means to protect property and lives from disasters and can contribute greatly to the prevention of human and property losses by ultimately controlling disaster risk areas, limiting urban development, and raising awareness of disaster mitigation programs [17]. Land use planning is a means of controlling and managing the timing of urban development as well as the design, development type, density, intensity, expansion of local infrastructure, and facilitating the protection of scarce natural resources. These factors represent the important goals of land use planning [18].

Table 2
Overview of structural and non-structural measures to deal with floods: classification [15]

Structural: mitigation	Non-structural: adaptation
Extensive • reshaping land surface • protecting from erosion • delaying runoff processes • increasing infiltration • urban works	Regulation • zoning • coding Flood defence • forecasting • warning • flood-proofing
Intensive • levees, dykes, floodwalls • dams and reservoirs • floodways and diversion works • polders and fills • drainage works	• evacuation • relocation • Insurance • governmental • private • mixed

Flood damage is more severe in urban areas with dense populations and high-value facilities so it is very important to prevent flood damage beforehand. Flood-related problems must be fundamentally resolved in terms of non-structural aspects by preparing land use plans and architectural measures with a long-term view.

2.3. Analysis area

Ulsan City was selected as the target area of this study and is shown in Fig. 2. Ulsan City can be divided into five administrative districts: Jung-gu, Nam-gu, Dong-gu, Buk-gu, and Ulju-gun. Ulsan City has a total population of 1,150,294 and an area of 1,061.54 km^2 for a population density of 1,083 persons/km^2. The city includes urban, farming, and coastal areas [19] with an annual average temperature of 13.8°C and an annual average precipitation of 1,274.6 mm, where 70% of the rainfall is concentrated between June and September, forming a vulnerable hydrologic condition. Because of the high elevation west and low elevation east, the Taehwa River flows from west to east across Ulsan City. On October 5, 2016, Typhoon Chaba caused the deaths of

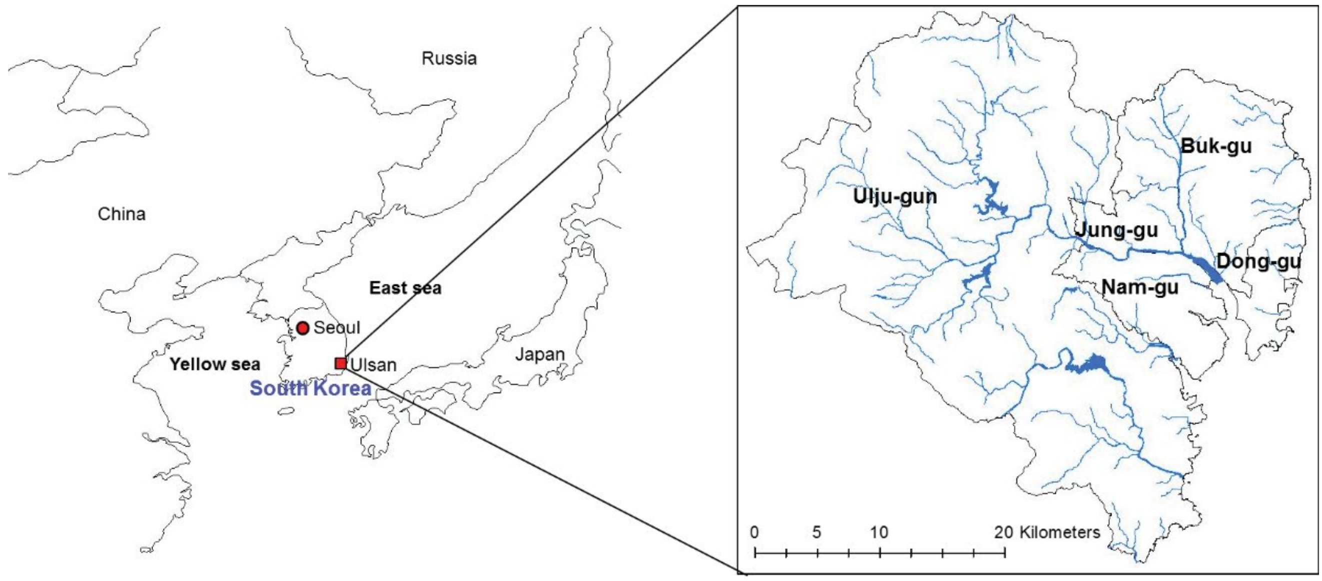


Fig. 2. Location of Ulsan City in Korea.

three people and approximately USD 61 million of property damage [12]. Ulsan City was selected as the target area as it recently experienced enormous flood damage, includes urban, farming, coastal areas, national and local streams, and has geographical and hydrological conditions that are vulnerable to flooding.

2.4. Fuzzy inferences method

Herein, weighted values were input into the fuzzy analysis based on indicators including land price, underground area, floor area ratio, building decline, and building material to examine the urban spatial characteristics including non-structural characteristics as an assessment unit for flood-induced damages. After inputting these variables, the urban flooding vulnerability was analyzed by individual buildings.

Flood vulnerability maps were constructed using building characteristics such as building location, total floor area, height, age, and material. In the flood damage vulnerability analysis, it is difficult to quantify and compare the damage caused in areas A and B numerically when flood damage occurs. Therefore, this study was conducted by analyzing the vulnerability of each building using the fuzzy inference system that can solve linguistic ambiguity to determine the relationship between indicators in a complex manner and develop a plan to minimize or reduce flood-related damage.

2.4.1. Fuzzy classification

In flood damage risk classification analysis, it is difficult to quantify and compare flood damage in commercial and residential areas when submerged. In other words, the expression of the level of flood damage as numerical values is ambiguous. Therefore, to overcome linguistic ambiguity for decision making and analyze complex relationships between various indicators and indices, the fuzzy logic method was adopted to achieve a more objective analysis of flood risk by deriving quantitative and accurate indicators [20].

Fuzzy set theory was developed in 1965 and has been extended in subsequent years [21]. It was designed to supplement the interpretation of linguistic or measured uncertainties for real-world random phenomena analysis. These uncertainties can originate from non-statistical natural characteristics that lack sharp boundaries in information. However, the main source of uncertainties in a large-scale complex decision-making process can be properly described via fuzzy membership functions [22].

Fuzzy classification, alongside neural networks [23] and probabilistic approaches [24], is a very powerful soft classifier method. As an expert system for classification [25], it considers the uncertainty in sensor measurements, parameter variations due to limited sensor calibration, vague (linguistic) class descriptions, and class mixtures due to limited resolution. Fuzzy classification consists of an n-dimensional tuple of membership degrees that describes the degree of class assignment, μ, of the considered object, obj, to the n considered classes.

$$f\ \text{class},\text{obj} = \left[\mu\ \text{class1}(\text{obj}), \mu\ \text{class\_2}(\text{obj}), \ldots \mu\ \text{class\_}n(\text{obj})\right] \quad (1)$$

Crisp classification only provides information regarding the identity of the highest membership degree, whereas this tuple contains all information regarding the overall reliability, stability, and class mixture. Fuzzy classification requires a complete fuzzy system comprised of the fuzzification of input variables, yielding fuzzy sets, fuzzy logic combinations of the fuzzy sets, and defuzzification of the fuzzy classification results to obtain the common crisp classification for map production. Fuzzy logic involves multi-valued logic quantifying uncertain statements. In this manner, the two Boolean logical statements ''true'' and ''false'' are replaced by a continuous range from 0 to 1, where 0 is ''false'' and 1 is ''true'', and all values between 0 and 1 represent a transition between true and false. To avoid arbitrary sharp thresholds, fuzzy logic can approximate real-world complexity much better than simplifying Boolean systems. Fuzzy logic can model imprecise human thinking and represent linguistic rules. Hence, fuzzy classification systems are well-suited for handling most sources of vagueness in remote sensing information extraction. The mentioned parameters and model uncertainties were considered by fuzzy sets, which are defined by the membership functions. Fuzzy systems consist of three main steps, fuzzification and the combination of fuzzy sets [26].

2.4.2. Fuzzy inference process

Fuzzy inference generally consists of three steps, as shown in Fig. 3. During the first stage, fuzzification, the value of the input variable measured with a single clear value is replaced with the appropriate fuzzy value. In the second stage, fuzzy inference rule, a rule is derived using the number of possible cases as conditional statements and the actual conditional statements. The third step, unfuzzification, converts the fuzzy value defined in the entire set of outputs into a identifiable fuzzy value.

2.4.3. Application of fuzzy inference system

The design of the fuzzy model was constructed as shown in Fig. 4 based on the data of the officially assessed land price, floor area ratio, underground area, building decline, and building material as the assessment unit.

For fuzzification, the standard-distribution method was used, and because the measurement values of individual indicators were different and variable, the standardization method was used to change the measurement unit of the indicator to a value between 0 and 1. The standardization method is described in Eq. (2). There are various methods of standardization, but the generally used Z-score values may be influenced by weighting for singular values (larger deviations), and some are expressed as negative values. Thus, the standardization method was used to adjust the value.

$$Z_{jk}^{t} = \frac{\mathrm{MAX}\left(x_k^t\right) - x_{jk}^t}{\mathrm{MAX}\left(x_k^t\right) - \mathrm{MIN}\left(x_k^t\right)} \quad or \; Z_{jk}^{t} = \frac{x_{jk}^t - \mathrm{MIN}\left(x_k^t\right)}{\mathrm{MAX}\left(x_k^t\right) - MIN\left(x_k^t\right)} \tag{2}$$

The standardized values of each indicator represent the membership function, as shown in Fig. 5.

The method for establishing fuzzy inference rules is generally untheorized. Herein, an expert questionnaire was evaluated to objectively establish the fuzzy inference rule and derive the weighting between indicators. The representative indicators for analyzing weights by land use and building characteristics affecting urban flooding were officially assessed land price, floor area ratio, underground area, building decline, and building material. The weight between the indicators is a linguistic function for specific indicators. However, when the damage during urban flooding damage is high, the vulnerability to flooding damage is also high and when the damage caused by urban flooding damage is low, the vulnerability to flooding damage appears low. After enumerating these fuzzy rules, the survey consisted of one low to five high scores and a fuzzy rule was established by calculating the average values. Thus, the average score range of the survey weight ranged from 0 to 1.5 (very low vulnerability); 1.6 to 2.4 (low vulnerability); 2.5 to 3.4 (medium vulnerability); 3.5 to 4.4 (high vulnerability); and 4.5 to 5.0 (very high vulnerability). The fuzzy inference rules for analyzing the land use and building characteristics indicators affecting urban flooding are as follows, and the fuzzy inference rules were set up with 243 rules for each situation.

1. If (land price is high) and (floor area ratio is high) and (the underground area is high) and (decline of the building is high) and (material of the building is high) then (weights is vulnerability very high)

2. If (land price is high) and (floor area ratio is high) and (the underground area is high) and (decline of the building is high) and (material of the building is moderate) then (weights is vulnerability very high)

3. If (land price is high) and (floor area ratio is high) and (the underground area is high) and (decline of the building is high) and (material of the building is low) then (weights is vulnerability very high)

4. If (land price is high) and (floor area ratio is high) and (the underground area is high) and (decline of the building is

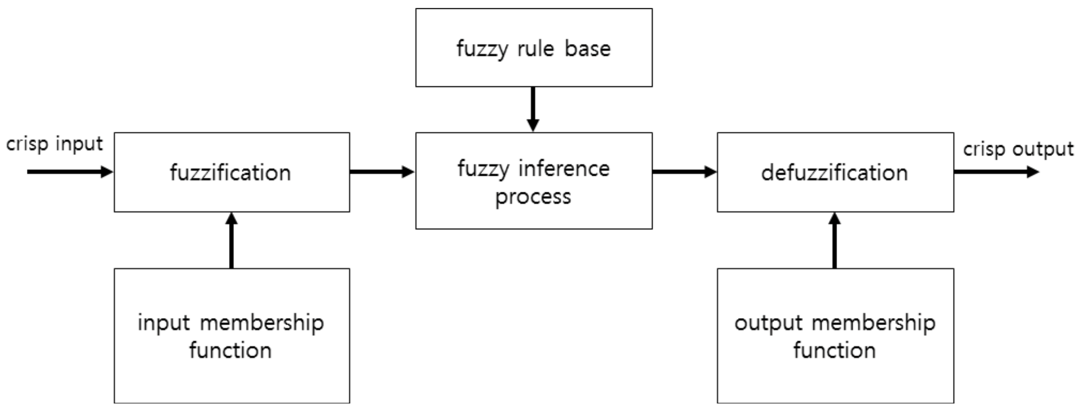


Fig. 3. Procedure of a fuzzy inference system.

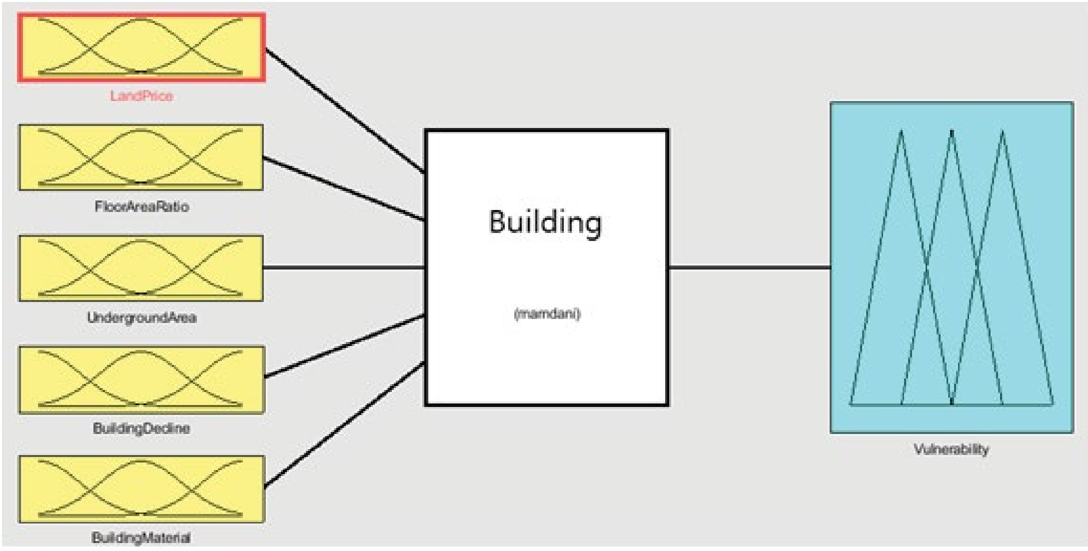
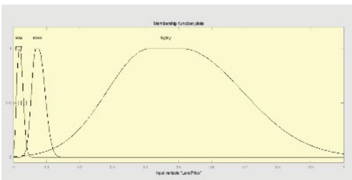
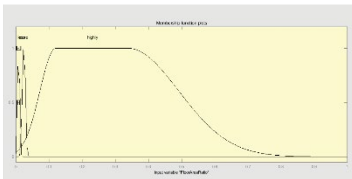


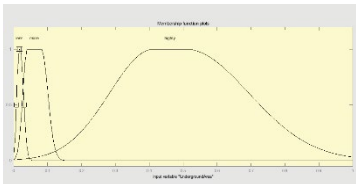
Fig. 4. Design of fuzzy model.



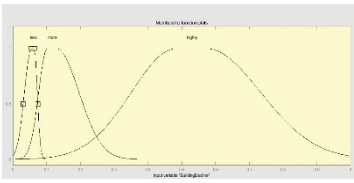
(a) Land Price



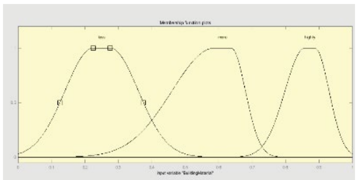
(b) Floor area ratio



(c) Underground area



(d) Decline of building



(e) Material of building

Fig. 5. Fuzzy membership function.

moderate) and (material of the building is high) then (weights is vulnerability very high)

5. If (land price is high) and (floor area ratio is high) and (the underground area is high) and (decline of the building is moderate) and (material of the building is moderate) then (weights is vulnerability very high)

:

:

:

241. If (land price is low) and (floor area ratio is low) and (the underground area is low) and (decline of the building is low) and (material of the building is high) then (weights is vulnerability very low)

242. If (land price is low) and (floor area ratio is low) and (the underground area is low) and (decline of the building is low) and (material of the building is moderate) then (weights is vulnerability very low)

243. If (land price is low) and (floor area ratio is low) and (the underground area is low) and (decline of the building is low) and (material of the building is low) then (weights is vulnerability very low)

The approximate inference results based on fuzzy inference were output as a fuzzy set and subjected to the defuzzification process, which expresses the set as a clear numerical value. This centroid method was used for this procedure and the defuzzification process is described in Eq. (3);

$$Z_0 = \frac{\int \mu_c(z) \times z dz}{\int \mu_c(z) dz} \quad \text{or} \quad Z_0 = \frac{\sum_{i=0}^{n} \mu_i \mu(u_i)}{\sum_{i=0}^{n} \mu(u_i)} \tag{3}$$

3. Results and discussion

To select the indicators for evaluating flood vulnerability to climate change, indicators related to land use and non-structural aspects of the building presented in the disaster yearbook and previous studies were selected, and the final indicators were selected through content validity analysis. To derive the indicators, the fuzzy methodology was used to derive the membership function, set the fuzzy inference rule, and fuzzified to analyze the vulnerability of buildings in Ulsan City. In addition, since all spaces and buildings in the city are subject to disaster prevention, this study analyzed the characteristics of building units that constitute major parts of urban functions and that are direct and indirect damage targets.

3.1. Analysis of indicators by buildings in Ulsan City

The officially assessed land price of each building was analyzed for each lot in Ulsan City as described by the Korea Appraisal Board, and 108,256 cases of data by building were developed and analyzed using each indicator as shown in Table 3 and Fig. 6. The land price indicator is the most important factor for estimating building damage in terms of land use as the standard economic scale because land damage is mainly caused by floods, and this study used the officially assessed land price of the lots belonging to the corresponding building. The floor area ratio indicator was applied as the damage increased due to the high density of urban buildings, which is expected to vary according to the building area and density. Because the actual flood damage would be determined by the area of the underground area, the underground area index was defined as "basement floors × building area". Since the building becomes less durable as it ages, the damage is greater for older buildings when any form of impact occurs. Building decline can be calculated by subtracting the year of construction approval from 2019, which is the current year. In other words, the building decline was defined as "2019-Year of Building Approval." According to Unanwa et al. [27], the building material, whether it is a steel, rebar, stone, or wood structure, has different strengths in response to flood damage. The ratio of the internal materials of the buildings was weighed by the composition ratio of the interior finishing work (%) in the table of unit price for the new building construction (KAB, 2012), and the weighted value for steel structures was set as 1.00, reinforced concrete structures as 2.00, masonry as 3.00, and wooden structures as 4.00.

3.2. Analysis of flood vulnerability by building

To determine the importance of the assessment items, the fuzzy inference was applied by plotting the membership function and was analyzed as shown in Fig. 7. The officially assessed land price was the most important factor compared to the other indicators, the underground area was more important than the volume rule, and the volume ratio was more important than the building decline or material. Thus, it was determined that as flood damage was inflicted, the land price and underground area directly increased property and physical damage, resulting in the relatively high vulnerability of these indicators. In contrast, the floor area ratio indicator was relatively less important as the building is directly damaged up to the corresponding height of the floodwater but can be indirectly damaged by the loss of urban functions on other floors. In addition, it was shown that the reason the building decline and material are relatively less important is that they related to durability and may inflict enormous damages only above a certain threshold.

An example of analyzing the vulnerability of urban flooding, the overall fuzzy inference is shown in Fig. 8. This

Table 3
Data for each building

Building (total # of items)	# of items	Land price (won/m^2)	Floor area ratio (%)	Underground area (m^2)	Decline of building	Material of building
Ulsan City (108,256)	1	1,863,000.00	34.37	266.73	25.00	2.00
	2	1,836,781.33	232.33	545.82	27.00	2.00
	3	698,259.83	132.30	97.80	21.00	3.00
	4	3,109,091.79	393.62	230.86	16.00	2.00
	5	1,414,109.96	171.39	155.32	27.00	2.00
	6	2,581,845.41	176.12	112.88	28.00	2.00
	7	1,610,000.00	242.66	159.56	25.00	2.00
	8	250,400.00	13.06	3,325.54	12.00	2.00
	9	732,910.08	83.87	106.92	25.00	3.00
	10	1,502,000.00	176.58	161.76	23.00	2.00
	11	1,900,445.34	154.44	133.59	22.00	2.00
				:		
				:		
	108,251	1,210,146.45	199.59	314.92	15.00	2.00
	108,252	2,068,147.79	142.41	205.60	24.00	2.00
	108,253	1,937,312.37	248.03	101.46	25.00	2.00
	108,254	4,843,000.00	736.21	462.00	8.00	2.00
	108,255	1,690,000.00	259.24	172.29	23.00	2.00
	108,256	5,273,000.00	207.44	3,616.64	21.00	1.00

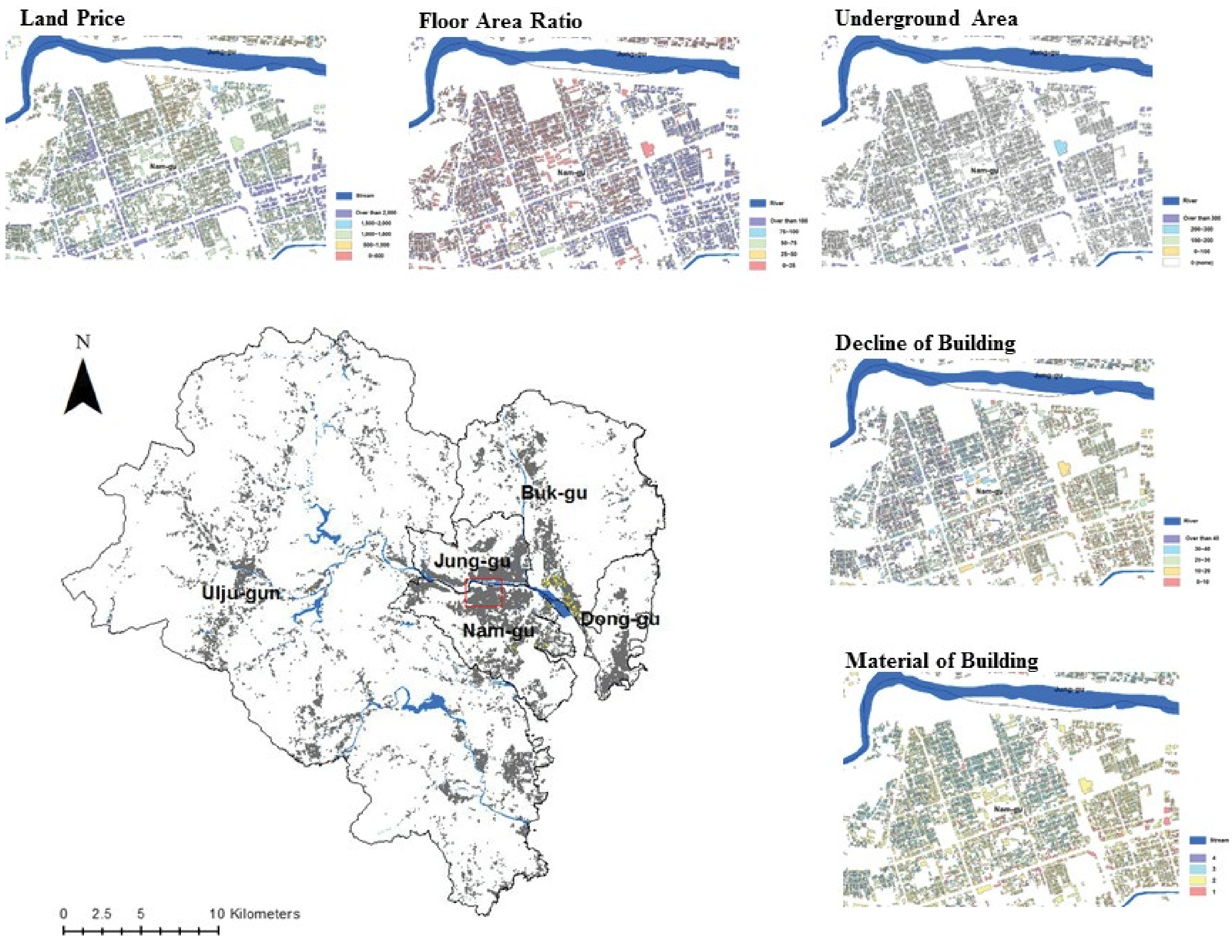


Fig. 6. Data for each building in Ulsan City map.

is an example of the min-max and centroid methods when the officially assessed land price, floor area ratio, underground area, building decline, and building material values are all set to 0.5. From the left, the minimum value was observed in the section showing the officially assessed land price, floor area ratio, underground area, building decline, and the membership function of the building material. For the officially assessed land price, the minimum value of the membership function corresponded to 0.5 for the floor area ratio, underground area, building decline, and building material. In the second stage, the minimum values were summed and the corresponding degree of vulnerability was the maximum value of the membership function. The degree of vulnerability obtained herein was represented as the final purge value obtained through the defuzzification process using the centroid method. The final purge value was analyzed as 0.928 for the above parameters.

Higher purge scores indicate higher risk ratings for flood damage (larger vulnerability), while lower purge scores indicate lower risk ratings for flood damage (lower vulnerability). The vulnerability of socio-economic and physical damages in flooded buildings was analyzed and the results are shown in Table 4. The unit of measurement is different because each indicator has its characteristics. To identify urban flooding vulnerability more easily, the Z-Score method was used to classify the vulnerability of the application area into 5 stages, which was standardized by setting criteria using the average value and standard deviation.

3.3. Classification by building according to urban flooding vulnerability analysis

The details of the analysis of the distribution characteristics according to the vulnerability assessment for each building during urban flooding in Ulsan City are shown in Table 5. Based on the fuzzy analysis value, the building vulnerability to flood damage was determined by dividing it into five levels. When the vulnerability level of the building was determined by weighting index standardization and Z-Score, it was classified and distinguished based on risk level. The standard colors were determined by defining a building with very high vulnerability as red, high vulnerability as orange, medium vulnerability as yellow, low vulnerability as yellowish-green, and very low vulnerability as green. Urban flooding vulnerability analysis of 108,256 buildings in Ulsan City showed that Red Buildings 2,156 (occupied 1.99%), Orange Buildings 927 (occupied 0.86%), Yellow Buildings 97,296 (occupied 89.88%), Yellowish-green Buildings 2,092 (occupied 1.93%) and Green Buildings 5,785 (occupied 5.34%). By imposed these results on the map of

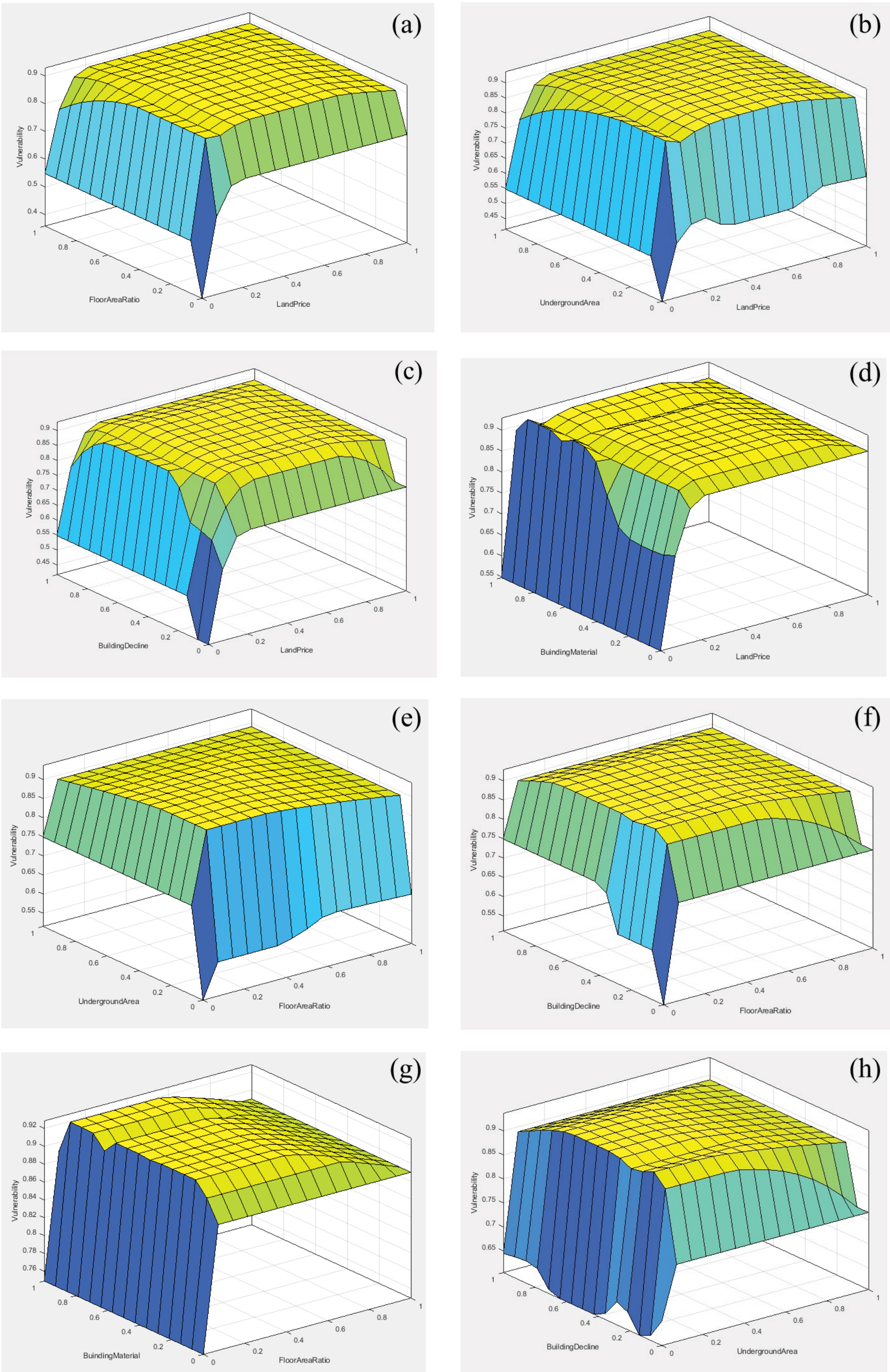


Fig. 7. *Continued*

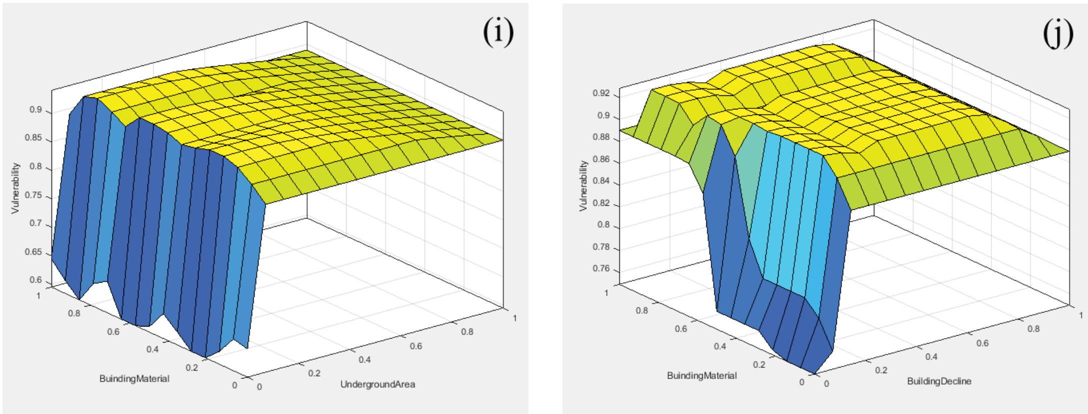


Fig. 7. Urban flood vulnerability scheme: (a) land price-floor area ratio, (b) land price-underground area, (c) land price-decline of building, (d) land price-material of building, (e) floor area ratio-underground area, (f) floor area-decline of building, (g) floor area ratio-material of building, (h) underground area-decline of building, (i) underground area-material of building, and (j) decline of building-material of building.

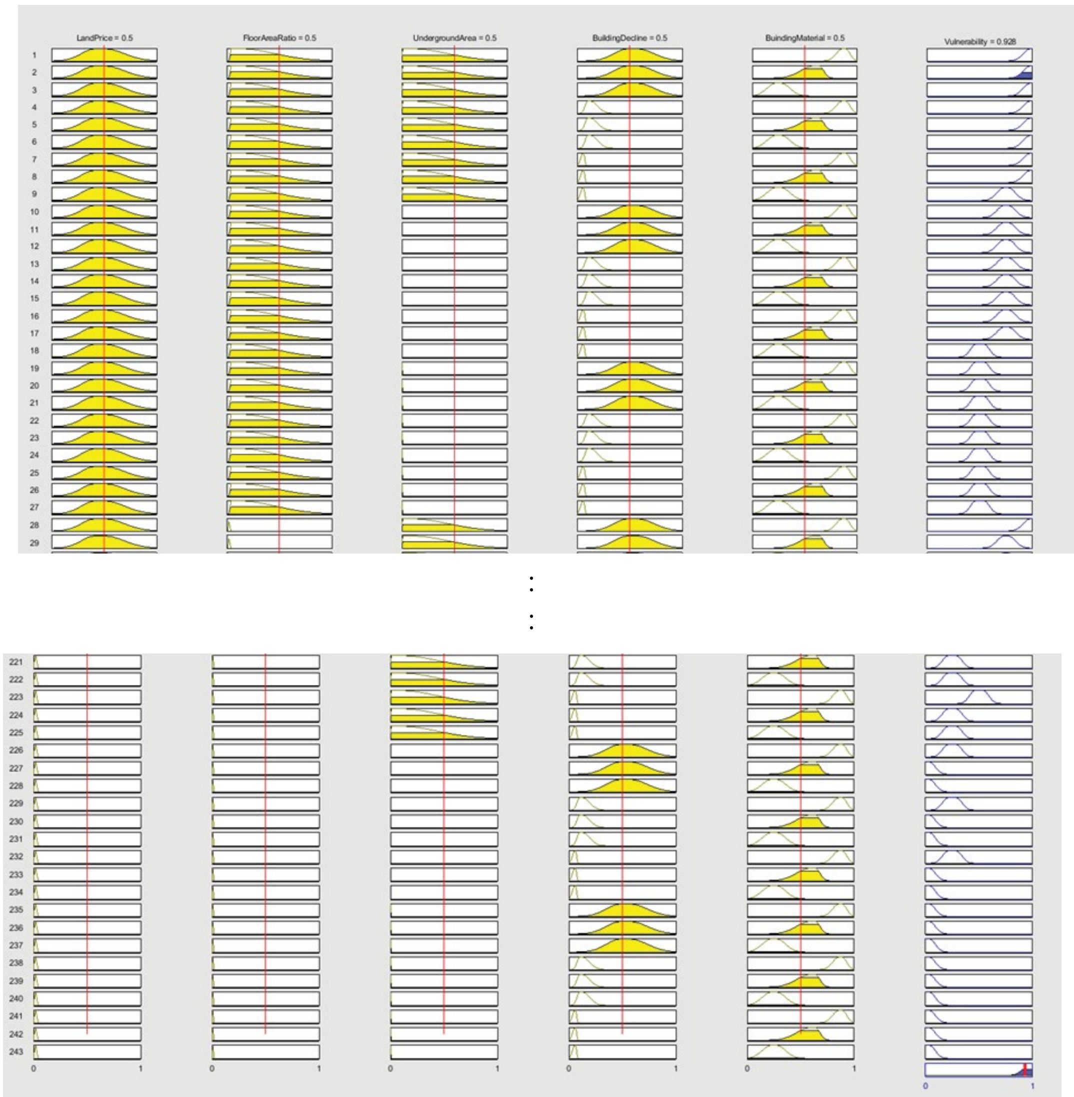


Fig. 8. Example of min-max and centroid method.

Table 4
Standardization and fuzzy score by buildings

Building (total # of items)	# of items	Land Price (won/m²)	Floor area ratio (%)	Underground area (m²)	Decline of building	Material of building	Fuzzy score
Ulsan City (108,256)	1	0.1581	0.0135	0.00347	0.1053	0.3333	0.6295
	2	0.1559	0.0912	0.00710	0.1140	0.3333	0.9087
	3	0.0593	0.0519	0.00127	0.0877	0.6667	0.6522
	4	0.2639	0.1545	0.00300	0.0658	0.3333	0.6693
	5	0.1200	0.0673	0.00202	0.1140	0.3333	0.5454
	6	0.2192	0.0691	0.00147	0.1184	0.3333	0.6855
	7	0.1367	0.0952	0.00208	0.1053	0.3333	0.6825
	8	0.0213	0.0051	0.04328	0.0482	0.3333	0.2638
	9	0.0622	0.0329	0.00139	0.1053	0.6667	0.6196
	10	0.1275	0.0693	0.00211	0.0965	0.3333	0.6328
	11	0.1613	0.0606	0.00174	0.092	0.3333	0.6713
				:			
				:			
	108,251	0.1027	0.0783	0.00410	0.0614	0.3333	0.6193
	108,252	0.1756	0.0559	0.00268	0.1009	0.3333	0.7793
	108,253	0.1645	0.0973	0.00132	0.1053	0.3333	0.6719
	108,254	0.4111	0.2889	0.00601	0.0307	0.3333	0.7624
	108,255	0.1435	0.1017	0.00224	0.0965	0.3333	0.7228
	108,256	0.4476	0.0814	0.04707	0.0877	0.0000	0.7764

Table 5
Classification by buildings on urban flood vulnerability

			green		yellowish-green		yellow		orange		red	
		Total # of buildings	# of buildings	%	# of buildings	%	# of buildings	%	# of buildings	%	# of buildings	%
Ulsan City	Jung-gu	24,059	1,297	5.39	835	3.47	20,842	86.63	234	0.97	851	3.54
	Nam-gu	24,302	2,567	10.56	821	3.38	19,221	79.09	578	2.38	1,115	4.59
	Dong-gu	10,343	808	7.81	216	2.09	9,073	87.72	89	0.86	157	1.52
	Buk-gu	11,909	543	4.56	209	1.75	11,098	93.19	26	0.22	33	0.28
	Ulju-gun	37,643	570	1.51	11	0.03	37,062	98.46	–	–	–	–

Ulsan City, it was possible to generate a building vulnerability classification map, as shown in Fig. 9. An example of enlarging the area for inspection of certain buildings is shown in Fig. 10.

During flooding, the areas with the highest socio-economic and physical flood damage were located in Nam-gu and Jung-gu, which show the highest distribution of red spots on the classification map. In addition, the highest ratio of the number of buildings constructed to their area was observed in the Jung-gu region, followed by Nam-gu, Dong-gu, Buk-gu, and Ulju-gun successively. By region, the area with the highest distribution of red and orange spots indicating very high and high vulnerability buildings was found in Nam-gu, followed by Jung-gu, Dong-gu, and Buk-gu successively, while these spots were not observed in Ulju-gun.

The Jung-gu area, an old district of Ulsan City, contains many old buildings and it the first place the city was settled long ago. As a result, buildings were more aged compared to the other regions. In contrast, many buildings have been recently built around the "Innovative City", which are improving the area in terms of floor area ratio and asset value, resulting in a number of red spots. The Nam-gu area was developed relatively recently centering on Ulsan City Hall and other public institutions with high asset values. In particular, the highly-dense commercial area raised the fuzzy value. The commercial area was formed and activated around Ulsan port, causing many buildings with high urban flooding vulnerability to appear. In Dong-gu and Buk-gu, most buildings are located in the areas adjacent to Ulsan Mipo National Industrial Complex, Hyundai Motors, and the Hyomun Industrial Complex. Many red and orange spots appeared in these districts as they contain many underground layers in the industrial complexes and industrial areas. Ulju-gun is mostly composed of mountainous areas

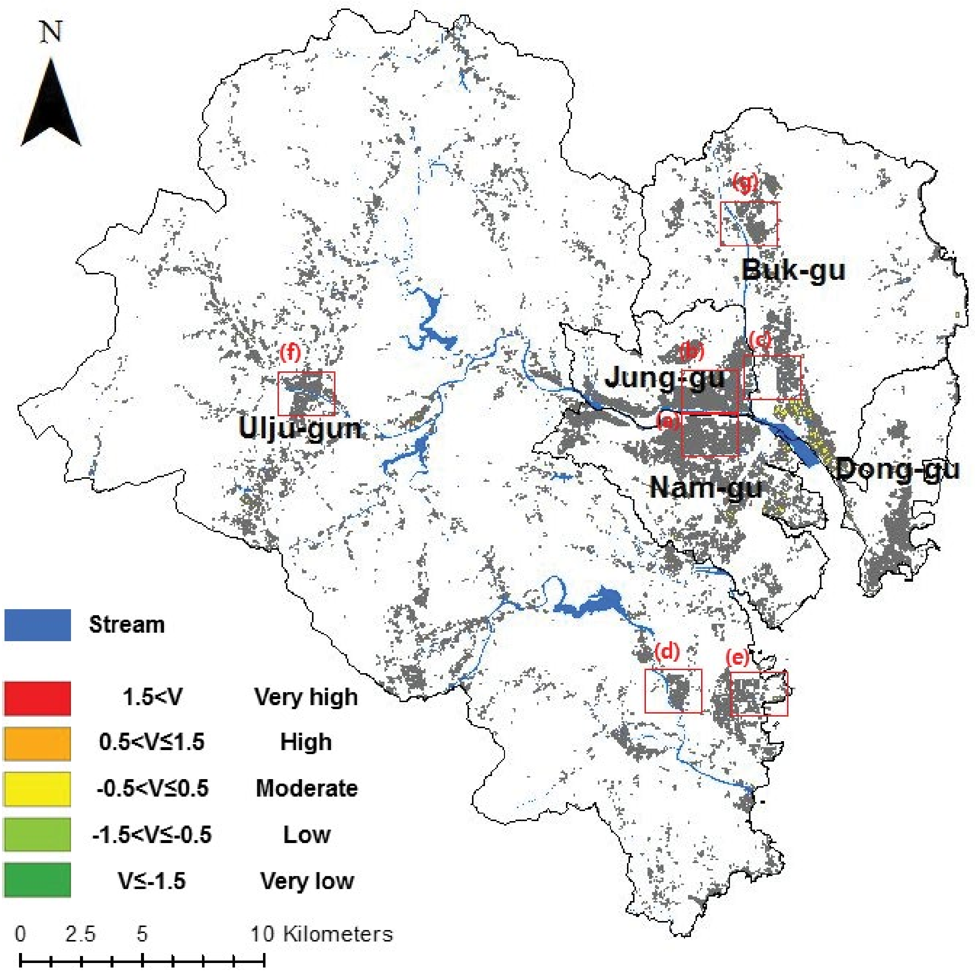


Fig. 9. Classification by building on urban flood vulnerability.

and Sinbulsan County Park. The number of buildings shows the smallest distribution ratio compared with the other areas of Ulsan and its vulnerability is mostly yellow. This was attributed to the low asset values due to the mountainous terrain, green areas, restricted areas, and reduced development activities.

In summary, buildings with high vulnerability are distributed as residential areas concentrated in the Jung-gu and Nam-gu areas of Ulsan City. The national industrial complexes and chemical complexes are mainly found in industrial lands on the east and south sides of Ulsan City. Analysis of the distribution characteristics of each building according to the urban flooding vulnerability assessment showed that the flood risk is high in the urbanized area and that major buildings of the city are distributed in areas with high flooding risks due to land use or human convenience and urban planning efficiency.

4. Conclusion

This study was conducted to adapt to climate change, which is emerging as a significant issue in the form of urban flooding. Recently, urban flooding has increased enormously in terms of frequency, but it remains difficult to predict at-risk areas due to the uncertainty of heavy rainfall. Therefore, when the same area is flooded in an urban setting, flooding vulnerability should be analyzed to minimize flood damage by selecting buildings that should be first prepared by grading inundation damage by building.

This study analyzed the flooding vulnerability of each building in four districts and one county in Ulsan City, Korea. The land use, land price, floor area ratio, underground area, building decline, and building material were selected as factors that may influence the vulnerability to flooding. As a result of the vulnerability analysis conducted through fuzzy inference of the major indicators, the distribution characteristics of the buildings were examined to minimize urban flooding damage.

By region, the vulnerability of the aged buildings was high in the old districts of the Jung-gu region. The recently developed Innovation City and public institutions in the Nam-gu area exhibit high property values and high density in commercial areas, resulting in high vulnerability. In addition, some vulnerability was found in the Dong-gu and Nam-gu areas in east Ulsan City due to the underground area of the respective industrial complexes. This indicates the possibility that the flooding vulnerability level may change depending on factors such as new developments in

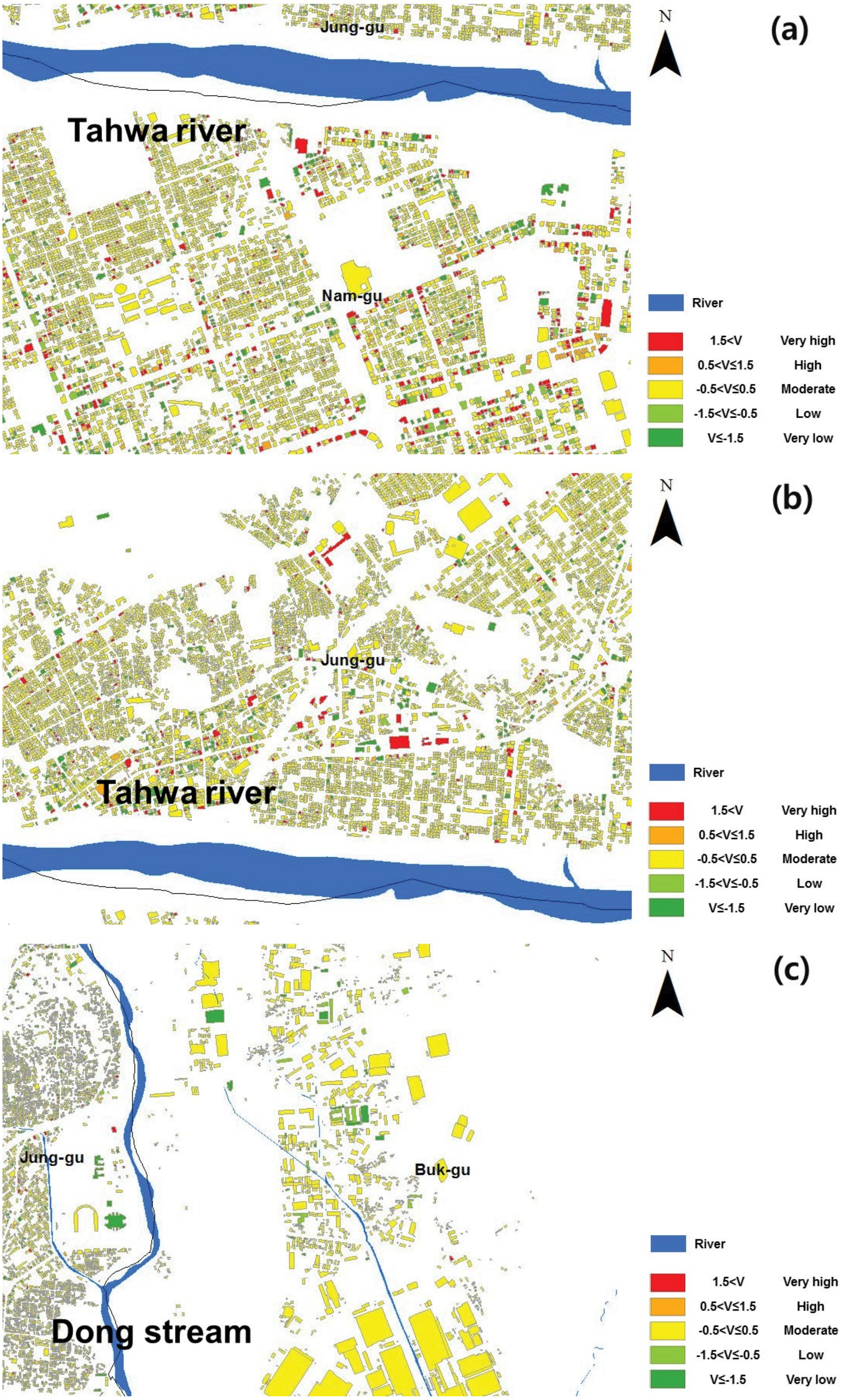


Fig. 10. *Continued*

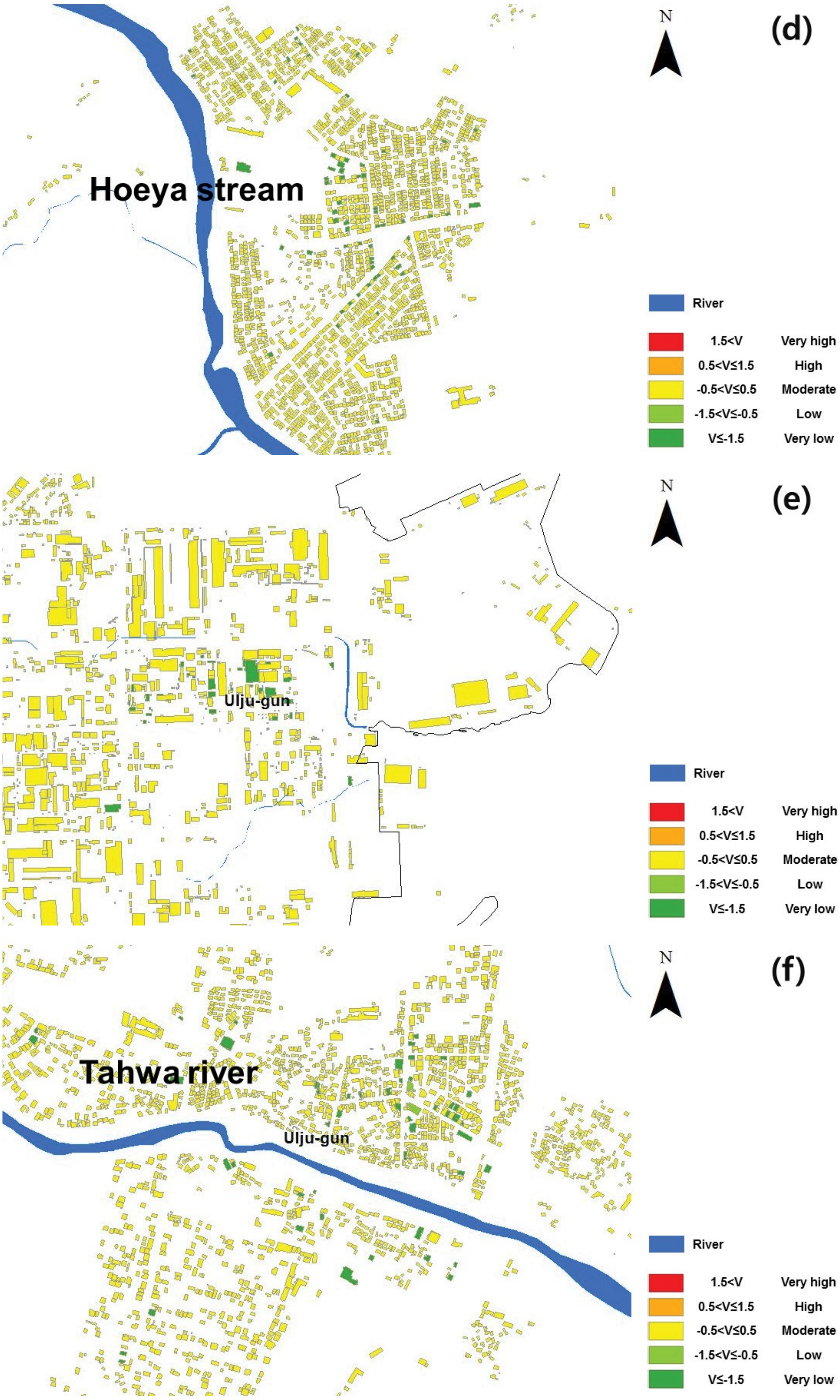


Fig. 10. *Continued*

Fig. 10. Micro view of classification by building on urban flood vulnerability.

the urban area, deterioration of older areas, and geographic location.

Based on the analysis of flooding vulnerability for each building, the following major findings were derived: In many cases, a lack of quantitative or spatial planning and measures related to urban flooding were not reflected. Herein, measures to prevent land damage and flood damage were developed by examining land use and buildings using quantitative figures in the spatial aspects of buildings, which are nonstructural measures important during urban flooding. By analyzing and evaluating urban flooding vulnerabilities as a characteristic of buildings, it became possible to identify buildings that should be prepared against damages. This provided direction to the planner to prepare various flood damage reduction measures that may include incentive policies and installation of disaster prevention facilities for buildings that are highly vulnerable to flooding. This will ensure that effective and systematic management of the flood damage to buildings will be implemented and flood-related damages reduced. In addition, visualized outputs, such as the vulnerability maps for each building, can provide users with convenience and easy identification of buildings that are potentially at risk of flood damage. In other words, it is possible to enact preventive measures by selecting relatively high-risk buildings and urban spaces by classifying the relative vulnerabilities by land use and individual buildings.

Further research is required with regards to the non-structural measures suggested herein and methods for supplementing the vulnerability classification should be performed by refining the facilities by building.

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References

[1] International Strategy for Disaster Reduction, Disaster Risk Reduction in the United Nations, Geneva, Switzerland: United Nations, 2011, pp. 1–155.
[2] K.Y. Park, M.H. Lee, Vulnerability analysis of urban district on the urban flood damage, Desal. Wat. Treat , 119 (2018) 27–35.
[3] K.Y. Park, Flood Risk Assessment Modelling Reflected upon Vulnerability and Exposure, Degree of Doctor of Philosophy, Chungbuk National University, 2018, pp. 1–179.
[4] T.R. Schueler, Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs, Metropolitan Washington Council of Governments, Washington, D.C., 1987.
[5] T. Beatley, Planning and sustainability: the elements of a new (improved?) paradigm, J. Plann. Lit., 9 (1995) 383–395.
[6] P.R. Berke, T. Beatley, After the Hurricane: Linking Recovery to Sustainable Development in the Caribbean, The Johns Hopkins University Press, Baltimore and London, 1997.
[7] J.P. Kossin, T.L. Olander, K.R. Knapp, Trend analysis with a new global record of tropical cyclone intensity, J. Clim., 26 (2013) 9960–9976.
[8] UNISDR, Sendai Framework for Disaster Risk Reduction 2015–2030, Geneva, Switzerland, 2015.
[9] S. Mannakkara, A Framework for Building Back Better During Post-Disaster Reconstruction and Recovery, Degree of Doctor of Philosophy in Civil Engineering, University of Auckland, 2014.
[10] S. Harrison, A. Silver, B. Doberstein, Post-storm damage surveys of tornado hazards in canada: implications for mitigation and policy, Int. J. Disaster Risk Reduct., 13 (2015) 427–440.
[11] M.G. Stewart, Cyclone damage and temporal changes to building vulnerability and economic risks for residential construction, J. Wind Eng. Ind. Aerodyn., 91 (2003) 671–691.
[12] Ministry of the Interior and Safety, 2018 Statistical Yearbook of Natural Disaster, Republic of Korea, 2019.
[13] K.Y. Park, J.H. Won, Analysis on distribution characteristics of building use with risk zone classification based on urban flood risk assessment, Int. J. Disaster Risk Reduct., 38 (2019) 101192.
[14] Water Directors, Core Group on Flood Protection of the Water Directors (Europe): Best Practices on Flood Prevention, Protection and Mitigation, European Initiative on Flood Prevention, 2003.
[15] B. Petry, Coping with Floods: Complementarity of Structural and Non-Structural Measures, Science Press, New York Ltd., 2002.

[16] E.J. Kaiser, J. David, Godschalk, F. Stuart Chapin Jr., Urban Land Use Planning, Fourth Edition, Chicago: University of Illinois Press, 1995.
[17] R.J. Burby, R.E. Deyle, D.R. Godschalk, R.B. Olshansky, Creating hazard resilient communities through land use planning, Nat. Hazard Rev., 1 (2000) 99–106.
[18] FEMA, The Oklahoma City Bombing: Improving Building Performance Through Multi-hazard Mitigation, Amercian Society of Civil Engineers, 1996.
[19] Ulsan Metropolitan City, 2030 Urban Masterplan for Ulsan, 2016, pp. 1–495.
[20] K. Park, M.H. Lee, The development and application of the urban flood risk assessment model for reflecting upon urban planning elements, Water, 11 (2019), https://doi.org/10.3390/w11050920.
[21] L.A. Zadeh, Fuzzy sets, Inf. Control, 8 (1965) 338–353.
[22] N. Chang, H.W. Chen, S.K. Ning, Identification of river water quality using the fuzzy synthetic evaluation approach, J. Environ. Manage., 63 (2001) 293–305.
[23] S. Gopal, C. Woodcock, Remote sensing of forest change using artificial neural networks, IEEE Trans. Geosci. Remote Sens., 34 (1996) 398–404.
[24] J. Curlander, W. Kober, Rule Based System for Thematic Classification in SAR Imagery, Proc. IGARSS, IEEE Press, New York, 1992, pp. 854–856.
[25] C. Tsatsoulis, Expert Systems in Remote Sensing Applications, IEEE Geosci. Remote Sens. Lett., 1993, pp. 7–15.
[26] U.C. Benz, P. Hofmann, G. Willhauck, I. Lingenfelder, M. Heynen, Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information, J. Photogramm. Remote Sens., 58 (2004) 239–258.
[27] C.O. Unanwa, J.R. McDonald, K.C. Mehta, D.A. Smith, The development of wind damage bands for buildings, J. Wind Eng. Ind. Aerodyn., 84 (2000) 119–149.