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Development of natural disaster risk map as reflected in flood, wind and snow in Ulsan City

Insang Yu[a], Taegeun Lee[b], Lee-hyung Kim[a], Sangman Jeong[a,*]

[a]*Department of Civil and Environmental Engineering, Kongju National University, 1223-24, Cheonan-daero, Seobuk-gu, Cheonan-si, Chungcheongnam-do, 331-717, Korea, Tel. +82 41 521 9316; Fax: +82 41 568 0287; email: isyu@kongju.ac.kr*
[b]*Department of Water resources/GIS Team, Dongbu Engineering Co., Ltd. 372, Hangang-daero, Yongsan-gu, Seoul, Korea, email: filwiths@dbeng.co.kr*

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ABSTRACT

In this study, grid-based flood inundation map, wind velocity map and snow load map were developed to calculate reasonable natural disaster insurance rate as one of the non-structural measures in Ulsan city, Korea. Flood inundation map based on 100-year flood shows that the maximum water depth was 12.04 m with 2.5% (26.44 km^2) of Ulsan city area (1057.50 km^2) inundated. In mapping wind velocity and snow load based on 100-year frequency return period, the wind velocity and snow load showed values ranging from 23.8 to 47.4 m/s and 0.44 to 0.54 kN/m^2, respectively. Based on the flood inundation map, the flood risk map was developed and 4 risk levels were determined: safe, warning, dangerous and severely dangerous water depth, which represents the degree of damage against lives and buildings inflicted by flood. The wind risk map and snow risk map made the same specified classifications for areas lower than the design wind velocity and snow load of the city. The flood risk map, wind risk map and snow risk map were applied with the proportionate damages from flood, wind and snow of Ulsan city for the last 10 years to develop the integrated natural disaster risk map. Each risk map and integrated natural disaster risk map developed by the study are assumed to be useful to build structural measures for disaster prevention such as prioritizing disaster prevention structures and determining where set them up in the future as well as non-structural prevention measures like reasonably natural disaster insurance against natural disasters and creating natural disaster evacuation map.

Keywords: Flood disaster, Snow disaster, Wind disaster, Disaster risk map

1. Introduction

The recent natural disasters are becoming massive, complex and various [1,2]. Their frequency is also rising and the scale of damage is increasingly enormous. For the last decade, typhoons took the largest toll at 60% among all types of natural disasters followed by torrential rain at 36% and heavy snow at 3% and this requires urgent countermeasures [3]. Measures against natural disasters are generally classified into structural and non-structural measures. Since, the Korean disaster prevention policy by structural measures aims to mitigate damage from natural disasters, applying systemized non-structural ones that are relatively vulnerable in parallel with the structural ones, will boost the disaster prevention capability in effect. As a non-structural measure, Korea implemented natural disaster insurance policy. It is a policy insurance managed by NEMA and operated by private insurance companies. This means it is an advanced disaster management system where a part of the payment of policy holders for premium insurance is subsidized by the central or local government, helping them better cope with unexpected natural disasters with inexpensive premium [4]. The natural

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* Corresponding author.

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disaster insurance covers damage from typhoon, flood, heavy rain, strong wind, storm, tsunami and heavy snow. The classification made from the insurance is reflected into the natural disaster insurance rate map through risk analysis.

Now, the biggest problem of the country is that the natural disaster insurance rate is unreasonable. Currently, the same insurance rate is applied to cities, Goon and Gu. However, they need a different rate based on grid, since it is obvious that each municipality has different risk factors with different geographical features such as proximity to river and elevation. This implies that the risks of flood, strong wind and heavy snow should be analyzed based on grid instead of the cities Goon and Gu. Among the studies on disaster risks that have been performed so far are: [5] the study on performed comparative rainfall characteristic at world cities for evaluation of flood risk and [6] conducted study on the assessment method for high-risk urban Inundation area using flood vulnerability index. In the meantime, [7] evaluated five comprehensive risk grades of fire, facility and evacuation vulnerability for each district in Cheongju city, while [8] and [9] evaluated the disaster risk for urban areas on inundation, fire, building collapse and evacuation vulnerability. and [10] developed a risk visualization system for natural disasters based on GIS.

Overseas studies generally suggested and evaluated disaster vulnerability and risk analysis technique using the vulnerability index due to climate change [11–15]. In 1996, The US Federal Emergency Management Agency (FEMA) developed National Emergency Management Information System (NEMIS) to manage overall disasters and also the Hazards U. S. Multi Hazard (HAZUS-MH), which estimates damages from the disasters and produces mitigation measures as part of NEMIS system. The US determines the design wind velocity of the areas that experience frequent typhoons with indirect method like Monte Carlo Simulation that was first used by [16–18]. The study on wind velocity estimation by the Monte Carlo Simulation was utilized as the basic theory of HAZUS-MH hurricane module, a natural disaster simulation software made by FEMA [19–22]. Cartographic design in flood risk mapping was evaluated to mitigate flood hazards and minimize associated losses [23]. Community map was built on participatory mapping and GIS practices and links to advanced spatial analysis in the context of disaster risk reduction and flood hazard assessment [24].

As above, many studies were performed on risk analysis for natural disasters. However, it is inappropriate to rate the insurance with the existing risks in Korea as they are calculated not by specific grid, but by the cities: Goon and Gu. Though other countries analyzed the risks of each type of damage, they do not have risks that combine all the disasters. Therefore, the study developed a 10-m grid-based flood, wind and snow risk map to be used as a base data for insurance rate to prevent more damages incurred by natural disasters.

2. Materials and methods

2.1. Study area

Ulsan city is a port city with a warm climate bordering the east sea as shown in Fig. 1 with an area of 1,058 km^2 and population of 1.11 milion. The average annual temperature is 13.8°C with annual precipitation of 1274.6 mm, in which 70% falls in Summer from June to September. Daily maximum instantaneous wind velocity is 10.3 m/s and the yearly maximum snowfall is 35 mm on average. Despite the small amount of snow, its unit weight is heavy due to the east sea and also, even a small amount of snow may put substantial weight on structures. The city has a meteorological station that can measure rain, wind velocity and snowfall.

2.2. Method of development of flood risk map

Developing the flood risk map requires flood inundation map first. The flood inundation map in this study refers to the map that includes submerged area because of inundating rivers. The flood risk map shows the four categories depending on the damage incurred to buildings and human life.

2.2.1. Flood inundation map

There are various ways to develop the flood inundation map such as, the use of numerical analysis models and GIS

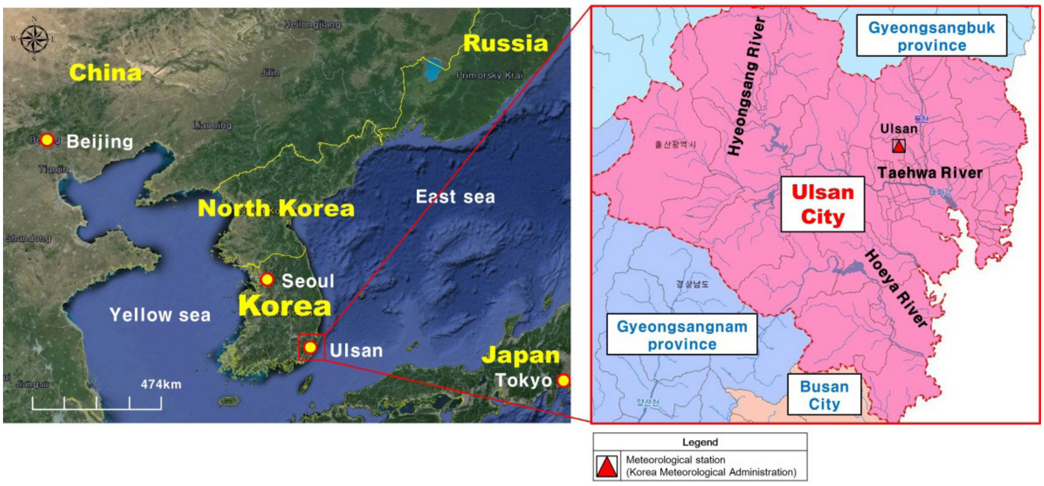


Fig. 1. Location of meteorological station and rivers in Ulsan city.

program, through flood level and topographic data [4]. Though numerical analysis model is accurate, it has limitations especially to a wide range of area (e.g., data collection for unmeasured area and the model simulation time). On the contrary, GIS program, in spite of less accuracy, has advantage on wider areas over the numerical analysis model. This implies that the numerical analysis is insufficient to cover an entire city as big as 1,058 km^2 and a river as long as 490.4 km as shown in Table 1 and develop a flood inundation map. Therefore, flood inundation map data were established for the 11.2 km national river in the form of shape file format that were already produced in Hec-Ras (one-dimensional) and FLUMEN (two-dimensional) models by the Ministry of Land, Transport and Maritime Affairs as shown in Fig. 2(a). Hec-Ras was used to develop inundation map for local river and FLUMEN was used for national river. Fig. 2(b) shows a converted 10m grid-based raster file format for developing the flood inundation map.

Flood inundation map was developed for the 479.18 km-long local rivers combined through the GIS program. These include the areas lower than the 100-year flood level of the river. It also considers inundated area which covers protected lowland lower than the 100-year flood level. To develop the flood inundation map (Fig. 3(c)) with the GIS program, the digital elevation map (DEM) of both the study area and flood level calculated with the 100-year flood level of the concerned river is needed. Any area whose flood level DEM is higher than topographic DEM (Fig. 3(a)) is used to obtain the inundation depth (Fig. 3(b)).

Table 1
The number of national and local rivers in Ulsan city

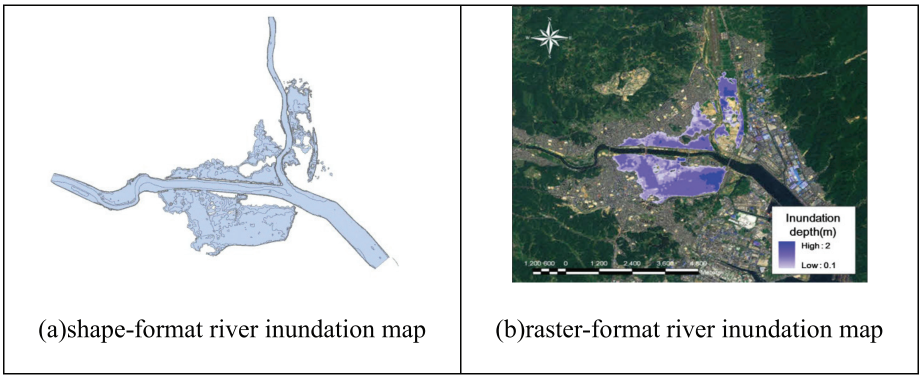
Division	National river	Local river	Sum
Number	1	101	102
River length (km)	11.27	479.18	490.45

2.2.2. Flood risk map

The flood risk grade found in the risk map is based on the inundation grade suggested as a special contract term of the current storm and wind insurance policy of Korea. Table 2 shows the classification of flood risk map. It is safe when the depth is 0 and less, warning until 0.3, dangerous from 0.3 to 1.0 and severely dangerous when it is more than 1.0.

Table 2
Classification of flood risk map

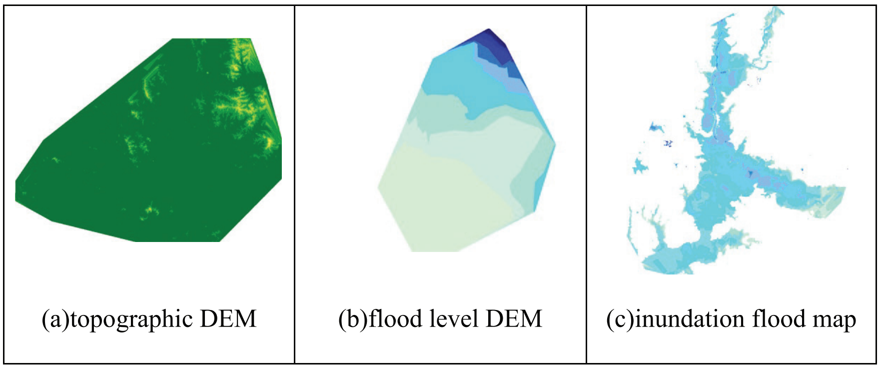
Inundation depth (m)	Classification	Intensity
0 and less	1	Safe
0.0 to 0.3	2	Warning
0.3 to 1.0	3	Dangerous
More than 1.0	4	Severely dangerous



(a)shape-format river inundation map

(b)raster-format river inundation map

Fig. 2. Inundation map of Taehwa river in shape and raster format; (a) shape-format river inundation map, (b) raster-format river inundation map.



(a)topographic DEM

(b)flood level DEM

(c)inundation flood map

Fig. 3. Required data for developing flood inundation map using the GIS; (a) topographic DEM, (b) flood level DEM, (c) inundation flood map.

2.3. Method of development of wind risk map

The wind risk map was developed with application of design wind velocity calculation method suggested in the Korean Building Code of Ministry of Land, Infrastructure and Transport [25] and the wind velocity estimation method described in the Development of Risk Assessment Technique for Strong Wind and Heavy Snowfall of National Emergency Management Agency [26]. Homogeneous wind model is first used to develop the wind risk map, so the surface roughness model and topographical effect model are applied to the homogeneous wind model to develop the wind velocity map. Homogeneous wind model gives the value of velocity when the elevation and roughness of earth surface is not applicable. The same goes with the surface roughness model and topographical effect model. The wind risk map has the same 4 classifications as shown in the previous table.

2.3.1. Homogeneous wind model

Homogeneous wind model does not include surface and topography effect, so the two other models are needed to developed the wind velocity frequency analysis. Annual maximum wind velocity data aged higher than 20 years are used for velocity frequency analysis while probability distribution used is the Gumbel distribution. On the other hand, the parameter estimation method used is the moment method. Cumulative probability distribution of the Gumbel distribution is shown in Eq. (1). Calculation about x and the inverse function of $F(x)$ is shown in Eq. (2).

$$\mathrm{F}(x) = e\left[-e\left(-\frac{x - x_0}{a}\right)\right] \tag{1}$$

$$x_t = x_0 - a\, ln\left[\ln T - \ln\left(T - 1\right)\right] \tag{2}$$

where, x, x_0 and α are variance, positional parameter and shape parameter, respectively. When the wind velocity is calculated from Eq. (2), homogeneous wind model will not take into account the surface and topography.

2.3.2. Surface roughness model

Typically, wind velocity on the surface is influenced by the earth surface roughness. Surface roughness model represents the varying wind velocity with weight depending on surface roughness. Korean Building Code [25] classifies the surface roughness for each surface condition as shown in Table 3. The area where 10-story or higher buildings are dense results in 0.58 times less velocity of homogeneous wind model. On the other hand, coastal, grassland, aerodrome areas were found to have 1.13 times higher velocity.

2.3.3. Topographical effect model

Wind velocity increases especially within the topographic features like in between hills and on the slope. The topographical effect model calculates the growing rate of velocity depending on the topographic features. To evaluate the increasing rate quantitatively, Korean Building Code [25] suggested the topographic factors depending on the topographic slope of hills, and mountains and land. The topographic factors use 1.05–1.27 for the slope land and 1.11–1.61 for the hills and mountains. The velocity of the homogeneous wind model can be multiplied with the topographic factors to estimate the speed added by the topography.

Table 3
Roughness according to surface conditions

Division	Explanation	Surface roughness
A	The region that building having height of 10 stories straggle	0.58
B	The region that structures having height of 3.5 m straggle	0.81
C	The region that obstacles having height of 1.5–10 m straggle	1.0
D	Coast, grassland, aerodrome regions	1.13

Table 4
Classification of wind risk map

Wind velocity (m/s)	Classification	Intensity
0 and less	1	Safe
0.0 to 35	2	Warning
35 to 45	3	Dangerous
More than 45	4	Severely dangerous

2.3.4. Wind risk map

Developing the wind risk map requires comparison between 100-year frequency velocity developed with the homogeneous wind model, surface roughness model and topographical effect model and the design wind velocity of the target area. This is based on the Korean Building Code [25] which established 100-year frequency velocity as standard to design structures. The design wind velocity of Ulsan city is 35 m/s. Accordingly, any area with estimated wind velocity of 0 and less was classified as safe, with the velocity lower than design standard is under warning, area with 5 m/s faster than the design standard is classified as dangerous and with 10 m/s faster is classified as severely dangerous as shown in Table 4.

2.4. Method of development of snow risk map

The snow risk map is developed with frequency analysis using annual maximum snowfall observed by the meteorological station of the study area. 10 m-grid based snowfall map is developed through frequency analysis and the unit weight of snowfall is also applied.

2.4.1. Snowfall frequency analysis

Snowfall frequency analysis is performed to calculate probability snowfall. The annual maximum snowfall data for at least 20 years or more should be constructed for snowfall frequency analysis and the probability distribution and parameter estimation method that best serve the

Table 5
Classification of snow risk map

Snow load (kN/m^2)	Classification	Intensity
0 and less	1	Safe
0.0 to 0.5	2	Warning
0.5 to 0.6	3	Dangerous
More than 0.6	4	Severely dangerous

data should be selected through goodness of fit test. There are various probability distributions for frequency analysis and extreme frequency analysis. Snow load frequency analysis applies Generalized Extreme Value, Type- I (Gumbel), Type- II (Log-gumbel) and Type- III (Weibull), Log-Pearson Type- III. Generalized Extreme Value is the most appropriate for snowfall frequency analysis, while probability weighted moment method is the most frequent parameter estimation used in Korea [27]. The study also used GEV distribution by the probability weighted moment method to perform snowfall frequency analysis. Eq. (3) is probability density function of GEV and Eq. (4) is the probability variance depending on return period.

$$\mathrm{F}(x) = e^{-\left[1-b\left(\frac{x-x_0}{a}\right)\right]^{\frac{1}{b}}} \tag{3}$$

$$x_t = x_0 + \frac{a}{b}\left[1-\left\{-\ln\left(1-\frac{1}{T}\right)\right\}^{b}\right] \tag{4}$$

where, *a* is the scale parameter, *b* is the shape parameter, x_0 is the positional parameter and *T* is the return period.

2.4.2. Snow load map

Snow load is calculated by multiplying unit weight of snow with 100-year snowfall by snowfall frequency analysis. In general, unit weight of dry snow is 100 kgf/m^3 and that of wet snow is 300 kgf/m^3. The study estimated the snow load by applying 200 kgf/m^3, the average value of the two and developed the 10 m-grid based snow load map of a 10-m grid unit using Kriging method of ArcGIS system.

2.4.3. Snow risk map

Developing the snow risk map requires comparison between 100-year snowfall through snowfall frequency analysis and design snow load of the study area. Like the wind velocity, snow load also has 100-year frequency as the standard design. The design snow load of Ulsan city is 0.5 kN/m^2. Table 5 shows that any area is safe with snow load of 0.0 kN/m^2 and less, warning at 0.0 to 0.5 kN/m^2, dangerous at 0.5 to 0.6 kN/m and severely dangerous at more than 0.6 kN/m^2.

3. Results and discussions

3.1. Results of development of flood risk map

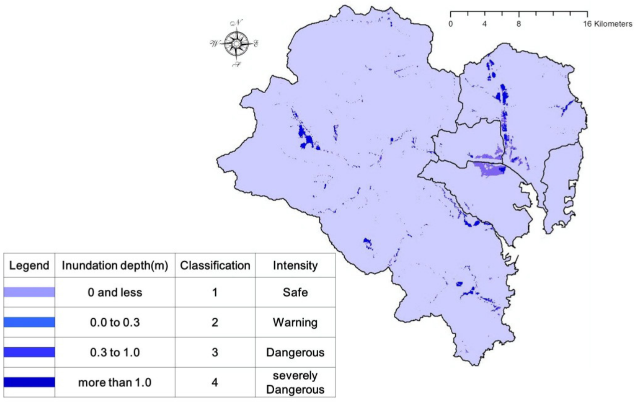


Fig. 4. Flood risk map.

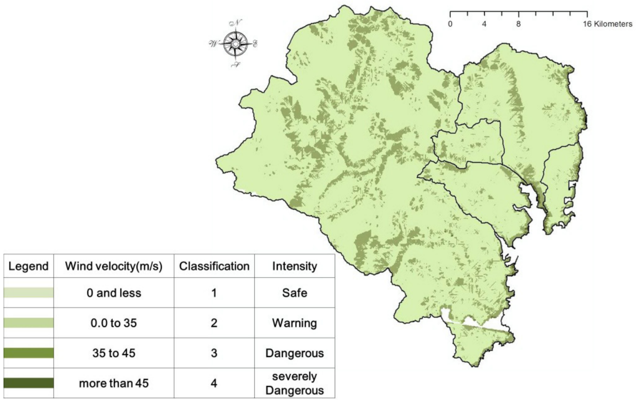


Fig. 5. Wind risk map.

Numerical model and GIS were used to develop the flood inundation map of Ulsan city and the 10 m grid-based flood risk map as shown in Fig. 4. Most submerged areas were located near the main streams and tributaries of Taehwa River, Hyeongsan River and Heoya River. It was analyzed that 26.44 km^2 submerged out of the total 1,058 km^2 and the remaining 1,031.56 km^2 was classified as a safe area. The study also showed that classification 2 area with depth at 0 to 0.3 m was 4.64 km^2, classification 3 at 0.3 to 1.0 m was 12.79 km^2 and classification 4 at more than 1.0 m was 9.01 km^2.

3.2. Results of development of wind risk map

Hundred-year wind velocity map was developed using homogeneous wind model, surface roughness model and topographical effect model. The 10 m grid-based wind risk map is shown in Fig. 5. As a result of developing the homogeneous wind model through wind velocity frequency analysis, 100-year wind velocity of 25.9 m/s is obtained. After topographical effect model and surface roughness model were applied to the homogeneous wind model, the minimum and maximum wind velocities were found to be 24 and 47 m/s, respectively. The design wind velocity of Ulsan city is 35 m/s and the developed wind velocity map is shown in Fig. 5, with classification 2 at 0 to 35 m/s, classification 3 at 35 to 45 m/s, and classification 4 at more than 45 m/s. It was analyzed that Ulsan city did not have a safe zone under the standard of 100-year wind velocity.

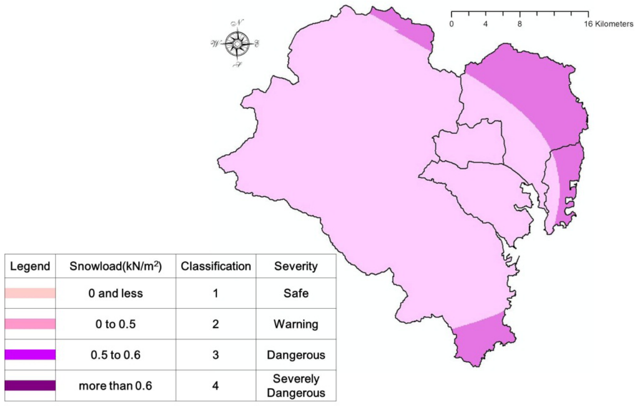


Fig. 6. Snow risk map.

3.3. Results of development of Snow risk map

Hundred-year snow load map by the snowfall frequency analysis was developed and the 10 m grid-based snow risk map is shown in Fig. 6. The minimum and maximum snow load of Ulsan city was estimated to be 0.44 and 0.54 kN/m^2, respectively. With the design snow load of the Ulsan city at 0.50 kN/m^2, classification 2 area has 0 to 0.5 kN/m^2 and classification 3 area has 0.5 to 0.6 kN/m^2 Based on the 100-year snow load, it was found that Ulsan city did not have safe and severely dangerous areas.

3.4. Results of development of natural disaster risk map

3.4.1. Calculation of weight by natural disasters

The natural disaster risk map was developed by combining the flood risk map, wind risk map and snow risk map. To combine the three maps, the damages from flood, wind and snow for the last 10 years was applied with weight. The damages done by each natural disaster from 2004 to 2013 were surveyed as shown in Table 6. Though typhoon has impact on flood and wind damage, there has never been data or related studies on separating flood and wind damage from typhoon damage. Consequently, 2 cases were weighted: Case 1 where typhoon affects flood damage; and Case 2 where typhoon affects wind damage.

The weight of flood risk, wind risk and snow risk in Case 1 were estimated to be 0.96, 0.01 and 0.03 respectively. Meanwhile, Case 2 showed 0.36 for flood risk, 0.61 for wind risk and 0.03 for snow risk as shown in Table 7.

3.4.2. Development of natural disaster risk map

Two natural disaster risk maps were developed by applying the weight of both Case 1 and Case 2 to flood, wind and snow risk map. The natural disaster risk map of Case 1 was developed using Eq. (5) while that of Case 2 using Eq. (6).

$$RC_{C1} = 0.96F_{c1} + 0.01W_{c1} + 0.03S_{c1} \tag{5}$$

$$RC_{C2} = 0.36F_{c2} + 0.61W_{c2} + 0.03S_{c2} \tag{6}$$

where, RC refers to risk classification, F to flood risk, W to wind risk, S to snow risk, C1 to Case 1 and C2 to Case 2.

Table 6
Damages by natural disaster for 10 years

Year	Typhoon	Heavy rainfall	Heavy snowfall	Strong wind
2004	2,360,885	0	0	0
2005	37,566,778	0	1,138,893	501,369
2006	31,240	23,904,704	0	0
2007	433,198	0	0	0
2008	0	3,234,377	0	187,730
2009	0	0	0	0
2010	0	0	0	0
2011	0	259,955	832,805	0
2012	4,155,525	102,752	63,223	19,453
2013	0	0	0	29,370
Sub total	44,547,626	27,501,788	2,034,921	737,922
Ratio (%)	60	36	3	1
Total				74,822,257

Table 7
The results of weight by natural disasters

Division	Flood risk	Wind risk	Snow risk
Case 1	0.96	0.01	0.03
Case 2	0.36	0.61	0.03

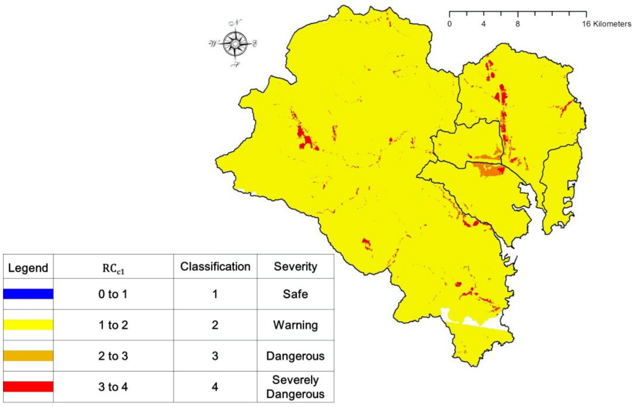


Fig. 7. Natural disaster risk map (Case 1).

The natural disaster risk map in which Case 1 weight result was applied were drawn similar to the flood risk map as shown in Fig. 7. As to Case 1, the weight of flood risk was 0.96 while that of wind and snow risk was 0.01 and 0.03 each. Since their weight is so small, they did not have any significant impacts on the development of the natural disaster risk map.

The natural disaster risk map applying weight in Case 2 was developed as shown in Fig. 8. And it is similar to the combination of the flood risk and snow risk maps. In Case 2, flood weight was 0.36, wind weight was 0.61 and snow weight was 0.03. Areas where high wind risk and high flood risk overlapped resulted in a severely dangerous area. Areas that had high wind risk and flood risk without overlapping were

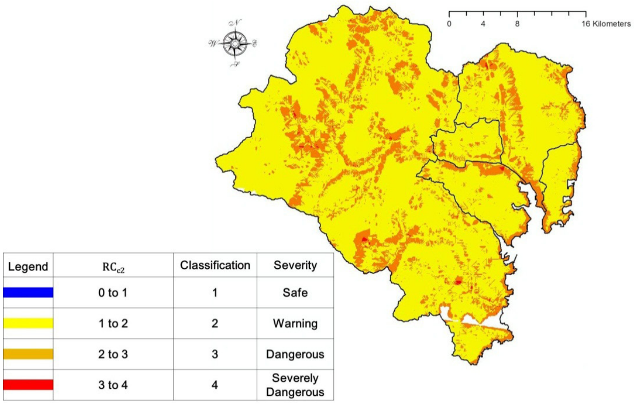


Fig. 8. Natural disaster risk map (Case 2).

classified to either 2 or 3. The natural disaster risk map of Case 2 did not offer safe areas unlike the wind risk map as shown in Fig. 8.

4. Conclusions

The study developed the flood, wind and snow risk map of Ulsan city and integrated natural disaster risk map by applying the weight of each natural disaster. One-dimensional and two-dimensional numerical modeling was applied to national rivers while GIS technique that used flood level was applied to local rivers to draw the flood inundation map. As a result, most submerged areas were located near the main streams and tributaries of Taehwa River, Hyeongsan River and Heoya River. It was analyzed that 26.44 km^2 (2.5%) of the city submerged out of the total 1,058 km^2 and the remaining 1,031.56 km^2 (97.5%) were classified as safe areas. The study also showed that, classification 2 area with depth of 0 to 0.3m was 4.64 km^2 (18%), classification 3 at 0.3 to 1.0 m was 12.79 km^2 (48%) and classification 4 at more than 1.0 m was 9.01 km^2 (34%) from the inundated area of 26.44 km^2. For developing the wind risk map, the wind velocity estimation method suggested by Korean Building Code (2009) was applied to develop homogeneous wind model, surface roughness model and topographical effect model and develop the wind velocity map of Ulsan city. The 100-year minimum and maximum wind velocity of Ulsan city were estimated to be 24 and 47 m/s, respectively. The design wind velocity of the city is 35 m/s and the wind risk map was developed with classification 2 at 0 to 35 m/s, classification 3 at 35 to 45 m/s, and classification 4 at more than 45 m/s. It was analyzed that Ulsan city did not have a safe zone under the 100-year wind velocity. Snowfall frequency analysis was performed to develop 100-year snow load map and snow risk map. Minimum and maximum snow load of Ulsan city were estimated to be 0.67 and 0.85 kN/m^2 respectively. With the design snow load of Ulsan city at 0.50 kN/m^2, classification 2 area has 0 to 0.5 kN/m^2, classification 3 area has 0.5 to 0.6 kN/m^2 and classification 4 area has more than 0.6 kN/m^2 for the snow risk map. Based on the 100-year snow load, it was found out that Ulsan city did not have safe and severely dangerous areas. To develop the natural disaster risk map, that combined the flood risk map, wind risk map and snow risk map, the weight for each natural disaster was applied. The study used two cases for the damages from natural disasters, which occurred for the last 10 years and calculated their weight. As a result, Case 1 has weight of flood risk at 0.96, weight of wind risk at 0.01 and weight of snow risk at 0.03. On the other hand, Case 2 estimated 0.36, 0.61 and 0.03 respectively. By applying the weight of each case, two natural disaster risk maps were developed. Since, the flood risk weight of Case 1 was 0.96, the developed natural disaster risk map was found similar to the flood risk map and the developed natural disaster risk map of Case 2 was similar to the combination of the wind risk map and flood risk map. Both cases described the weight of snow risk at 0.03 giving insignificant impact on the natural disaster risk map. Each risk map and integrated natural disaster risk map that were developed in this study are assumed to be useful to build structural measures for disaster prevention such as prioritizing disaster prevention structures and determining where to set them up in the future. This study can also help in the development of non-structural prevention measures like reasonable insurance rate against natural disasters and natural disaster evacuation map.

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