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ORIGINAL PAPER

Finding key vulnerable areas by a climate change vulnerability assessment

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Abstract Extreme climate events such as typhoons, heat waves, and floods have increased in frequency with climate change. Many municipalities within the Republic of Korea (ROK) have experienced damage from these events, necessitating countermeasures. Vulnerability assessment has been suggested in the implementation of a national plan for reducing damage resulting from climate change. Thus, in this study, we assess the vulnerability of the ROK and identify key vulnerable municipalities in support of the national adaptation plan. We create a framework for assessing the vulnerability of all 232

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municipalities of the ROK with respect to 32 items in 7 fields. The framework regards decision makers' comprehension and availability of data as important factors. We assess the vulnerability index of each municipality by using variables of climate exposure, sensitivity, and adaptation capacity. The weights of variables are determined by the Delphi method. We used the representative concentration pathways 8.5 climate scenario to reflect future climate exposure for the vulnerability assessment. From the analysis, vulnerability maps are prepared for the 32 items of 7 fields, and key vulnerable municipalities are identified by aggregating the maps. The distribution of vulnerable municipalities changes with the future climate conditions. These maps provide a scientific and objective basis for the ROK government to establish adaptation plans and allocate resources. The ROK government can utilize the results to identify the characteristics of highly vulnerable areas, and municipalities can use the results as a basis for requesting support from the national government.

Keywords Mapping vulnerability · National climate change adaptation strategies · Resource allocation · RCP scenario

1 Introduction

Development activities of humankind have emitted a significant quantity of greenhouse gases to cause climate change (Moreno and Becken 2009; European Environment Agency 2012), which in turn causes negative or positive effects in various fields on a global scale (IPCC 2012). These effects simultaneously encompass short-term effects including extreme weather such as typhoons, heavy rainfall, heat waves, and cold waves and long-term effects such as gradual increases or decreases in the temperature and rainfall (e.g., Arnell et al. 2005; Wang et al. 2013; Mikami et al. 2014; Silva and Pereira 2014). Thus, the assessment and solution of problems caused by climate change affecting a large area require the consideration of a variety of human activity sectors and environmental characteristics, expressed by means of very diverse variables.

The Intergovernmental Panel on Climate Change (IPCC 2012), a representative community focusing on research relevant to climate change, separated this research theme into three working groups. Group I assesses the climate system and climate change; group II assesses the vulnerability of systems and adaptation options to reduce damages; and group III assesses mitigation options related to preventing greenhouse gas emissions (Lee et al. 2013). The present study focuses on the work of group II in assessing vulnerabilities, predicting negative effects, and supporting adaptation options to reduce damage. Many researchers have attempted to assess the impacts and vulnerability to climate change (Füssel and Klein 2006; Fekete 2012; Varazanashvili et al. 2012; Siagian et al. 2014). Moreover, many studies have determined that diverse events are related to climate change and have demanded proper adaptation plans for counteracting its effects.

Such studies have focused mainly on specific items or fields of certain areas. For example, studies on landslide risk have focused only on the identification of landslide hazard area without interest in other items or fields (Al-Adamat et al. 2003; Allison et al. 2009; Moreno and Becken 2009; Camarasa Belmonte et al. 2011; Antwi-Agyei et al. 2012; Eckert et al. 2012; Houghton et al. 2012; Menoni et al. 2012). Although such research can help to improve existing methodologies and supports municipalities within the study area, the government cannot utilize the results to prepare national adaptation plans and options. This is an issue because climate change affects large areas rather than only small or local areas. Therefore, the entire extent of the Republic of Korea (ROK) and various fields should be assessed to support a national adaptation plan.

The objectives of this study are to determine methods for assessing the vulnerability of various fields and areas by using a single framework and to identify their mechanisms. Moreover, this study identifies municipalities with most urgent areas in which to establish adaptation plans and attempts to develop a framework for assessing various fields in many municipalities. The framework is developed to incorporate a combination of quantitative and qualitative methods for improving the comprehension and availability of data of decision makers and considers limitations of time, cost, and data. The properties of the vulnerability fields are analyzed by checking variables. This study identifies key vulnerable areas to support the establishment of a national adaptation plan. The developed framework and method for finding these such areas can also serve as an effective tool for use by governments of other countries.

2 Methods

2.1 Scope of study

This study comprises two parts (Fig. 1): vulnerability assessment and the identification of key vulnerable areas. The first part focuses on the selection of fields and items, establishment of data, and assessment of vulnerability. The second part concentrates on classifying vulnerability grades, creating first-grade and key vulnerability maps, and analyzing the characteristics of key vulnerable municipalities.

The study area is the ROK, which consists of 232 municipalities. The municipalities are used as spatial units for vulnerability assessment because each spatial unit is appropriate for formulating and implementing policies (Allison et al. 2009). Additionally, each municipality of the ROK must establish its own climate adaptation plan according to the basic act on low-carbon green growth. Seven fields are considered, including health, forests, water management, ecosystem, agriculture, fisheries, and disasters, which consist of 32 specific items. The fields and items were selected on the basis of climate change adaptation strategies of the ROK.

The temporal scope was established to include the present (2001–2010) and future (2046–2055) years. In the national adaptation strategy, the ROK government set 2050 as the long-term target year for adaptation. This study considers only the change in climate conditions to identify its effects, as there are not enough data to estimate the future condition of the ROK. In addition, the government of ROK determined that future data have considerable uncertainty.

The variables for sensitivity and adaptive capacity were selected by reviewing previous studies provided by national institutes of various fields. Climate exposure variables were provided by the Korea Meteorological Administration (KMA). The representative concentration pathways (RCP) 8.5 climate change scenario was applied to establish future climate data. This scenario, known as the business-as-usual (BAU) scenario, is the worst of RCP scenarios and assumes that insufficient effort is put forth in reducing greenhouse gas emissions. The KMA used the HadGEM3-RA model to produce the RCP 8.5 scenario data. An average of 10 years of climate data pertaining to climatic prediction was used in the assessment for anticipating future conditions.

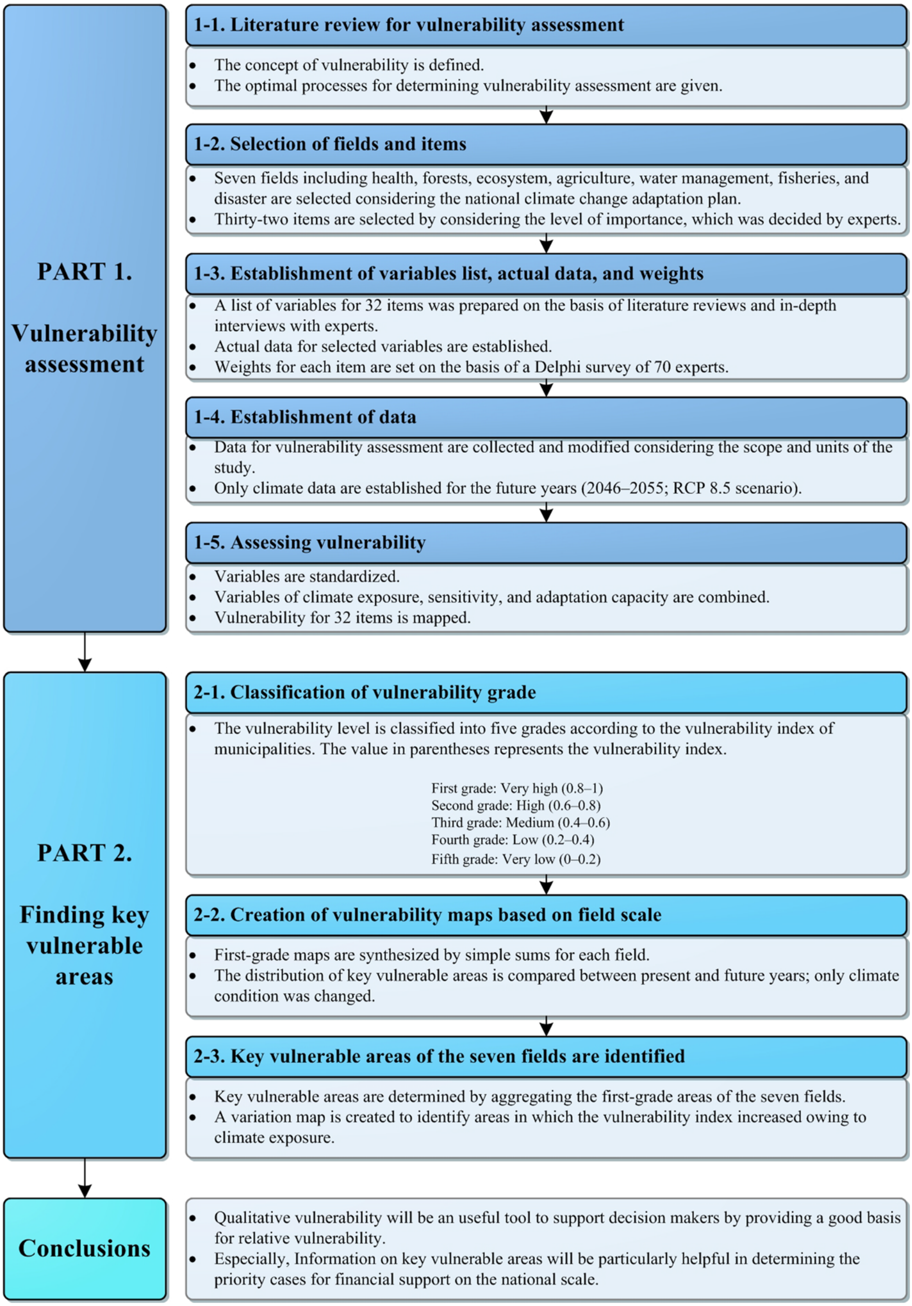

Fig. 1 Flowchart of this study

2.2 Methods of vulnerability assessment

Vulnerability is the degree to which a system is susceptible to negative effects of climate change, such as climate variation and extreme weather (White et al. 2001). Vulnerability is defined as a function of climate exposure, sensitivity, and adaptive capacity based on the assessment of the magnitude of climate change and variations (Schneider et al. 2007). Climate exposure is the degree to which a system is exposed to significant climatic variations that can cause damage. Sensitivity is the degree to which a system is affected, either negatively or positively, by climate-related stimulation. The adaptive capacity is the ability of a system to adjust to climate change variability and extreme weather, to reduce potential damage, or to address the results (White et al. 2001; Füssel and Klein 2006; Allison et al. 2009).

The process of this study is detailed in Fig. 1. The seven fields selected are the same as those used by the government in the national climate change adaptation strategy. Thirty-two items for the seven fields were selected considering experts' opinions and important issues of the ROK. Representative variables were then selected for the items of each field. Three characteristics were considered for the seven fields, each of which was assessed by using a series of variables.

Variables for the vulnerability assessment were selected on the basis of article reviews and in-depth interviews with experts. The 32 items were assessed by using categories of climate exposure, sensitivity, and adaptation capacity, and each category included four to six variables. Thus, the theoretical number of variables was greater than 360. However, because duplicate variables were applied to various fields and items in some cases, the actual number of variables was approximately 200. The selected variables were improved and verified by consultation with the climate change consulting group of the Korea Environment Institute, which consists of experts in climate change impacts and adaptation in various fields (Table 1).

After selection of the variables, their weights were developed to determine the contribution of each. Because it was difficult to set weights on the basis of the literature reviews and interviews, the Delphi method was used to reach a consensus value from a large number of experts by synthesizing their subjective value and using a feedback process.

Seventy experts were selected for application of the Delphi method for the seven fields. The experts consisted of professors and researchers who performed research relevant to climate change. The execution of the Delphi method required three months, from July to September 2011. The weights were surveyed twice to reach agreement. Each expert set weights by comparing his or her own weights with the average weights of the other experts. Two types of weights were identified in the vulnerability assessment (Table 2). The first weights (FW) were set for climate change (FWce), sensitivity (FWs), and adaptation capacity (FWac), and the sum of the first weights was set as one. The second weights (SW) were set for specific variables in the three categories. The sum of the second weights for climate exposure, sensitivity, and adaptation capacity was also set as one.

Data were established for assessment after variable selection and weight setting. Climate data for the present years (2001–2010) and future years (2046–2055; RCP 8.5) were obtained from the KMA. The climate data were converted to various types, considering the properties of the field, such that shown in Table 3. For sensitivity, the sources of data varied because the properties differ among fields and items. Data for the forest and ecosystem fields were collected from the Korea Forest Service, the Korea Environment

Table 1 List of items considered for vulnerability assessment

No.	Field	No.	Item
1	Health	1	Health vulnerability due to floods
		2	Health vulnerability due to typhoons
		3	Health vulnerability due to heat waves
		4	Health vulnerability due to cold waves
		5	Health vulnerability due to ozone enhancement
		6	Health vulnerability due to fine dust
		7	Health vulnerability due to air pollutants
		8	Health vulnerability due to infectious diseases
		9	Health vulnerability by waterborne epidemics
2	Forests	10	Landslides due to heavy rainfall
		11	Vulnerability of trails due to landslides
		12	Vulnerability to forest fire
		13	Vulnerability of pine trees to disease and pests
		14	Vulnerability of pine trees to pine fungi
		15	Vulnerability of forest productivity
		16	Vulnerability of vegetation due to drought
3	Ecosystem	17	Vulnerability of vegetation growth
		18	Vulnerability of insects
		19	Vulnerability of management of protected areas
4	Agriculture	20	Vulnerability of farmlands to erosion
		21	Vulnerability of cultivation facility
		22	Vulnerability of productivity of rice crops
		23	Vulnerability of productivity of apple crops
		24	Vulnerability of productivity of livestock
5	Water management	25	Vulnerability of flood regulation
		26	Vulnerability of water utilization
		27	Vulnerability of water quality
6	Fisheries	28	Vulnerability of fisheries due to change in water temperature
7	Disaster	29	Vulnerability of infrastructure to floods
		30	Vulnerability of infrastructure to heat waves
		31	Vulnerability of infrastructure to heavy snow
		32	Vulnerability of infrastructure to sea level increase

Institute, and the Ministry of Environment. Data on the water management and disaster fields were provided by the Korea Water Resources Corporation and Korea Ministry of Land, Infrastructure, and Transport. Data relevant to the health field were established by using data from the Korea Ministry of Health and Welfare and the National Health Insurance Service. Information on the agriculture field was constructed by using data from the Korea Rural Community Corporation. Fishery field data were obtained from the Korea Ministry of Oceans and Fisheries. Data for adaptation capacity were provided by the National Statistical Office.

The vulnerability assessment processes included several variables, each with different scales. The objective of the vulnerability assessment was to compare relative

Table 2 Method of setting weights

Item	Variable	First weights	Sum of weights	Specific variable	Second weights	Sum of weights
Item A	Climate exposure	FWce	1	Variable a	SWa	1
				Variable b	SWb	
				Variable c	SWc	
				Variable d	SWd	
	Sensitivity	FWs		Variable e	SWe	1
				Variable f	SWf	
				Variable g	SWg	
				Variable h	SWh	
	Adaptation capacity	FWac		Variable i	SWi	1
				Variable j	SWj	
				Variable k	SWk	
				Variable l	SWl	

Table 3 Variables and weights for landslide vulnerability due to heavy rainfall

Item	Variable	First Weight	Specific variable	Second weight
Landslide due to heavy rainfall	Climate exposure	0.40	Number of dates with more than 80 mm of precipitation	0.24
			Daily maximum precipitation (mm)	0.39
			Summer daily precipitation (mm)	0.21
			Five days of maximum precipitation (mm)	0.16
	Sensitivity	0.37	Average slope of regional forest (°)	0.35
			Area of coniferous forest (ha)	0.24
			Average height of regional forest (m)	0.12
			Denuded area (ha)	0.29
	Adaptation capacity	0.23	Government officials per population	0.20
			Area of preventing forest destruction (ha)	0.24
			GRDP (trillion won)	0.18
			Financial independence (%)	0.38

vulnerabilities. Therefore, this study normalized all of the variables to make the vulnerability indices comparable. The selected variables were standardized by

$$Z_{i,j} = \frac{X_{i,j} - X_i^{\mathrm{MIN}}}{X_i^{\mathrm{MAX}} - X_i^{\mathrm{MIN}}}, \quad (1)$$

where $Z_{i,j}$ is the standardized value of the variable i (climate exposure, sensitivity, or adaptation capacity) of item j; $X_{i,j}$ is the unstandardized value of variable i of item j; X_i^{MAX} is the maximum value of the variable for item j; and X_i^{MIN} is the minimum value of the variable for item j. The scale of the variables was normalized from 0 to 1 by Eq. (1). In addition, the vulnerability indices were normalized considering the vulnerability values of present and future years according to climate change scenarios. A similar standardization method was used for the Human Development Index (McGillivray and White 1993; Noorbakhsh 1998).

Numerous methods use climate exposure (CE), sensitivity (*S*), and adaptation capacity (AC) to assess vulnerability, which may differ according to the scale of analysis, property of field, and availability of data (Turner et al. 2003; Sullivan and Meigh 2007). This study used Eqs. (2) and (3) for assessing vulnerability (Adger and Vincent 2005; Allison et al. 2009). In Eq. (2), FWce, FWs, and FWac are the first weights for the variables, and CE_n, S_n, and AC_n are the normalized CE, S, and AC. In Eq. (3), SW is the second weight for each variable, and the variable is normalized from 0 to 1.

$$V = \mathrm{FWce} \times \mathrm{CE}_n + \mathrm{FW}_n \times S_n - \mathrm{FWac} \times \mathrm{AC}_n \tag{2}$$

$$\begin{aligned} \mathrm{CE} &= \sum (\mathrm{SW}_i \times \mathrm{Variable}_i) \\ S &= \sum (\mathrm{SW}_i \times \mathrm{Variable}_i) \\ \mathrm{AC} &= \sum (\mathrm{SW}_i \times \mathrm{Variable}_i) \end{aligned} \tag{3}$$

The first and second weights were applied to the equations to reflect the relative importance of the variables. This simple equation has advantages for clarifying the impacts of the weights and facilitating the understanding of decision makers. Additionally, municipalities can easily adjust the equation when more detailed data are needed for vulnerability assessment.

The most vulnerable case has the highest value in the equations and the lowest possible level of adaptation capacity; the least vulnerable cases have the lowest value. The highest and lowest values differed among items. However, because this study focused only on relative levels of vulnerability, such differences did not affect the results. In addition, operators should be aware that although the vulnerability index is expressed as a quantitative value, it has a qualitative meaning according to the properties of the vulnerability assessment.

2.3 Methods of identifying key vulnerable areas

The objective of the second part is this study was to create key vulnerability maps for identifying highly vulnerable municipalities and analyzing their properties. The vulnerability level was classified into five grades according to the vulnerability index of municipalities. The first grade, which represents the highest vulnerability, had a normalized vulnerability value of 0.8–1 (Fig. 1).

After classification of the vulnerability grades, the first-grade maps were synthesized on the basis of each field. This was done for two reasons. The first is that the government considers fields and municipalities when allocating financial resources, and the second is that it is difficult to show every map in this study owing to space limitations. Synthesized maps were made for the seven fields. Future maps considered only the changes in climate exposure to determine the effects of climate change. As previously stated, sensitivity and adaptation capacity data were not available for future conditions, and the existing data were not evaluated because of their large uncertainties.

The key vulnerability map was created by synthesizing the seven first-grade maps for each field; thus, the map included the first-grade areas of 32 items. The 232 municipalities were classified into five grades, considering the number of the first grade of each item. The first grade of the key vulnerability map included the most vulnerable areas, and the fifth grade included the least vulnerable areas. The key vulnerability map was created to describe the most vulnerable areas, considering whole fields in the ROK. Therefore, this map could be utilized as an important basis for the allocation of financial resources.

3 Results and discussion

3.1 Vulnerability assessment for representative item

The results were too numerous to include comprehensively in this paper. Therefore, a representative item, "landslides due to heavy rainfall," in the forest field was selected to show a specific result of the vulnerability assessment. Table 3 shows the variables and weights of the landslide item. Information on the variables and weights for the other 31 items is included in Appendix. Each of the three variables—climate exposure, sensitivity, and adaptation capacity—consists of four specific variables (Table 3). A map of each of the three main variables was created by multiplying the standardized variables and weights. The vulnerability map was derived from the three maps by using Eqs. (2) and (3).

Figure 2 shows the result of the vulnerability assessment for landslides due to heavy rainfall in the present years (2000–2010). Four maps, each for climate exposure, sensitivity, adaptation capacity, and vulnerability, included approximately 232 municipalities. The map legends are classified into five grades to show the relative levels of vulnerability. The highest grade includes municipalities with values of 0.8–1; the lowest grade includes those with values of 0–0.2. The five grades were categorized as highest, high, medium, low, and lowest in reference to a previous study (o'Brien et al. 2004).

The climate exposure map was derived by using four specific variables and the weights of each variable (Table 2). Daily maximum precipitation had the highest weight among the variables; therefore, the distribution of the climate exposure map is strongly affected by the daily maximum precipitation. The northwestern and southeastern regions of the ROK showed high climate exposure (Kil et al. 2015).

The sensitivity map also considered four specific variables and weights (Table 3); the slope of the forests, area covered by coniferous trees, and denuded area were important standards for assessing the sensitivity. The sensitivity was affected by the area of forests in municipalities because most of the variables are related to forests. In particular, the eastern region of the ROK is steeper and has higher altitudes than the western region. Thus, the western region showed a high sensitivity value on the map.

The adaptation capacity map was calculated by using four specific variables and their weights (Table 3). The variables were focused on the ability of municipalities to address landslides. Financial independence and areas resistant to forest destruction were important variables in reacting to landslides. Moreover, the adaptation capacity was higher in the northwestern and southeastern regions than those in other areas.

The vulnerability map was derived from climate exposure, sensitivity, and adaptation capacity (Eq. 2). Vulnerable areas had high climate exposure, high sensitivity, and low adaptation capacity. Therefore, areas with high adaptation capacity could still have low

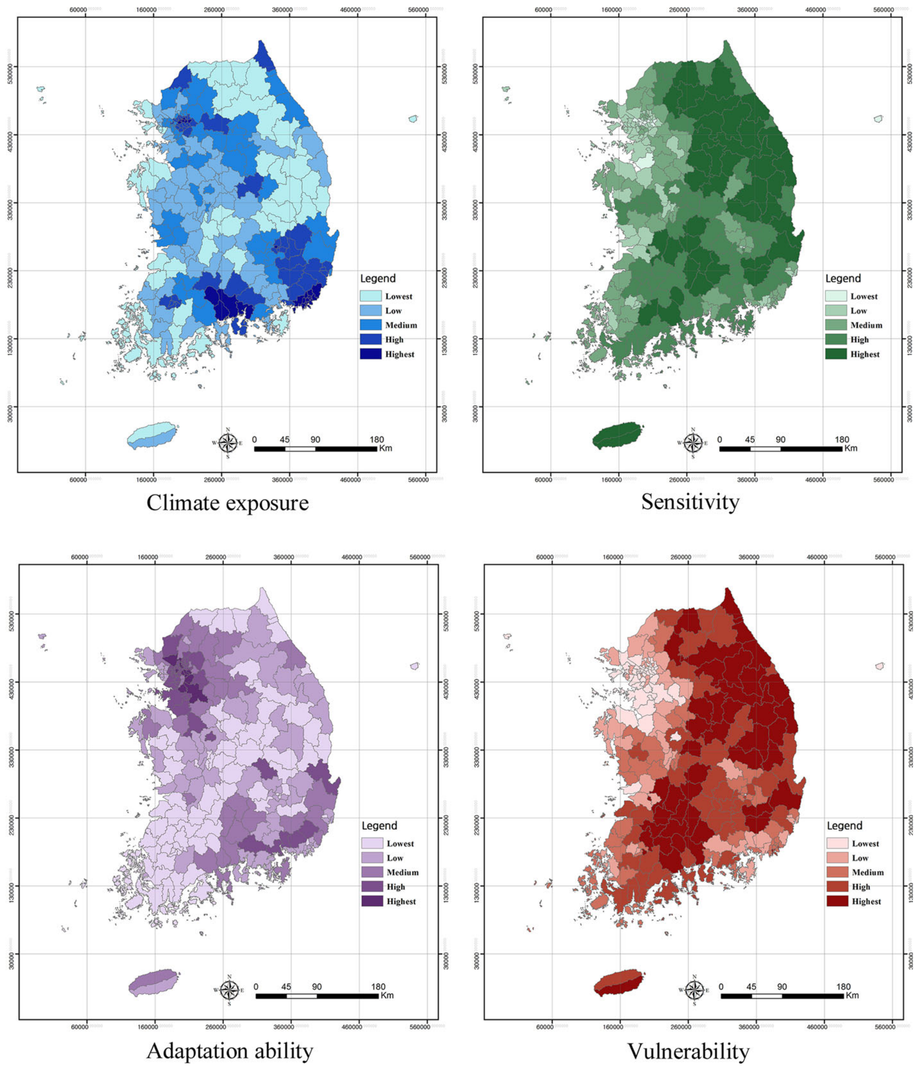

Fig. 2 Maps of vulnerability to landslides due to heavy rainfall

vulnerability (o'Brien et al. 2004). In the vulnerability map, the northwestern and south-eastern regions showed low vulnerability because they had a high adaptation capacity.

3.2 Validation for representative item

The validation process was conducted for the vulnerability of landslides due to heavy rainfall by comparing the vulnerability index with records of past landslide occurrences. The records contain landslide occurrence areas and the number of landslide occurrences in the 232 municipalities for the years 2001–2010. Table 4 shows an example of 2006 landslide occurrence data for the representative province, Gangwon-do, which includes 18

Table 4 Example of landslide occurrence records and vulnerability index

Province	Name of municipality	Area of landslide (ha) (Temporal scope: 2006)	Number of occurrences	Vulnerability index
Gangwon-do	Chuncheon-si	9.88	148	0.80
	Wonju-gun	2.60	15	0.72
	Gangneung-gun	7.20	116	0.77
	Donghae-si	0	0	0.72
	Taebaek-si	1.80	12	0.68
	Sokcho-si	0	0	0.63
	Samcheok-si	2.50	11	0.73
	Hongcheon-gun	11.00	137	0.76
	Hoengseong-gun	27.44	205	0.82
	Yeongwol-gun	3.80	57	0.80
	Pyeongchang-gun	279.41	2269	0.83
	Jeongseon-gun	7.3	93	0.74
	Cheorwon-gun	0	0	0.59
	Hwacheon-gun	2.00	50	0.67
	Yanggu-gun	24.66	224	0.81
	Inje-gun	106.20	801	0.81
	Goseong-gun	0	0	0.61
	Yangyang-gun	3.70	79	0.78

Source: Gangwon-do, 2006

municipalities, and 81.7 % forestland. These characteristics indicate that Gangwon-do is highly vulnerable to landslides.

The Pearson correlation analysis for the 232 municipalities revealed a correlation coefficient for the vulnerability index and landslide occurrence areas (ha) of 0.594, significant at the 0.01 level according to the two-tailed test. The correlation coefficient of the vulnerability index and landslide number (counts) was 0.457, significant at the 0.05 level also according to the two-tailed test. The vulnerability index for landslides was considered to be reliable based on a high correlation with independent data. Landslide occurrence data for other areas was not available for security reasons.

This study also conducted Pearson correlation analysis as validation for other items using independent data, including the frequency of events, damage from events, and monitoring information. In addition, correlation of vulnerability indices and independent data was made by Pearson analysis. The correlation coefficient and significance were checked to assess the reliability of the vulnerability indices. Every item showed reliable results upon conducting a feedback process considering the correlation coefficient with independent data.

The results and data related to validation were too lengthy to include in this paper. Thus, to provide detailed information, Table 5 shows the data type and source for validation. Each field required various data types for validation of the vulnerability index. In many cases, alternative data were used because it was difficult to find optimal data for all items. For example, the water management field compared the vulnerability of the water quality with the budget of purifying the contaminated water in each municipality.

Table 5 Validation data for vulnerability items

Fields	No.	Item	Data type for validation (unit)	Source of data
Health	1	Health vulnerability due to floods	Mortality rates due to floods, morbidity of waterborne epidemics (ratio)	National Emergency Management Agency, Ministry of Health and Welfare
	2	Health vulnerability due to typhoons	Mortality rates due to typhoons (ratio)	National Emergency Management Agency, Ministry of Health and Welfare
	3	Health vulnerability due to heat waves	Mortality rates due to heat waves, records of emergency room visits during heat waves (ratio)	Ministry of Health and Welfare, National Emergency Department Information System
	4	Health vulnerability due to cold waves	Mortality rates due to cold waves, records of emergency room visits during cold waves (ratio)	Ministry of Health and Welfare, National Emergency Department Information System
	5	Health vulnerability due to ozone enhancement	Records of emergency room visits during ozone warning (ratio)	Ministry of Health and Welfare, National Emergency Department Information System
	6	Health vulnerability due to fine dust	Morbidity of lung disease and respiratory disease (ratio)	Ministry of Health and Welfare
	7	Health vulnerability due to air pollutants	Morbidity of lung disease and respiratory disease, records of allergy patients (ratio)	Ministry of Health and Welfare
	8	Health vulnerability due to infectious diseases	Morbidity of infectious diseases (ratio)	Ministry of Health and Welfare, National Health Insurance Corporation
	9	Health vulnerability by waterborne epidemics	Morbidity of waterborne epidemics (ratio)	Ministry of Health and Welfare, National Health Insurance Corporation
Forests	10	Landslides due to heavy rainfall	Landslide occurrence records (area, number)	Korea Forest Service, National Emergency Management Agency
	11	Vulnerability of trails due to landslides	Landslide occurrence records, restoration records for forest trails (area)	Korea Forest Service, Korea National Park Service
	12	Vulnerability to forest fire	Forest fire records (area, number)	Korea Forest Service, National Emergency Management Agency
	13	Vulnerability of pine trees to disease and pests	Records of disease and pests in pine trees (area)	Korea Forest Service, Korea National Park Service

Table 5 continued

Fields	No.	Item	Data type for validation (unit)	Source of data
	14	Vulnerability of pine trees to pine fungi	Records of damage due to pine fungi (area)	Korea Forest Service, Korea National Park Service
	15	Vulnerability of forest productivity	Gross primary production, net primary production data (number)	Korea Forest Service, Korea Forest Research Institute
	16	Vulnerability of vegetation due to drought	Records of dead trees due to drought (number)	Korea Forest Service
Ecosystem	17	Vulnerability of vegetation growth	Age class of vegetation, gross primary production, net primary production data (number)	Korea Forest Service, Korea Forest Research Institute
	18	Vulnerability of insects	Records of damage to trees due to insects (area)	Korea Forest Service, Korea Forest Research Institute, Korea National Park Service
	19	Vulnerability of management of protected areas	Damage of protected areas due to extreme weather (cost)	Korea National Park Service, Ministry of Environment
Agriculture	20	Vulnerability of farmlands to erosion	Damage of farmlands due to erosion (area)	Ministry of Agriculture, Food and Rural Affairs
	21	Vulnerability of cultivation facility	Damage of cultivation facility due to extreme weather (cost)	Ministry of Agriculture, Food and Rural Affairs, National Emergency Management Agency
	22	Vulnerability of productivity of rice crop	Decrease in rice productivity due to extreme weather (yield)	Ministry of Agriculture, Food and Rural Affairs
	23	Vulnerability of productivity of apple crop	Decrease in apple productivity due to extreme weather (yield)	Ministry of Agriculture, Food and Rural Affairs
	24	Vulnerability of productivity of livestock	Decrease in livestock productivity due to extreme weather, decrease in dairy productivity due to climate change (yield)	Ministry of Agriculture, Food and Rural Affairs
Water management	25	Vulnerability of flood regulation	Records of flood inundation (area)	Korea Water Resources Corporation, Ministry of Land, Infrastructure and Transport
	26	Vulnerability of water utilization	Records of water supply decrease due to drought (amount)	Korea Water Resources Corporation, Ministry of Land, Infrastructure and Transport
	27	Vulnerability of water quality	Budget for water purification (cost)	Korea Water Resources Corporation, Ministry of Land, Infrastructure and Transport

Table 5 continued

Fields	No.	Item	Data type for validation (unit)	Source of data
Fisheries	28	Vulnerability of fisheries due to change in water temperature	Decrease in fishery productivity due to water temperature change (yield)	Ministry of Maritime Affairs and Fisheries, National Fisheries Research and Development Institute
Disaster	29	Vulnerability of infrastructure to floods	Damage of infrastructure due to floods (area)	Ministry of Land, Infrastructure and Transport, National Emergency Management Agency
	30	Vulnerability of infrastructure to heat waves	Damage of infrastructure during heat waves (cost)	Ministry of Land, Infrastructure and Transport, National Emergency Management Agency
	31	Vulnerability of infrastructure to heavy snow	Damage of infrastructure due to heavy snow (cost)	Ministry of Land, Infrastructure and Transport, National Emergency Management Agency
	32	Vulnerability of infrastructure to sea level increase	Damage of infrastructure due to sea level increase (area)	Ministry of Land, Infrastructure and Transport, Korea industrial complex corporation

3.3 Vulnerability maps based on field scale

The first-grade municipalities of each item were synthesized for each field, and the resultant synthesized vulnerability map provides information about highly vulnerable areas in each field. Each field unit has an important indication for the establishment of adaptation plans and the allocation of financial resources because when establishing the climate change adaptation strategy, the government separated these seven fields considering the characteristics of government ministry. These maps were created for the present years (2001–2010) and future years (2046–2055; RCP 8.5) to compare changes in the first-grade areas resulting from climate change (Fig. 3).

The health field consists of various items directly or indirectly related to temperature and rainfall. Most municipalities showed values of 0–2 (first grade) for the present years. However, approximately 10 % of the 232 municipalities showed high vulnerability to four–eight items of the health field. These vulnerable municipalities were separated into the following four types according to the property of vulnerability: (a) the climate exposure is higher than that in other municipalities, (b) the sensitivity is higher than that in other municipalities, (c) the adaptation capacity is lower than that in other municipalities, and (d) a combination of (a), (b), and (c). For example, Busan, which is located in the southern area, showed type (d) vulnerability.

Future vulnerability was assessed by using only the change in climate conditions. That is, the results were obtained by simulating future vulnerability using the present conditions of sensitivity and adaptation capacity. Items related to rainfall showed much higher vulnerability than that in the present years. The health vulnerability of Seoul, which is the capital of the ROK, showed a particularly dramatic increase in future climate conditions, which demonstrates that the present condition of the adaptation capacity may not be sufficient in the future. Moreover, Busan showed a continuously high vulnerability in the present and future years, which shows that improvement in the adaptation capacity is very important for type (d) municipalities for reducing climate impacts.

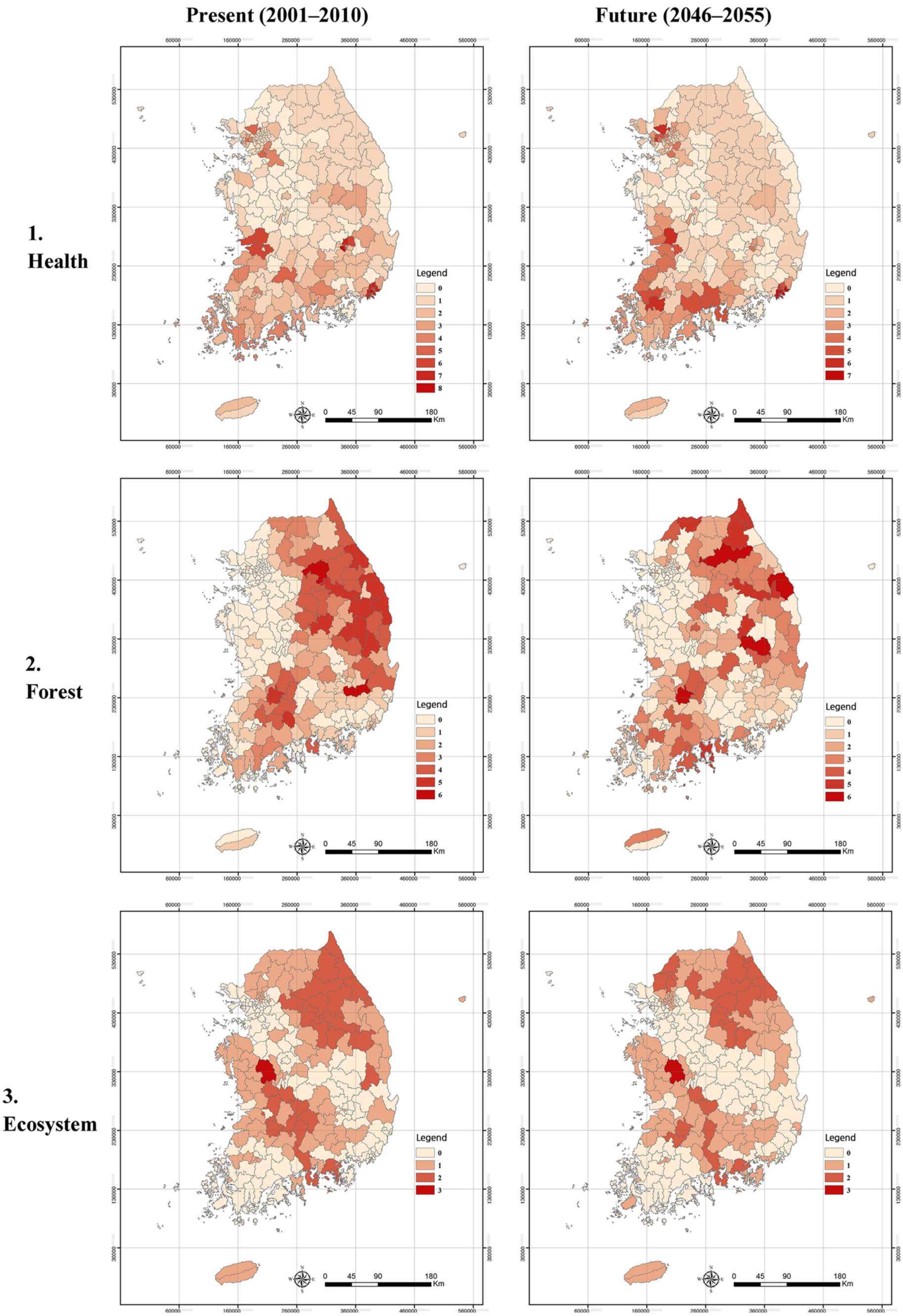

Fig. 3 Distribution of the first-grade areas for the seven fields in the present and future

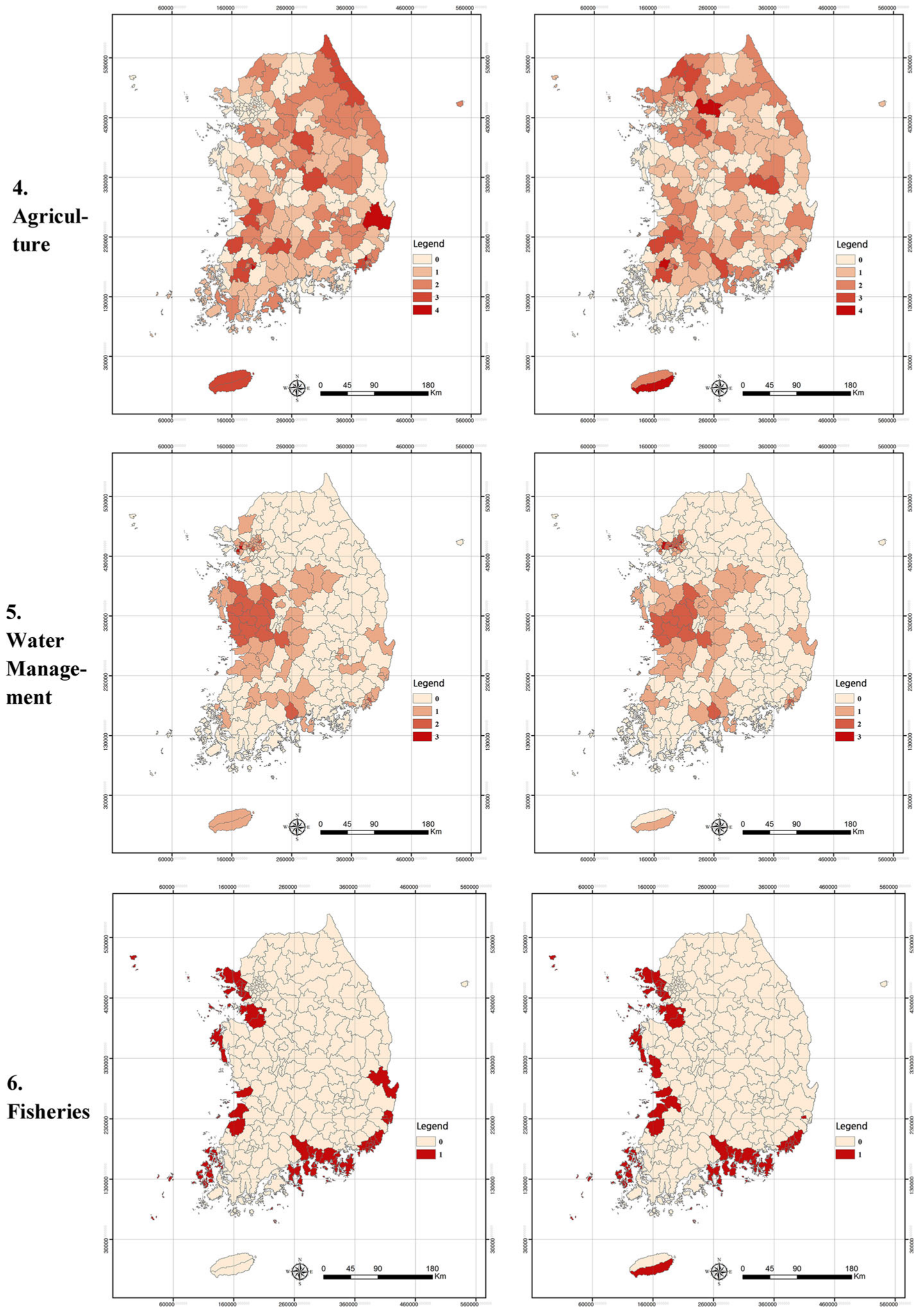

Fig. 3 continued

7. Disaster

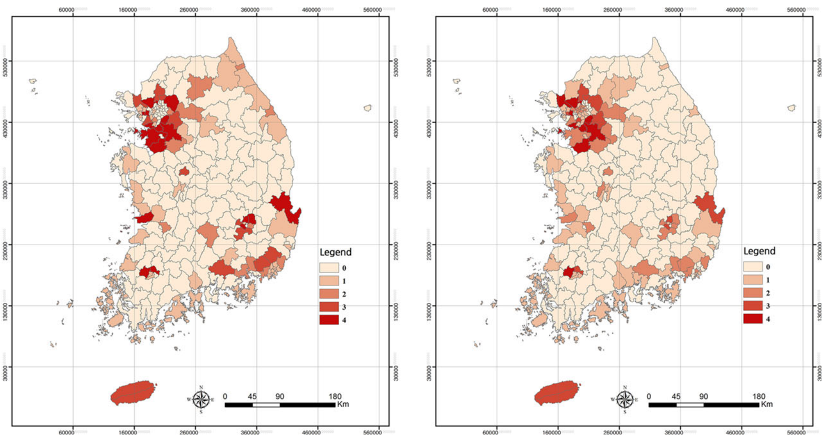

Fig. 3 continued

The forest field includes seven items that are affected by rainfall and temperature, and its vulnerability is strongly affected by areas of forest in the municipality. The eastern and southwestern areas of the ROK have more forestland than the other areas and therefore showed many first-grade vulnerability items in the present years. These highly vulnerable areas of the forest field were classified as type (a) vulnerability; therefore, these areas should extend their adaptation capacities to reduce damage related to forests.

The future vulnerability of the forest was increased for items related to rainfall such as landslide, vulnerability of trails, drought, and forest fire. The reason for the increase in some eastern areas that showed much higher vulnerability than that in the present years was determined to be the increased prevalence of extreme weather such as heavy rainfall and severe drought.

The ecosystem field had three items for vulnerability assessment, all of which were related to long-term changes in rainfall and temperature. The areas with high ecological value were determined to have higher vulnerability than other area and were classified as type (a) vulnerability. The eastern and southwestern areas had many first-grade vulnerable areas, similar to that in the forest field. The vulnerability was more highly affected by sensitivity variables than climate exposure and adaptation capacity. The distribution of first-grade areas did not change significantly in the future because the sensitivity is more important than climate conditions for the ecosystem field.

Five items were included in the agriculture field. Productivity of rice, apples, and livestock was related to gradual changes in rainfall and temperature. The other two items, erosion of farmlands and damage to cultivation facility, were related to extreme weather such as heavy rainfall. The first-grade areas of the agriculture field were classified as type (d) vulnerability. Thus, the items were similarly affected by all three characteristics of climate exposure, sensitivity, and adaptation capacity.

The water management field included three items. Flood and water utilization were related mainly to rainfall variables, and water quality was related to temperature and rainfall. However, the adaptation capacity is a more important factor than climate exposure for assessing vulnerability in this field. The vulnerable municipalities of water management were classified as type (c) vulnerability.

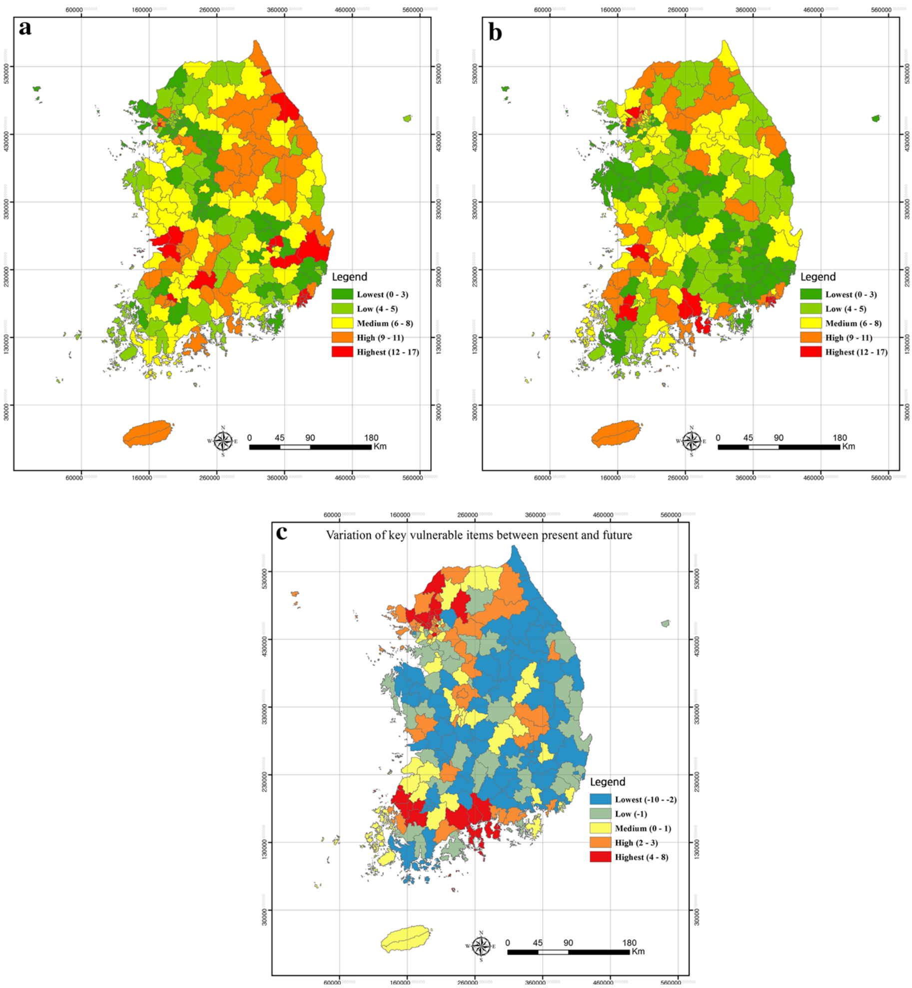

Fig. 4 Key vulnerability areas of the seven fields

The first-grade areas are concentrated in the capital area and western areas at the present. The capital area vulnerability is due to its high population density, and the western areas are vulnerable to water management because most of the rivers are located in the eastern areas of the ROK. The future vulnerability did not differ significantly from that of the present according to the important role of the adaptation capacity.

The fisheries field focused on assessing the negative effects of the increase in water temperature, and the analysis targets were limited to municipalities near the sea. The western and southern areas showed higher vulnerability than other areas. Climate exposure and sensitivity are important factors for this field; therefore, it was categorized as both (a) and (b) types. The future vulnerability showed a distribution similar to that of the present.

The disaster field focused on damages to infrastructure, and all of the items were strongly affected by climate exposure and sensitivity, and the vulnerable areas were classified as (a) and (b) vulnerability types. The capital area showed many first-grade items because of its greater infrastructure relative to other municipalities. Some municipalities in the southeastern areas showed high vulnerability due to sensitivity variables related to areas of infrastructure, and the future vulnerability was similar to that of the present. These results indicate that sensitivity is a more important factor than climate exposure in the disaster field.

3.4 Key vulnerable areas of the seven fields

The first-grade maps of each field were aggregated as synthesis maps to describe the most vulnerable areas of the present and future years (Fig. 4a, b) in order to support the government program. The government has the authority to allocate financial resources for establishing adaptation plans. Government decision makers can utilize these synthesis maps to determine the most urgent needs of municipalities in the establishment of adaptation plans.

The classification of the first-grade areas in the synthesis map was used to compare the relative vulnerability among municipalities. The highest grade includes 12–17 items assessed as first grade (Fig. 4a, b). The northeastern, southwestern, and southeastern areas had the highest grade of municipalities at the present including 9–11 items distributed in the northeastern and southwestern areas (Fig. 4a).

The main reasons for these high-grade areas are the health, forest, agriculture, and disaster fields, which showed distributions similar to those in the present first-grade map. Highly vulnerable municipalities that were assessed with the highest and high grades showed all vulnerability types, although type (c) was the most common. Moreover, the municipalities of type (c) vulnerability showed the highest grade in the future synthesis map (Fig. 4b). Thus, the municipalities that had a high climate exposure and sensitivity and low adaptation capacity showed the greatest vulnerability to climate change impacts.

The variation map shows different values of a number of first-grade items between the present and future years (Fig. 4c). This map helps to easily identify municipalities in which first-grade items are abruptly increased in the future. The highest grade municipalities appeared in the northwestern and southwestern areas of the ROK, where the climate exposure increased in the future, and the adaptation capacity was relatively low. The lowest grade municipalities showed highest or high grades at the present.

4 Conclusions

This study used a combination of quantitative and qualitative methods for vulnerability assessment of 32 items in 7 fields in 232 municipalities. The suggested framework can reduce the subjectivity and clarify the assessment process because the variables, weights, and integration method are explicit ("Appendix"). Therefore, all operators can obtain the same results as those reported in this study, and readers can understand the exact results and methods used (Jeffers 2013; Wang et al. 2013). Equations (2) and (3) reflect the direct impact of weights on variables by following the basic concept of vulnerability (Adger and Vincent 2005).

Setting priorities and allocating resources are the most difficult processes for the government in adapting to climate change (Allison et al. 2009; Tran et al. 2010; IPCC 2012;

Frazier et al. 2014), and identification of the most urgent municipalities poses further challenges. Thus, information about the priority of vulnerability is helpful for allocating financial resources to highly threatened municipalities. In this context, the present study can provide useful knowledge and serve as an important basis in establishing adaptation plans. By using the results of this vulnerability assessment, decision makers can clearly identify vulnerable areas, vulnerable fields of a particular municipality, and the reason for the vulnerability. Moreover, this study can be utilized as a reference or a basic tool for more specific vulnerability assessments than those on the national scale.

Readers should consider that the vulnerability indices cannot provide objective values or absolute vulnerabilities. The Delphi method, one of the important methods used in this study, is an effective tool for reaching a consensus value; however, it cannot provide objective weights. Additionally, only the climate conditions are changed in the future vulnerability assessment even though damage can have a significantly stronger dependence on other conditions such as land surface modification (Bonachea et al. 2010; Bruschi et al. 2013). This limitation is attributed to the lack of future environmental and socioeconomic data. Although several studies have predicted changes in socioeconomic information for the ROK, the results have not been validated and have a large amount of uncertainty (Lee et al. 2007; Park et al. 2007; Kim et al. 2013; Ryu et al. 2014). Therefore, the government of the ROK analyzed future vulnerability by using only future climate data. This method has merit in identifying negative and positive effects according to changes in climate condition (Kim et al. 2015). However, improvement is needed in further studies to obtain more reliable results.

Acknowledgments This work was supported by the Climate Change Vulnerability Assessment of Local Government for Establishment of Adaptation Plan project (Korea Environment Institute, National Institute Environmental Research), the 2015 BK 21 Plus Project (Seoul National University Interdisciplinary Program in Landscape Architecture, a global leadership program toward innovative green infrastructure), the Development of Economic Assessment Technique for Climate Change Impact and Adaptation Considering Uncertainties (Korea Ministry of Environment, Project No. 2014001310010), the Development of Climate Change Adaptation, Management Techniques, and Supportive System (Korea Ministry of Environment, Project No. 416-111-014), the Development of Climate Change Policy Supporting Model for Impact Assessment and Adaptation Planning (Korea Ministry of Environment, Project No. 2014001310005).

Appendix

See Table 6.

Table 6 Variables and weights for seven fields

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
1. Health							
1	Health vulnerability due to floods	Climate exposure	1	0.50	Daily maximum precipitation (mm)	1	0.30
					Number of dates with over 80 mm of precipitation (times)		0.15
					Flooding area (ha)		0.55
		Sensitivity		0.23	Population over 65 years (persons)	1	0.07
					Population under 13 years (persons)		0.07
					Rate of senior citizen who lives alone (%)		0.12
					Rate of basic living security received people (%)		0.11
					Lowland area under 10 m (km^2)		0.07
					The number of households located in lowland of <10 m height above sea level (number)		0.14
					The number of flood victims (persons)		0.31
					The number of waterborne disease (persons)		0.11
		Adaptation capacity		0.27	GRDP (million KRW)	1	0.23
					Financial independence (%)		0.30
					Health insurance coverage population ratio (%)		0.11
					Public health labor per ten thousand people (persons)		0.11
					The number of emergency medical institution per million people (place)		0.11
					GRDP of healthcare services and social welfare services sector (million KRW)		0.14

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
2	Health vulnerability due to typhoons	Climate exposure	1	0.50	Daily maximum precipitation (mm)	1	0.27
					Number of dates with over 80 mm of precipitation (times)		0.25
					Number of dates with over 14 m/s of daily maximum wind speed (times)		0.48
		Sensitivity		0.23	Population over 65 years (persons)	1	0.10
					Population under 13 years (persons)		0.10
					Rate of senior citizen who lives alone (%)		0.18
					Rate of basic living security received people (%)		0.14
					Lowland area under 10 m (km^2)		0.14
					The number of households located in lowland of <10 m height above sea level (number)		0.20
					The number of waterborne disease (persons)		0.14
		Adaptation capacity		0.27	GRDP (million KRW)	1	0.23
					Financial independence (%)		0.28
					Health insurance coverage population ratio (%)		0.11
					Public health labor per ten thousand people (persons)		0.12
					The number of emergency medical institution per million people (place)		0.14
					GRDP of healthcare services and social welfare services sector (million KRW)		0.12

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
3	Health vulnerability due to heat waves	Climate exposure	1	0.50	Daily maximum precipitation (mm)	1	0.11
					Number of dates with over 33 °C of daily maximum temperature (times)		0.26
					Number of dates with over 25 °C of daily minimum temperature (times)		0.10
					Wind chill (°C)		0.13
					Discomfort index (–)		0.15
					Heat wave index (–)		0.15
					Relative humidity (%)		0.10
		Sensitivity		0.25	Population over 65 years (persons)	1	0.20
					Population under 13 years (persons)		0.10
					Rate of senior citizen who lives alone (%)		0.20
					Rate of basic living security received people (%)		0.10
					Number of death due to cardiovascular disease (persons)		0.16
					Number of death due to heat stroke (persons)		0.24
		Adaptation capacity		0.25	GRDP (million KRW)	1	0.21
					Financial independence (%)		0.21
					Health insurance coverage population ratio (%)		0.10
					Public health labor per ten thousand people (persons)		0.16
					The number of emergency medical institution per million people (place)		0.16
					GRDP of healthcare services and social welfare services sector (million KRW)		0.16

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
4	Health vulnerability due to cold waves	Climate exposure	1	0.50	Number of dates with daily minimum temperature below zero (times)	1	0.24
					Number of dates with daily average temperature below zero (times)		0.36
					Maximum dates of continuous no rainy day (days)		0.10
					Number of dates with over 14 m/s of daily maximum wind speed (times)		0.14
					Snowfall (cm)		0.16
		Sensitivity		0.27	Population over 65 years (persons)	1	0.15
					Population under 13 years (persons)		0.08
					Rate of senior citizen who lives alone (%)		0.24
					Rate of basic living security received people (%)		0.18
					Number of inpatient of a respiratory disease (persons)		0.19
					Number of death due to cerebrovascular disease (persons)		0.20
		Adaptation capacity		0.23	GRDP (million KRW)	1	0.18
					Financial independence (%)		0.26
					Health insurance coverage population ratio (%)		0.09
					Public health labor per ten thousand people (persons)		0.16
					The number of emergency medical institution per million people (place)		0.15
					GRDP of healthcare services and social welfare services sector (million KRW)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
5	Health vulnerability due to ozone enhancement	Climate exposure	1	0.48	Daily maximum precipitation (mm)	1	0.14
					Number of dates with over 100 ppb of the ozone concentration (times)		0.31
					Ozone alert days (days)		0.29
					Number of dates with over 60 ppb/8 h of the cumulative ozone concentration (times)		0.26
		Sensitivity		0.27	Population over 65 years (persons)	1	0.16
					Population under 13 years (persons)		0.13
					Rate of senior citizen who lives alone (%)		0.15
					Rate of basic living security received people (%)		0.13
					Number of inpatient of a respiratory disease (persons)		0.25
					Number of death due to cerebrovascular disease (persons)		0.18
		Adaptation capacity		0.25	GRDP (million KRW)	1	0.17
					Financial independence (%)		0.25
					Health insurance coverage population ratio (%)		0.11
					Public health labor per ten thousand people (persons)		0.16
					The number of emergency medical institution per million people (place)		0.16
					GRDP of healthcare services and social welfare services sector (million KRW)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
6	Health vulnerability due to fine dust	Climate exposure	1	0.50	Daily maximum precipitation (mm)	1	0.20
					Concentration of fine dust ($\mu g/m^3$)		0.30
					Number of dates with over 100 $\mu g/m^3$ of the hourly concentration of fine dust (times)		0.50
		Sensitivity		0.28	Population over 65 years (persons)	1	0.14
					Population under 13 years (persons)		0.16
					Rate of senior citizen who lives alone (%)		0.14
					Rate of basic living security received people (%)		0.14
					Number of inpatient of a respiratory disease (persons)		0.26
					Number of death due to cerebrovascular disease (persons)		0.16
		Adaptation capacity		0.22	GRDP (million KRW)	1	0.18
					Financial independence (%)		0.26
					Health insurance coverage population ratio (%)		0.11
					Public health labor per ten thousand people (persons)		0.15
					The number of emergency medical institution per million people (place)		0.15
					GRDP of healthcare services and social welfare services sector (million KRW)		0.10

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
7	Health vulnerability due to air pollutants	Climate exposure	1	0.50	Daily maximum precipitation (mm)	1	0.10
					CO (except warming in residential sector) (kg)		0.14
					CO (in industrial sector) (kg)		0.16
					Sox (except warming in residential sector) (kg)		0.14
					Sox (in industrial sector) (kg)		0.16
					NOx (except warming in residential sector) (kg)		0.14
					NOx (in industrial sector) (kg)		0.16
		Sensitivity		0.23	Population over 65 years (persons)	1	0.14
					Population under 13 years (persons)		0.15
					Rate of senior citizen who lives alone (%)		0.14
					Rate of basic living security received people (%)		0.14
					Number of inpatient of a respiratory disease (persons)		0.25
					Number of death due to cerebrovascular disease (persons)		0.18
		Adaptation capacity		0.27	GRDP (million KRW)	1	0.16
					Financial independence (%)		0.24
					Health insurance coverage population ratio (%)		0.13
					Public health labor per ten thousand people (persons)		0.16
					The number of emergency medical institution per million people (place)		0.15
					GRDP of healthcare services and social welfare services sector (million KRW)		0.16

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
8	Health vulnerability due to infectious diseases	Climate exposure	1	0.47	Number of dates with over 33 °C of daily maximum temperature (times)	1	0.22
					Number of dates with over 25 °C of daily minimum temperature (times)		0.30
					Daily maximum precipitation (mm)		0.20
					Number of dates with over 80 mm of precipitation (times)		0.28
		Sensitivity		0.30	Population over 65 years (persons)	1	0.13
					Population under 13 years (persons)		0.13
					Rate of senior citizen who lives alone (%)		0.13
					Rate of basic living security received people (%)		0.10
					Annual average number of malaria pathogenesis (persons)		0.26
					Annual average number of Riclieltsia tsuisugamushi pathogenesis (persons)		0.25
		Adaptation capacity		0.23	GRDP (million KRW)	1	0.18
					Financial independence (%)		0.23
					Health insurance coverage population ratio (%)		0.11
					Public health labor per ten thousand people (persons)		0.15
					The number of emergency medical institution per million people (place)		0.18
					GRDP of healthcare services and social welfare services sector (million KRW)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
9	Health vulnerability by waterborne epidemics	Climate exposure	1	0.47	Number of dates with over 33 °C of daily maximum temperature (times)	1	0.25
					Number of dates with over 25 °C of daily minimum temperature (times)		0.25
					Daily maximum precipitation (mm)		0.26
					Number of dates with over 80 mm of precipitation (times)		0.24
		Sensitivity		0.30	Population over 65 years (persons)	1	0.14
					Population under 13 years (persons)		0.19
					Rate of senior citizen who lives alone (%)		0.16
					Rate of basic living security received people (%)		0.13
					The number of waterborne disease (persons)		0.38
		Adaptation capacity		0.23	GRDP (million KRW)	1	0.19
					Financial independence (%)		0.25
					Health insurance coverage population ratio (%)		0.11
					Public health labor per ten thousand people (persons)		0.16
					The number of emergency medical institution per million people (place)		0.14
					GRDP of healthcare services and social welfare services sector (million KRW)		0.15
2. Forest							

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
10	Landslides due to heavy rainfall	Climate exposure	1	0.40	Number of dates with over 80 mm of precipitation (times)	1	0.24
					Daily maximum precipitation (mm)		0.39
					Summer daily precipitation (mm)		0.21
					5 days of maximum precipitation (mm)		0.16
		Sensitivity		0.37	Average slope of regional forest (°)	1	0.35
					Area of coniferous forest (ha)		0.24
					Average height of regional forest (m)		0.12
					Denuded area (ha)		0.29
		Adaptation capacity		0.23	Government officials per population (persons)	1	0.20
					Area of preventing forest destruction (ha)		0.24
					GRDP (million KRW)		0.18
					Financial independence (%)		0.38
11	Vulnerability of trails due to landslides	Climate exposure	1	0.38	Number of dates with over 80 mm of precipitation (times)	1	0.26
					Daily maximum precipitation (mm)		0.43
					Precipitation from June to August (mm)		0.20
					Maximum precipitation per 5 days (mm)		0.11
		Sensitivity		0.34	Average slope of regional forest (°)	1	0.30
					Area of coniferous forest (ha)		0.18
					Average attitude of regional forest (m)		0.10
					Area of unstocked land (ha)		0.25
					Distance of Forest trail (m)		0.17
		Adaptation capacity		0.28	Government officials per population (persons)	1	0.20
					Area of preventing forest destruction (ha)		0.25
					GRDP (million KRW)		0.15
					Financial independence (%)		0.40

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
12	Vulnerability to forest fire	Climate exposure	1	0.43	Number of dates with over 33 °C of daily maximum temperature (times)	1	0.11
					Number of dates with over 14 m/s of daily maximum wind speed (times)		0.19
					Number of dates with under 35 % of effective humidity (times)		0.32
					Maximum dates of continuous no rainy day (days)		0.38
		Sensitivity		0.27	Area of coniferous forest (ha)	1	0.19
					Area of broadleaf forest (ha)		0.24
					Area of mixed forest (ha)		0.19
					Soil moisture for 10 cm of underground (m^3/m^3)		−0.11
					Average slope of regional forest (°)		0.14
					Population (persons)		0.13
		Adaptation capacity		0.30	Government officials per population (persons)	1	0.24
					Area of preventing forest destruction (ha)		0.39
					GRDP (million KRW)		0.16
					Financial independence (%)		0.21

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
13	Vulnerability of pine trees to disease and pests	Climate exposure	1	0.37	Precipitation from June to August (mm)	1	0.26
					Daily minimum temperature from June to August (mm)		0.23
					Daily maximum temperature from June to August (mm)		0.31
					Number of dates with over 14 m/s of daily maximum wind speed (times)		0.20
		Sensitivity		0.38	Area of pine forest (m^2)	1	0.49
					Average slope of regional forest (°)		0.12
					Average attitude of regional forest (m)		0.13
					Occurrence area of pest (ha)		0.26
		Adaptation capacity		0.25	Government officials per population (persons)	1	0.21
					Employment for pest control (persons)		0.18
					Area of preventing forest destruction (ha)		0.35
					GRDP (million KRW)		0.11
					Financial independence (%)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
14	Vulnerability of pine trees and pine fungi	Climate exposure	1	0.48	Precipitation from June to August (mm)	1	−0.30
					Daily average temperature from June to August (°C)		0.23
					Precipitation (mm/day)		0.17
					Soil moisture for 10 cm of underground (m^3/m^3)		−0.15
					Maximum dates of continuous no rainy day (days)		0.15
		Sensitivity		0.30	Area of pine forest (m^2)	1	0.47
					Average attitude of regional forest (m)		0.25
					Amounts of forest products (ton)		0.28
		Adaptation capacity		0.22	Government officials per population (persons)	1	0.20
					Area of preventing forest destruction (ha)		0.45
					GRDP (million KRW)		0.20
					Financial independence (%)		0.15
15	Vulnerability of forest productivity	Climate exposure	1	0.44	Precipitation (mm/day)	1	0.21
					Daily maximum temperature (°C)		0.19
					Daily minimum temperature (°C)		0.19
					Maximum dates of continuous no rainy day (days)		0.41
		Sensitivity		0.28	Area of coniferous forest (ha)	1	0.40
					Area of broadleaf forest (ha)		0.35
					Area of mixed forest (ha)		0.25
		Adaptation capacity		0.28	Government officials per population (persons)	1	0.15
					Area of preventing forest destruction (ha)		0.30
					Area of forest which is applied nature rest year policy (m^2)		0.16
					Area of conservation for natural forest (ha)		0.15
					Financial independence (%)		0.10
					GRDP (million KRW)		0.14

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
16	Vulnerability of vegetation due to drought	Climate exposure	1	0.45	Precipitation (mm/day)	1	0.35
					Maximum dates of continuous no rainy day (days)		0.45
					Number of dates with under 35 % of effective humidity (times)		0.20
		Sensitivity		0.30	Area of coniferous forest (ha)	1	0.23
					Area of broadleaf forest (ha)		0.23
					Area of mixed forest (ha)		0.17
					Area of plantation (ha)		0.37
		Adaptation capacity		0.25	Government officials per population (persons)	1	0.20
					Area of preventing forest destruction (ha)		0.35
					GRDP (million KRW)		0.15
					Financial independence (%)		0.15
					Area of conservation for natural forest (ha)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
3. Ecosystem							
17	Vulnerability of vegetation growth	Climate exposure	1	0.46	Daily average temperature from January to March (°C)	1	0.19
					Temperature (°C)		0.20
					Precipitation (mm/day)		−0.23
					Daily average temperature from June to August (°C)		0.19
					Daily maximum temperature from June to August (°C)		0.19
		Sensitivity		0.31	Area of coniferous forest (ha)	1	0.23
					Timber production of coniferous (m^3)		0.18
					Coniferous forestry by-products (m^3)		0.09
					Number of workers in forest (persons)		0.10
					Cutover area (ha)		0.20
					Number of companies in agriculture and forestry (numbers)		0.10
					Number of workers in agriculture and forestry (persons)		0.10
		Adaptation capacity		0.23	Area of coniferous forest plantation (ha)	1	0.40
					Area of conservation for natural forest (ha)		0.40
					Government officials per population (persons)		0.20

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
18	Vulnerability of insects	Climate exposure	1	0.48	Daily average temperature from January to March (°C)	1	−0.15
					Number of dates with daily average temperature below zero (times)		0.17
					Daily average temperature in April (°C)		−0.15
					Average relative humidity in April (%)		−0.08
					Maximum dates of continuous no rainy day (days)		0.12
					Evapotranspiration (mm/day)		0.07
					Insolation (W/m2)		−0.10
					Daily average temperature from June to August (°C)		−0.16
		Sensitivity		0.34	Forest insect pests (number of cases)	1	0.19
					Pine pitch canker (number of cases)		0.18
					Number of honeybee farmhouse (numbers)		0.15
					Honeybee breeding size (barrel)		0.15
					Number of arthropod-borne infectious disease (persons)		0.16
					Cutover area by pest damage (ha)		0.08
					Cutting volume by pest damage (m^3)		0.09
		Adaptation capacity		0.18	Time of pest control—Psylla pyricola Foerster (cumulative days)	1	0.23
					Area of preventing forest destruction (ha)		0.22
					Employment for pest control (persons)		0.13
					Number of companies in bioindustry (numbers)		0.13
					Number of farmhouse of environment-friendly fruit (households)		0.16
					Number of farmhouse of environment-friendly special purpose crops (households)		0.13

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
19	Vulnerability of management of protected areas	Climate exposure	1	0.51	Precipitation (mm/day)	1	0.16
					Maximum dates of continuous no rainy day (days)		0.10
					Number of dates with daily average temperature below zero (times)		0.09
					Number of dates with over 33 °C of daily maximum temperature (times)		0.07
					Precipitation from March to May (mm)		−0.11
					Precipitation from June to August (mm)		0.11
					Precipitation from September to November (mm)		0.09
					Precipitation from December to February (mm)		−0.09
					Number of dates with over 80 mm of precipitation (times)		0.11
					Number of dates with over 14 m/s of daily maximum wind speed (times)		0.07
		Sensitivity		0.28	Number of plant species in National Park (species)	1	0.18
					Number of animal species in National Park (species)		0.18
					Number of visitors (persons)		0.12
					Increase or decrease of visitors compared with the previous year (%)		−0.10
					Number of endangered plant species (species)		0.16
					Number of endangered animal species (species)		0.17
					Number of linked administrative areas for National Park management (numbers)		0.09

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
		Adaptation capacity		0.21	Number of National Park employees (persons)	1	0.12
					Number of groups in National Park (numbers)		0.10
					Number of National Park offices (numbers)		0.10
					Increase or decrease of National Park Area (km^2)		−0.15
					Operating number of times National Park commentator (times)		0.08
					Area of Buddhist temple in National Park (km^2)		0.08
					Applied area of nature rest system (m^2)		0.20
					Applied length of nature rest system (m^2)		0.17
4. Agriculture							
20	Vulnerability to erosion of farmlands	Climate exposure	1	0.39	Precipitation (mm/day)	1	0.26
					Number of dates with over 80 mm of precipitation (times)		0.50
					Number of dates with precipitation over 10 mm (times)		0.24
		Sensitivity		0.37	Area of rice paddy (ha)	1	0.20
					Area of field (ha)		0.30
					Average slope of regional farmland (°)		0.50
		Adaptation capacity		0.24	Ownership in farm mechanization per agricultural land unit (numbers/ha)	1	0.28
					PC advantage farmhouse/total farmhouse		0.12
					Agricultural population per agricultural land unit (persons/ha)		0.10
					Maintenance business employees per cultivation area (persons/ha)		0.10
					GRDP (million KRW)		0.10
					Financial independence (%)		0.24

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
21	Vulnerability of cultivation facility	Climate exposure	1	0.31	Number of dates with over 14 m/s of daily maximum wind speed (times)	1	0.37
					Number of dates with over 20 cm of snowfall (times)		0.28
					Number of dates with over 160 mm of precipitation (times)		0.35
		Sensitivity		0.39	Cultivation area of greenhouse crop (ha)	1	0.15
					Area of breeding facilities (m^2)		0.20
					Damaged area of greenhouse per cultivation area of greenhouse crop		0.40
					Damaged buildings per area of farm (number/ha)		0.25
		Adaptation capacity		0.30	Agricultural population per cultivation/breeding facilities area (persons/ha)	1	0.20
					PC advantage farmhouse/total farmhouse		0.15
					Maintenance business employees per cultivation area (persons/ha)		0.15
					GRDP (million KRW)		0.25
					Financial independence (%)		0.25

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
22	Vulnerability of productivity of rice crops	Climate exposure	1	0.45	Number of dates with daily minimum temperature below 13 °C from April to June (times)	1	0.10
					Number of dates with daily minimum temperature below 17 °C from July to September (times)		0.15
					Number of dates with daily minimum temperature below 14 °C from September to October (times)		0.10
					Number of dates with daily minimum temperature below 30 °C from April to October (times)		0.10
					Number of dates with over 100 ppb of the ozone concentration from April to October (times)		0.05
					Log (Amount of insolation between April to October) (number)		−0.25
					Number of dates with over 160 mm of precipitation (times)		0.15
					Number of dates with over 14 m/s of daily maximum wind speed (times)		0.10
		Sensitivity		0.26	Area of rice paddy (ha)	1	0.30
					Crop damaged area per area of farm (ha)		0.25
					Possibility of pest damage (%)		0.45
		Adaptation capacity		0.29	Rice production per cultivation area (ton/ha)	1	0.20
					Farmers per cultivation area (persons/ha)		0.25
					Rate of land planning (%)		0.20
					PC advantage farmhouse/total farmhouse		0.05
					Maintenance business employees per cultivation area (persons/ha)		0.05
					GRDP (million KRW)		0.10
					Financial independence (%)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
23	Vulnerability of productivity of apple crops	Climate exposure	1	0.43	Annual average temperature from 8 °C to 11 °C	1	0.15
					Daily average temperature in October (°C)		0.10
					Daily average temperature from April to August (°C)		0.15
					Daily average temperature in August (°C)		−0.10
					Daily maximum temperature from April to August (°C)		0.10
					Precipitation from April to October (mm)		0.15
					Number of dates with over 14 m/s of daily maximum wind speed from April to October (times)		0.25
		Sensitivity		0.28	Cultivation area of apple (ha)	1	0.41
					The previous damaged crop areas per unit area (%)		0.59
		Adaptation capacity		0.29	Apple production per cultivation area (kg/10a)	1	0.20
					Farmers per cultivation area (persons/ha)		0.20
					Ownership in farm mechanization per cultivation area of apple (numbers/ha)		0.20
					PC advantage farmhouse/total apple farmhouse		0.05
					Maintenance business employees per cultivation area (persons/ha)		0.10
					GRDP (million KRW)		0.10
					Financial independence (%)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
24	Vulnerability of productivity of livestock	Climate exposure	1	0.34	Number of dates with over 27 °C of daily maximum temperature (times)	1	0.40
					Number of dates with over 72 of temperature humidity index (times)		0.34
					Number of dates with over 20 cm of snowfall (times)		0.14
					Number of dates with over 14 m/s of daily maximum wind speed (times)		0.12
		Sensitivity		0.29	Livestock numbers (thousand KRW)	1	0.25
					Damaged buildings per area of farm (number/ha)		0.35
					Potential occurrence probability of livestock disease (%)		0.40
		Adaptation capacity		0.37	Population of livestock raiser per unit area of breeding facility (persons/ha)	1	0.30
					Capacity of livestock waste water processing (%)		0.10
					PC advantage farmhouse/total stockbreeding farmhouse		0.10
					Maintenance business employees per cultivation area (persons/ha)		0.10
					GRDP per capita (million KRW)		0.15
					Financial independence (%)		0.25

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
5. Water management							
25	Vulnerability of flood regulation	Climate exposure	1	0.37	Daily maximum precipitation (mm)	1	0.13
					Number of dates with over 80 mm of precipitation (times)		0.31
					5 days of maximum precipitation (mm)		0.23
					runoff (mm/day)		0.19
					Precipitation from June to September (summer season) (mm)		0.16
		Sensitivity		0.30	Lowland area under 10 m (km^2)	1	0.11
					Buildings in lowland area under 10 m (numbers)		0.10
					Rate of bank area in territory (%)		0.10
					Population density (person/km^2)		0.07
					Population (persons)		0.12
					Average slope of region (°)		0.10
					Rate of road (%)		0.11
					Flood damage cost during last 3 years (thousands KRW)		0.07
					Flood damage victims during last 3 years (persons)		0.16
		Adaptation capacity		0.33	Financial independence (%)	1	0.15
					Government officials per population (persons/ten thousand people)		0.13
					GRDP (million KRW)		0.07
					Water management government officials per area (person/km^2)		0.11
					Rate of river improvement (%)		0.13
					Drainage capability of facilities (m^3/min)		0.14
					Flood regulation capacity of reservoir (million m^3)		0.21

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
26	Vulnerability of water utilization	Climate exposure	1	0.31	Maximum dates of continuous no rainy day (days)	1	0.21
					Precipitation from December to February (mm)		0.22
					Precipitation from March to May (mm)		0.18
					Evapotranspiration from December to February (mm)		0.21
					Evapotranspiration from March to May (mm)		0.10
					Underground runoff (mm/day)		0.13
		Sensitivity		0.31	Population density (person/km^2)	1	0.15
					Population (persons)		0.11
					Water supply: daily consumption per capita (L)		0.10
					Grain production per unit area (ton/km^2)		0.07
					Livestock production per unit area (numbers/km^2)		0.07
					Groundwater usage (m^3/year)		0.06
					Stream water usage (m^3/year)		0.08
					Living water usage (thousands m^3/year)		0.09
					Industrial water usage (thousands m^3/year)		0.15
					Agricultural water usage (thousands m^3/year)		0.14
					Financial independence (%)		0.13
		Adaptation capacity		0.38	Government officials per population (persons/ten thousand people)	1	0.12
					GRDP (million KRW)		0.05
					Water management government officials per area (person/km^2)		0.09
					Rate of water supply (%)		0.09
					Capacity of underground water (thousands m^3/year)		0.15
					Reservoir capacity per unit area (thousands m^3)		0.14
					Water reuse per unit area (thousands m^3/year)		0.21

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
27	Vulnerability of water quality	Climate exposure	1	0.34	Daily maximum temperature (°C)	1	0.14
					Daily maximum precipitation (mm)		0.13
					Number of dates with over 80 mm of precipitation (times)		0.14
					Maximum dates of continuous no rainy day (days)		0.33
					Number of dates with over 33 °C of daily maximum temperature (times)		0.13
					Number of dates with over 25 °C of daily minimum temperature (times)		0.13
		Sensitivity		0.321	Average slope of region (°)	1	0.08
					Rate of river improvement (%)		0.11
					Population of livestock raiser (persons/ten thousand people)		0.08
					Livestock products per unit area (number/km^2)		0.13
					Fertilizer usage per unit cultivation area (ton/ha)		0.15
					Distribution of major animal species (numbers)		0.09
					Distribution of major plant species (numbers)		0.09
					Rate of forest area (%)		0.14
					Rate of managed land area (%)		0.13
		Adaptation capacity		0.34	Percent of sewered population (%)	1	0.32
					Government officials per population (persons/ten thousand people)		0.11
					Population density (person/km^2)		−0.26
					Rate of road area (%)		−0.18
					Road length per unit area (km)		−0.13

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
6. Fisheries							
28	Vulnerability of fisheries due to change in water temperature	Climate exposure	1	0.44	Surface sea temperature (°C)	1	0.22
					Rate of rise of ocean temperature (°C/year)		0.25
					Number of dates with daily average temperature below zero (times)		0.17
					Number of dates with over 33 °C of daily maximum temperature (times)		0.15
					Number of dates with over 80 mm of precipitation (times)		0.11
					Number of jellyfish damage occurrence (times)		0.09
		Sensitivity		0.34	Farm facilities area (fishery households-cage-aquaculture) (ha)	1	0.25
					Farm facilities area (company-cage-aquaculture) (ha)		0.25
					Farm facilities area (fishery households-cultivating fishery) (ha)		0.16
					Farm facilities area (company-cultivating fishery)(ha)		0.16
					Status of fishery households (cage-aquaculture) (places)		0.09
					Status of fishery households (cultivating fishery) (places)		0.09
		Adaptation capacity		0.22	Financial independence (%)	1	0.28
					Government officials per population (persons/ten thousand people)		0.25
					Farm facilities area (fishery households-land-based seawater) (ha)		0.17
					Farm facilities area (company-land-based seawater) (ha)		0.15
					Status of fishery households (land-based seawater) (places)		0.15

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
7. Disaster							
29	Vulnerability of infrastructure to floods	Climate exposure	1	0.45	Number of dates with over 80 mm of precipitation (times)	1	0.41
					Daily maximum precipitation (mm)		0.59
		Sensitivity		0.29	Road area (m^2)	1	0.25
					Water supply facilities area (m^2)		0.09
					Electricity supply facilities area (m^2)		0.09
					Gas supply facilities area (m^2)		0.06
					Heat supply facilities area (m^2)		0.05
					Oil storage and pipeline area (m^2)		0.06
					Sewerage area (m^2)		0.34
					Water pollution prevention facilities area (m^2)		0.06
		Adaptation capacity		0.26	GRDP per capita (million KRW)	1	0.35
					Government officials per population (persons/ten thousand people)		0.15
					Rate of river improvement (%)		0.50
30	Vulnerability of infrastructure to heat waves	Climate exposure	1	0.43	Number of dates with over 33 °C of daily maximum temperature (times)	1	0.65
					Number of dates with over 25 °C of daily minimum temperature (times)		0.35
		Sensitivity		0.21	Road area (m^2)	1	1.00
		Adaptation capacity		0.36	GRDP per capita (million KRW)	1	0.30
					Government officials per population (persons/ten thousand people)		0.14
					Greenspace area per capita (m^2)		0.56

Table 6 continued

No.	Item	Variables	Sum of weights	First weights	Specific variables	Sum of weights	Second weights
31	Vulnerability of infrastructure to heavy snow	Climate exposure	1	0.45	Snowfall (cm)	1	1.00
		Sensitivity		0.28	Road area (m^2)	1	0.68
					Railroad area (m^2)		0.20
					Airport area (m^2)		0.12
		Adaptation capacity		0.27	GRDP per capita (million KRW)	1	0.65
					Government officials per population (persons/ten thousand people)		0.35
32	Vulnerability of infrastructure to sea level rise	Climate exposure	1	0.50	Annual rate of rising ocean temperature (%)	1	1.00
		Sensitivity		0.20	Road area (m^2)	1	0.30
					Port area (m^2)		0.58
					Water pollution prevention facilities area (m^2)		0.12
		Adaptation capacity		0.30	GRDP per capita (million KRW)	1	0.28
					Government officials per population (persons/ten thousand people)		0.12
					Area of embankment (m^2)		0.60

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