

## Article

# Comparison of Flood Vulnerability Assessments to Climate Change by Construction Frameworks for a Composite Indicator

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**Abstract:** As extreme weather conditions due to climate change can cause deadly flood damages all around the world, a role of the flood vulnerability assessment has become recognized as one of the preemptive measures in nonstructural flood mitigation strategies. Although the flood vulnerability is most commonly assessed by a composite indicator compiled from multidimensional phenomena and multiple conflicting criteria associated with floods, directly or indirectly, it has been often overlooked that the construction frameworks and processes can have a significant influence on the flood vulnerability indicator outcomes. This study has, therefore, compared the flood vulnerability ranking orders for the 54 administrative districts in the Nakdong River Watershed of the Korean Peninsula, ranked from composite indicators by different frameworks and multi-attribute utility functions for combining the three assessment components, such as exposure, sensitivity, and coping, presented in the IPCC Third Assessment Report. The results show that the different aggregation components and utility functions under the same proxy variable system can lead to larger volatility of flood vulnerability rankings than expected. It is concluded that the vulnerability indicator needs to be derived from all three assessment components by a multiplicative utility function for a desirable flood vulnerability assessment to climate change.

**Keywords:** flood vulnerability assessment; climate change; composite indicator framework; multi-attribute utility function

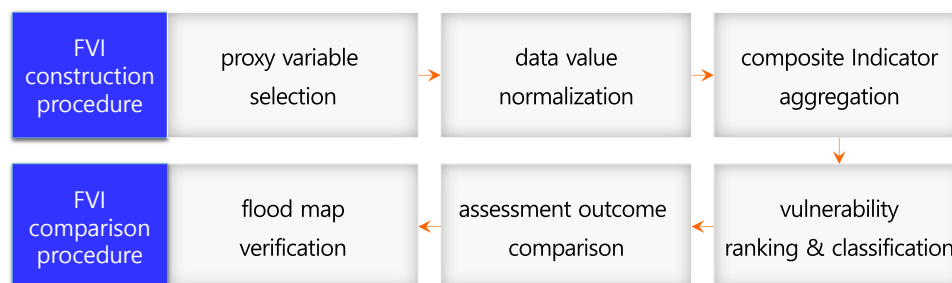
## 1. Introduction

As global and regional climate change has been irrefutably occurring due to global warming [1], extreme weather conditions, such as severe torrential storms and super typhoons, recently and frequently occur at, and cause damage to, the Korean peninsula. Since it is geographically located on the east coast of the Eurasian Continent and also adjacent to the Western Pacific, it has much more precipitation than the continental average because of typhoons in summer and a rainy period from the East-Asian Monsoon. Such complex geographical and climatological circumstances require studies on the assessment of the regional flood vulnerability for each administrative district to establish the customized mitigation plans. Furthermore, as the occurrence of heavy floods increases due to climate change, the flood vulnerability assessment is recognized as an essential tool to provide the preventative information in nonstructural flood mitigation measures, especially concerning climate variability, changes, and impacts. One of the most well-known definitions on the vulnerability to climate change is presented in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report [2] as a degree to which a system is exposed to, sensitive to, and/or unable to cope with adverse effects of climate change. The exposure denotes the degree of extrinsic factors exposed to significant variations. The sensitivity means the degree of intrinsic factors affected by dangerous phenomena likely to suffer

harm. The lack of coping indicates the degree of limitations and incapacity of a system to adapt and reduce adverse effects of experienced hazards. The IPCC [2] framework for the vulnerability assessment to climate change has been used to interpret elusive issues in a wide range of fields, science, environment, economy, society, etc. [3–11].

In case that it is almost impossible in decision making to represent a multi-dimensional issue by individual attribute variables especially under multiple conflicting criteria, they can be aggregated into a composite indicator to measure the overall performance of the multi-dimensional concept [12]. Accordingly, a composite indicator are derived from individual constituent components most commonly by multi-attribute utility functions, which can provide the significant information on the prioritization of alternatives for policy and decision problems. However, the vulnerability composite indicators have been compiled by the conventional aggregation methods without concerns for any effect of frameworks or methods. Some previous studies [13–15] generated the vulnerability indicators from the constituent attribute components by additive multi-attribute utility functions while the composite indicators were combined by multiplicative multi-attribute utility functions in some other studies [16–18]. In addition, the potential impact component were also used as a function of the exposure and sensitivity components to compile with the coping (or lack of coping) component into a composite indicator by additive or multiplicative aggregations in some literature [19–23].

This study has, therefore, compared and investigated the flood vulnerability assessment outcomes derived by various construction frameworks and processes that have influence on the composite indicators for the use in the process of prioritizing and selecting flood mitigation strategies. In this study, the flood vulnerability indicator (*FVI*) to climate change is derived by the following construction processes; (1) a theoretical framework is selected from the IPCC [2] vulnerability assessment to climate change, comprising the three assessment components, exposure, sensitivity (or susceptibility or fragility), and coping (or adaptive capacity or resilience); (2) proxy variables for the three individual components are selected in terms of measurability, representatives, soundness, etc.; (3) all proxy variables at different scales and units are normalized into ratios to the maximum value of each variable for a common scale 1 to 0; (4) an equal weighting is assumed and assigned to the proxy variables and the three assessment components; (5) an additive multi-attribute utility function is employed to combine individual proxy variables into each component indicator; and (6) component indicators are aggregated into a composite indicator by either additive or multiplicative utility functions. The flood vulnerability ranking orders are then placed and compared for each administrative district under study from the composite indicator outcomes derived by different construction frameworks. The flood vulnerability assessment results for the 54 administrative districts are classified into the three levels, and the 18 administrative districts ranked at the high level are finally compared with flood hazard areas managed by a government office. The analysis procedure of this study is summarized in Figure 1.

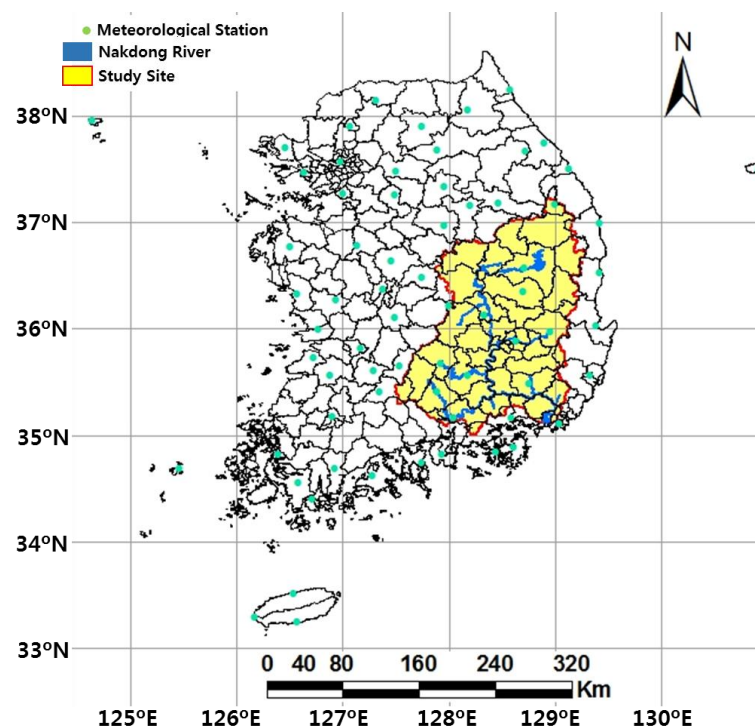


**Figure 1.** The analysis procedure diagram for the *FVI* (flood vulnerability indicator) construction and comparison.

## 2. Study Site

To compare the flood vulnerability assessment outcomes to climate change by a variety of construction frameworks for the vulnerability composite indicators, the administrative districts in

the Nakdong River Watershed of the Korean peninsula were chosen for study because this study site, located between  $127^{\circ}29' \sim 129^{\circ}18' \text{ E}$  and  $35^{\circ}03' \sim 37^{\circ}13' \text{ N}$ , has various characteristics in geophysical, climatological, and socio-economic aspects for each administrative district. The size of the study watershed is  $23,690.32 \text{ km}^2$ , the second largest one in Korea, and the main channel length is  $511.92 \text{ km}$ , the nation's longest river that flows from the Taebaek Mountains ( $1945.15 \text{ EL.m}$ ) over the north region to the South Sea, as shown Figure 2. The mean elevation is  $290.51 \text{ EL.m}$  and the averaged slope is  $37\%$  over the Nakdong River Watershed. The annual mean rainfall depth is  $1337.4 \text{ mm}$  over the study site for the past decade during 2007 to 2016 years, and there is difference between  $1247.8 \text{ mm}$  for the upstream and  $1430.2 \text{ mm}$  near the Nakdong River estuary area. The study site is composed of a total of 54 administrative districts, such as the three metropolitan cities comprising 14 districts (Gu in Korean), along with 19 cities (Si in Korean) and 21 counties (Gun in Korean) in five provinces (Do in Korean).



**Figure 2.** The localization of 54 administrative districts (yellow) under study along with 75 gauge stations (green) managed by the Korea Meteorological Administration and the main streamlines (blue) in the Nakdong River Watershed (red).

### 3. Construction Processes of FVI

#### 3.1. Framework and Variables

The selection of a sound theoretical framework is the most important process in constructing the flood vulnerability composite indicator. This study adopts a conceptual framework of vulnerability to climate change in the IPCC [2] that comprises the three assessment components, such as exposure, sensitivity, and coping, or the two assessment components, such as potential impact and coping, as shown in Table 1.

To measure the three constituent components of the flood vulnerability indicator to climate change, the three proxy variables are selected for each assessment component as shown in Table 1 in the light of previous studies on flood vulnerability assessments [15–17,23,24]. The selection of the nine total proxy variables is based on the simplicity of data acquisition and construction, as well as the principles of measurability, representativeness, and integrity.

**Table 1.** The assessment components and selected proxy variables for the *FVI* (flood vulnerability indicator) based on the vulnerability assessment concept in the IPCC [2].

Indicator	Components <sup>1</sup>	No.	Proxy Variables	Units
<i>FVI</i>	exposure	E1	maximum daily rainfall	mm/day
		E2	rainfall intensity	mm/hr
		E3	heavy rainy days	days
	sensitivity	S1	population density	inhabitants/km <sup>2</sup>
		S2	urban area ratio	km <sup>2</sup> /km <sup>2</sup>
		S3	basin slope	m/m
	coping	C1	river improvement ratio	km/km
		C2	pumping station capacity	m <sup>3</sup> /min
		C3	civil servant ratio	people/inhabitants

<sup>1</sup> The exposure and sensitivity components can be combined into the potential impact component.

Exposure is defined as the nature and degree to which a system is exposed to significant perturbations [2]. The proxy variables for the exposure component are composed of the maximum daily rainfall (E1) (mm/day), rainfall intensity (E2) (mm/hr), and days of heavy rainfall greater than 80 mm per day (E3) (days). For the consideration of climate change impacts the three proxy variables are temporally averaged for the past decade during 2007 to 2016 years, and then spatially averaged for 54 administrative districts by the inverse distance weighted interpolation from observations at 75 gauge stations managed by the Korea Meteorological Administration (KMA) in the Korean Peninsula.

Sensitivity is defined as the degree to which a system is affected by disturbances [2]. The sensitivity component is measured by the number of the population per district area (S1) (inhabitants/km<sup>2</sup>) for the human feature, a ratio of the houses, buildings, and infrastructure area to the district area (S2) (km<sup>2</sup>/km<sup>2</sup>) for the property feature, and the averaged terrain slope over a district (S3) (m/m) for the geographical feature.

Coping is defined as the ability of a system to adjust to disturbance, moderate damage, or cope with consequences [2]. The coping component comprises the three proxy variables such as a ratio of the river improvement length to the total river length in district (km/km) (C1) representative for coping with river flooding, drainage rate capacity of stormwater pumping stations in district (C2) (m<sup>3</sup>/min) representative for coping with inland flooding, and the number of civil servants working for water management per inhabitants in a district (people/inhabitants) representative for nonstructural flood countermeasures.

### 3.2. Normalizations

Since variables with different characteristics from different sources are usually measured at different scales and units, they need to be transformed into a commensurate scale by a proper normalization method. This study divides all data by each maximum value for normalized scores in consideration of the functional relationship between variables and vulnerability. As previous studies computed the normalized values based on each variable's positive or negative contribution to vulnerability [18,24,25], the variable that has a positive elasticity to vulnerability is normalized by Equation (1) and the variable that has a negative elasticity to vulnerability is normalized by Equation (2) as follows:

$$u_i = \frac{x_i}{\max(x_i)} \quad (1)$$

$$u_i = \frac{\max(x_i) - x_i + \min(x_i)}{\max(x_i)} \quad (2)$$

where  $u_i$  is the normalized score,  $x_i$  is the actual value of the proxy variable  $i$ , and  $\max(x_i)$  and  $\min(x_i)$  are, respectively, the maximum and minimum values of the proxy variable  $i$  for the vulnerability assessment components. The two opposite values can correspond bilaterally and symmetrically to each other by the above two equations. Note that this method can generate normalized scores while preserving the distribution of the original data values without distorting outliers.

The variables  $E1$ ,  $E2$ ,  $E3$ ,  $S1$ , and  $S2$  are normalized by Equation (1) because they have the positive (increasing vulnerability) functional relationship between variables and vulnerability, while Equation (2) is employed to normalize the variables  $S3$ ,  $C1$ ,  $C2$ , and  $C3$  whose higher values decrease the vulnerability due to the negative functional relationship with vulnerability. Thus, all the proxy variables are transformed into the normalized scores with the positive elasticity to vulnerability.

### 3.3. Aggregations

The next process is to aggregate the normalized proxy variables for each assessment component  $j$  into each indicator  $I_j$  as:

$$I_j = (EI, SI, CI) = \sum_{i=1}^k w_i u_i \quad (3)$$

where  $I_j$  denotes  $EI$ ,  $SI$ , and  $CI$  for the exposure indicator, sensitivity indicator, and coping indicator, respectively,  $w_i$  is the weight of the normalized score of the proxy variable  $i$  for which the value of  $1/3$  is assigned equally to the proxy variables by adopting an equal weighting method, and  $k$  is the number of variables for each component  $E$ ,  $S$ , and  $C$ .

The three component indicators  $EI$ ,  $SI$ , and  $CI$  are then aggregated into a composite indicator for the flood vulnerability to climate change using either an additive or a multiplicative multi-attribute utility function as:

$$FVI_a(3) = \sum_{j=1}^n w_j I_j = \frac{1}{3}(EI + SI + CI) \quad (4)$$

or:

$$FVI_m(3) = \prod_{j=1}^n I_j^{w_j} = (EI \times SI \times CI)^{\frac{1}{3}} \quad (5)$$

where  $FVI_a(3)$  and  $FVI_m(3)$  are the flood vulnerability composite indicators from the three components by additive and multiplicative forms, respectively.  $w_j$  is the weight of the component indicator  $I_j$  under the equal weighting value of  $1/3$  for each component.  $n$  is the number of component indicators. Note that all the three component indicators from Equation (3) have the positive elasticity to the flood vulnerability because all the proxy variables are normalized with the functional relationship for increasing vulnerability as mentioned in Section 3.2. A mixed use of both positive and negative functional relationships between the component indicators and the vulnerability indicator can cause undesirable vulnerability outcomes especially when quite low values of a component indicator employed as a divisor (for the negative contribution in the multiplicative utility form) may generate abnormally large composite indicator outcomes numerically.

When the potential impact indicator  $PI$  is used as a function of the exposure indicator  $EI$  and the sensitivity indicator  $SI$  as:

$$PI_a = \frac{1}{2}(EI + SI) \quad (6)$$

or:

$$PI_m = (EI \times SI)^{\frac{1}{2}} \quad (7)$$

where  $PI_a$  or  $PI_m$  is the potential impact indicator by an additive form or a multiplicative form.

Then, the flood vulnerability indicator can be compiled from the two component indicators by an additive utility form  $FVI_a(2)$  or a multiplicative utility form  $FVI_m(2)$  as:

$$FVI_a(2) = \frac{1}{2}(PI_a + CI) \quad (8)$$

or:

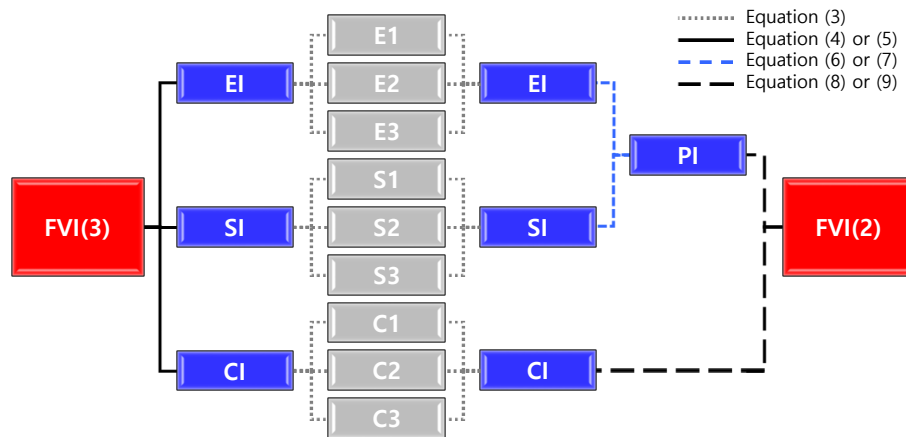
$$FVI_m(2) = (PI_m \times CI)^{\frac{1}{2}} \quad (9)$$

Thus, the flood vulnerability indicators  $FVI_a(2)$  and  $FVI_m(2)$  are aggregated from the coping component weighted by  $1/2$  and the exposure and sensitivity components with  $1/4$  weight for each.

Note that all the component indicators  $EI$ ,  $SI$ ,  $CI$ ,  $PI_a$ , and  $PI_m$  aggregated from proxy variables need to be normalized with the same maximum value of 1 to affect a composite indicator equally,

which can prevent any unintended weighting effects for further comparison of assessment components in the aggregation process by Equations (4), (5), (8), or (9). The computational framework for the *FVIs* is presented in Figure 3.

Finally, the ranking orders can be assigned to the composite indicator outcomes in the process of ordering priority or selecting alternatives for policy and decision making.



**Figure 3.** The process diagram for the *FVI* (flood vulnerability indicator) computations.

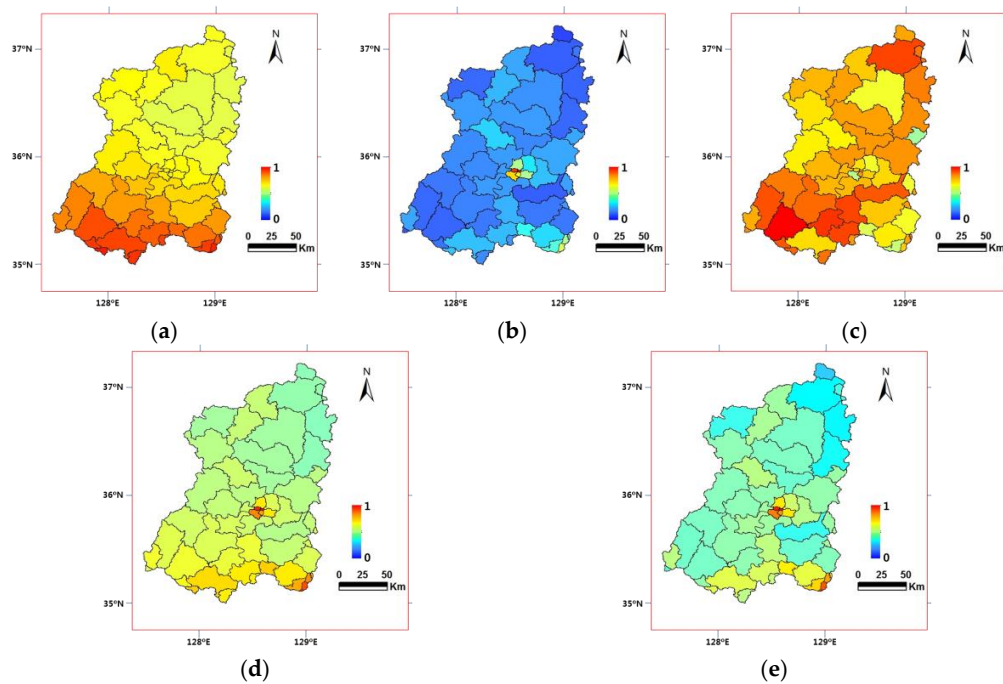
## 4. Results

### 4.1. Comparison of Indicators

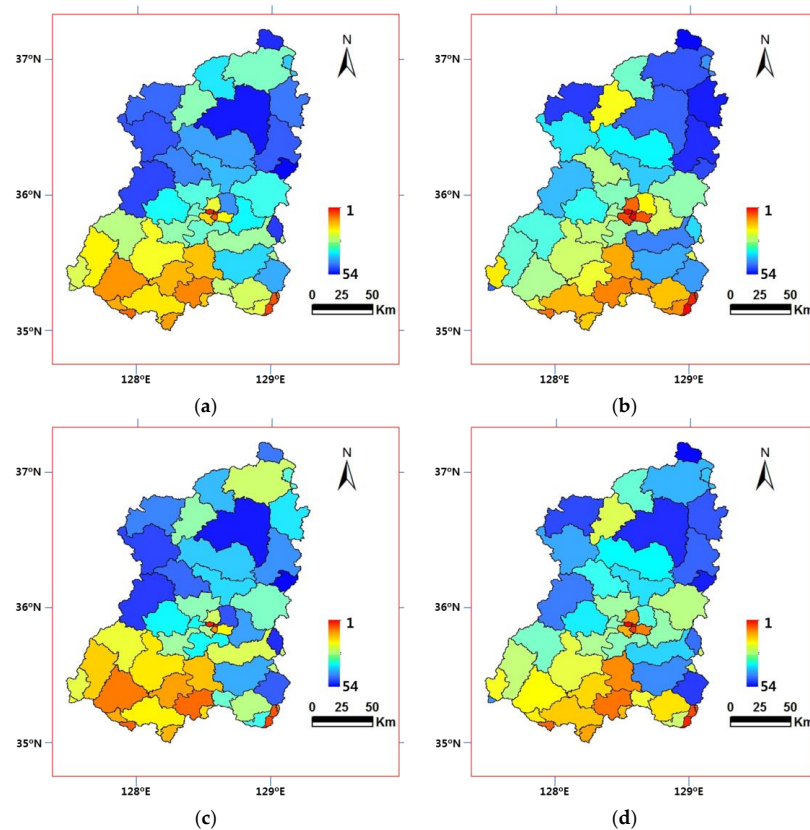
Figure 4 shows the spatial distribution of three constituent component indicators, *EI*, *SI*, and *CI*, along with the two kinds of potential impact indicators,  $PI_a$  and  $PI_m$ . The value of the exposure indicator *EI* is higher in the south part close to the coastline where typhoons and the summer monsoon effects are more dominant. The value of the sensitive indicator *SI* is higher in the middle and the right bottom parts where the large cities with higher population densities and urbanization rates are located. The value of the coping (lack of coping) indicator *CI* is higher in the southwestern part of the study site under relatively poor conditions of structural and nonstructural countermeasures for flood disasters. Such a greater vulnerable condition in the coping component can lead to higher flood vulnerability outcomes despite relatively lower sensitivity conditions, particularly for additive composite indicators, as a result of higher compensability in aggregation schemes. In the potential impact indicators  $PI_a$  and  $PI_m$  combined from the two component indicators *EI* and *SI*, the sensitivity indicator *SI* with large variations is more influential one generating higher values for the large metropolitan cities. A peculiar feature in the component indicator outcomes is that the values of exposure and coping indicators *EI* and *CI* are highly distributed over this study site with accordingly higher minimum values.

Figure 5 shows the spatial distribution of the flood vulnerability ranks based on the four different composite indicator outcomes  $FVI_a(3)$  and  $FVI_m(3)$  from the three components, and  $FVI_a(2)$  and  $FVI_m(2)$  from the two components by additive and multiplicative utility functions. Regardless of the construction frameworks for the flood vulnerability indicator, higher flood vulnerability to climate change is evaluated for most of districts in the three metropolitan cities, Busan, Ulsan (right lower), and Daegu (around center) that have relatively higher values of *SI*, and for the administrative districts in the southwestern part of the study site that have relatively higher values of *EI* and *CI*. Meanwhile, lower flood vulnerability to climate change is shown in the mid-northern administrative districts that have relatively lower or moderate values of all the three components. It is also found that the volatility of rankings and rank reversals occur in the four flood vulnerability results for some administrative districts. A greater interpretation on the differences in flood vulnerability results is presented in the following sections.





**Figure 4.** Spatial distribution of the vulnerability assessment component indicators for the study site: (a) exposure indicator  $EI$ ; (b) sensitivity indicator  $SI$ ; (c) coping indicator  $CI$ ; (d) additive potential impact indicator  $PI_a$ ; and (e) Multiplicative potential impact indicator  $PI_m$ .



**Figure 5.** Spatial distribution of the flood vulnerability ranking results based on the four composite indicators for the study site: (a) ranking orders from  $FVI_a(3)$ ; (b) ranking orders from  $FVI_m(3)$ ; (c) ranking orders from  $FVI_a(2)$ ; and (d) ranking orders from  $FVI_m(2)$ .

#### 4.2. Comparison of FVIs by Aggregation Functions

Figure 5a,b compares the rank ordering results of the two flood vulnerability indicators  $FVI_a(3)$  and  $FVI_m(3)$  aggregated from the three components by additive and multiplicative utility functions, respectively in Equations (4) and (5). Table 2 denotes the ten administrative districts that have large differences between the two flood vulnerability rank results from  $FVI_a(3)$  and  $FVI_m(3)$ . The ranking orders from  $FVI_a(3)$  are much higher (with smaller numbers) than those from  $FVI_m(3)$  when any two of the three component indicators have very large values and the value of the other component indicator is quite low. Meanwhile, the ranking orders from  $FVI_m(3)$  are much higher than those from  $FVI_a(3)$  when all the three component indicators have moderate or relatively higher level values. Such features of differences between the two rank results are due to higher compensability in the additive aggregation function and lower compensability in the multiplicative aggregation function. Thus, the additive composite indicator  $FVI_a(3)$  is influenced by the three component values altogether, while the multiplicative composite indicator  $FVI_m(3)$  is dramatically swayed by a lower value of one of the three components.

**Table 2.** The comparison of flood vulnerability ranks from the two composite indicators  $FVI_a(3)$  and  $FVI_m(3)$  along with the three component values for the top ten administrative districts with large differences between the two rank results.

Administrative Districts	Component Indicator Values			Flood Vulnerability Ranks		Rank Differences <sup>1</sup>
	<i>EI</i>	<i>SI</i>	<i>CI</i>	$FVI_a(3)$	$FVI_m(3)$	
Dong-Gu, Daegu Metropolitan City	0.663	0.306	0.638	44	21	23
Gurye-Gun, Jeollanam-Do	0.892	0.104	0.835	25	47	−22
Sancheong-Gun, Gyeongsangnam-Do	0.933	0.124	1.000	10	30	−20
Hamyang-Gun, Gyeongsangnam-Do	0.858	0.131	0.927	18	35	−17
Cheongdo-Gun, Gyeongsangbuk-Do	0.723	0.117	0.915	29	46	−17
Bonghwa-Gun, Gyeongsangbuk-Do	0.642	0.116	0.943	32	49	−17
Gumi City, Gyeongsangbuk-Do	0.642	0.275	0.677	45	29	16
Hadong-Gun, Gyeongsangnam-Do	0.958	0.144	0.919	12	24	−12
Changwon City, Gyeongsangnam-Do	0.891	0.351	0.589	26	14	12
Gyeongju City, Gyeongsangbuk-Do	0.691	0.207	0.632	51	40	11

<sup>1</sup>  $FVI_a(3)$  minus  $FVI_m(3)$ .

#### 4.3. Comparison of FVIs by Assessment Components

The flood vulnerability rank ordering results of the additive and multiplicative composite indicators  $FVI_a(3)$  and  $FVI_m(3)$  aggregated from the three components in Figure 5a,b are, respectively, compared with those of the additive and multiplicative composite indicators  $FVI_a(2)$  and  $FVI_m(2)$  aggregated from the two components in Figure 5c,d. The ten administrative districts that have large differences between the two flood vulnerability rank results from  $FVI_a(3)$  and  $FVI_a(2)$  are presented in Table 3, and those from  $FVI_m(3)$  and  $FVI_m(2)$  are listed in Table 4. The ranking orders from  $FVI_a(2)$  and  $FVI_m(2)$  are higher than those from  $FVI_a(3)$  and  $FVI_m(3)$  when the value of the component indicator *CI* is very large and one or both of the two component indicators *EI* and *SI* have low values. On the contrary, it is expected that the ranking orders from  $FVI_a(3)$  and  $FVI_m(3)$  are higher than those from  $FVI_a(2)$  and  $FVI_m(2)$  when the component indicator *CI* is quite low and one, or both, of the two component indicators *EI* and *SI* have large values. The ranking orders from  $FVI_a(2)$  and  $FVI_m(2)$  become lower for the administrative districts where the component *CI* is around the minimum value of 0.472 and one of the two component indicators *EI* and *SI* has a relatively large value. Such different vulnerability ranking results are induced by the framework using another indicator *PI* combining the two components *EI* and *SI*. The vulnerability ranks from the composite indicators  $FVI_a(2)$  and  $FVI_m(2)$  are influenced more by the coping indicator *CI* weighted one-half than by exposure and sensitivity indicators *EI* and *SI* with one-quarter weight for each, when compared with



rank results from the composite indicators  $FVI_a(3)$  and  $FVI_m(3)$  compiled from the three equally weighted components.

**Table 3.** The comparison of flood vulnerability ranks from the two composite indicators  $FVI_a(3)$  and  $FVI_a(2)$  along with the constituent component values for the top ten administrative districts with large differences between the two rank results.

Administrative Districts	Component Indicator Values				Flood Vulnerability Ranks		Rank Differences <sup>1</sup>
	<i>EI</i>	<i>SI</i>	<i>PI<sub>a</sub></i>	<i>CI</i>	$FVI_a(3)$	$FVI_a(2)$	
Gangseo-Gu, Busan Metropolitan City	0.955	0.369	0.791	0.536	22	35	−13
Dalseo-Gu, Daegu Metropolitan City	0.691	0.724	0.845	0.512	16	28	−12
Sancheong-Gun, Gyeongsangbuk-Do	0.601	0.120	0.431	0.863	46	38	8
Changwon City, Gyeongsangnam-Do	0.891	0.351	0.742	0.589	26	33	−7
Bonghwa-Gun, Gyeongsangbuk-Do	0.642	0.116	0.452	0.943	32	25	7
Gyeongsan City, Gyeongsangbuk-Do	0.676	0.253	0.554	0.725	37	43	−6
Yangsan City, Gyeongsangnam-Do	0.819	0.152	0.580	0.641	42	48	−6
Taebaek City, Gangwon-Do	0.651	0.075	0.434	0.797	52	46	6
Cheongdo-Gun, Gyeongsangbuk-Do	0.723	0.117	0.502	0.915	29	23	6
Uljin-Gun, Gyeongsangbuk-Do	0.608	0.150	0.452	0.878	40	34	6

<sup>1</sup>  $FVI_a(3)$  minus  $FVI_a(2)$ .

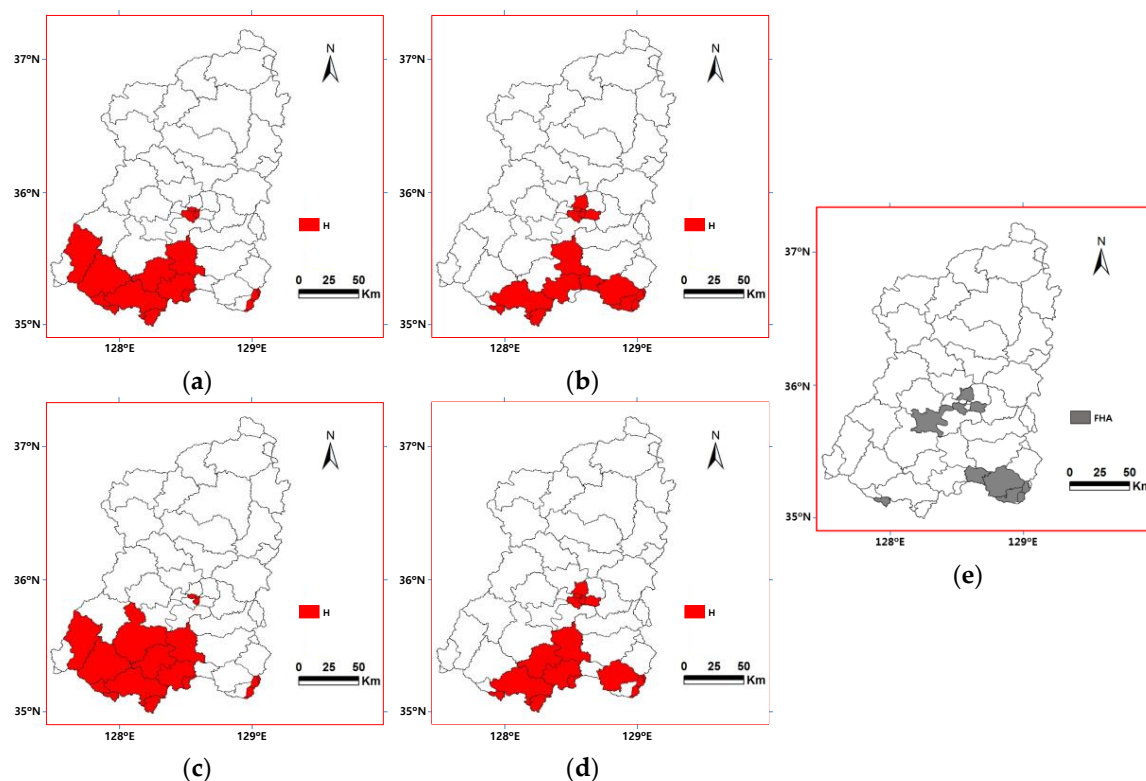
**Table 4.** The comparison of flood vulnerability ranks from the two composite indicators  $FVI_m(3)$  and  $FVI_m(2)$  along with the constituent component values for the top ten administrative districts with large differences between the two rank results.

Administrative Districts	Component Indicator Values				Flood Vulnerability Ranks		Rank Differences <sup>1</sup>
	<i>EI</i>	<i>SI</i>	<i>PI<sub>m</sub></i>	<i>CI</i>	$FVI_m(3)$	$FVI_m(2)$	
Dong-Gu, Daegu Metropolitan City	0.663	0.306	0.548	0.638	21	35	−14
Gangseo-Gu, Busan Metropolitan City	0.955	0.369	0.723	0.536	13	26	−13
Sancheong-Gun, Gyeongsangnam-Do	0.933	0.124	0.414	1.000	30	20	10
Changwon City, Gyeongsangnam-Do	0.891	0.351	0.681	0.589	14	22	−8
Hamyang-Gun, Gyeongsangnam-Do	0.858	0.131	0.409	0.927	35	27	8
Yangsan City, Gyeongsangnam-Do	0.819	0.152	0.430	0.641	44	51	−7
Gumi City, Gyeongsangbuk-Do	0.642	0.275	0.511	0.677	29	36	−7
Gyeongju City, Gyeongsangbuk-Do	0.691	0.207	0.461	0.632	40	47	−7
Bonghwa-Gun, Gyeongsangbuk-Do	0.642	0.116	0.332	0.943	49	42	7
Dalseo-Gu, Daegu Metropolitan City	0.691	0.724	0.861	0.512	8	14	−6

<sup>1</sup>  $FVI_m(3)$  minus  $FVI_m(2)$ .

#### 4.4. Comparison of FVIs and FHAs

As a means of evaluating the four  $FVIs$  to find the flood vulnerability assessment result suitable to the study site, this study compares the  $FVI$  outcomes with one of official flood vulnerability maps, the flood hazard areas (FHA) in 2010 managed by the Ministry of the Interior and Safety (MOIS) [26]. For the comparison with the flood hazard map, the 54 administrative districts are classified into the three levels, such as high (H), middle (M), and low (L), with respect to the flood vulnerability by the four  $FVIs$ . Thus, the 18 administrative districts ranked at Level H are compared with the 10 administrative districts including FHA rated at Class 1 by the MOIS as shown in Figure 6. The total 4, 9, 3, and 7 administrative districts in Level H, respectively, from  $FVI_a(3)$ ,  $FVI_m(3)$ ,  $FVI_a(2)$ , and  $FVI_m(2)$  match the FHA Class 1. This implies that the flood vulnerability assessment using  $FVI_m(3)$  can provide better information on flood mitigation strategies for this study site than vulnerability results from other aggregation schemes. It is also found that the actual flood hazard feature is relatively different from the additive composite indicators  $FVI_a(3)$  and  $FVI_a(2)$  derived with higher compensability of attribute components. It is, therefore, expected that for the southwestern part of the study site that shows higher  $FVI_a(3)$  and  $FVI_a(2)$  by lower  $SI$  and higher  $EI$  and  $CI$ , the future flood mitigation strategies can reduce the flood vulnerability by additive composite indicators as well.



**Figure 6.** Spatial distribution of the 18 administrative districts with high vulnerability level (H) based on the four composite indicators for the study site: (a) districts rated H from  $FVI_a(3)$ ; (b) districts rated H from  $FVI_m(3)$ ; (c) districts rated H from  $FVI_a(2)$ ; and (d) districts rated H from  $FVI_m(2)$  along with (e) the 10 administrative districts including flood hazard areas (FHA) rated Class 1 by the MOIS in 2010.

## 5. Discussion and Limitations

Many composite indicators have been proposed and used to illustrate multidimensional and complex issues in a variety of fields, such as science, environment, economy, society, etc. The composite indicators need to be properly constructed and interpreted not to provide misleading information for policy and decision making. There have been, however, limited studies conducted on the influence of aggregation frameworks and methods on the composite indicator outcomes. As disastrous floods occur recently and frequently due to extreme weather conditions, such as severe torrential storms and super typhoons, the flood vulnerability assessment becomes recognized as an essential tool to provide the preemptive and preventative information on nonstructural flood mitigation measures to climate change. One of remarkable frameworks to measure the vulnerability to climate change comprises the three contributing components, such as exposure, sensitivity, and coping presented in IPCC [2], and the vulnerability composite indicators have been compiled by various multi-attribute utility functions, representatively additive or multiplicative forms. This study has, therefore, investigated the influence of aggregation processes for constructing flood vulnerability composite indicators based on the framework for the vulnerability measurement to climate change in IPCC [2]. The comparison of flood vulnerability composite indicator outcomes by different aggregation frameworks and methods are implemented for the 54 administrative districts of the Nakdong River Watershed in the Korean peninsula where severe torrential storms and super typhoons occur and districts with high population density and urbanization ratio exist. This study has focused on the comparison of the flood vulnerability ranking orders from different composite indicator outcomes by various aggregation schemes, and demonstrated that a selection of the better aggregation framework for constructing a vulnerability composite indicator is required because the different frameworks and methods can lead to quite different vulnerability ranking results than expected. In comparison of the two vulnerability

rank results based on the additive and the multiplicative composite indicators  $FVI_a(3)$  and  $FVI_m(3)$  from the three components  $EI$ ,  $SI$ , and  $CI$ , some administrative districts present the considerable ranking changes around 20 levels higher or lower in the total 54 ranking levels. It can be attributed to the functional feature differences in aggregation schemes. The additive aggregation function has higher compensability that the composite indicator is influenced by the three component values altogether, while the multiplicative aggregation function has lower compensability that decreases the indicator outcome by a low value of one of the three components. The vulnerability ranks based on  $FVI_a(2)$  and  $FVI_m(2)$  from the framework comprising the two assessment components  $CI$  and  $PI$  (combined by  $EI$  and  $SI$ ) are also compared with those based on  $FVI_a(3)$  and  $FVI_m(3)$  from the three assessment components. It is expected that the ranking results from  $FVI_a(2)$  and  $FVI_m(2)$  are more sensitive to the component indicator  $CI$  weighted by one-half than the other indicators  $EI$  and  $SI$  with one-quarter weight for each. The ranking changes can occur especially for the administrative districts with very high or low values of  $CI$ , and the considerable ranking changes are around 10 levels in the total 54 ranking levels in comparison of the two results by different assessment component frameworks. Such underestimated or overestimated vulnerability results by aggregation schemes may provide misleading information on decision making. When the four  $FVI$  outcomes for the 54 districts are classified into the three levels, such as high, middle, and low, and compared with an official hazard map by a government office, the 18 administrative districts ranked at Level H by the  $FVI_m(3)$  shows the best agreement with the FHA ranked at Class 1, whereas there is worse agreement for the additive composite indicators aggregated by higher compensability. It is more reasonable in the IPCC framework [2] that the region where all the assessment components increase in vulnerability can have a higher flood vulnerability rather than the flood vulnerability can be compensated for by any surplus values of some components. Additionally, the flood vulnerability indicators compiled from a more weighted component  $CI$  can be less robust in the concern that the assessment of coping is on the nature of more uncertainty since it is usually measured by behavior and politics rather than by data and observations [27]. In conclusion, a composite indicator aggregated from the three assessment components by the multiplicative utility function is recommended for the flood vulnerability assessment to climate change for this study site. It is expected that the proposed framework for constructing the flood vulnerability indicator can provide basis and precedence information on mitigation or adaptation policies to climate change.

As in previous studies [28–33], this study has evaluated the influence of construction frameworks on the composite indicator outcomes and additionally proposed the proper scheme by comparison with a flood hazard map for the study site. However, this study has the following limitations. Although a composite indicator is useful in decision making for multidimensional phenomena and multiple conflicting issues, it is difficult, or almost impossible, to have a precise mathematical scheme for the vulnerability assessment by a composite indicator because the vulnerability indicators might be technically problematic and have limitations and drawbacks in construction processes. In addition to the construction frameworks for the vulnerability indicators, the selection of proxy variables for assessment components has a large influence on the vulnerability outcomes. The proxy variables relevant to individual components need to be selected and identified by concerns of mutual independency, as well as representatives based on a complete understanding of the analysis system, since the preference independence among constituent assessment components is a necessary and sufficient condition for the existence of a proper composite indicator aggregated from them. There are a number of methods in normalization for data types and distribution, and this study uses a method that can conserve the value distribution of the original data. This study also adopts an equal weighting assumption for the proxy variables and assessment components for which the proper weighting coefficients need to be determined and assigned in a logical process as following some studies in the Korean Peninsula [34–36]. Differences and uncertainties in the normalization and weight determination methods can have another impact on composite indicator outcomes. The upcoming study is, therefore, required to scrutinize these important issues affecting composite indicator outcomes, particularly for

the selection of representative proxy variables through the multivariate analysis, and the uncertainty in normalization and weighting methods for each variable and component contributing to the analysis.

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## References

1. Intergovernmental Panel on Climate Change (IPCC). *The Regional Impacts of Climate Change: An Assessment of Vulnerability*; A special Report of IPCC Working Group II, Published for the Intergovernmental Panel on Climate Change; ISBN 92-9169-110-0; Watson, R.T., Zinyowera, M.C., Moss, R.H., Dokken, D.J., Eds.; Cambridge University Press: Cambridge, UK, 1997; p. 27.
2. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*; McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2001; p. 1032.
3. Cutter, S.L.; Mitchell, J.T.; Scott, M.S. Revealing the vulnerability of people and places: A case study of Georgetown County, South Carolina. *Ann. Am. Assoc. Geogr.* **2000**, *90*, 713–737. [[CrossRef](#)]
4. Brooks, N. *Vulnerability, Risk and Adaptation: A Conceptual Framework*; Tyndall Centre for Climate Change Working Paper 38; University of East Anglia: Norwich, UK, 2003; p. 20.
5. Turner, B.L.; Kasperson, R.E.; Matson, P.A.; McCarthy, J.J.; Corell, R.W.; Christensen, L.; Eckley, N.; Kasperson, J.X.; Luers, A.; Martello, M.L.; et al. A framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 8074–8079. [[CrossRef](#)] [[PubMed](#)]
6. O'Brien, K.; Eriksen, S.; Schjolen, A.; Nygaard, L. *What's in a Word? Conflicting Interpretations of Vulnerability in Climate Change Research*; CICERO Working Paper 2004:04; CICERO, Oslo University: Oslo, Norway, 2004; p. 16.
7. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007; p. 976.
8. Fussler, H.-M.; Klein, R.J.T. Climate change vulnerability assessments: An evolution of conceptual thinking. *Clim. Chang.* **2006**, *75*, 301–329. [[CrossRef](#)]
9. Fussler, H.-M. Vulnerability: A generally applicable conceptual framework for climate change research. *Glob. Environ. Chang.* **2007**, *17*, 155–167. [[CrossRef](#)]
10. O'Brien, G.; O'Keefe, P.; Meena, H.; Rose, J.; Wilson, L. Climate adaptation from a poverty perspective. *Clim. Policy* **2008**, *8*, 194–201. [[CrossRef](#)]
11. Preston, B.L.; Smith, T.F.; Brooke, C.; Gorrard, R.; Measham, T.G.; Withycombe, G.; Beveridge, B.; Morrison, C.; McInnes, K.; Abbs, B. *Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group*; Report prepared for the Sydney Coastal Councils Group; CSIRO: Canberra, Australia; Sydney Coastal Councils Group Inc.: Sydney, Australia, 2008; p. 117.
12. Organisation for Economic Co-Operation and Development (OECD). The OECD-JRC handbook on practices for developing composite indicators. In Proceedings of the OECD Committee on Statistics, Paris, France, 7–8 June 2004.
13. Allison, E.H.; Perry, A.L.; Badjeck, M.C.; Adger, W.N.; Brown, K.; Conway, D.; Halls, A.S.; Pilling, G.M.; Reynolds, J.D.; Andrew, N.L.; et al. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.* **2009**, *10*, 173–196. [[CrossRef](#)]
14. Yusuf, A.A.; Francisco, H.A. *Climate Change Vulnerability Mapping for Southeast Asia*; Economy and Environment Program for Southeast Asia (EEPSEA): Singapore, 2009; p. 26.

15. Balica, S.F.; Wright, N.G. Reducing the complexity of the flood vulnerability index. *Environ. Hazards* **2010**, *9*, 321–339. [CrossRef]
16. Balica, S.F.; Douben, N.; Wright, N.G. Flood Vulnerability Indices at Varying Spatial Scales. *Water Sci. Technol.* **2009**, *60*, 2571–2580. [CrossRef] [PubMed]
17. Balica, S.F.; Wright, N.G.; Van Der Meulen, F. A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Nat. Hazards* **2012**, *64*, 73–105. [CrossRef]
18. Weis, S.W.M.; Agostini, V.N.; Roth, L.M.; Gilmer, B.; Schill, S.R.; Knowles, J.E.; Blyther, R. Assessing vulnerability: An integrated approach for mapping adaptive capacity, sensitivity, and exposure. *Clim. Chang.* **2016**, *136*, 615–629.
19. Moss, R.H.; Brenkert, A.L.; Malone, E.L. *Vulnerability to Climate Change: A Quantitative Approach*; PNNL-SA-33642; Pacific Northwest National Laboratory: Richland, WA, USA, 2001; p. 70.
20. Allen Consulting Group. *Climate Change: Risk and Vulnerability: Promoting an Efficient Adaptation Response in Australia*; Final Report to the Australian Greenhouse Office; Department of the Environment and Heritage: Canberra, Australia, 2005; p. 159.
21. Cochrane, K.; De Young, C.; Soto, D.; Bahri, T. *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge*; FAO Fisheries and Aquaculture Technical Paper No. 530; FAO: Rome, Italy, 2009; p. 212.
22. Schauser, I.; Otto, S.; Schneiderbauer, S.; Harvey, A.; Hodgson, N.; Robrecht, H.; Morchain, D.; Schrandt, J.-J.; Khovanskaia, M.; Celikyilmaz-Aydemir, F.; et al. *Urban Regions: Vulnerabilities, Vulnerability Assessments by Indicators and Adaptation Options for Climate Change Impacts—Scoping Study*; Technical Paper 2010/12; The European Topic Centre on Air and Climate Change (ETC/ACC): Bilthoven, The Netherlands, 2010; p. 200.
23. Chang, L.-F.; Huang, S.-L. Assessing urban flooding vulnerability with an emergy approach. *Landsc. Urban Plan.* **2015**, *143*, 11–24. [CrossRef]
24. Kablan, M.K.A.; Dongo, K.; Coulibaly, M. Assessment of social vulnerability to flood in urban Côte d'Ivoire using the MOVE framework. *Water* **2017**, *9*, 292. [CrossRef]
25. Liu, D.; Hao, S. Ecosystem health assessment at county-scale using the pressure-state-response framework on the Loess Plateau, China. *Int. J. Environ. Res. Public Health* **2017**, *14*, 2. [CrossRef] [PubMed]
26. Ministry of the Interior and Safety of Korean Government. Available online: <http://www.mois.go.kr/frt/a01/frtMain.do> (accessed on 20 February 2018).
27. Adger, W.N.; Vincent, K. Uncertainty in adaptive capacity. *C. R. Geosci.* **2005**, *337*, 399–410. [CrossRef]
28. Clemen, R.T. *Making Hard Decisions: An Introduction to Decision Analysis*; Duxbury Press: Boston, MA, USA, 1996.
29. Rygel, L.; O'sullivan, D.; Yarnal, B. A method for constructing a social vulnerability index: An application to hurricane storm surges in a developed country. *Mitig. Adapt. Strateg. Glob. Chang.* **2006**, *11*, 741–764. [CrossRef]
30. Munda, G.; Nardo, M. Noncompensatory/nonlinear composite indicators for ranking countries: A defensible setting. *Appl. Econ.* **2009**, *41*, 1513–1523. [CrossRef]
31. Hinkel, J. Indicators of vulnerability and adaptive capacity: Towards a clarification of the science-policy interface. *Glob. Environ. Chang.* **2011**, *21*, 198–208. [CrossRef]
32. Tonmoy, F.N.; EL-Zein, A.; Hinkel, J. Assessment of vulnerability to climate change using indicators: A meta-analysis of the literature. *Wiley Interdiscip. Rev. Clim. Chang.* **2014**, *5*, 775–792. [CrossRef]
33. El-Zein, A.; Tonmoy, F.N. Assessment of vulnerability to climate change using a multi-criteria outranking approach with application to heat stress in Sydney. *Ecol. Indic.* **2015**, *48*, 207–217. [CrossRef]
34. Jun, K.S.; Sung, J.Y.; Chung, E.S.; Lee, K.S. Development of spatial water resources vulnerability index considering climate change impacts. *Sci. Total Environ.* **2011**, *409*, 5228–5242. [CrossRef] [PubMed]
35. Jun, K.S.; Chung, E.S.; Kim, Y.G.; Kim, Y. A fuzzy multi-criteria approach to flood risk vulnerability in South Korea by considering climate change impacts. *Expert Syst. Appl.* **2013**, *40*, 1003–1013. [CrossRef]
36. Lee, G.M.; Jun, K.S.; Chung, E.S. Integrated multi-criteria flood vulnerability approach using fuzzy TOPSIS and Delphi technique. *Nat. Hazard Earth Syst. Sci.* **2013**, *13*, 1293–1312. [CrossRef]

