Scientific Research Publishing

Journal of Water Resource and Protection, 2024, 16, 767-779
https://www.scirp.org/journal/jwarp
ISSN Online: 1945-3108
ISSN Print: 1945-3094

National Drought Vulnerability Assessment for Preemptive Drought Response

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How to cite this paper: Kim, S., Jo, D. and Park, J. (2024) National Drought Vulnerability Assessment for Preemptive Drought Response. *Journal of Water Resource and Protection*, **16**, 767-779.
https://doi.org/10.4236/jwarp.2024.1612043

Received: October 24, 2024
Accepted: November 30, 2024
Published: December 3, 2024

Abstract

South Korea has experienced drought cycles every 5 to 7 years since 1970, with a severe drought lasting five years from 2013 to 2018. To prepare for these recurring drought risks, the South Korean government deliberated and approved a comprehensive drought response plan in August 2017. As part of this plan, research on a national-scale drought vulnerability assessment and the development of a drought vulnerability map was initiated to enhance proactive drought response measures. The objective of this study is to develop a methodology for assessing drought vulnerability, conduct a nationwide drought vulnerability evaluation, and visualize the results through a drought vulnerability map to assist in decision-making and information sharing. The drought vulnerability assessment was based on the water supply capacity of regional water systems under different scenarios, with exposure, sensitivity, and secondary water resource capacity quantified and weighted in the evaluation. As a result of conducting a drought vulnerability assessment on 250 municipalities nationwide, regions that rely primarily on river or groundwater source for water intake were found to be more vulnerable to drought than those supplied by dams. Furthermore, municipalities located along the east coast, where rivers tend to be steep and short, exhibited higher vulnerability to drought.

Keywords

Drought Vulnerability, Drought Response Capacity, Drought Vulnerability Map

1. Introduction

The increasing variability in hydrological and climatic conditions due to climate change is exacerbating the uncertainty surrounding water resource management.

Over the past 67 years (from 1965 to 2021), South Korea's total amount of water resources has increased from 110 billion cubic meters to 126.4 billion cubic meters per year annually, a 1.2-fold rise [1]. However, the population has surged from 2.9 million to 5.2 million, representing a 1.8-fold increase, while the demand for domestic, industrial, and agricultural water has escalated by 4.8 times, from 5.1 billion cubic meters to 24.4 billion cubic meters annually. These growing demands have led to an increase in water conflicts among stakeholders regarding the use and regulation of limited water resources. The return period of extreme droughts in South Korea was generally estimated at 30 to 50 years, with clear distinctions observed between years experiencing regional droughts and those marked by nationwide droughts [2].

According to the 2019 Abnormal Climate Report [3], South Korea has experienced drought cycles every 5 to7 years since 1970, with a severe drought lasting five years from 2013 to 2018. The national average precipitation in 2015 was 965 mm, just 72 percent of the normal level, marking the third-lowest on record. Similarly, precipitation within the multi-purpose dam catchment areas was only 66 percent of the normal level.

To prepare for these recurring drought risks, the South Korean government was deliberated and approved a comprehensive drought response plan in August 2017. The plan aimed to establish fundamental solutions for areas prone to chronic drought while also strengthening the disaster response capabilities of both central and local governments. As part of this plan, research on a national-scale drought vulnerability assessment and the development of drought vulnerability map was initiated to enhance proactive drought response measure.

Drought vulnerability is typically estimated by a combination of relevant, subjectively weighted vulnerability factors [4]-[8]. Blauhut *et al.* [8] provided insights into sector specific differences in drought risk on a pan-European scale, and also focused on an approach that allows mapping the hazard level to communicate complex spatial and temporal information. Naumann *et al.* [9] proposed the Drought Vulnerability Indicator (DVI), a composite index of drought vulnerability, to reflect various indicators assessed across four components determined by drought vulnerability. Rajsekhar *et al.* [10] developed a drought risk map by incorporating a drought index that accounts for meteorological factors and socio-economic elements vulnerable to disasters, there by presenting a practical methodology for drought assessment.

The objective of this study is to develop a methodology for assessing drought vulnerability, conduct a nationwide drought vulnerability evaluation, and visualize the results through a drought vulnerability map to assist in decision-making and information sharing. The drought vulnerability assessment was based on regional water supply capacity under various drought scenarios, with additional weighting given to exposure, sensitivity, and secondary water resource capacity.

2. Methods

The Intergovernmental Panel on Climate Change defines vulnerability as a function of the characteristics, scale, and speed of climate variability that a system is exposed to, combined with the system's sensitivity and adaptive capacity [11]. This definition incorporates both external factors, such as the system's exposure to climate variability, and internal factors like sensitivity and adaptive capacity to cope with those stressors. Applying this concept, the evaluation framework for drought vulnerability in this study is divided into four categories: drought response capacity, exposure, sensitivity, and secondary water resource capacity. Drought vulnerability (DV) is given as

$$DV = RC \times W_1 \times W_2 \times W_3$$

where RC represents the drought response capacity, W_1 represents drought exposure coefficient, W_2 represents drought sensitivity coefficient, and W_3 represents secondary water resource capacity coefficient.

Drought response capacity is assessed based on the number of days water supply can be sustained during a drought, with scores ranging from 10 to 100. The coefficients for exposure, sensitivity, and secondary water resource capacity were determined using the Analytical Hierarchy Process (AHP) based on surveys of 100 drought experts in South Korea. Exposure was assigned the highest weighting at 20 percent, followed by sensitivity at 18 percent, and secondary water resource capacity at 12 percent. The consistency index (CI) of the AHP survey was 0.032, indicating a high level of reliability.

The final drought vulnerability scores were categorized into five levels as **Table 1**. A drought vulnerability score below 30 indicates very low vulnerability, 30 to less than 50 indicates low vulnerability, 50 to less than 70 indicates moderate vulnerability, 70 to less than 90 indicates high vulnerability, and 90 or above indicates very high vulnerability.

Table 1. Drought vulnerability assessment score ratings.

Score Range	Drought Vulnerability Score				
	<30	30 - 50	50 - 70	70 - 90	>90
Vulnerability Grade	I (very low)	II (low)	III (moderate)	IV (high)	IV (very high)

2.1. Drought Response Capacity

Drought response capacity was evaluated by calculating the potential number of days water can be supplied during a drought, based on water balance analysis of each water source. A water balance model, incorporating regional water supply systems and drought scenarios, was developed to estimate the number of days water supply could be maintained under various drought frequencies. Based on the investigation of major drought damages that occurred in the past in South Korea, the return period of the drought scenario was set as 30 years, with the maximum drought duration set as 730 days. The water balance analysis model uses daily time series data for natural flow, supply (from dams, weirs, and agricultural reservoirs), water intake, and return flow (from wastewater treatment and paddy drainage). The estimation of natural flow was simulated using the GR4J continuous rainfall-runoff model [12], which has four parameters: Maximum soil moisture storage, Water exchange coefficient, Maximum routing store storage, and Flow delay. The supply is based on the discharge from dams, weirs and agricultural reservoirs. Unmeasured agricultural reservoirs were estimated by applying the same storage rate changes as measured reservoirs. Water intake data includes domestic and industrial water intake from water intake stations, and river water intake was based on authorized river water usage. The return flow was calculated based on the performance data of wastewater treatment plants, while paddy drainage was estimated using a drainage model.

To design a drought scenario, the watershed average precipitation was calculated using Thiessen method based on daily precipitation time series data from 60 weather stations nationwide from 1973 to 2020. Additionally, a bivariate drought frequency analysis was performed using the Copula function, which allows simultaneous consideration of the drought duration and severity. Through this drought frequency analysis, the annual precipitation deficit for a 12-month drought duration and a 30-year drought frequency was estimated. The precipitation time series reflecting the drought scenario was then used as input data for the rainfall runoff model. Through the water balance analysis model, the number of days of available water supply is estimated, and this number is converted into scores based on the defined ranges of possible days, as shown in **Table 2**.

2.2. Drought Exposure

The drought exposure was measured by combining the frequency and severity of drought occurrences in each region. The standardized Precipitation-Evaporation Index (SPEI), which considers variability in both precipitation and temperature, was used to evaluate the drought occurrence frequency and average drought severity. SPEI calculates the Potential Evapotranspiration (PET) using data such as precipitation and temperature, and expresses the results as an index over a specified time unit. The Potential Evapotranspiration (PET) was estimated using the empirical Hargreaves method. Drought conditions based on the SPEI range are classified as follows: values of −2.0 or below indicate Extreme Dry, −2.0 to −1.5 represent Severely Dry, −1.5 to −1.0 indicate Moderate Dry, −1.0 to −0.5 represent Slightly Dry, −0.5 to 0.5 indicate Normal, 0.5 to 1.0 represent Slightly Wet, 1.0 to 1.5 indicate Moderately Wet, 1.5 to 2.0 represent Very Wet, and value above 2.0 indicate Extremely Wet.

Table 2. Drought response capacity scores by range of feasible water supply days.

Range	Feasible water supply days									
	0 - 75	76 - 150	151 - 225	226 - 300	301 - 375	376 - 450	451 - 525	526 - 600	601 - 675	676 - 730
Score	100	90	80	70	60	50	40	30	20	10

In this study, the SPEI with a duration of 6 months was used to assess medium- to long-term drought vulnerability. The Drought Hazard Index (DHI) was calculated using a rating technique that incorporates the frequency of drought occurrences and the average severity as factors [10], as shown in **Figure 1**. The rating method classified drought severity into four levels and calculates the occurrence probability for each level to determine the corresponding weights. In the case of drought occurrence frequency, the maximum and minimum occurrence probabilities for each drought severity are divided into four equal parts, with weights of 4, 3, 2, and 1 are assigned, as shown in **Table 3**.

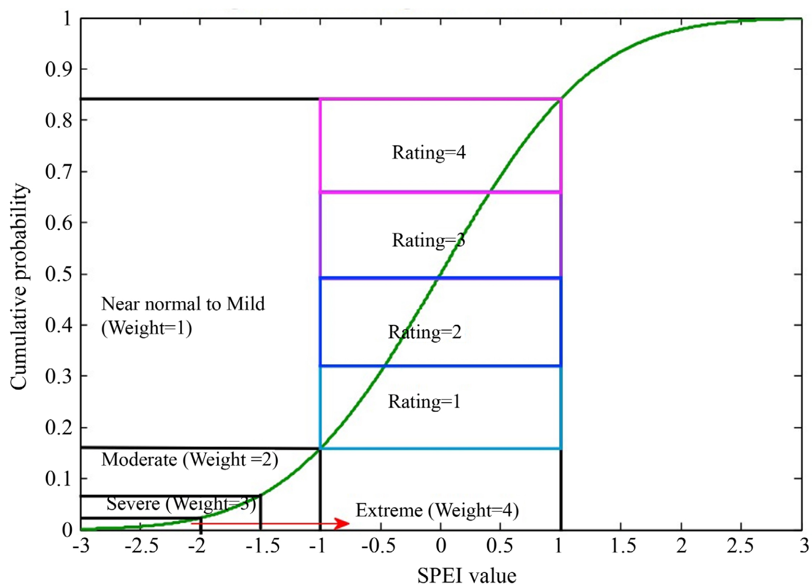

Figure 1. Weight and rating scheme based on the cumulative distribution of SPEI values [10].

Table 3. Drought severity and frequency weights using the SPEI (6-month duration).

Drought Severity	Range of SPEI (6)	Severity Weight	Range of Frequency (%)	Frequency Weight	
Near Normal Drought	−1.0 ≤ SPEI ≤ −0.5	1 (*NDr*)	3x - max.	4	(*NDw*)
			2x - 3x	3	
			x - 2x	2	
			min. - x	1	
Moderate Drought	−1.5 ≤ SPEI ≤ −1.0	2 (*MDr*)	3x - max.	4	(*MDw*)
			2x - 3x	3	
			x - 2x	2	
			min. - x	1	
Severe Drought	−2.0 ≤ SPEI ≤ −1.5	3 (*SDr*)	3x - max.	4	(*SDw*)
			2x - 3x	3	
			x - 2x	2	
			min. - x	1	

Continued

Extreme Drought	SPEI < −2.0	4 (*EDr*)	3x - max.	**4**	(*Edw*)
			2x - 3x	**3**	
			x - 2x	**2**	
			min. - x	**1**	

x = (max. of occurrence probability − min. of occurrence probability)/4.

The Drought Hazard Index (DHI) is given as

$$DHI = (NDr \times NDw) + (MDr \times MDw) + (SDr \times SDw) + (EDr \times EDw)$$

Where *NDr* represents the rating for drought severity falling under the "Near normal drought" category, *NDw* represents the weight for drought severity falling under the "Near normal drought" category, *MDr* represents the rating for drought severity falling under the "Moderate drought" category, *MDw* represents the weight for drought severity falling under the "Moderate drought" category, *SDr* represents the rating for drought severity falling under the "Severe drought" category, *SDw* represents the weight for drought severity falling under the "Severe drought" category, *Edr* represents the rating for drought severity falling under the "Extreme drought" category, and *Edw* represents the weight for drought severity falling under the "Extreme drought" category.

The drought exposure coefficient values range from a maximum of 1.20 to a minimum of 1.00, with higher exposure corresponding to larger values, as shown in **Table 4**.

2.3. Drought Sensitivity

The drought sensitivity refers to the potential impact of a drought on a region based on its water demand for domestic and industrial uses. Regions with higher water demand are considered more sensitive to drought impacts. Sensitivity coefficient were assigned values between 1.00 and 1.18, with regions exhibiting higher water demand receiving higher coefficient, as shown in **Table 5**.

Table 4. Drought exposure coefficient.

Range	Drought exposure based on severity and frequency (DHI)									
	37 - 40	34 - 36	31 - 33	28 - 30	25 - 27	22 - 24	19 - 21	16 - 18	13 - 15	10 - 12
Coefficient	1.20	1.17	1.14	1.12	1.10	1.08	1.06	1.04	1.02	1.00

Table 5. Drought sensitivity coefficient.

Range	Water demand for domestic and industrial uses (thousand m^3/day)									
	>13.0	10.0 - 13.0	8.5 - 10.0	7.0 - 8.5	6.0 - 7.0	5.0 - 6.0	4.0 - 5.0	3.0 - 4.0	1.5 - 3.0	0 - 1.5
Coefficient	1.18	1.16	1.14	1.12	1.10	1.08	1.06	1.04	1.02	1.00

2.4. Secondary Water Resource Capacity

Secondary water resource capacity refers to the ability of secondary infrastructure (such as reservoir and groundwater) to support the primary water source during droughts. In order to evaluate the secondary water supply capacity, which can directly affect the mitigation and recovery of drought damage during droughts, the available capacity of agricultural reservoirs and the potential for groundwater development were designated as secondary water resources. The secondary water resource capacity coefficient was calculated by comparing the secondary water supply capacity to the amount of water demand for domestic and industrial uses in the target area.

W_3 = Secondary water resource capacity/Domestic and industrial water usage

After determining the minimum and maximum range of the secondary water resource capacity, it is divided into 10 grades, with the lowest value assigned as 1.00 and the highest value assigned as 1.12, as shown in Table 6.

Table 6. Coefficient of secondary water resource capacity.

Range	Secondary water capacity to domestic and industrial water demand									
	0 - 0.01	0.1 - 0.25	0.25 - 1	1 - 2	2 - 5	5 - 10	10 - 20	20 - 35	35 - 70	>70
Coefficient	1.12	1.11	1.09	1.08	1.06	1.05	1.03	1.02	1.01	1.00

3. Results

Drought response capacity, drought exposure, drought sensitivity, and secondary water resource capacity were evaluated for 250 municipalities in South Korea, as shown in Figure 2.

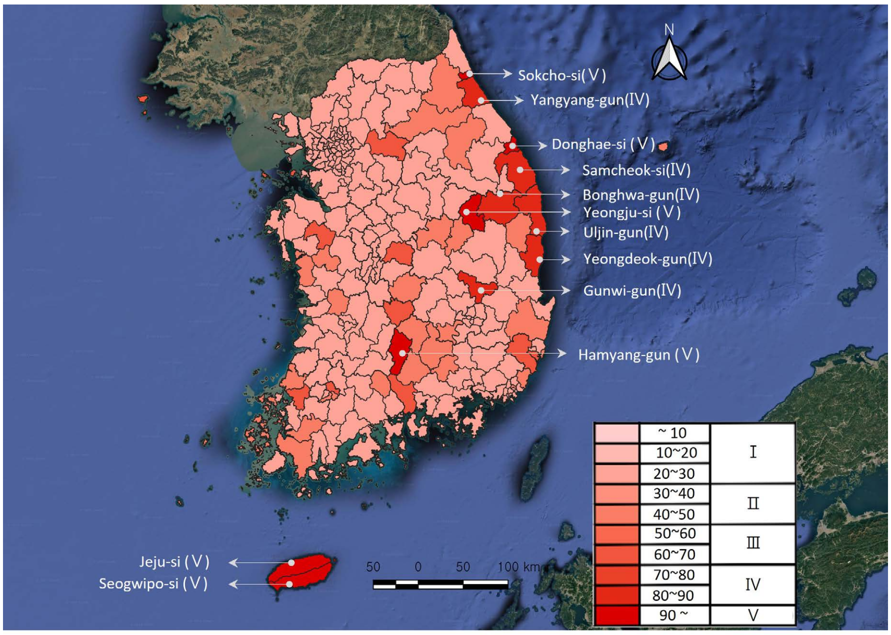

Figure 2. Results of the national drought vulnerability assessment.

As a result of the drought response capacity evaluation, out of 250 municipalities, one municipality (Sokcho-si) was able to supply water for 75 days or less (100 points) during a drought. One municipality (Donghae-si) could supply water for 76 to 150 days (90 points), six municipalities for 151 to 225 days (80 points), four municipalities for 226 to 300 days (70 points), and three municipalities for 301 to 375 days (60 points) during a drought.

The results of drought exposure assessment indicated that two municipalities (Gunwi-gun and Uiseong-gun) had a DHI of 37 - 40 (Coefficient 1.20), while one municipality (Yeongcheon-si) had a DHI of 34 - 36 (Coefficient 1.17). The municipalities with a DHI of 31 - 33 (Coefficient 1.14) numbered 14, those with a DHI of 28 - 30 (Coefficient 1.12) numbered 7, those with a DHI of 25 - 27 (Coefficient 1.10) numbered 10.

The drought sensitivity assessment results indicated that there were 20 municipalities with a domestic and industrial water usage of 13,000 m^3 per day or more (Coefficient 1.18), 12 municipalities with usage between 10,000 and 13,000 m^3 per day (Coefficient 1.16), 20 municipalities with usage between 8500 and 10,000 m^3 per day (Coefficient 1.14), and 42 municipalities with usage between 7000 and 8500 m^3 per day (Coefficient 1.12).

The evaluation results of the secondary water resource capacity indicated that there were 34 municipalities with a capacity coefficient 1.12, 32 municipalities with a capacity coefficient 1.11 and 39 municipalities with a capacity coefficient 1.09.

The integrated assessment of national drought vulnerability revealed that among 250 municipalities, 80% (201 municipalities) were categorized as very low vulnerability (Grade I), 11% (27 municipalities) as low vulnerability (Grade II), 4% (10 municipalities) as moderate vulnerability (Grade III), 2% (6 municipalities) as high vulnerability (Grade IV), and 2% (6 municipalities) as very high vulnerability (Grade V).

The municipalities classified with very high vulnerability (Grade V) were Sokcho-si, Donghae-si, Jeju-si, Seogwipo-si, Yeongju-si, and Hamyang-gun, as shown in **Table 7** and **Figure 3**. Sokcho-si was analyzed to have a water supply availability of 75 days out of a potential 730 days of drought. It relies primarily on river water as its main source, and the river serving as the main intake has a steep gradient and a short length, making it more vulnerable to drought. Additionally, as a tourist city with high demand for domestic water, it has been assessed as having high sensitivity.

Donghae-si receives water supply from dam reservoir, but in the event of a drought, only 102 days out of 730 days of water supply are possible. As a tourist city, the demand for domestic water is high, which makes it highly sensitive to drought. Jeju-si and Seogwipo-si rely primarily on groundwater as their main water source, and in case of drought, the amount of alternative water sources available is very limited, which leads to a high level of drought vulnerability. In Yeongju-si and Hamyang-gun, where rivers are the main water source, the number of day

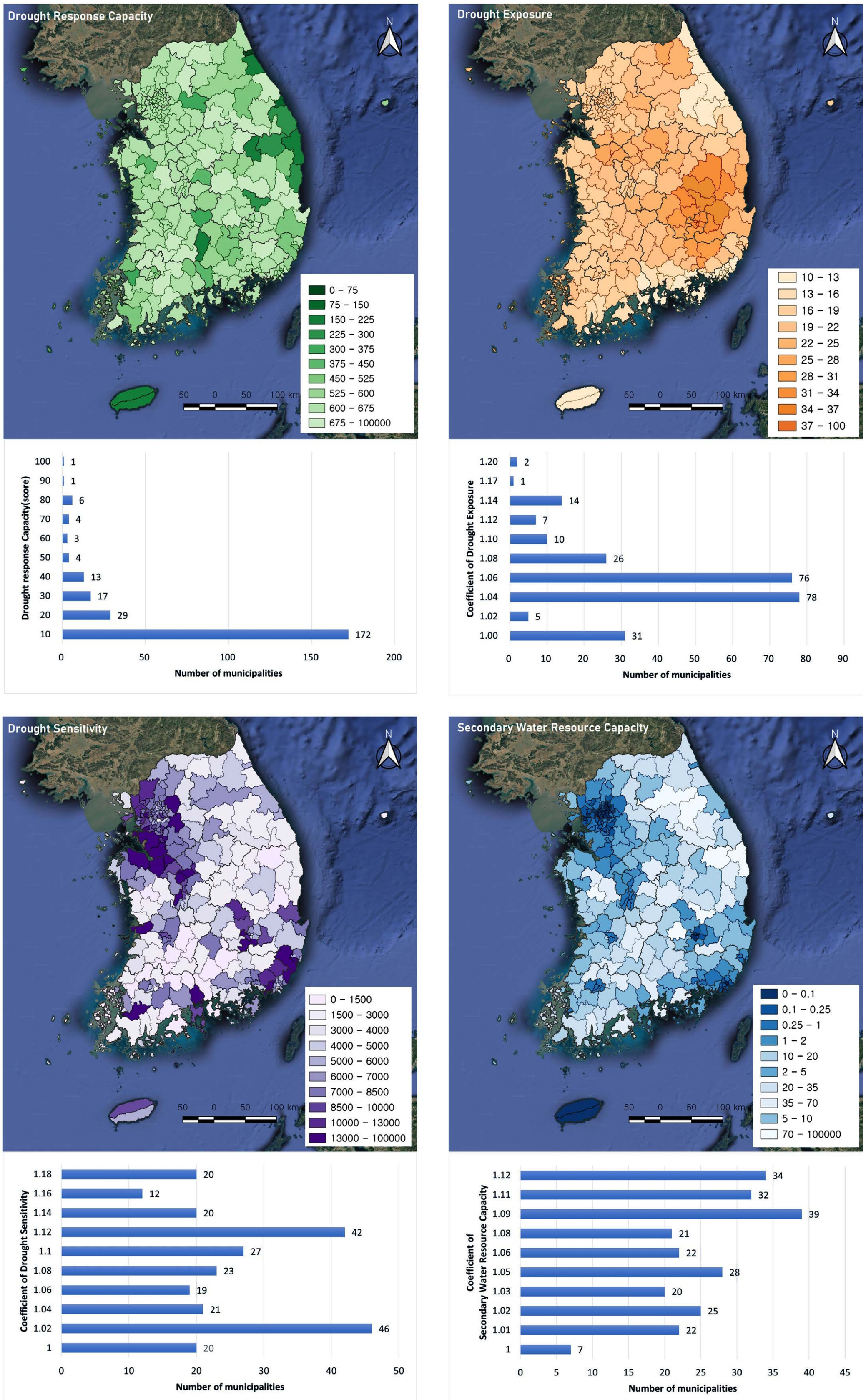

Figure 3. Results of drought vulnerability assessment.

Table 7. Results of drought vulnerability assessment (level IV and V).

Municipality	Drought Vulnerability		Drought Response Capacity	Drought Exposure	Drought Sensitivity	Secondary water resource capacity
	Score	level	Score	Coefficient	Coefficient	Coefficient
Sokcho-si	117	V	100	1.00	1.08	1.08
Donghae-si	103	V	90	1.00	1.08	1.06
Jeju-si	102	V	80	1.00	1.14	1.12
Seogwipo-si	97	V	80	1.00	1.08	1.12
Yeongju-si	91	V	80	1.06	1.02	1.05
Hamyang-gun	90	V	80	1.08	1.02	1.02
Uljin-gun	86	IV	80	1.06	1.02	1.00
Gunwi-gun	86	IV	70	1.20	1.02	1.00
Yangyang-gun	83	IV	80	1.00	1.02	1.02
Yeongdeok-gun	82	IV	70	1.12	1.02	1.03
Samcheok-si	76	IV	70	1.04	1.02	1.02
Bonghwa-gun	74	IV	70	1.06	1.00	1.00

water can be supplied during a drought is 191 and 164 days, respectively. Due to their low drought response capacity, their drought vulnerability was rated as level V.

The municipalities with high vulnerability (Grade IV) were assessed as Uljin-gun, Gunwi-gun, Yangyang-gun, Yeongdeok-gun, Samcheok-si, and Bonghwa-gun, as shown in Table 7 and Figure 3. Except for Samcheok-si, which receives it water supply from a dam reservoir, the other five municipalities rely mainly on river water and groundwater as their primary water source. Gunwi-gun was evaluated as having the highest exposure to drought nationwide, and Yeongdeok-gun was also assessed as having a high level of drought exposure.

4. Discussion

The assessment of drought response capabilities indicated that municipalities relying on groundwater or river water as their primary water source exhibited lower drought water supply capacity compared to those utilizing dam reservoirs.

The drought vulnerability assessment was based on the water supply capacity of regional water systems under different scenarios, with exposure, sensitivity, and secondary water resource capacity quantified and weighted in the evaluation. Drought response capacity is evaluated by calculating the number of days water can be supplied during a drought, using water balance analysis that considers regional water supply systems. Drought exposure is assessed by calculating the Drought Hazard Index (DHI), which takes into account both frequency and severity of drought events. Drought sensitivity is measured by the total usage of domestic and industrial water, referred to as domestic and industrial water demand. Secondary water resource capacity is assessed by comparing the region's potential for groundwater development and reservoir storage with the local demand for domestic and industrial water, providing an estimate of additional water resources that could be utilized during a drought.

Drought sensitivity was observed to be elevated in areas with large industrial complexes, popular tourist destinations, and densely populated urban areas, where industrial and domestic water demands are markedly high. The capacity of secondary water sources is assessed based on domestic and industrial water usage volumes in each region, suggesting that areas with smaller populations or lower industrial water demand may receive higher evaluation in secondary water source capacity. Drought exposure is measured using historical data on drought frequency and severity, which may lead to variations in assessment outcomes depending on the period under review.

Especially, recent changes in climate have led to increased regional and seasonal variations in precipitation, with rainfall becoming more concentrated in specific areas. As a result, localized droughts are occurring more frequently. Regions that are chronically affected by drought due to their topographical characteristics are experiencing escalating damage. In this study, drought exposure was assessed using historical meteorological data and the current level of drought vulnerability was evaluated. However, this assessment does not predict future changes in drought occurrence. Although past drought patterns suggest that the frequency and severity of droughts will likely increase in the future, this assessment does not reflect the potential impact of climate change on drought trends.

Therefore, to develop a dynamic drought vulnerability map, it is essential to establish a digital water supply and demand map and integrate it with a water cycle assessment system. This would enable the creation of a platform capable of monitoring, evaluating, and forecasting drought response capacity. Such a web-based water cycle platform can provide valuable decision-support information, helping local governments proactively enhance their drought response capabilities in the context of climate change.

5. Conclusions

The national-scale vulnerability assessment not only supports decision-making for drought response policies but also aims to enhance the ability of local governments to actively respond to droughts. To achieve this, a methodology for evaluating drought vulnerability has been established.

As a result of conducting a drought vulnerability assessment on 250 municipalities nationwide, regions that rely primarily on river or groundwater source for water intake were found to be more vulnerable to drought than those supplied by dams. Furthermore, municipalities located along the east coast, where rivers tend to be steep and short, exhibited higher vulnerability to drought.

Drought response capacity, represented by the number of days water can be supplied during drought, was assessed to be lower when rivers or groundwater are the primary sources of water compared to receiving water from dam reservoirs. In addition, municipalities located on the east coast, where rivers are steep and short, exhibited higher vulnerability to drought.

To improve drought resilience, the most effective measure is to implement strategies that extend the number of days water can be supplied during a drought. Additionally, securing secondary water resources that can be utilized during drought periods would significantly enhance drought response capabilities.

Acknowledgements

This work was supported by Korea Environment Industry & Technology Institute (KEITI) through Water Management Program for Drought, funded by Korea Ministry of Environment (MOE) (2480000175).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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