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Assessment of Agricultural Drought Vulnerability with Focus on Upland Fields and Identification of Primary Management Areas

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Abstract: Robust water management systems are crucial for sustainable water use, particularly considering rapidly changing, ever-improving water supply system technologies. However, the establishment of specific management standards in upland fields is challenging, as several types of crops are cultivated in upland fields. Hence, the timing and required amount of water vary greatly, further rendering drought response challenging. In this study, we evaluated the agricultural drought vulnerability of South Korean upland fields, considering the lack of water resources, to establish preliminary drought damage prevention measures. The Technique for Order of Preference method was used for the drought vulnerability assessment, and the assessment indicators used were annual rainfall, number of dry days, upland field area, available soil water capacity, and groundwater usage. The 20 areas of highest vulnerability comprised large cultivation areas with minimal subsurface-water usage, except for areas where the number of dry days appeared to be the major factor for drought vulnerability. Damage caused by recurring droughts accumulated over time; thus, upland-field-oriented management may be required and can even be used in cases where insufficient drought information is available. Future studies can use the proposed method while considering assessment factors that describe upland field conditions.

Keywords: agricultural drought vulnerability; South Korean upland fields; multiple-criteria decision making; hybrid weights method; Technique for Order of Preference; modified Delphi method

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1. Introduction

Agriculture is one of the sectors with high water consumption. In South Korea, this sector is the largest water consumer, accounting for 61% of the total water usage of the country annually [1]. Most of the agricultural water managed by the irrigation network is used for rice cultivation, with 83.1% of water being used for the irrigation of paddy fields in 2020 [2]. This is because rice, the staple food of South Korea, is the most important crop in the country. However, unlike rice, the upland crops in South Korea rely mostly on groundwater as a water source. Groundwater is relatively easy to manage in quality and quantity; thus, it is used in the cultivation of most field crops. However, groundwater usage requires pumping which expends energy, limiting its use for low-value crop farming. As such, considering the relatively small-scale field cultivation in South Korea, rain is typically the only source of water available for upland crop cultivation. Irrigation fields equipped with water supply facilities cover 1400 km^2, accounting for only 18.5% of the country's total upland field area.

Water supply systems have changed rapidly beyond the scope of frequency-based management techniques that use cumulative measurements and historical data; therefore, the optimal use of the available water resources within the range of established management strategies has become challenging [3]. In paddy fields that rely on rainfall, ensuring a stable supply of water is challenging, owing to South Korea's climate. The distinct dry and rainy seasons cause recurring damage to upland fields, particularly in areas vulnerable to drought. Agricultural droughts occurred an average of 0.67 times/year (2000–2015), and the occurrence rate is steadily increasing. This was particularly evident from 2014 to 2019, when a series of continuous droughts resulted in substantial crop damage across large farm areas [4]. In 2018, 247.87 km^2 of farmland was damaged by droughts. In 2019, the national average number of rainy days during the rainy season was 15.8 days, lower than the annual average of 17.2 days, and precipitation was 197.6 mm, 54% of the annual average (366.4 mm) [5,6]. These data highlight the increasingly severe impacts of climate change on various aspects of agriculture, emphasizing the need for more efficient management strategies.

When a drought occurs, the water supply in domestic and industrial sectors, including agriculture, becomes scarce, resulting in extensive damages, such as withering crops and the drying of rice paddies [7]. Emergency water supply schemes, including decreased or alternative water supply or the transport of water from other water basins, are applied across sectors in stages [8,9]. Considering the severity of the latest drought damages in South Korea, major focus has been on the agricultural sector. While the domestic and industrial sectors have established efficient networks, this has not been developed for the water supply of the agricultural sector, particularly for upland fields [10,11]. In addition, establishing management standards is challenging, as there are several different types of crops cultivated in the upland fields, and the timing and required amount of water vary greatly. Therefore, it is difficult to respond to droughts, as various parameters, such as the type of cultivated crops and the cultivation period and scale, must be considered. To resolve this problem, it is important to customize water management measures to correspond to regional characteristics.

In terms of commonly used methods in the existing literature, most studies of drought vulnerability assessments have used the drought index based on rainfall as the main indicator. Fan et al. [12] used the drought index to conduct a drought vulnerability assessment of the Yangtze River Delta. Another study used the meteorological drought composite index (MDCI) of the standard precipitation index (SPI) and relative moisture index (RMI) to calculate the drought risk in western Bangladesh [13]. They selected seven factors that best reflected the agricultural sector, the sector most affected by drought, as vulnerability factors to evaluate agriculture drought vulnerability. A similar study of the London water system (England) used the likelihood of drought occurrence and resulting damages to assess the impact of climate change on drought risk [14]. The Dutch drought risk quantification method, designed to support national drought risk management, includes an assessment of drought-related socioeconomic outcomes and consideration of potential future scenarios [15,16]. Zhang et al. [17] investigated the correlation between meteorological, agricultural, and groundwater droughts. Several studies have been conducted on various aspects connected to droughts, such as public water supply [18], agricultural systems [19], and electricity production [20]. A drought vulnerability assessment should consider the interplay between various factors [21]. However, securing a variety of data on upland fields for agricultural drought vulnerability assessments is difficult. In addition, owing to the varying conditions and characteristics of crops cultivated in upland fields, their specific management standards are not applicable to all regions. Consequently, establishing an assessment approach for the drought vulnerability of upland fields and selecting priority management areas while considering the regional field characteristics is necessary.

Hence, we evaluated the drought vulnerability of upland fields in South Korea and identified the preliminary cultivation areas affected by water shortages for drought damage prevention. The drought vulnerability assessment method applied in this study can be used as a reliable framework to determine vulnerable sites and establish priority management areas in upland fields.

2. Materials and Methods

2.1. Study Procedure

The procedure applied for evaluating vulnerability, presented in Figure 1, consisted of selecting appropriate criteria, determining their weight, constructing a database, and deriving resulting priority areas. First, a survey was conducted to select appropriate criteria, and their weights were determined. Then, experts with experience in drought-related work and investigations surveyed water resources and agricultural areas using the modified Delphi surveying technique. The resulting data on the selected criteria were collected and analyzed to build a database. Considering that the data consisted of various units and scales, we standardized the formats and normalized our data by re-scaling to a range of 0–1. Additionally, data were standardized via the Z-score method, which distributes the data and forces both sides to be approximately 0, counteracting the problems caused by wide gaps in the data. Additionally, since the weights of individual factors considerably affected the assessment results, both the questionnaire survey and statistical methods were used for our calculations. For our database, the relevant data from 161 administrative districts in South Korea were obtained from the respective managing organizations, such as the Meteorological Administration, Rural Community Corporation, and Ministry of Environment (Water Resources Corporation). Finally, vulnerable areas were determined, and a drought vulnerability map was created using geographic information systems (GIS). As an assessment technique, we applied the Technique for Order of Preference (TOPSIS) method, which has recently been used in multiple-criteria decision making (MCDM) [22,23].

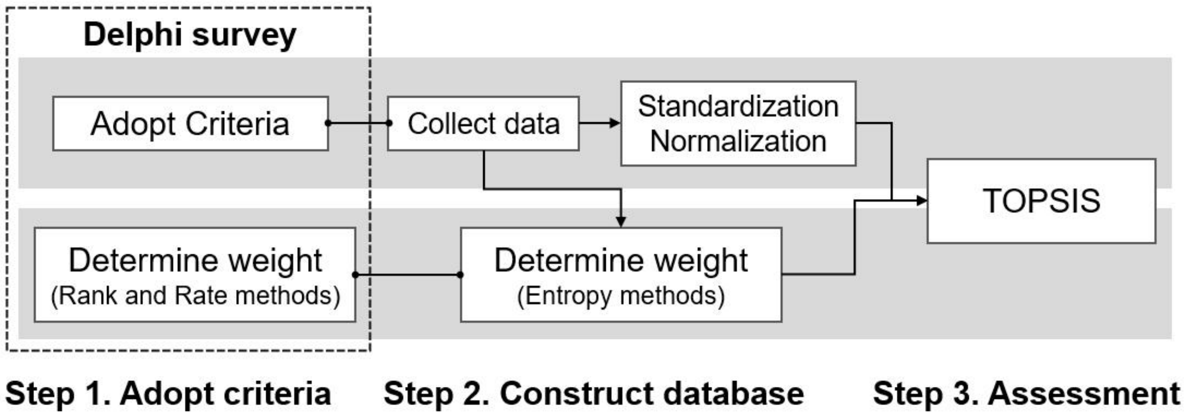

Figure 1. Illustration of the methodology used in this study (Technique for Order of Preference [TOPSIS]).

2.2. Survey Technique for Criteria Selection

Generally, drought vulnerability assessments determine relevant criteria and their importance, calculate the degree of inherent vulnerability, and derive the relative priority. Therefore, the selection of assessment factors and their weights are important for the accuracy of the assessment [24]. However, when determining these factors using a multi-criteria approach, uncertainties may arise owing to variation in expertise, objectivity, and methodology [25–27]. Therefore, in this study, we used the modified Delphi survey technique (Figure 2) in combination with a group of experts to select the appropriate criteria and their importance.

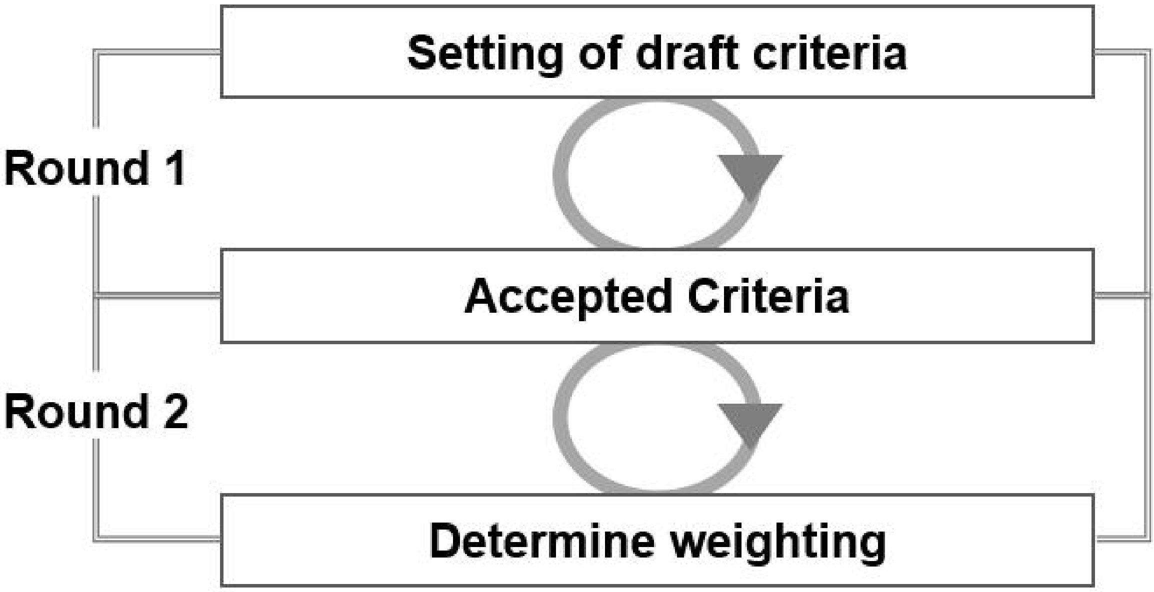

Figure 2. Illustration of the modified Delphi survey applied in this study.

The first step of the modified Delphi survey was to select the main factors for evaluating drought vulnerability based on the relevant literature. Then, individual anonymous surveys were conducted, ensuring objective results by preventing participating members from influencing each other [28]. In general, the success of the modified Delphi survey relies on a combination of expert opinions. In this study, a group of 13 panelists was formed, as Okoli and Pawlowski [29] had suggested that 10–18 panelists are sufficient. Participants indicated their opinions on each item by stating the degree to which they agreed with each statement. The variation in the collected opinions was analyzed, and the survey was redistributed among participants. While doing so, they were given an opportunity to reconsider their answers. This procedure was repeated several times until a consensus was reached on each item, with a consensus defined as an agreement of more than 80% of the participants' opinions. This study required a total of two rounds of the Delphi survey to determine the evaluation factors and weights.

2.3. Hybrid Weights Set

The weight of each factor represents its relative importance and can considerably affect the assessment results. Therefore, weight determination is one of the main concerns in MCDM studies and should be considered as part of the assessment process [30,31]. The weight of an assessment factor is one of the most crucial and challenging problems in applying the multiple-criteria decision analysis methodology and holds considerable uncertainty [32,33]. Several weight-related studies suggest that only adopting a single approach does not produce accurate results. Thus, different weights should be used to calculate and apply various approaches [34,35]. Thus, in this study, the weights were calculated through a principal component analysis of the results of our expert surveys. After conducting the surveys, we determined the weight of each factor using both the ranking and ratio methods, which are the two representative weighting methods.

Weights calculated through the ranking method were ranked by importance for each given variable. To quantify this, each survey participant was asked to rank factors by importance from highest to lowest. The rank of the factor was determined using the same ranking system, and the resulting ranks were converted as follows: Rank 1 was converted to m = 1; Rank 2 was converted to m = 2; and so on. These converted ranks were then compiled using Equation (1), and their weights (w_i^{Rank}) were calculated using Equation (2).

$$r_i = \sum_{j=1}^{n} r_{ij} \tag{1}$$

$$w_i^{Rank} = r_i / \sum_{i=1}^{m} r_i \tag{2}$$

where r_i is the sum of the conversion order of factor i, r_{ij} is the conversion order of factor i determined by panel j, n is the number of panelists participating in the survey, and m is the total number of factors.

In the ratio method, we used a questionnaire to compare the variables, evaluate their importance, and allocate their weights. The survey participants provided each factor a weight value between 0 and 1. The sum of the weights of all variables was equal to the maximum of the given range. A factor close to the lower limit (0) indicated little importance and, conversely, the maximum value (1) corresponded to the highest importance. The weights determined by the rating method (w_i^{Rate}) were calculated using Equations (3) and (4), and the weight was determined by the survey (w_i^{SUR}) using Equation (5). Here, objective weights by ranking method and subjective weights by rating method were given equal relative importance to avoid disproportionate opinions.

$$r_{ij} = p_{ij} / \sum_{i=1}^{m} p_{ij} \tag{3}$$

$$w_i^{Rate} = \sum_{j=1}^{n} r_{ij} / \sum_{j=1}^{n} \sum_{i=1}^{m} r_{ij} \tag{4}$$

$$w_i^{SUR} = \left(w_i^{Rank} + w_i^{Rate} \right) / \sum_{i=1}^{m} \left(w_i^{Rank} + w_i^{Rate} \right) \tag{5}$$

where r_{ij} is the weight of factor i determined by panel j, w_i^{Rate} is the weight of factor i determined by the rating method, and w_i^{SUR} is the weight of factor i determined by the rating method.

Shannon's entropy method is one of the most commonly used methods for determining weights in related studies. Shannon and Weaver [36] proposed the entropy concept, a measure of uncertainty of information, in terms of the probability theory [37]. Because the entropy concept is well-suited for measuring the relative contrast intensities of criteria to represent the average intrinsic information transmitted to the decision maker, our study used Shannon's entropy method, in which *H(P)* is the entropy value, with p_{ij} being the probability of the joint occurrence of the first event, i, and the second, j. The only function that satisfies these properties is as follows:

$$H(P) = -\sum_{i} p_{ij} \log(p_{ij}) \tag{6}$$

Shannon's concept can be used as a means of calculating weights using the following steps:
Step 1: Normalize the assessment indicator:

$$p_{ij} = \frac{x_{ij}}{\sum_i x_{ij}} \tag{7}$$

Step 2: Calculate the entropy measure of each index:

$$e_j = -K \sum_{i=1}^{m} P_{ij} \ln(P_{ij}) \tag{8}$$

where $K = (\ln(m))^{-1}$.

Step 3: Define the divergence:

$$div_j = 1 - e_j \quad (9)$$

The higher the value of div_j, the more important the criterion *j*.

Step 4: Obtain the normalized weights of all indices:

$$w_i^{ENT} = \frac{div_j}{\sum_j div_j} \quad (10)$$

The hybrid weight (w_i) of each factor was calculated using the following equation:

$$w_i = w_i^{SUR} + w_i^{ENT} \quad (11)$$

2.4. TOPSIS Method

The TOPSIS method proposed by Hwang and Yoon [22] has been widely used for various recent vulnerability assessments [38,39]. TOPSIS is a concept that preferentially selects an alternative that is closest to the positive ideal solution (PIS) and farthest from the negative ideal solution (NIS). It is a technique used for inducing rational human choice, while simultaneously considering the best and worst alternatives [40,41]. Therefore, we selected the TOPSIS method because its logic can express the rational choice of humans by simultaneously considering the best and worst alternatives. In addition, it has the advantage of being able to easily calculate and display the evaluation results for all alternatives from a multi-attribute perspective. In our study, the PIS was the region most vulnerable to drought, and the NIS was the region with the lowest degree of vulnerability. The assessment procedure of the TOPSIS is explained below. The weight (w_i) was reflected in the normalized data (Figure 3), as shown in Equation (12).

$$v_{ij} = w_i x_{ij} \ (i = 1, \cdots, m,\ j = 1, \cdots, n) \quad (12)$$

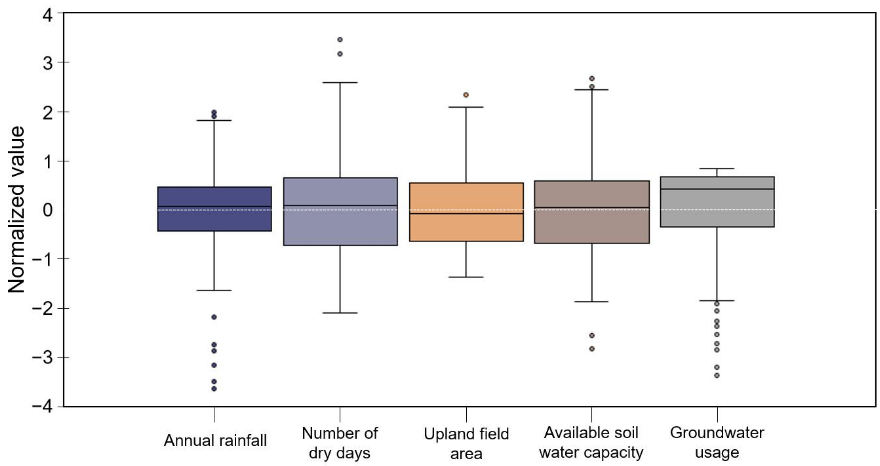

Figure 3. Boxplot of the normalized data for each of the five criteria.

From the assessment values calculated for each assessment unit, the values of A^+ and A^- were determined by applying Equations (13) and (14), respectively.

$$A_j^+ = v_1^+, \cdots, v_m^+ \quad (13)$$

$$A_j^- = v_1^-, \cdots, v_m^- \quad (14)$$

Furthermore, $v_i^+ = \max(v_{ij})$; $v_i^- = \min(v_{ij})$; the distance between the ideal solutions, PIS(d_i^+) and NIS(d_i^-); and each assessment unit were calculated using Equations (15) and (16), respectively.

$$d_i^+ = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^+ \right)^2 \right\}^{1/2} \quad (15)$$

$$d_i^- = \left\{ \sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2 \right\}^{1/2} \quad (16)$$

The proximity coefficient was calculated from Equation (17) and used to determine the ranks.

$$D^+ = \frac{d_i^-}{d_i^+ - d_i^-} \quad (17)$$

3. Results

3.1. Establishment of Assessment Criteria and Database Construction

In this study, we evaluated the drought vulnerability of upland fields. For our survey, a group was created comprising experts experienced in water resources and drought-related work. The relevant participant characteristics are presented in Figure 4; notably, 80% of the participants worked in academia or at research institutes and were experts in fields such as water resources work and the agriculture sector.

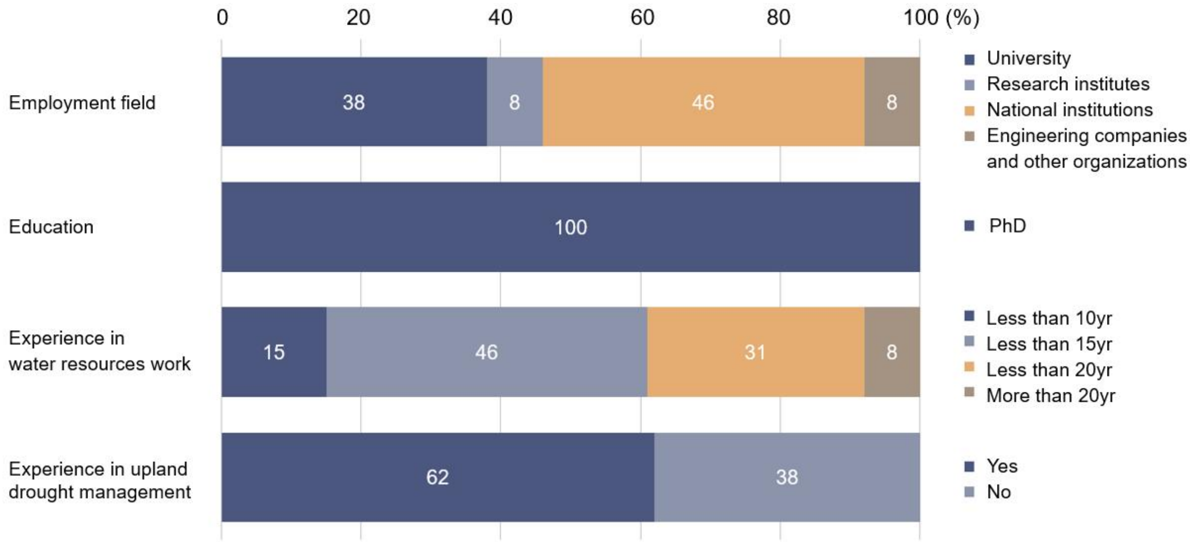

Figure 4. Relevant characteristics of participating experts.

The modified Delphi survey applied in this study was conducted with 13 experts, and the results from a total of two rounds were used. Based on our survey, the following factors were selected as assessment indicators (Table 1): the area of cultivated upland fields, the amount of rainfall, the number of dry days (which cause drought), the available soil water content (which can provide information regarding the growth of upland field crops), and the amount of groundwater used as a water resource.

Table 1. Assessment criteria used to investigate the upland field drought conditions in this study.

Criteria	Sub-Criteria	Definition	Unit	Period
Threat factor	Annual rainfall	Annual rainfall	mm/year	2020
	Number of dry days	Number of minimum 10 consecutive dry days (average)	Days/year	2009–2018
Damage factor	Upland field area	Upland field area	m^2	2020
Mitigation factor	Available soil water capacity	Upland field capacity, available moisture capacity, and permanent wilting point.	%	2020
	Groundwater usage	Amount of groundwater used for upland field/total amount of groundwater used	%	2007–2016

The average annual rainfall during the data collection period (Figure 5a) was found to be 1316 mm/year; the highest precipitation value was 1893 mm/year in Jeju City, and the lowest was 1032 mm/year in Gunwi-gun and Uiseong-gun. In general, the assessment areas in the Chungcheongnam-do and Gyeongsangbuk-do regions were characterized by low rainfall. The minimum and maximum numbers of dry days were 10.6 and 13.1 days, respectively; the variation was relatively small (Figure 5b). Yeongdeok, Yeongyang, Uljin, and Ulleung in Gyeongsangbuk-do were identified as regions with extended dry periods. Water must be supplied regularly for optimum crop growth and to prevent crops from reaching the permanent wilting point, after which the crop cannot be fully revived, resulting in a loss of yield. Hence, periods of consecutive dry days must be short, and the annual rainfall and precipitation rate are important. Figure 5c shows the upland field area. The total area of cultivation includes upland field crops, such as cabbages, radishes, garlic, and onions; orchards; and protected cultivation. The largest area is Jeju City, which has an upland field cultivation area (268.6 km^2) five times greater than the average value of the administrative district (46.6 km^2). The upland field areas of large cities, such as Seoul (4.8 km^2), Busan (32.5 km^2), and regions of Gyeonggi-do (24.6 km^2) are relatively small. The available soil water capacity is calculated weekly by the Rural Development Administration in South Korea, and a map of the availability in each area is shown in Figure 5d. This indicator reflected the permanent wilting point in our calculations and was considered the standard for assessing the resilience of an upland field to drought. Similarly, including groundwater usage as an assessment factor for investigating upland field drought vulnerability is important considering that groundwater is the main water resource for irrigation in upland crop cultivation in South Korea. Few upland fields have irrigation networks installed, making it difficult to obtain water from reservoirs. Groundwater use considerably varies among regions (Figure 5e), primarily because of water resource conditions and economic feasibility. Even within the same province, regional variations are large. The regions of Jeongseon, Sokcho, and Inje in Gangwon-do have large groundwater usage volumes, whereas those of Taebaek and Hoengseong are relatively small.

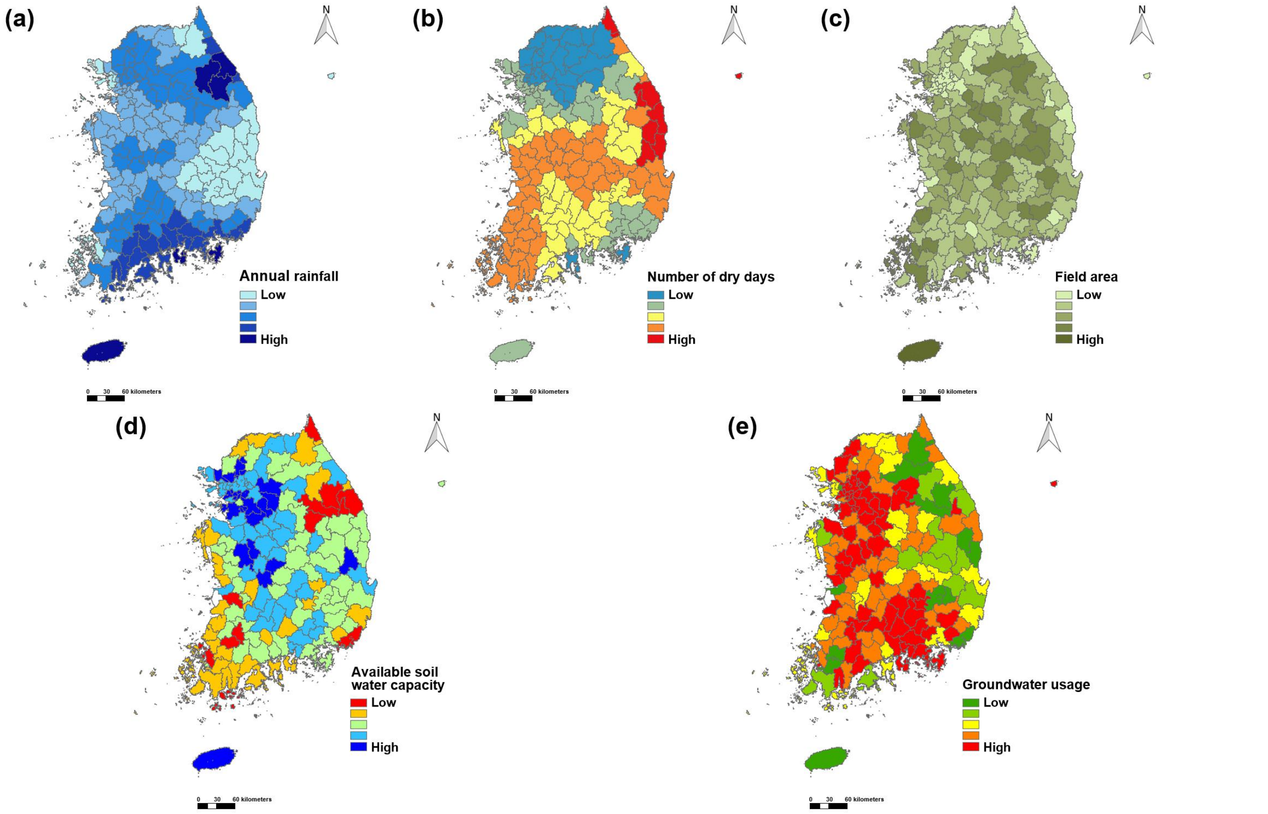

Figure 5. Criteria data on (**a**) annual rainfall, (**b**) number of dry days, (**c**) field area, (**d**) available soil water capacity, and (**e**) groundwater usage by administrative districts in Korea.

Most experts performing field-drought-related tasks classified the type of upland field crop as another crucial assessment factor. Nonetheless, these factors could not be included in our assessment owing to the lack of available data.

3.2. Weight Sets for Criteria

The Delphi survey weighting results, w_i^{Rank} and w_i^{Rate}, reflected high weights for the number of dry days and the available water capacity of the soil. Most experts who participated in the survey concluded that the number of dry days was the most important assessment factor. Overall, crops die when the water supply is insufficient. In addition, the available water capacity of the soil was considered crucial. In turn, the weights calculated by the entropy method indicated small weights for the "upland field area" and "groundwater usage" factors, differing from their numerical values derived from the assessment data. The weights (w_i) calculated using the hybrid weighting method that combined subjective and objective methods resulted in the following factor ranking, from high to low: number of dry days, available soil water capacity, upland field area, annual rainfall, and groundwater usage. The calculated weights are listed in Table 2.

Table 2. Calculated weights of the five criteria considered in this study, by method.

	Annual Rainfall	Number of Dry Days	Upland Field Area	Available Soil Water Capacity	Groundwater Usage
w_i^{Rank}	0.128	0.308	0.221	0.246	0.097
w_i^{Rate}	0.098	0.307	0.198	0.299	0.098
w_i^{SUR}	0.113	0.307	0.209	0.273	0.098
w_i^{ENT}	0.175	0.313	0.163	0.228	0.121
w_i	0.144	0.310	0.186	0.250	0.109

3.3. Upland Field Drought Vulnerability Assessment

In terms of the results of the upland field drought assessment conducted in this study, the central eastern regions of Yeongdeok-gun and Yeongyang-gun in Gyeongsangbuk-do; Taebaek-si and Goseong-gun in Gangwon-do; the southern part of the West Sea in Muan-gun, Sinan-gun, and Gochang-gun in Jeollanam-do; and Gimje-si in Jellabuk-do are most vulnerable to drought (Figure 6).

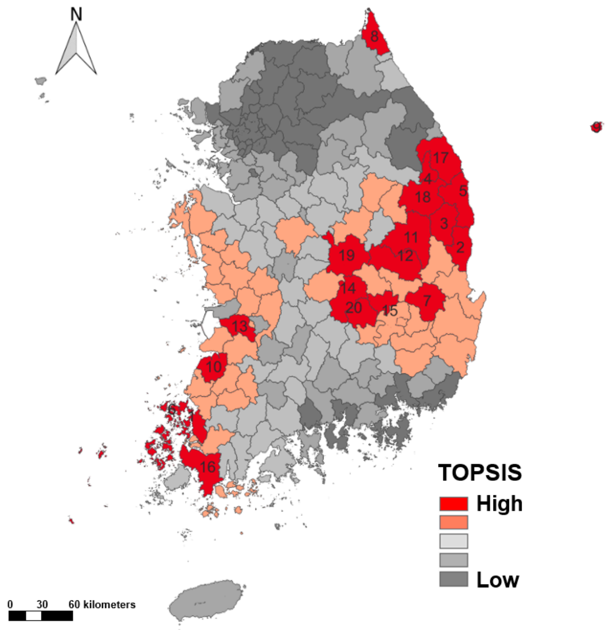

Figure 6. Assessment results of the TOPSIS method applied for the study area.

Figure 7 shows the drought damage area of the upland field by administrative district when severe drought occurred from 2016 to 2018. Comparing the state of upland field drought damage with the vulnerability evaluation results of this study, the largest differences were found in the island regions of Jeju Island, Ulleung-gun, Yeongdeok-gun, Goseong-gun, Andong-si, Uiseong-gun, and Samcheok-si. Of these regions, Jeju Island has the highest density of upland fields in the country, and groundwater and rainfall are used as the sources of agricultural water. However, Jeju Island is also an area where drought damage continues to occur, and groundwater development continues in response to this. Therefore, Jeju Island did not appear as a vulnerable area in our evaluation, owing to the extensive groundwater usage through groundwater development and the relatively high average annual rainfall.

Figure 8 shows the relative influence of our assessment indicators on the 20 most vulnerable regions. The closer the indicator is to 1, the more vulnerable it renders an area to upland field drought (when the impact of weight is not reflected). Notably, the 20 regions showed five distinct patterns, with the number of dry days and the upland field area significantly affecting the assessment results.

Uljin, Ulleung, Chilgok, Taebaek, and Samcheok were influenced by annual rainfall, number of dry days, available soil water capacity, and groundwater usage, except in upland field areas. Yeongdeok and Yeongyang were influenced by annual rainfall, number of dry days, and available soil water capacity. Goseong, Gimje, Gimcheon, Bonghwa, Seongju, and Gochang were influenced by annual rainfall, available soil water capacity, and groundwater usage. Yongcheon, Uiseong, and Andong were influenced by annual rainfall and groundwater usage. Haenam, Sangju, Sinan, and Muan were influenced by annual rainfall, available soil water capacity, and groundwater usage.

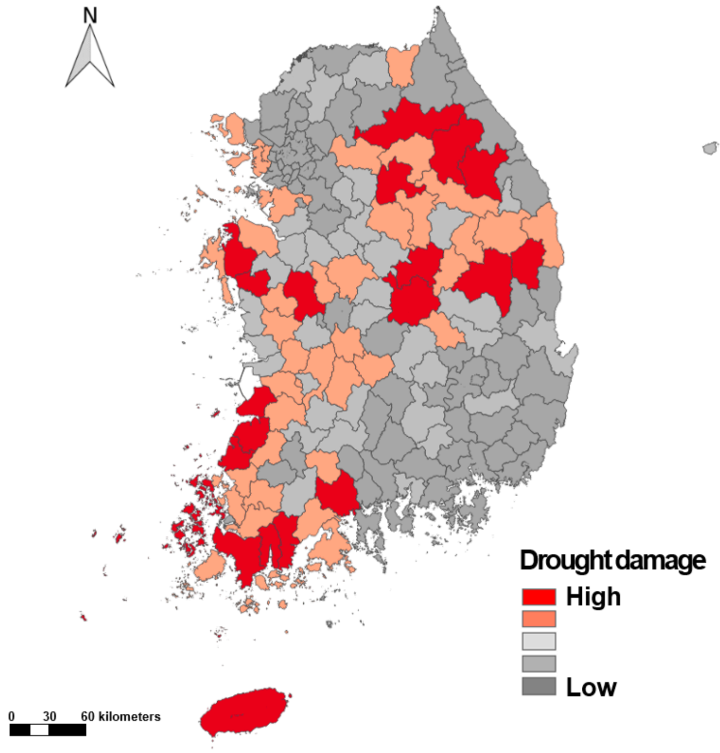

Figure 7. Drought damage area of the upland fields by administrative district (2016–2018).

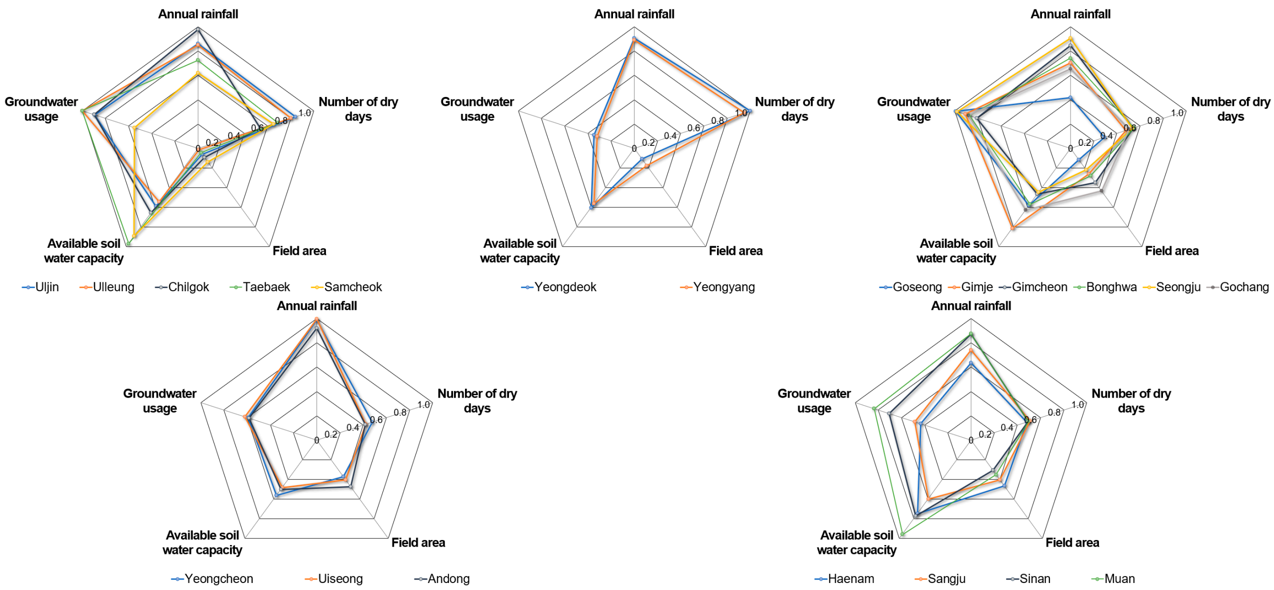

Figure 8. Radar charts portraying the relative influence of the assessment indicators for the 20 most vulnerable areas.

Overall, annual rainfall seemed to be a major factor in vulnerable areas, followed by groundwater usage, number of dry days, and available soil water capacity. Table 3 provides a summary of the 20 most vulnerable regions in the study area.

Table 3. Summary of the 20 most vulnerable regions in the study area.

Rank	City	Province	Characteristics
1	Muan	Jeollanam-do	Island area
2	Yeongdeok	Gyeongsangbuk-do	Coastal area
3	Yeongyang	Gyeongsangbuk-do	Mountainous area
4	Taebaek	Gangwon-do	Mountainous area
5	Uljin	Gyeongsangbuk-do	Coastal area
6	Sinan	Jeollanam-do	Island area
7	Goseong	Gangwon-do	Coastal area
8	Ulleung	Gyeongsangbuk-do	Island area
9	Yeongcheon	Gyeongsangbuk-do	Mountainous area
10	Gochang	Jeollabuk-do	Coastal area
11	Gimje	Jeollabuk-do	Coastal area
12	Chilgok	Gyeongsangbuk-do	Mountainous area
13	Andong	Gyeongsangbuk-do	Mountainous area
14	Gimcheon	Gyeongsangbuk-do	Mountainous area
15	Uiseong	Gyeongsangbuk-do	Mountainous area
16	Samcheok	Gangwon-do	Coastal area
17	Haenam	Jeollanam-do	Coastal area
18	Bonghwa	Gyeongsangbuk-do	Coastal area
19	Seongju	Gyeongsangbuk-do	Mountainous area
20	Sangju	Gyeongsangbuk-do	Mountainous area

Table 4 contains the correlations between the vulnerability assessment factors and their results, with the Pearson correlation coefficient used to examine the linear relationship between the two variables. The variable with the strongest correlation with upland field drought vulnerability was the number of dry days, which showed a strong quantitative linear relationship. Annual rainfall and available soil water capacity showed a high correlation and had an evident negative linear relationship. In addition, the number of dry days, annual rainfall, and available soil water capacity showed a negative linear relationship, and groundwater usage showed a weak positive linear relationship with the number of dry days and upland field area. Therefore, considering the correlation analysis, the variables affecting upland field drought were determined to be the number of dry days, annual rainfall, available soil water capacity, upland field area, and groundwater usage.

Table 4. Results of correlation analysis of vulnerability assessment factors.

	Annual Rainfall	Number of Dry Days	Upland Field Area	Available Soil Water Capacity	Groundwater Usage	Drought Vulnerability
Annual rainfall	1					
Number of dry days	−0.32293	1				
Upland field area	−0.02655	0.060771	1			
Available soil water capacity	−0.06765	−0.31462	−0.01616	1		
Groundwater usage	−0.05504	0.146895	0.270231	−0.28286	1	
Drought vulnerability	−0.55231	0.818706	0.374502	−0.49249	0.128777	1

4. Discussion

In this study, we performed a drought vulnerability assessment of upland fields in South Korea. The issues discussed in this study comprise the selection of assessment indicators, application of assessment techniques, and an extensive review of the status of water management in the upland fields.

First, in many cases, there is sporadic available data on the assessment indicators. For example, data on the amount of water required and used for upland fields within the study area are unavailable. Additionally, water use and timing did not consider crop characteristics. This is because upland field cultivation in South Korea is generally operated on a small-scale, primarily as a self-employed business. The selection of cultivated crops and cultivation type is by individual choice; therefore, conducting systematic management of the situation becomes challenging. In addition, in South Korea, there is insufficient irrigation network construction, making it difficult to determine the amount of water supplied to and used in the agricultural sector.

Second, it is important to review the verification and assessment methods of the data collected under the assessment process, evaluate the assessment targets, and reflect on and review the distribution characteristics of the database on individual assessment indicators. Our assessment may not be appropriate for investigating the seasonal drought events because it was conducted using annual data. Hence, we must question the appropriate application period of our data. Our assessment was performed based on annual data, as drought and water resource policies of each administrative district are typically based on the annual assessment results. However, there is substantial support for separate assessments of drought vulnerability of rain-fed upland fields without alternative water supply systems during the rainy and dry seasons. Such an analysis is considered to be more accurate than one based on annual data that does not distinguish between different seasons. Therefore, an appropriate assessment procedure should be established to allow for the effective implication of the relevant measures in policy.

Third, highlighting the current status of the water management system is important. Most upland fields rely on rainfall, using groundwater only for high-income crops. Therefore, successful water management is required for stable upland field cultivation. Establish an upland-field-based maintenance project is recommended, creating a stable water supply chain. However, this would require extensive data collection and assessments. Nonetheless, the installation of upland field irrigation networks is likely to have a positive effect on the management of the water supply volume. Additionally, based on the type of upland field, the quality of water should be considered and managed appropriately.

The Gyeongbuk region lies east of the Taebaek Mountains, which separate the central and eastern parts of the country. This region is vulnerable to drought due to relatively low springtime precipitation, owing to the lack of rain clouds coming in from the Asian continent and the Yellow Sea, as well as the region's high elevation. Additionally, these conditions make it difficult to use groundwater in the region. The southern areas of the West Sea experienced a severe drought during the spring of 2022, and discussions about potential countermeasures are ongoing. The area receives limited annual precipitation, and there is a lack of water storage and utilization facilities. Furthermore, the prospects for installing and managing such facilities in this region are uncertain. Unlike other areas, where river water can be stored by the use of dams and in reservoirs, establishing permanent facilities here is difficult because of limited water resources with relatively small watershed areas.

Our study indicates that, in the eastern region of South Korea, Yeongdeok-gun, Yeongyang-gun, Taebaek, Uljin-gun, Goseong, Ulleung-gun, and Yeongcheon-si should be priority management targets. Yeongdeok, Yeongyang, Taebaek, Uljin, and Ulleung are adjacent to the East Sea. Although there are relatively few upland fields in this region, they experience scarce rainfall and extended dry periods, rendering them vulnerable to droughts. Furthermore, the Yeongcheon stream is vulnerable owing to its low rainfall and comparatively large area of upland-field-cultivated land. Muan, Sinan, and Gimje, which are vulnerable areas in the southwestern region, are characterized by very low soil water capacity. Muan and Sinan are island areas with significantly negative impacts due to the sea.

In future studies, whether the vulnerable areas identified herein become subject to priority management must be studied. Moreover, the current status of upland field cultivation in these areas should be identified, and the necessary water quantity and timing should be reviewed. We believe that our results can help create an efficient system for managing agricultural water.

5. Conclusions

In this study, we established different procedures, such as the selection of assessment items, weight calculation, and application of assessment techniques, for evaluating the drought vulnerability of upland fields in South Korea. We included 13 experts with sufficient experience in drought-related work to determine the most important assessment criteria. "Annual rainfall" and "number of dry days" were classified as threat factors, whereas "upland field area" was selected as a damage indicator. "Groundwater usage" and "available soil water capacity" were considered to be mitigation factors.

The results of the subjective weight calculation based on our survey reflected the following order of importance: number of dry days, available soil water capacity, upland field area, annual rainfall, and groundwater usage. The objective weighting based on information from assessment data showed that the number of dry days, available soil water capacity, upland field area, and annual rainfall had high weights. Combining these two weighting methods, "number of dry days" and "available soil water capacity" were found to be the primary factors. The TOPSIS assessment revealed that Muan, Yeongdeok, Yeongyang, Taebaek, and Uljin were vulnerable. In general, the areas vulnerable to upland field drought were largely divided into areas adjacent to the East Sea east of the Taebaek Mountains and islands on the west coast adjacent to the Yellow Sea. Both regions experienced significant droughts in the first half of 2022.

To further improve the accuracy and applicability of the method proposed herein, we aim to increase the size of our dataset and incorporate other factors that could influence the results. For example, although annual rainfall data were used in this study, rainfall in Korea is concentrated in summer. With a wide variation in rainfall by month and season, the results may be different when monthly or seasonal data are applied as a rainfall factor. We plan to review various methods that could be used for data collection and apply different models to identify the amount of water required for different crops at varying growth stages.

The methods presented in this study should be used in situations where the available information required for managing upland field drought is limited. Agricultural drought forecasts and alerts are currently based on meteorological information, and specialized management for upland field droughts is primarily focused on post-drought recovery and support from local governments. Therefore, this study provides a framework for identifying practical information for upland field drought management.

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