Water quality risk assessment for drought conditions: A case study of the Korean Nakdong River basin

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Abstract. As the frequency of drought from climate change increases and the severity of drought becomes worse, it is imperative to prepare appropriate countermeasures against severe droughts. Despite the severe impacts of droughts on coupled humans and environmental systems, we do not fully understand the consequences of severe droughts affecting the environment. Therefore, the present study proposes a quantitative assessment index for water quality risk for extreme droughts to improve the safety of water environment management by providing flows to areas vulnerable to the drought. The application of this study is the Nakdong River basin in Korea, which has assessed the vulnerability of water quality to severe droughts as water quality deterioration problems continue to be experienced event after the river restoration project was completed. The results of this study are expected to provide scientific environmental drought monitoring information in a changing climate.

1. Introduction
The frequency and severity of droughts caused by climate change are causing considerable stress not only in humans but also in all creatures living next to us [1-4]. Accordingly, even if water shortages are experienced during droughts, as well as in ordinary times, the risks should be established with advanced water management systems to provide stable water to humans and the natural environment system. The preservation of the healthy ecosystem not only helps to ensure the survival and maintenance of the ecosystem itself but also to ensure the safety of human society after all by making human lives richer and reducing the risk of diseases and disasters [5]. If the environmental or river maintenance flow is not smoothly supplied due to severe drought, enhanced water quality and ecosystem management systems are needed to improve the safety of water environment management by providing stable flows to areas vulnerable to the drought [6,7].

The quality of freshwater systems can be controlled by climatic variability, hydrological, biochemical and anthropogenic effects, which act as various time and space scales [3]. Drought can also change the transfer pattern of water content, keep it in the basin during dry conditions, and release it under wet conditions [8].

Despite the severe impacts of drought on the combination of humans and the environment, little attention has been given to assess environmental drought risk quantitatively. Therefore, this study proposes an approach of monitoring water quality using the probability of exceeding target water quality and water quality risk indicator under the different drought conditions.
2. Data and methods

2.1. Data
In this study, the daily precipitation data of 21 stations during the period 1976-2016 obtained from the automatic Synoptic observation system (ASOS) in the Korea Meteorological Administration (KMA). The daily flow data provided by the Korean Water Management Information System were used. The water quality data (2007-2016) such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), total of nitrogen (TN), and Chlorophyll-a provided by the Water Information System was applied to water vulnerability assessment. The evaluation regulations for water quality and water ecosystem (Ministry of Environment, Republic of Korea) were selected as the target water quality criteria in the analysis.

2.2. Drought classification criteria
The study basin is the Nakdong River basin where problems of water degradation have been continuously raised since the four-river project [9], and vulnerability in water quality to extreme drought was assessed among the 22 sub-basins of the Nakdong River (Figure 1).

![Figure 1. Study area of the Korean Nakdong River basin.](image)

To assess droughts, the Standardized Precipitation Index (SPI) was used in the Korean drought assessment. In order to apply extreme drought, the characteristics of change in water quality/water ecosystem were analyzed, and the vulnerability assessment was presented by considering conditions of severe drought (SPI < -1.2) and extreme drought (SPI < -1.5) considering the drought classification criteria and the effects factors for each drought stage proposed by the U.S. Drought Mitigations Center (http://droughtmonitor.unl.edu/). In addition, water quality risk (WQR) was proposed to assess water vulnerability to severe drought conditions. The WQR can be defined as the ratio of conditional extreme drought probability to the unconditional exceedance probability of each water quality index and target criterion (Eq. 1).

\[ WQR = \frac{P \left[ (WQ \geq WQ_{\text{criteria}}) \mid DI \leq DI_{\text{criteria}} \right]}{P (WQ \geq WQ_{\text{criteria}})} \]  \hspace{1cm} (1)

where \( WQR \) is the water quality risk, \( WQ \) is water quality index, \( DI \) is the drought index, and the evaluation criteria for water quality and drought index are given by \( WQ_{\text{criteria}} \) and \( DI_{\text{criteria}} \).
3. Results

3.1. Correlation analysis

The correlation analysis between drought indices and water quality factors showed that BOD, COD, Chlorophyll-a, and TP have negative correlations. Results for the entire Nakdong River were not presented here. However, the results for the representative Nam River basin can be found in Figure 2.

As the value of the drought index decreases, the value of the water quality factor increases. As such, water quality tends to deteriorate when a drought situation occurs. As the duration increases to 180D, the correlation coefficient increases relatively. This is particularly appropriate when considering droughts in which water quality changes due to prolonged drought. However, in the case of TN, the correlation with droughts was not significant. Nitrogen loadings are most often linked to precipitation. Based on the correlation results, we found that when a drought occurred, the BOD and TP values increased and the water quality deteriorated. In particular, as BOD had a higher correlation than TP, the frequency of point source contamination was relatively frequent. Also, the longer the duration of drought, the higher the correlation with the water quality factor and the water quality change was sensitive to the long-term drought situation.

![Figure 2. Correlation matrix between hydrometeorological variables and water quality data.](image)

3.2. Frequency analysis of extreme drought

In order to assess droughts, short- and medium-term droughts were assessed with daily rainfall data of 22 Nakdong River Estates from 1976-2016. Figure 3 shows the frequency of drought in severe drought (SPI < -1.2), extreme drought (SPI < -1.5) and exceptional drought (SPI < -2.0) by applying SPI90D. In severe drought, more than 45 times a year have occurred annually, and the frequency is high in the upper part of the Nakdong River and the lower part of the Nakdong River. In extreme drought, 25 or more occur annually, and in exceptional drought below SPI - 2.0, more than 10 occur each year.
3.3. Water quality changes according to drought conditions
As a result of applying SPI90D for the period of water quality data from 2007-2016, 63 severe droughts and 32 extreme droughts were occurred respectively. It was analyzed that the water quality target standard in the Nam River basin is classified as the 2nd Class, which is based on 2.0 mg/L of BOD, 0.04 mg/L of T-P, and 95.2% of severe drought and 90.5% of extreme drought exceeds the BOD and T-P standards.

3.4. Vulnerability in water quality
Figure 4 shows an example of an analysis of water quality risk to drought conditions. Figure 4a is based on an analysis of the exceedance probability of water quality (EPWQ) to target criteria before and after the four-river project and in case of severe drought in the Gumi basin (sub-basin ID: 2009). The EPWQ to the target water quality is increased after the four-river project. The Nam River basin, located downstream of the Nakdong River, was also a relatively vulnerable area to drought (Figure 4b). The analysis results showed that WQR was 1.240 on a BOD basis and 1.085 based on the TP. In addition, EPWQ for the BOD was above 78.2% and the TP target water quality was 89.6%. Therefore, the basin needs to adjust its target water quality rating from 2nd Class to 3rd Class or establish additional water quality management measures.

![Figure 3. Frequency of extreme drought based on SPI90D.](image)

![Figure 4. Results of water quality risk to drought conditions. In the figure on the left, the vertical dotted-line indicates the first-class water quality threshold (WQTS-la). In the figure on the right, the contour lines show the joint probability distribution function using the kernel approach. The distribution of water quality under each condition (Case 1: non-condition, Case 2: extreme drought condition, and Case 3: low flow condition below the lower quartile) is shown in the upper and right panel plots, respectively.](image)
4. Conclusion
With the frequency of droughts caused by climate change increasing and the severity of droughts getting worse, proper countermeasures against extreme droughts are urgently needed. Despite the serious effects of drought on combined human and environmental systems, we do not fully understand the consequences of the extreme drought affecting the environment. Therefore, the present study proposed a quantitative evaluation index for water quality risk for the extreme drought to improve the safety of water quality environment management by providing proper flow to drought-prone areas. The results of this study are expected to provide scientific environmental drought monitoring information through real-time EPWQ and WQR to target criteria.

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References
[1] Spinoni J, Naumann G, Carrao H, Barbosa P and Vogt J 2014 World drought frequency, duration, and severity for 1951–2010 Int. J. Climatol. 34 2792-804
[2] Nam W H, Hayes M J, Svoboda M D, Tadesse T and Wilhite D A 2015 Drought hazard assessment in the context of climate change for South Korea Agric. Water Manage. 160 106-17
[3] Mosley L M 2015 Drought impacts on the water quality of freshwater systems; review and integration Earth-Sci. Rev. 140 203-14
[4] Park S Y, Sur C, Kim J S and Lee J H 2018 Stoch. Environ. Res. Risk Assess. 32 2551-63
[5] Jackson D 2014 Sizing up your innovation ecosystem Transl. Mater. Res. 1 020301
[6] Acreman M, Arthington A H, Colloff M J, Couch C, Crossman N D, Dyer F, Overton I, Pollino C A, Stewardson M J and Young W, 2014 Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world Front. Ecol. Environ. 12 466-73
[7] Brown C M, Lund J R, Cai X, Reed P M, Zagona E A, Ostfeld A, Hall J, Characklis G W, Yu, W and Brekke L 2015 The future of water resources systems analysis: Toward a scientific framework for sustainable water management Water Resour. Res. 51 6110-24
[8] Worral F and Burt T 2008 The effect of severe drought on the dissolved organic carbon (DOC) concentration and flux from British rivers J. Hydrol. 361 262-74
[9] Kim J S, Moon Y I, Yoon S K and Choi M 2015 A case study of regional risk assessment of river restoration projects: Nakdong River Basin, South Korea J. Water Climat. Chang. 6 628-37