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Drought assessment for real-time hydrologic drought index of the Nakdong River Basin in Korea

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ABSTRACT

Hydrological droughts are known as the occurrence of surface and subsurface water resources inadequacy, for a specific period of time, for water consumption. This study performed the development and the application of Real-time Drought Index (RDI) for the drought assessment of the Nakdong River Basin in Korea. The hydrologic drought index was analyzed for residential, agricultural, industrial water supplies, and water demands; to investigate the occurrence of both water shortages and droughts. This study showed that the utilization of RDI for drought assessment was proven to be feasible. Results of drought assessment may be used for disaster management to mitigate the effects of the inevitable occurrence of drought.

Keywords: Drought; Hydrologic drought index; Nakdong River Basin

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1. Introduction

The increase in water demand was observed to be caused by urbanization and industrialization [1]. In the case of Korea, the demand for water supply is continuously increasing. Both water supply and water demands are necessary to be evaluated for the purpose of drought analysis and water shortage researches. Drought is generally defined as the damage caused by precipitation deficiency for a long period of time, affecting all human, animals, and also the ecosystem [2]. The World Meteorological Organization defined drought as a sustained, extended deficiency in precipitation [3].

The general classifications of drought are divided into four categories. These four classifications are known as the Meteorological drought, Agricultural drought, Hydrological drought, and the Socioeconomic drought [4,5].

Meteorological drought is defined as the regional occurrence of precipitation deficiency that occurs for a

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long period of time. Analysis of the meteorological drought commonly uses precipitation data [6–9].

Hydrological drought is known as the occurrence of inadequate surface and subsurface water resources for a specific period of time; these water resources are utilized for water consumption through water resources management system. The analysis of hydrologic drought is determined through the use of streamflow data [10–16].

Finally, the socioeconomic drought is associated with the failures of water resources systems to meet the water demands; and thus, associating droughts with supply and demand with the economic profit [5].

Numerous countries in the world monitor and evaluates drought, through the use of drought indices. In case of the USA, the US Drought Monitor Map has been constructed by the National Drought Mitigation Center to reduce drought damage. This map has been continuously updated once a week. Furthermore, Africa is monitored through the use of Experimental African Drought Monitor system. The monitored data is open to public, through a web-based interface system. This interface enables quick access to the data and plots the current and past conditions of Africa and its river basins. Moreover, Global Integrated Drought Monitoring and Prediction System, which is operated by the University of California at Irvine, maps the Standardized Precipitation Index (SPI) [17]; Soil Moisture Index [18]; and the Multivariate Standardized Drought Index [19] in the whole world. Most of the systems does not provide hydrologic drought index; and thus, studies related to hydrologic drought index are essential.

The objective of this study was to develop and apply the Real-time Drought Index (RDI) for drought assessment of the Nakdong River Basin in Korea. Wherein, the hydrologic drought indices for residential, agricultural, industrial water supplies, and demands were analyzed; to investigate the presence of either water shortages or drought.

2. Materials and research methods

RDI is an index which is used to classify drought, through the classification of water shortage in a real-time operation. The assessment process of the RDI is shown in Fig. 1. First, the water supply and demand databases, for the residential, agricultural, and industrial sectors; and for each administrative divisions of Gyeongsang province in Korea, are established.

After the establishment of both water supply and water demand databases, the evaluation of RDI was divided into two parts: the irrigation water supply system and the non-irrigation water supply system. Drought can be evaluated on a daily basis by measuring the water supply, determining the water demand, and systematizing the RDI assessment process.

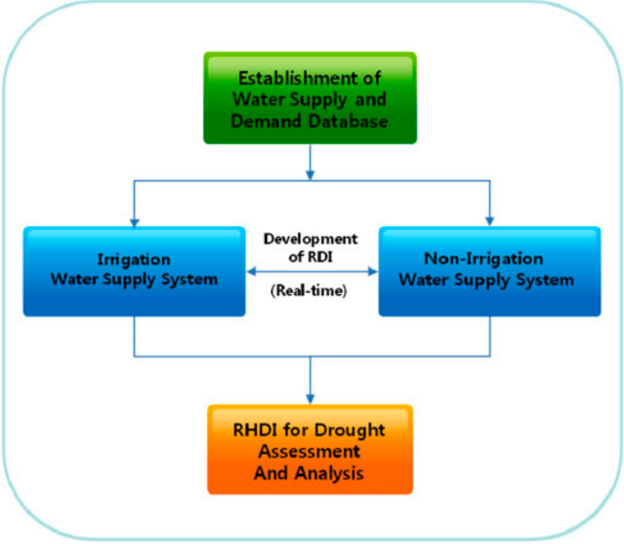

Fig. 1. Drought assessment process of the RDI.

2.1. Study area

This study was conducted at Gyeongsan province located in the Nakdong River Basin in Korea shown in Fig. 2. The Gyeongsan province is comprised of three metropolitan cities (i.e. Busan, Daegu and Ulsan cities) and two provinces (i.e. Gyeongbuk and Gyeongnam provinces). Provinces are further subdivied into 10 cities and 12 districts for the Gyeongbuk province; and, 10 cities and 10 districts for Gyeongnam province.

2.2. Water demand database

The water demands for residential, agricultural, and industrial sectors were further subdivided into either irrigation system or non-irrigation system. Water demand for irrigation system was further subdivided to provincial water supply for residential sector; or irrigation water supply for agricultural (paddy, farms, and livestock) sector; or industrial water supply for the industrial sector. While, the water demand for non-irrigation system was further subdivided to either non-provincial water supply for residential sector; or non-irrigation water supply for the agricultural (paddy and farming fields) sector.

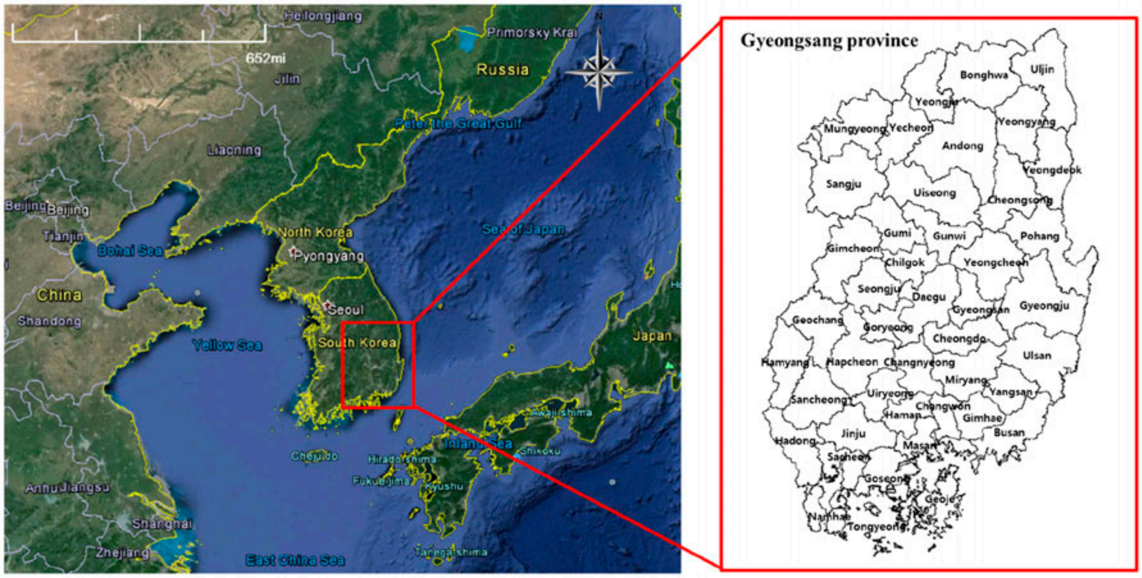

Fig. 2. Study area (Nakdong River Basin, Korea).

Table 1
Water demand data

	Water demand	
Sector	Irrigation system	Non-irrigation system
Residential	Provincial water supply	Non-provincial water supply
Agricultural	Irrigation water supply (paddy)	Non-irrigation water supply (paddy)
	Irrigation water supply (farming)	Non-irrigation water supply (farming)
	Irrigation water supply (livestock)	
Industrial	Organized area	
	Disorganized area	

Table 1 shows the summary of the water demand data used in this study. All of the water demand data were retrieved from Water Vision (2011–2020) [20].

The annual demand for both residential sector and industrial sectors was evaluated for 365 d. For agricultural sectors (i.e. water supply intended for paddies), the annual demand was evaluated from April to September; which corresponds with the growth period in paddies, with 182 d. The annual demand of the remaining agricultural sectors (i.e. water supply intended for farming and livestock), were evaluated for 365 d. Table 2 shows the summary of the evaluation methods used to determine the daily water demands.

Table 2
Evaluation methods to determine the daily water demands

Sector	Types of water demand	Evaluation methods
Residential	Provincial water supply	Annual demand/365 d
	Non-provincial water supply	Annual demand/365 d
Agricultural	Irrigation water supply (paddy)	Annual demand/182 d (April to September for growth periods paddy)
	Non-irrigation water supply (paddy)	
	Irrigation water supply (farming)	Annual demand/365 d
	Non-irrigation water supply (farming)	
	Irrigation water supply (livestock)	
Industrial	Organized area	Annual demand/365 d
	Disorganized area	

2.3. Water supply database

The water supply database is composed of irrigation system and non-irrigation systems. Water sources of irrigation systems are made up of stream flow, dam storage, and reservoir; while, the water source of non-irrigation systems is only supplied with rainfall.

Stream flow and dam storage are used for residential and industrial water; while, the reservoir storage is used for residential, industrial, and agricultural waters. In the case of the non-irrigation systems, rainfall is the only source used for residential and agricultural waters (Fig. 3).

The water level observation stations selected for the real-time water supply evaluation in streams, approaching the intake stations, are shown in Fig. 4. Real-time water level observations, of the selected stations, were obtained. The real-time total streamflow was adjusted due to the instream flow (i.e. 10 years average drought flow).

Temporal calibrations of the observation stations were necessary, due to temporal variations between the observed stations with the intake station. Thus, the application of the temporal calibration coefficient is significant for accurate evaluations of real-time water supplies.

2.4. Water shortage evaluation

RDI equations of water supply and demand databases were used for the evaluation of water shortages. The RDI was divided into irrigation water supply system and non-irrigation water supply system.

2.4.1. Water shortage evaluation (irrigation system)

The applications of water demand, to evaluate water shortage for irrigation systems, are shown in Tables 1 and 2. Water supply, intake from streams, for daily evaluation, was calculated using Eq. (1).

$$\mathrm{ITQ_s(d)} = (q_\mathrm{S} \times r) - (q_\mathrm{Si} \times r) \tag{1}$$

where $\mathrm{ITQ_S(d)}$ is the daily discharge from water supply intake stations; q_S is the observed daily discharge; q_Si is the 10-year average drought flow or instream flow for the observation station; and r is temporal calibration coefficient. r is the ratio of the ungauged basin area to the downstream basin area. Furthermore, r was used to estimate the discharge from ungauged basins. The daily shortage of water supply from intake stations or $\mathrm{ITQ_{ST}(d)}$ was calculated using Eq. (2).

$$\mathrm{ITQ_{ST}(d)} = \mathrm{Max}\,[\mathrm{ITQ_D(d)} - \mathrm{ITQ_S(d)}, 0] \tag{2}$$

where in $\mathrm{ITQ_D(d)}$ is the water demand for irrigation system; and $\mathrm{ITQ_S(d)}$ can be calculated using Eq. (1).

If ($\mathrm{ITQ_{ST}} > 0$), the intake station has water shortage. The weight for each water demand sector (i.e. residential, agricultural, and industrial) calculated from Eq. (2) is divided with the total water shortage of all

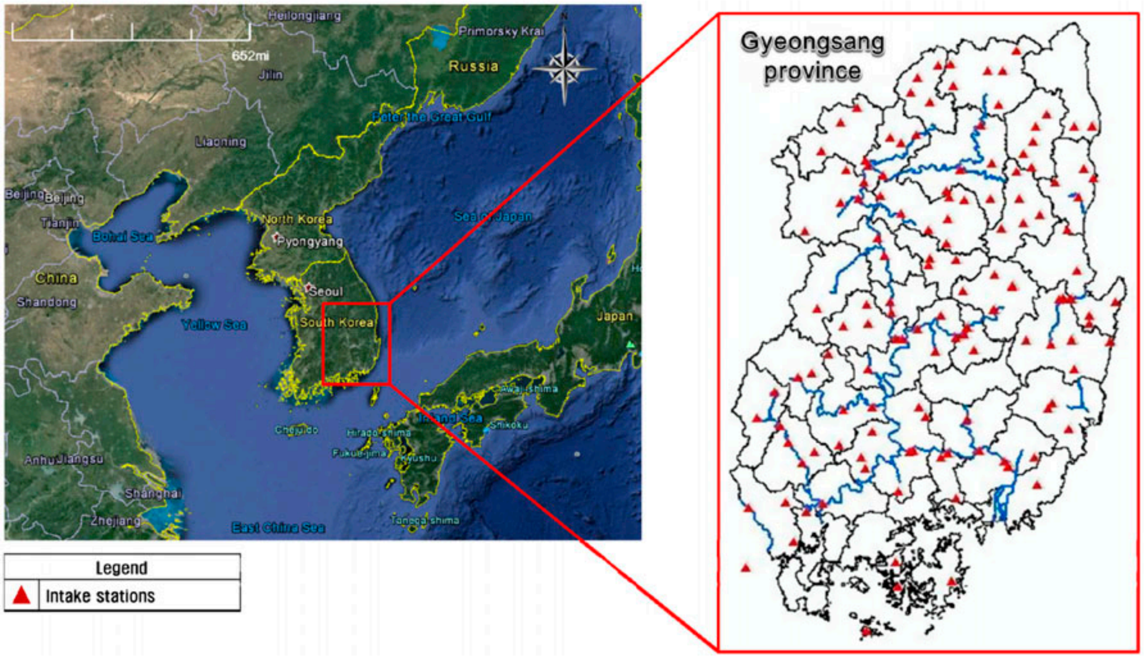

Fig. 3. Intake stations in the Nakdong River Basin in Korea.

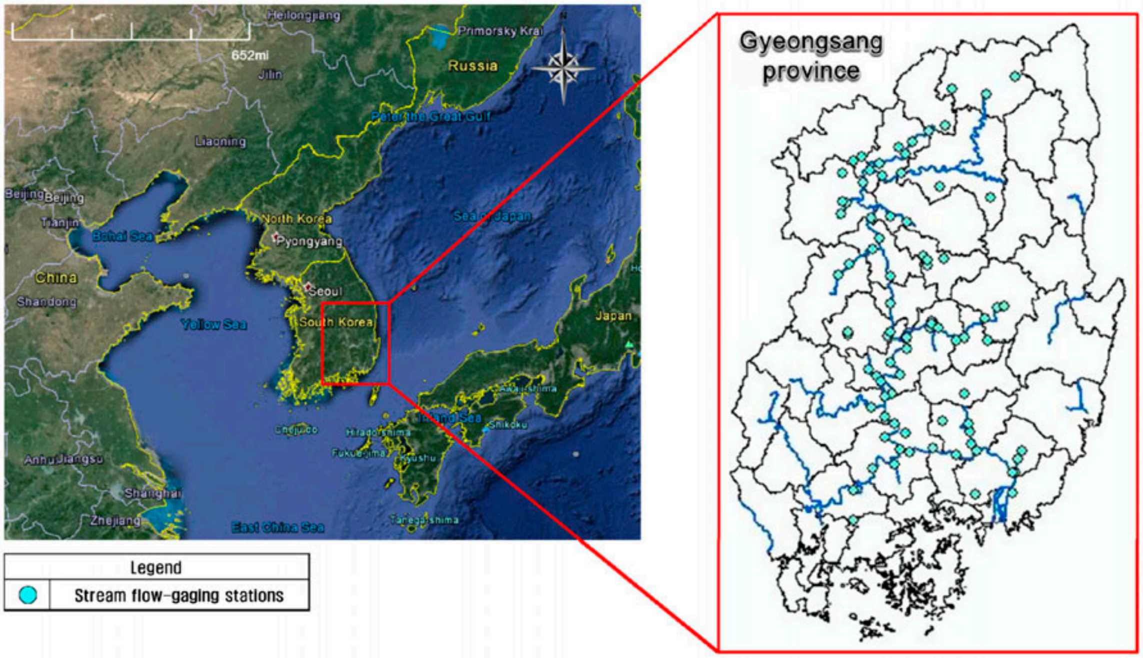

Fig. 4. Water level observation stations in the Nakdong River Basin in Korea.

sectors. The daily discharge of agricultural reservoirs or $ARQ_S(d)$, can be calculated using Eq. (3).

$$ARQ_S(d) = \text{Reservoir capacity} \times \text{Water reserve rate} \tag{3}$$

Furthermore, the daily water shortage of the agricultural reservoir or $ARQ_{ST}(d)$ can be calculated using Eq. (4).

$$ARQ_{ST}(d) = \text{Max}\left[Q_{Da}(d) + ITQ_{ST_a}(d) - ARQ_S,\ 0\right] \tag{4}$$

wherein $Q_{Da}(d)$ is the total water demand of the agricultural sector (irrigation system); $ITQ_{STa}(d)$ is the intake station shortage for the agricultural sector; and ARQ_S can be calculated using Eq. (3).

The evaluation of the daily water shortages from the residential intake station, $ITQ_{ST}(d)$; agricultural intake station and agricultural reservoir (i.e. & $ARQ_{ST}(d)$; and the industrial intake stations, $ITQ_{STi}(d)$; are necessary.

2.4.2. *Water shortage evaluation (non-irrigation system)*

The daily residential water demand shortage can be computed as follows:

$$NQ_{STr}(d) = \text{Min}\left[\text{Max}\left[-\frac{NQ_{Dr}(d)}{\bar{R}^m_{90} - R^m_{90}} \times \left(R_{90}(d) - \bar{R}^m_{90}\right),\ 0\right],\ NQ_{Dr}(d)\right] \tag{5}$$

where $NQ_{STr}(d)$ is the daily residential water shortage for non-irrigation system; $NQ_{Dr}(d)$ is the daily residential water demand for non-irrigation system; $R_{90}(d)$ is the 90-d cumulative precipitation; $\bar{R}^m_{90}$ is the averaged 90 d cumulative precipitation for 30 years data; and $\bar{R}^m_{90}$ is the minimum cumulative precipitation for 90 d.

Ninety-days SPI was used to calculate the shortage in daily water demand. This versatility allows SPI to monitor short-term water supplies, such as soil moisture, which is an important factor for agricultural production. Agricultural drought was replicated best with SPI, on a scale of 2–3 months [21].

The daily agricultural water demand shortage can be computed as follows:

$$NQ_{STa}(d) = \text{Min}\left[\text{Max}\left[NQ_{Da}(\text{month}) \times \frac{SPI(d)}{SPI^m_M},\ 0\right],\ NQ_{Da}(\text{month})\right] \tag{6}$$

where $NQ_{STa}(d)$ is the daily agricultural water shortage for non-irrigation system; SPI(d) is the daily standard precipitation index (SPI) [19]; $\mathrm{SPI}_{\mathrm{M}}^{\mathrm{m}}$ is the 90-d minimum SPI, for 30 years duration; and $\mathrm{NQ}_{\mathrm{Da}}$(month) is the monthly agricultural water demand for non-irrigation systems.

3. Results and discussion

3.1. RDI classification

The RDI for drought assessment is classified into five categories. Each classification was categorized based from water shortage rates. The water shortage rates were determined from dividing the water shortage with the water demand, multiplied to 100; to achieve drought rate percentage. The summary of the RDI classification and its corresponding rate ranges are shown in Table 3.

3.2. Drought assessment for RDI

The drought index can be calculated after drought assessment with RDI. Table 4 shows the comparison of the actual drought occurrence and the results from RDI calculations for 6 February, 2009. The water supply was restricted, in a countrywide scale, during the period of the actual drought occurrence, and was investigated by the National Disaster Management Institute (NDMI).

Verification was performed through the comparison of the observed drought data with the calculated RDI shown in Table 4. The results of the assessments showed that drought mostly occurred in Gyeong-buk province rather than with Gyeong-nam province. Most areas in Gyeong-nam province are supplied by regional water works, multipurposed dams, and large-scale rivers, like the Nakdong River. However, most of the areas in Gyeong-buk province are mainly supplied by local water works and small streams.

Results of the detailed drought assessment showed that some provinces (i.e. Tongyeong, Namhae, Uiseong, Uljin, Yeongcheon, Yeongdeok, Andong, Mungyeong, Gimcheon, and Gyeongju) also experienced drought on 6 February, 2009. However, the agricultural water sector had no drought occurrences observed. Furthermore, both residential and industrial water sectors were observed to have diverging drought

Table 3
RDI classification

Drought classifications	Drought intensity	Water shortage rate (%)	Evaluation
D0	Normal	$R \leq 0$	$R = \frac{\text{Water Shortage}}{\text{Water Demand}}$
D1	Moderate	$0 < R \leq 25$	
D2	Severe	$25 < R \leq 50$	
D3	Extreme	$50 < R \leq 75$	
D4	Exceptional	$R > 75$	

Table 4
Actual drought situation and RDI (6 February, 2009)

Province	City	Actual drought situation (observed data)	Res.	Agri.	Indust.
Gyeong-nam	Hapcheon	–	D1	D1	D0
	Hamyang	–	D1	D1	D0
	Haman	–	D0	D0	D0
	Hadong	–	D0	D0	D0
	Tongyeong	R*	D3	D3	D3
	Changwon	–	D0	D0	D0
	Changnyeong	–	D0	D0	D0
	Jinhae	–	D0	D0	D0
	Jinju	–	D1	D0	D1
	Uiryeong	–	D0	D0	D0
	Yangsan	–	D0	D	D0
	Sancheong	–	D4	D0	D4
	Sacheon	–	D1	D0	D0
	Miryang	–	D4	D0	D4
	Masan	–	D0	D0	D0
	Namhae	R*	D1	D4	D1
	Gimhae	–	D4	D0	D4
	Goseong	–	D1	D0	D0
	Geochang	–	D1	D0	D0
	Geoje	–	D0	D0	D0
Gyeong-buk	Pohang	–	D0	D0	D0
	Chilgok	–	D0	D0	D0
	Cheongsong	–	D0	D0	D0
	Cheongdo	–	D0	D0	D0
	Uiseong	R*	D1	D0	D0
	Uljin	R*	D1	D0	D0
	Yecheon	–	D0	D0	D0
	Yeongcheon	R*	D0	D4	D0
	Yeongju	–	D4	D0	D4
	Yeongyang	–	D0	D0	D0
	Yeongdeok	R*	D1	D1	D0
	Andong	R*	D1	D1	D0
	Seongju	–	D1	D0	D1
	Sangju	–	D1	D0	D0
	Bonghwa	–	D0	D0	D0
	Mungyeong	R*	D4	D0	D4
	Gimcheon	R*	D4	D0	D4
	Gunwi	–	D0	D0	D0
	Gumi	–	D1	D0	D0
	Goryeong	–	D0	D0	D0
	Gyeongju	R*	D0	D0	D0
	Gyeongsan		D0	D0	D0
Metropolitan city	Busan	–	D0	D0	D0
	Ulsan	–	D0	D0	D0
	Daegu	–	D0	D0	D0

R* = Restricted water supply.

classifications. Unlike residential and industrial waters, agricultural water supply retrieves water from reservoirs. Therefore, agricultural water supply can be made available, if water is stored in reservoirs, even during drought periods.

Table 4 shows the summary of the calculated RDI in comparison with the observed data, which was gathered from the 6 February, 2009 drought event. The result of the analysis shows that the calculated RDIs are relatively higher as compared with the observed results. This is due to the fact that RDI easily recognizes drought, even when the water demand is a little higher as compared with the water supply; which is different with the evident actual drought situations. The RDI intensity was calculated to be high (i.e. D1–D4) in areas with water supply restrictions, during actual drought situations. Therefore, the utilization of RDI for drought assessment is feasible.

Results of the detailed drought assessment showed that majority of the provinces experienced moderate drought for the month of January in year 2009. However, sector-based drought assessment showed that the agricultural water sector had no drought occurrences; while, both residential and industrial water sectors were observed to have diverging drought classifications.

4. Conclusions

In this study, the RDI for hydrologic drought was assessed through the utilization of real-time water supply and demand data for the Nakdong River Basin. The applicability of the RDI was evaluated through the comparison between the data gathered from an actual drought situation with the calculated values for the RDI, for the 6 February, 2009 drought event.

The result of this study shows that the utilization of RDI accurately determines the presence of small drought occurrences as compared with the evident drought situation. This is due to the fact that RDI easily recognizes drought, even when the water demand is just a little larger than the water supply. The RDI intensity was calculated to be high (D1–D4) in areas with water supply restrictions, during the actual drought situation. Thus, the result of the drought assessment performed in this study, matches the actual drought event in the Nakdong River Basin; and is proven to be feasible for further applications. The results of this study may be used for future disaster management practices; to further mitigate the effects of inevitable drought occurrences.

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