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Enhanced Prediction and Determination of Hydrological Drought at Ungauged River Intake Stations under Changing Climate

Dian Wu [1], Jong-Suk Kim [1,*], Seo-Yeon Park [2], Guyoung Park [3], Woosung Nam [3] and Joo-Heon Lee [2,*]

[1] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[2] Department of Civil Engineering, Joongbu University, Goyang 10279, Korea
[3] National Drought Information-Analysis Center, K-Water, Daejeon 34350, Korea
* Correspondence: jongsuk@whu.edu.cn (J.-S.K.); leejh@joongbu.ac.kr (J.-H.L.)

Abstract: Droughts, which are expected to worsen under global climate change, have major impacts on human life and the natural environment. In this study, an analysis system was established for predicting and determining hydrological drought conditions at ungauged water stations and in watersheds connected to municipal river water intake facilities. The aim was to help prevent drought damage or minimize its effects based on an immediate response to severe drought events. A system is presented for the selection of ungauged watersheds that take in river water, and three methodologies are proposed for identifying and forecasting hydrological drought conditions. Two South Korean pilot sites among the numerous ungauged water intake plants that lack local data collection facilities were selected as study areas. In addition, a roadmap for the establishment of standards for the determination of drought conditions in ungauged river basins was proposed. The methodologies introduced in this study assume nationwide expansion and construction. Their utilization can facilitate effective drought responses, based on drought forecasting and restricted water supply criteria for each phase of water intake, at local (and other) waterworks.

Keywords: ungauged river; water intake plant; water intake capacity; drought

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1. Introduction

Drought has complex environmental impacts that affect the quality, structure, and diversity of many systems (e.g., soil, air, plants, forests, aquatic systems, and wildlife) [1–3]. Drought increases the possibility of forest fires and degrades the health of vegetation [4]. Global warming induces the increased evaporation of lake water, leading to desiccation in semi-arid regions, the replacement of forests by grasslands, and ecological degradation [5]. Woody plant mortality due to widespread drought is observed worldwide and may be exacerbated by future climate change [6]. Over the last 10–20 years, the number of studies on the effects of drought on water quality has increased, mainly in North America, Europe, and Australia [7]. Drought fundamentally alters nutrient cycling and biota in watersheds and reservoirs, and has long-term negative effects on drinking water quality [8]. Drought also affects the biodiversity by changing habitat conditions. Changes in water environments are associated with increased mortality and decreased birth rates of aquatic organisms [9]. Cook et al. [10] predicted that global warming will increase drought risk and severity throughout the subtropics and mid-latitudes in both hemispheres over the next century. Drought events have wide-ranging transboundary, environmental, and socioeconomic effects on various sectors, including agriculture, energy production, public water supply, and water quality [11–13].

Under the combined influence of climate change and human activities, a series of water problems, such as insufficient supply, are being observed worldwide [14].

Jackson et al. [15] reported that more than 50% of Earth's accessible freshwater runoff is utilized for human use, and more than one billion people have no access to clean drinking water. In addition, almost three billion people lack basic sanitation services. Semi-arid and arid regions primarily rely on precipitation or glacial meltwater; therefore, climate change greatly affects the water supply in such areas [16]. Most urbanized coastal cities lack freshwater resources and rely on supplies from adjacent inland watersheds [17]. Owing to economic development and population concentrations in coastal areas, the water supplies therein face significant challenges under climate change. Water shortages have led to the increased utilization of alternative sources such as imported water, desalinated seawater, and reclaimed water [18,19]. In addition, methods for the enhancement of the water supply, such as water recovery, reuse, and recycling (including rainwater harvesting) have been proposed and implemented [19]. Climate change will lead to new challenges for water supply planning and management in many regions in the 21st century [20].

Since 2012, South Korea has experienced major challenges due to drought. According to the national drought information portal [21], the number of people affected by a drought-limited local water supply was 508 in 2012. The water supply for domestic use was adjusted (20% reduction in seven cities in the Chungnam Province) in 2015. In 2016, 11,123 people in 35 cities and municipalities were affected by water shortages. This number increased to 26,853 (51 cities) in 2017 and to 111,473 (22 municipalities) in 2018. In 2019, 9789 people in 15 municipalities were affected by water shortages. However, with respect to the local water supply, preemptive responses to drought (e.g., controlling the water supply as river flow decreases) are challenging, owing to the absence of river flow monitoring facilities. Hydrological drought is defined as a significant decrease in water availability in all its forms appearing in the land phase of the hydrological cycle [22]. Runoff data are often used to assess hydrological droughts [23]. Hydrological drought indices, such as the Palmer Hydrological Drought Index (PHDI) [24] or the Surface Water Supply Index (SWSI) [25], have problems with complex data collection and large computational efforts. Based on the concept of the Standardized Precipitation Index (SPI), Shukla and Wood [26] defined a standardized runoff index (SRI) as the unit standard normal deviation associated with the percentile of hydrologic runoff accumulated over a specific duration. A similar one is the Streamflow Drought Index (SDI) developed by Nabaltis and Tsakiris [22], where the streamflow sequence fits a particular distribution. Based on this, Vicente-Serrano et al. [27] preferred the distribution parameters.

The quantification of hydrological shortages along with drought indices is based on periods when hydrological variables, such as river flows, are below a certain threshold [27]. The selection of this level can use the average of a series [28], a percentile [29], or relative values for the average [30]. Additionally, a flow duration curve (FDC) is one of the most informative methods of displaying the range of river discharge from low flows to flood events [31]. In the United States, the most widely used indices are the 7-day, 10-year low flow (7Q10) and the 7-day, 2-year low flow (7Q2), which are defined as the lowest average flow occurring on seven consecutive days within the 10-year and 2-year recurrence intervals, respectively [32]. In the UK, the average of the annual series of minimum 7-day flows was used [33]. The definition of low flow varies from country to country and region to region. For example, the low flow definition in ungauged catchments is designed to predict specific low flow indices (e.g., Q95 or 7Q2) or to generate continuous flow time series using hydrologic simulation methods [32].

To respond to drought conditions (as determined by information on water sources and a drought warning system), it is necessary to determine the drought conditions in ungauged areas based on river and groundwater information. The aim of this study was to effectively prevent and respond to the negative effects of limited or disrupted water supplies (e.g., widespread inconvenience or damage to economic activity at a national scale) by proposing a plan to predict droughts and formulate appropriate responses, by judging the number of water abstraction days for local water sources or ungauged river intake stations, under changing climate conditions.

2. Materials and Methods

2.1. Drought Determination Criteria Considering Measurement Data and Hydrologic Models

Low flow (LF) refers to the minimum flow of natural rivers, which humans and nature share during the dry season. LF functions as the reference flow for setting intake volumes based on the evaluation of the capacity of river water to meet demand. In Japan and South Korea, average and standard LFs are used, whereas the 10-year frequency and 7-day flow are used as LF indicators in the U.S. and U.K. [34]. Although historical observation flow data are required to calculate the amount of water, water level observation facilities are limited in Korea. Therefore, it is difficult to calculate the amount of water that might be available during the dry season.

In this study, the average water intake amount and actual or simulated flow were calculated by applying a drainage–area ratio (DAR). The DAR is commonly used to transfer a measured streamflow time series to an ungauged basin based on the ratio of the respective drainage areas (Equation (1)). The daily average volume provided by the water source was subtracted from the result. Subsequently, the value was divided by the absolute water supply volume and the amount of water insufficiency at the supply facility was noted as a drought-index as a percentage value:

$$DAR = A_{WIC} \ / \ A_{WLOS} \tag{1}$$

where DAR is the drainage–area ratio, and A_{WIC} and A_{WLOS} are areas of the water intake station and water level observation stations, respectively. The water intake capacity (WIC) was simply estimated using the following equation (Equation (2)).

$$WIC = DAR \times (DF_{WLOS} - LF_{WLOS}) \tag{2}$$

where WIC is the water intake capacity (m^3/day), and DF_{WLOS} and LF_{WLOS} are the daily flow and low flow at the water level observatory, respectively.

Detailed methods for calculating the measurement data, hydrologic model-based water intake, application of DAR, and water insufficiency calculations at the water intake facility are presented in Figure 1.

Flow data are required for calculating water intake. In this study, three methods were used to calculate the water intake:

(1) When data from a nearby water level observatory were available, the measurement data-based water intake capacity (WIC) was calculated using the flow data derived from the flow rating curve.

(2) At the intake point, a localized rainfall–runoff model was applied to calculate the WIC of the water source when data from a nearby water level observatory were not available. In this study, the Tank model, which is a storage-type hydrologic model widely used to determine runoff processes, was applied, but the hydrologic model can be selected depending on the status of the basin.

(3) If data were missing because of winter freezing, or for other reasons, the WIC of the water source was calculated based on the two above-mentioned methods, even if daily flow data could be obtained from the flow duration curve (FDC) obtained at a water level observation station nearby.

Based on the WIC, the drought index of water shortage in water intake facilities was calculated as the ratio of WIC minus daily average water intake to WIC value (Equation (3)):

$$WSI\ (\%) = 100 \ * \ \frac{WIC - WIC_{AVG}}{|WIC|} \tag{3}$$

where WIC_{AVG} is the daily average water intake capacity of the water intake sources.

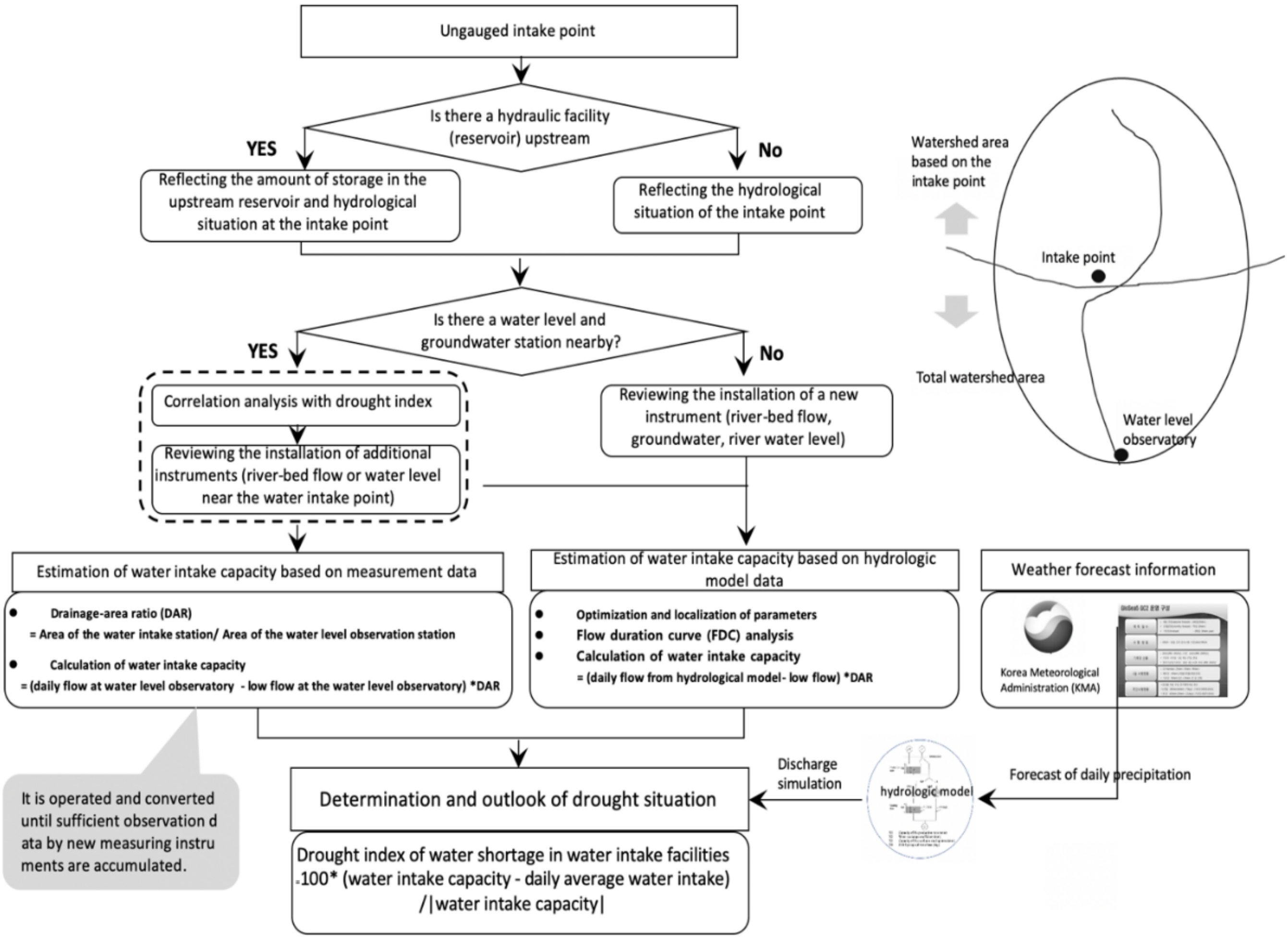

Figure 1. Drought condition criteria and monitoring procedure for the ungauged intake point.

2.2. Field Survey and Testbed Site Selection

Data from Korean local governments indicated that 433 domestic and industrial water intake facilities were in operation at the end of 2019. Among these, 183 intake facilities (42%) in 77 cities and counties used river water; of these, 56 (30.6%) and 118 (64.4%) were riverbed (sub-surface) water intake facilities, respectively (Figure 2).

Water level and flow information are required for evaluating and predicting hydrological drought conditions at water intake points. Unfortunately, nearby water level observation data are only available for 109 intake points (Figure 3). Among the 109 water intake plants, facilities with an unspecified form of intake and those with a water intake tower were excluded. Water intake stations without water level and groundwater observation stations in the basin were also excluded. Finally, 13 sites were selected as preliminary candidates, among which two were finally selected based on their potential, with respect to the collection of various information, such as the river water level and groundwater data.

Considering the pilot site selection criteria, continuous observation data on river water levels were required to determine the hydrological drought conditions at unmeasured river intake points. However, river water levels may not be measured during periods of drought. The main selection criteria for locations at which the groundwater level can be observed in the river and compared with the surrounding groundwater level were as follows:

- Points without linkable water sources, such as dams, weirs, and reservoirs upstream, or where the main-stream water level is less affected by upstream structures.
- Points for which observation data for water and groundwater levels are available nearby.

- Drought analysis is possible, and the correlation between observed data is assured.
- Areas vulnerable to drought.
- Points with few site-specific restrictions, such as the ability to install new flow measurement sensors.
- Points at which the water level can be observed in the river and groundwater adjacent to the water intake point.
- Ability to identify where the alluvial aquifer connects horizontally to the upstream water intake point.
- Points where monitoring equipment can be installed, such as locations where underground equipment is not present.

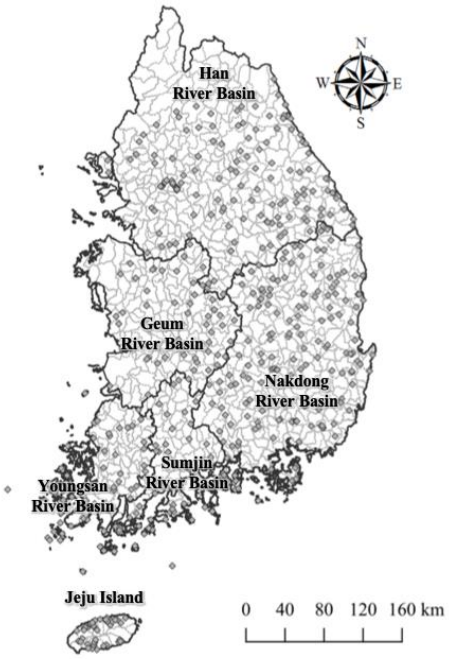

Figure 2. Riverbed water intake facilities in South Korea.

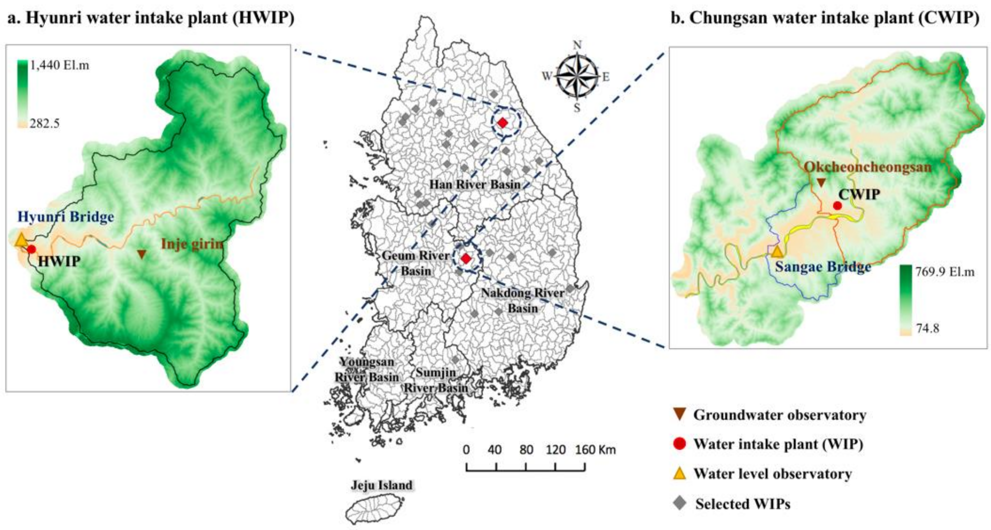

Figure 3. Study area. (**a**) Hyunri water intake plant (HWIP); (**b**) Chungsan water intake plant (CWIP). Gray symbols represent the 21 water intake sites selected in this study.

2.3. Pilot Site and Hydrometeorological Data

Criteria were established for the determination of drought conditions at water intake points based on the analysis of observation data and hydrologic models of pilot locations (Figure 3). The first site, Hyunri water intake plant (HWIP), is located in Gangwon Province, South Korea. The plant was completed in 1997 and takes water from Bantae Stream. The facility has a capacity of 3300 m^3/day, a minimum water intake of 1525 m^3/day, a maximum water intake of 3136 m^3/day, and an average daily water intake of 2383 m^3. A shallow well is utilized for water intake and the water level and flow are observed at the nearby Hyunri Bridge. The National Water Management Information System (WAMIS) of Korea provides real-time river water level and flow data (observatory code 1012640) from 2014 to 2020 for the HWIP. However, 18.2% of the data are missing because of freezing during winter; therefore, for the analysis of the FDC, intake calculations were compared using the following two methods; (1) existing data measurements were compared with the simulated daily runoff derived from the Tank model; and (2) simulation results were used to substitute for data that were missing owing to freezing. As the water intake point and water level observatory are in close proximity, the DAR was not separately applied.

The second site, Chungsan water intake plant (CWIP), is located in North Chungcheong Province, South Korea. Riverbed water enters through a catchment conduit from the Bocheong Stream, with a facility capacity of 1000 m^3/day and average daily intake of 602 m^3 as of 2018. Water levels and flow data observed at the nearby Sangae Bridge (observatory code 3007660) were obtained from the WAMIS (2007–2020). Given the separate locations of the CWIP and water level observatory station, the average low flow volume was calculated by applying a DAR of 0.81 based on the ratio of the respective drainage areas.

In this study, the drought conditions were determined based on the lack of water at supply facilities, considering the average daily intake of each facility. Depending on the state of the water source, water intake volumes may be present at nearby water level observation stations, enabling the straightforward calculation of the water level and flow relationship curve, and thus the quick determination of water shortage at each supply facility. However, the water level and flow observation stations associated with most local water sources are located downstream of the basin, making it relatively more challenging to calculate the water shortage at a given supply facility. Thus, in the present study, the water supply volume was calculated by applying a DAR, considering the surface area of the water source and reference area of the water level observatory. However, if the water level observation station was not located nearby, or if measurement data were missing, the discharge amount was simulated using the Tank model built by K-water; that is, localized parameters were applied to calculate the water quantity using a rainfall–runoff model. Finally, LF was calculated based on the FDC obtained from the simulated daily runoff analysis. In addition, the meteorological drought index was calculated based on the standardized precipitation index (SPI) provided by the Korean Meteorological Administration (KMA). The SPI was developed by McKee et al. [35] and is the most used drought index, owing to its simple calculation and ability to evaluate drought at different time scales. The SPI value is based on rainfall observation stations. Thus, if the intake site basin is located at the boundary of the Theisen network, the spatial weighting factor of the polygon that includes the water intake site is used to calculate the SPI.

3. Results

In this study, drought determination criteria based on the analysis measured data and hydrological model of two pilot water intake sites (HWIP and CWIP in the Han and Geum river basins, respectively) were applied for the riverbed water intake point. Special attention was paid to the evaluation of the WIC and number of water intake days (WIDs).

3.1. Evaluation of WIC and WIDs for Pilot Basins

Figure 4 shows the WIC obtained for HWIP by combining observed flow data with simulation results from the Tank model, a widely used storage-type hydrological model for determining runoff processes. The WIC was calculated by subtracting the average water intake, which was estimated by analyzing the FDC for 7-year flow data from 2014 to 2020, using the simulated daily runoff or FRC data. In the case of HWIP, the DAR was not applied, and the number of water intake days was evaluated based on the average water intake (2421 m^3/day) in 2018, yielding an average number of WIDs of 332 (90.9%) for the period 2014–2020. When the observed flow data and Tank simulation results were combined, the number of WIDs was 13.7 days (4.13%), higher than that obtained with the Tank model. In 2015, the Tank model simulation yielded 273 (74.8%) WIDs. The number of WIDs was 320 (47 additional days; 87.7%) when the observed flow data and the hydrological model were used. These results indicate that the simulated daily runoff data yielded an estimated average LF of 0.12 m^3/s, whereas the estimated LF was 0.16 m^3/s when a combination of observed flow and hydrologic model data was used, yielding 13.7 additional WIDs. The WIC calculated from the runoff data simulated by the Tank model is smaller than the actual situation. Nevertheless, based on the results above, in the absence of human intervention, people who rely on water collection at HWIP stations have an unreliable water supply for about 10% of the year during the period 2014–2020.

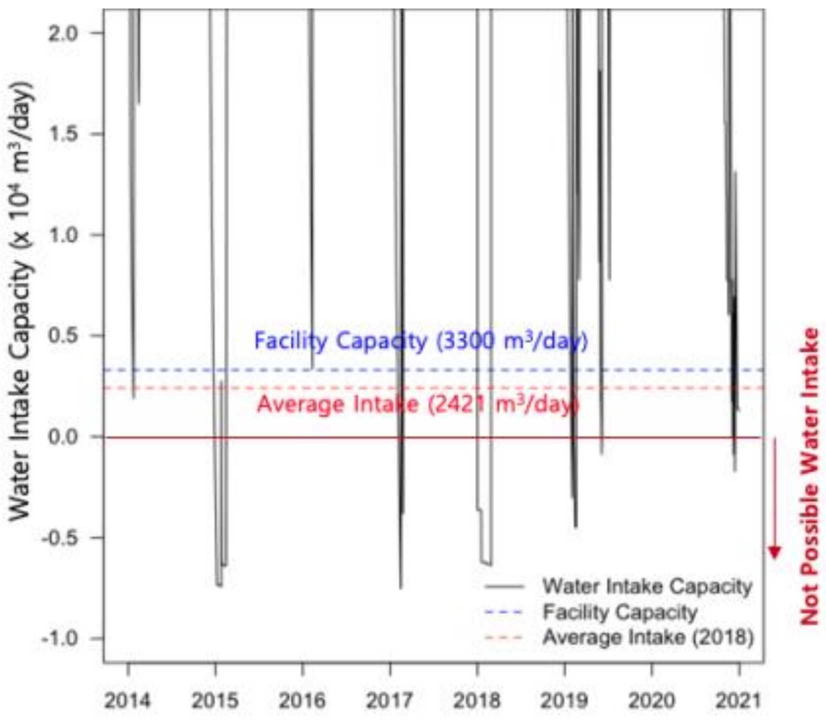

Figure 4. Water intake capacity (WIC) at the Hyunri water intake plant (HWIP) based on combining observed flow data with hydrologic simulations from 2014 to 2020.

Figure 5 shows the comparison results between the estimated WIC derived from observed flow data and actual water intake at the CWIP. In the case of CWIP, the average LF from 2007 to 2020 was estimated to be 0.65 m^3/s based on the daily flow determined using the FDC. DAR was applied to the observed daily flow to determine the WIC and analyze the FDC for the 14-year data series, from 2007 to 2020, and the WIC was calculated by subtracting the average LF. By analyzing data from 2017 to 2020, which has actual operating data, for average WIDs based on a flow of 0.65 m^3/s, it was estimated that water intake was possible on 306 days (83.8%) in 2017, 337 days (92.3%) in 2018, 353 days (96.7%) in 2019, and 343 days (93.7%) in 2020. Like the HWIP, the CWIP has had an average of 30 days per year without guaranteed water intake based on the low flow over the past four years.

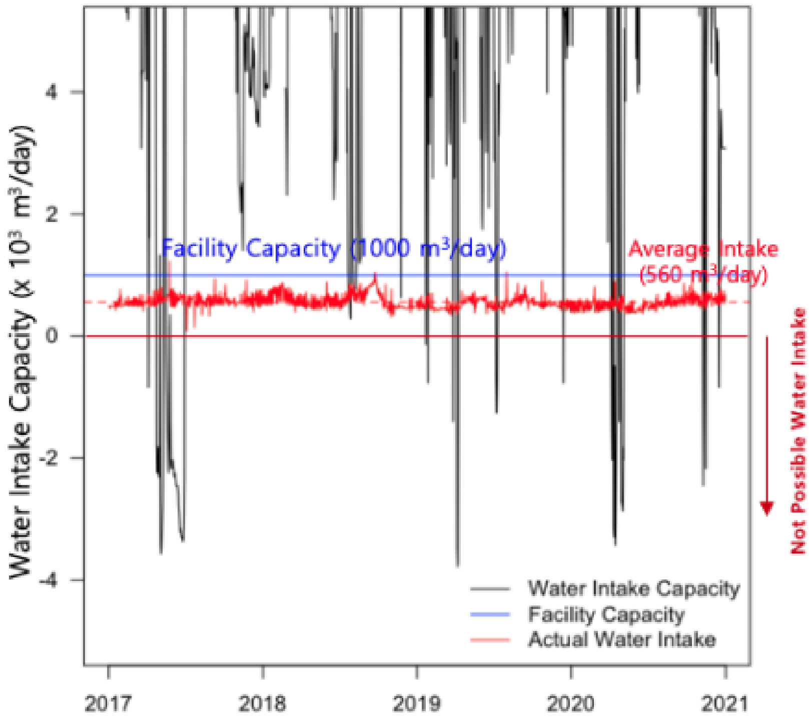

Figure 5. Comparison results between the estimated water intake capacity (WIC) and actual water intake at the Chungsan water intake plant (CWIP) from 2017 to 2020.

3.2. Criteria for Determining Drought Conditions in Ungauged Watersheds

In this study, the WIC was applied to define four-stage drought conditions at the HWIP and CWIP pilot locations to indicate potential water shortages at these water intake facilities. If a water level–flow observation station was near the ungauged river intake station, the drought conditions were determined based on observation data by applying a DAR. In cases without nearby observation stations, hydrological simulations based on the Tank model were used to calculate the LF volumes required to maintain the normal functioning and conditions of the river, thereby calculating the sustainable average water intake that could be diverted from the daily flow. During the evaluation of WIC shortfalls, the WIC_{AVG} of the water intake sources was subtracted from the WIC and the result was divided by the absolute value of the water intake capacity and presented as a drought index (percentage). The result was compared with the five-stage drought determination criteria, considering the meteorological or hydrological drought index and the cumulative number of days on which water could not be extracted. Based on this novel approach, the stage of drought deepening can be adjusted.

The drought classification for the ungauged WIP was determined by using the matrix shown in Table 1. Table 1 shows the water shortage at the WIP. The value obtained by subtracting the WIC_{AVG} of the water intake source from the calculated WIC was divided by the absolute WIC value to obtain the drought index (percentile) for the water insufficiency at the WIP. The result corresponds to one of the five classification levels for the determination of the drought severity. Drought monitoring and forecasting were conducted on a conditional basis by using designated model-based representative variables until observational data for a new observation location were accumulated. Figure 6 shows an example of a five-stage drought classification based on the percentile water shortage at the HWIP from 2014 to 2020.

As shown in Figure 6, most of the water shortages calculated by combining the WIC and SPI/SDI drought index in the HWIP from 2017 to 2020 were in the alert stage, which means that the SPI/SDI drought index reflects moderate or severe drought conditions, or there is a from 0.5 to 1.5 times water shortage occur on certain days. Accurate identification and statistics for droughts and water shortages can provide early warning information to help managers maximize the amount of water available to human–environmental systems in river shortages in ungauged catchments.

Table 1. Criteria for determining the drought conditions at ungauged water intake plants (WIPs).

Drought Index (SPI or SDI)	No Possible Water Intake Days (NPWIDs)	Water Shortages = [(WIC − WIC_{AVG}) / ∣WIC∣] × 100 (%)				
		>0	0 to −50	−50 to −100	−100 to −150	<−150
>0	<15	Normal	Attention	Caution	Alert	Serious
0 to −1.0	15–30	Attention	Caution	Alert	Serious	Serious
−1.0 to −1.5	30–45	Caution	Alert	Serious	Serious	Serious
−1.5 to −2.0	45–60	Alert	Serious	Serious	Serious	Serious
<−2.0	>60	Serious	Serious	Serious	Serious	Serious

Grey to red color representing the drought conditions from stage one to stage five.

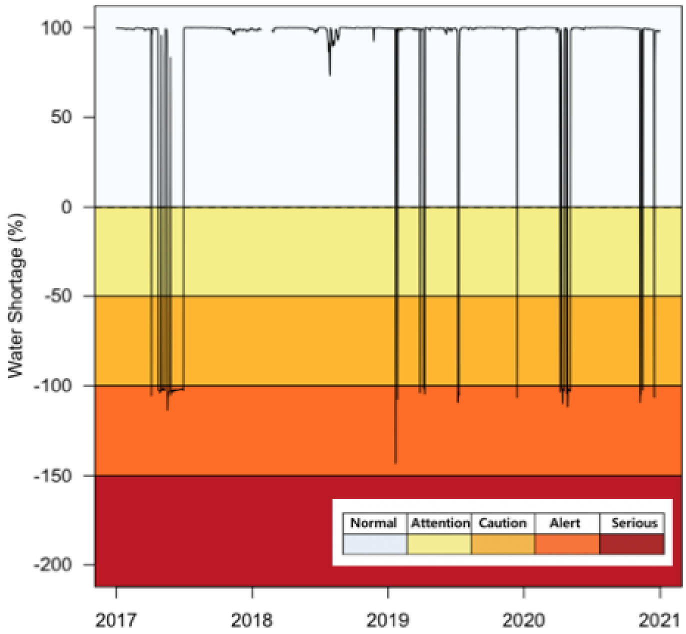

Figure 6. Water shortage and five-stage drought conditions for the Hyunri water intake plant (HWIP).

4. Discussion and Conclusions

Water is an important natural resource related to social and economic development and human survival, and it forms the basis for the formation and development of cities [36]. Owing to scientific and technological advances, seawater desalination [37] and reclaimed water [38] can be used to alleviate water scarcity. However, local waterworks that use river water often lack the facilities to monitor river flow, making it challenging to take preemptive actions such as restricting water intake volumes in the event of decreased river flow during a drought or dry season [39]. Therefore, it is necessary to analyze the drought conditions at WIPs, and to establish a drought assessment and response system for WIPs that lack observational data by using a long-term runoff model.

Pursuant to Article 51 of the Korea River Act (PA51), the instream flow required to maintain the normal functions and conditions of rivers must consider domestic, industrial, and agricultural uses; environmental improvement; generation of electric power; and ship transportation. Accordingly, in this study, a method for assessing the number of days on which water can be extracted is proposed in order to expand and apply similar monitoring efforts nationwide and to establish water intake volumes that are appropriate for each river's maintenance or environmental flow. In addition, the outputs from a hydrological model based on the statistical downscaling of the KMA's global seasonal forecasting system version 5 can be utilized for drought forecasting, weather predictions, and long-term runoff analysis [40].

According to survey data from the National Drought Information Center, South Korea has 430 domestic and industrial water facilities among which 182 (42%) in 76 cities and counties utilize rivers as water sources. These include 109 riverbed water intakes (60%); however, corresponding flow observation data are only available for 65 WIPs. Therefore, in this study, the criteria for determining drought at ungauged river basins were determined by calculating WICs based on three data types (hydrological model, nearby measurement data, and hybrid method) and by evaluating WIDs and water insufficiency levels at WIPs.

This study proposes a methodology for predicting and responding to drought evolution, specifically at locations that lack nearby data collection stations. The approach was tested at two pilot sites in South Korea, which has large numbers of ungauged water intake plants that lack local data collection facilities. Based on the findings of on-site surveys and candidate sites for the installation of watershed monitoring stations, the following drought management measures are proposed for ungauged riverbed WIPs. Additional observation facilities should be installed at ungauged riverbed WIPs as acquisition budgets permit. If there is a nearby water level-flow observatory, the DAR should be applied to determine the drought conditions, which should be based on available observation data observed prior to the installation of an observation station at the water intake site. In areas without observational data obtained at nearby ungauged water intake facilities, it is necessary to begin monitoring by initially utilizing hydrological models (to be subsequently replaced by future observatories) and specify hydrologically based surrogate variables until observation data have been accumulated to conduct drought monitoring and forecasting of the riverbed intake point on a conditional basis.

Based on the methodology proposed in this study, the nationwide expansion of water monitoring would lead to a high usability of local water intake sources, effective drought responses through forecasting and warning, and water supply standards for different drought stages.

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