Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25159

182 (2020) 38–48
April

Optimal local water resource diversification model for drought vulnerability reduction in water supply system

Taehyeon Kim, Jeewon Seo, Kibum Kim, Jinseok Hyung, Jayong Koo*

Department of Environmental Engineering, University of Seoul, Seoulsiripdae-ro 163, Dongdaemun-gu, Seoul 02504, Korea, Tel. +82-2-6490-2866; Fax: +82-2-6490-5465; email: jykoo@uos.ac.kr (J. Koo)

Received 1 July 2019; Accepted 18 November 2019

ABSTRACT

Droughts occurring under the influence of recent climate change are causing water deficit phenomenon and economic loss in most countries. To prepare a water supply system's countermeasure against severe droughts that occur under the influence of recent abnormal climate, this research developed an optimal local water resource diversification model. The developed model was utilized to assess drought vulnerability, and then a local water resource diversification/decentralization plan was proposed that can satisfy drought water supply safety as well as tolerable drought vulnerability level at minimum cost. The developed model verified the applicability of the model through a case study of a city in Korea that is vulnerable to drought. As a result of applying the developed model to the study area, it was judged desirable to secure 46.60% local water resources to cope with drought with a 30-year return period as specified in drought water supply safety. It is expected that the drought vulnerability assessment method and optimal local water resource diversification model proposed in this research could be used in the design of the water supply system to cope with severe drought occurring under the influence of recent abnormal climate.

Keywords: Water supply system; Drought vulnerability; Water resource diversification; Genetic algorithm; Cost effectiveness analysis

1. Introduction

There are steadily increasing water demands in many regions of the world as a consequence of population increase and industrial development. On the other hand, the world is suffering enormous damage from the water deficit phenomenon caused by frequent droughts under the influence of worldwide and simultaneous occurrences of abnormal climate. Drought refers to a phenomenon of below-average rainfall in a wide area over a certain length of period [1]. All the regions of the world are affected by drought regardless of their climate conditions, while every year more than half of the earth enters a status vulnerable to drought [2]. For such a reason, abnormal climate and water resource supply risks have been included in the list of the highest global risks by [3], which analyzes risk occurrences of the world every year. Although there are a variety of causes for water resource supply risk which include natural disasters such as drought, flood, and earthquake, drought can be considered the most direct cause of water supply risk.

In South Korea also drought caused by abnormal climate has been pointed out as a persisting problem. The reason is not only that South Korea's climate is characterized by large variations of precipitation among different years, seasons and regions, but also South Korea has an adverse condition for water resource management due to the topographical environment of small land area preventing aquifer formation. Therefore, in consideration of such climate characteristics, South Korea's countermeasure against drought focuses on dam construction and operation to store precipitation during a flood period, so that stored water can be used until the next flood period. However, the climate pattern of South

* Corresponding author.

Korea has recently changed to involve even larger variations of precipitation-as characterized by the steady occurrence of dry rainy season, which means little rain during flood period in summer-and now demands the improvement of the existing water supply method. It is notable that the severity of drought damage greatly depends on the social situation [4]. In the case of South Korea, the severity of drought damage is all the more serious because many cities have closed local water resources to receive water from the multi-regional water supply systems that offer advantages in terms of maintenance convenience and cost. Particularly, in 2015 when there was a severe drought, B dam in South Korea, because of reduced water storage rate, had to restrict water supply for 127 d to the 8 cities whose water supply depended on that dam, and spent about 3.4 billion KRW (1 USD = 1,200 KRW as of September 25, 2019) as a support fund for water-saving [5].

The increase in drought damage caused by the droughts of the recent few years suggests that drought vulnerability is increasing. Meanwhile, as for drought response management, the preparation of countermeasures against drought now demands a paradigm shift from post-active to pro-active approach. Table 1 shows prior researches for water resource management strategies that can pro-active approach to drought in many countries. Prior researches have proposed a methodology to assess the effects of drought in current water supply systems by using indicators such as resilience, vulnerability, and drought risk. Prior researches have suggested various drought response strategies based on the assessment results, but the quantitative analysis of the diversification of water resources was insufficient and the results were not presented with the cost.

Therefore, accordingly, this research aimed to suggest a methodology for assessing drought vulnerabilities. In addition, the optimal local resource diversification model based on a genetic algorithm was developed to propose optimal design measures for local water purification plants that are appropriate for coping with drought at minimum cost.

2. Methods

The local water resource diversification model for reducing drought vulnerability was developed according to the flow shown in Fig. 1. Rainfall frequency analysis was used to estimate the probability of drought rainfall, while water supply damage during drought was calculated through drought simulation of dam. Based on the results, a genetic algorithm, an optimization method, was utilized to propose an optimal local water source diversification rate. In addition, a cost-effectiveness analysis was used to propose a water resource diversification rate that would yield the highest ratio of expected effect to investment cost.

2.1. Drought vulnerability assessment

The concept of vulnerability refers to the extent of damage caused by risk, as described by preceding researches, and vulnerability is subject to change according to the ability to cope with risk [12]. Therefore, in this research, drought vulnerability in the water supply system is an index representing the extent of water supply damage caused by drought occurrence. It is calculated by multiplying the probability of drought, a consequence of drought and redundancy together, as shown in Eq. (1). An assumption was made, however, that drought occurs along watershed rather than within a particular region, and therefore causes damage not only to the dam of multi-regional water supply but also to the water resource of local water supply, as shown in Eqs. (1) and (2).

$$\mathrm{DV} = \mathrm{PoD} \times \mathrm{CoD} \tag{1}$$

$$R = \left(\frac{\mathrm{MWS}_i}{\mathrm{DWS}_i} + \frac{\mathrm{LWS}_i}{\mathrm{DWS}_i}\right) \times \left(1 - \frac{\mathrm{RQ}_j}{\mathrm{LWC}_i}\right) \tag{2}$$

where DV is the drought vulnerability (m^3/year), PoD is the probability of drought (N/year), CoD is the consequence of

Table 1
Prior researches on drought response management of water resource

References	Study area	Assessment methods	Result indicators
[6]	Fukuoka, Japan	Reservoir continuity equation	Reliability, resiliency, vulnerability, drought risk index
[7]	Yorkshire, England	Rainfall modeling, potential evapotranspiration modeling, hydrologic modelling	Water supply reliability, total system resilience
[8]	All regions, Korea	Drought frequency analysis, cluster analysis	Drought risks, return period of duration, return period of severity
[9]	National Capital Region, US	Dynamic inoperability analysis, water-use dependency analysis, event tree analysis	Inoperability, cumulative economic loss
[10]	Queensland, Australia	System dynamics modeling	Resilience
[11]	Dallas, US	General circulation models, Monte Carlo simulation	Resilience metrics

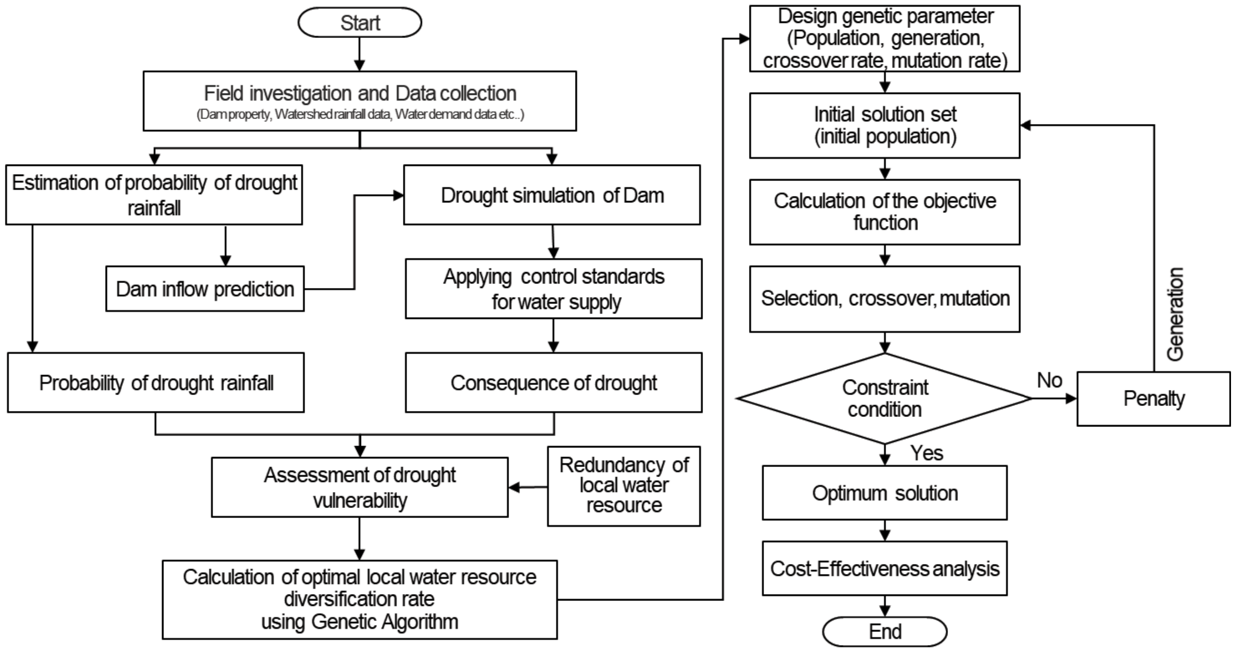


Fig. 1. Development flow for local water resources diversification model.

drought (m^3/year), DWS_i is the daily water supply for i reservoir (m^3/d), MWS_i is the multi-regional water supply for i reservoir (m^3/d), LWS_i is the local water supply for i reservoir (m^3/d), LWC_i is the local water purification plant capacity for i reservoir(m^3/d) and RQ_j is the reserve quantity of j local water resource (m^3/d).

2.2. Case study area

The multi-regional water supply system of B dam has been supplying water to 8 cities of Korea, including T city, the study area of this research. After B dam was constructed and began to supply water in 1998, T city, the study area of this research, closed all the 4 local water resources as shown in Fig. 2 for the reason that water supply from the multi-regional water supply system of B dam was advantageous in terms of maintenance cost and operation efficiency, and since then has been receiving water from that multi-regional water supply system. This multi-regional water supply system has a facility capacity of 2,852,000 m^3/d, while its daily maximum production is 2,436,000 m^3/d. This means that this system has been operated at an operation rate of 85.4%, which is higher than the proper operation rate of 75% proposed by [13], and therefore has been in a status that can cause supply stability problems when drought occurs. This is the reason the water storage rate of B dam decreased below 10% in 2015 when a severe drought occurred so that the 8 cities whose water supply depended on the B dam suffered great damages and had to restrict water supply. B dam was designed according to drought water supply safety shown in Table 2, which allows water deficit once in 20~30 years, yet the dam revealed drought vulnerability only 16 years after the completion of its construction.

As an area that has experienced severe drought damage in the past, T city has needed a drought countermeasure, such as the drought vulnerability assessment-based decentralization of the provincial city's water resource. T city has 11 distinct distribution areas, and its design daily maximum water supply is 46,422 m^3/d. Table 3 presents the current water supply status of T city, whereas Table 4 presents the water supply amounts of the closed local water resources. In case all the local water resources are used, T city can achieve a maximum self water supply of 22,245 m^3/d (47.91%).

2.3. Estimation of the probability of drought rainfall

The probability of drought rainfall in the watershed of the study area was estimated by rainfall frequency analysis, using the rainfall data measured over 47 years (1972–2018) by A weather station located near the watershed. Rainfall frequency analysis estimates the probability of drought rainfall by probability distribution. The probability of drought rainfall was based on Gumbel distribution, which has been widely used because its adequacy for the measurement of severe rainfall-related risk has been supported by both theoretical and empirical grounds. Gumbel distribution has also been described as the most prevalent distribution type for all regions of South Korea [15]. The parameters of probability distribution were estimated using the probability-weighted moments, which assumes that the probability-weighted moments of population and sample are the same. The following Eq. (3) is the cumulative distribution function for the Gumbel distribution estimated based on the rainfall data measured over 47 years by A weather station.

$$F(x) = \exp\left[-\exp\left\{-\frac{(x-1077.5)}{235.1}\right\}\right] \tag{3}$$

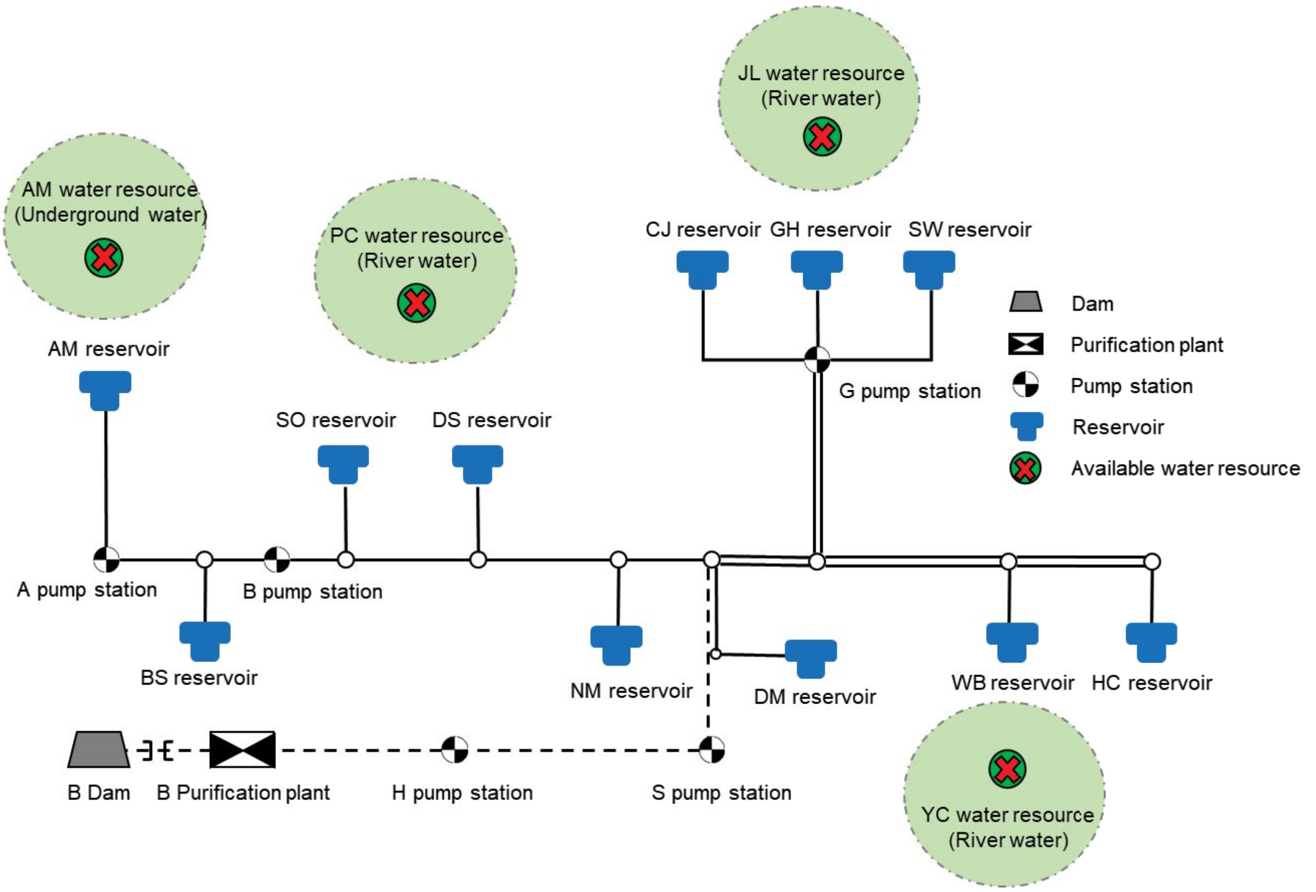


Fig. 2. Case study area (B-multi-regional water supply).

Table 2
Drought water supply safety in Korea [14]

Water resource	Multipurpose dam
Drought water supply safety	Response to 20~30 years return period drought
Supply area	City

Table 3
Reservoir characteristic of case study area

Category		Capacity (m^3)	Daily water supply (m^3/d)
Reservoir	NM	4,700	4,700
	AM	5,000	8,518
	BS	1,750	2,589
	SO	430	841
	DS	4,000	6,438
	CJ	2,000	2,418
	GH	1,000	974
	SW	3,000	5,507
	WB	500	869
	HC	2,000	2,992
	DM	8,000	11,460

Table 4
Available water resource characteristic of case study area

Category		Type	Available quantity of water intake (m^3/d)
Available water resource	AM	Underground water	4,700
	PC	River	8,518
	JL	River	2,589
	YC	River	6,438

where $F(x)$ is the cumulative distribution function (–) and x is the annual total rainfall (mm/year).

This research conducted a drought vulnerability assessment using the probability of drought rainfalls and drought return periods estimated by Eq. (3). Table 5 presents the probability of drought rainfalls by drought return periods.

According to the result of analysis on the total rainfall measured over the past 47-year period by A weather station, the average annual total rainfall was 1,208 mm/year. This can be interpreted as corresponding to the probability of drought rainfall with a return period of 2–3 years. As for the variance of annual total rainfall, the highest rainfall value was about 2.6 times the lowest. Also, based on the annual total rainfalls measured over the 47 years, it was found that drought

Table 5
Probability of drought rainfall according to drought return periods

Drought return period (year)	Probability of drought rainfall (mm/year)
2	1,257
3	1,132
5	992
10	816
15	717
20	648
30	551
50	429
100	266

recurred at intervals of 7–8 years, and accordingly, the years of 2014–2016 were judged to correspond to drought years.

Dam inflow according to the probability of drought rainfall was predicted through the dam inflow prediction model developed in this research. The model for predicting dam inflow is shown in Eq. (4).

$$y = 0.146x_1 - 0.024x_2 - 0.921 \tag{4}$$

where y is the monthly total dam inflow ($10^6 m^3$/month), x_1 is the monthly total rainfall (mm/month, $x_1 \geq 30$) and x_2 is the monthly total evaporation (mm/month, $x_2 \leq 142$).

2.4. Drought simulation of dam

The simulation model and optimization model are representative methods for assessing the water supply capacity of the dam [16]. This research employed the drought simulation of the dam analysis method, which is a deterministic analysis method that simulates dam operation based on the dam operation rules that have been set. As shown in Eq. (5), drought simulation of dam judged water supply availability based on the consecutive monthly analysis of the relations between the inflow amount, outflow amount, evaporation amount and water storage amount of dam.

$$S_t = S_{t-1} + I_t - O_t - E_t \tag{5}$$

where S_t is the storage of capacity at t (m^3/month), S_{t-1} is the storage of capacity at t–1 (m^3/month), I_t is the inflow at t (m^3/month), O_t is the outflow at t (m^3/month) and E_t is the evaporation loss at t (m^3/month).

Based on the actual dam operation rules [17], Table 6 presents the assumptions applied to the drought simulation of the dam. In addition, drought simulation of dam applied water supply adjustment guidelines [18], prepared to cope with dam water deficit during drought by adjusting the supply amount.

2.5. Genetic algorithm to find out optimal diversification rate for local water resource

Water resource diversification can be considered as a method for reducing the drought vulnerability caused by receiving water from a single water source. Accordingly, this research developed an optimal local water resource diversification model that the water supplier can utilize to set up a drought vulnerability reduction plan. That is, this model is for the optimization of a new local water purification plant construction plan that aims at the utilization of available local water resources as a measure against the probable occurrence of large scale water suspension caused by centralized water resource operation.

This research utilized a genetic algorithm, an optimization method, to develop a model for determining the location, capacity and diversification rate of the local water purification plant. Cost minimization was set as the objective function of the model, as shown in Eqs. (6)–(8), to set up a plan that can achieve the tolerable drought vulnerability level at a minimum cost. The cost was calculated by utilizing the approximate cost of construction function presented by [19], which includes newly constructed intake facilities, water purification plants, and pipelines. A newly constructed pipelines must be able to satisfy such conditions as the flow velocity and water pressure inside the pipe. Therefore this research determined the pipe diameter of a newly constructed pipeline in consideration of the design daily maximum water supply of the distribution area. Total pipe length was assumed to be the same as the

Table 6
Assumptions of drought simulation of dam

Items	Assumptions
Water release assumption	If the dam water level has reached a normal high water level, waster is released until the dam water level reaches a restricted water level.
Low water level supply assumption	If the water storage amount is less than the design water supply, water is supplied only until the dam water level reaches a low water level.
Drought simulation period of dam	Drought simulation of the dam was carried out for 24 months, assuming that drought occurs during the first 12 months and then average rainfall occurs during the following 12 months. This assumption was made in consideration of the rainfall characteristics of South Korea, that is, if drought occurs and there is no rainfall during flood period (July–September), damage usually occurs in the drought period (spring) of the following year.
Initial water level of dam	The initial water level (January) of drought simulation of the dam was assumed to be 66.59 m (storage rate: 56.27%), which was the average water level during January after the construction of the B dam.

linear distance between the water purification plant and the distribution reservoir.

$$\text{Objective function} = \text{Minimize}\left(C_{\text{WPP}} + C_P\right) \quad (6)$$

$$C_{\text{WPP}} = 705.42 \times \left(\frac{\text{WP}_c}{1{,}000}\right)^{0.6944} + 5{,}175 \times \left(\frac{\text{WP}_c}{1{,}000}\right)^{0.6147} \quad (7)$$

$$C_P = C_{\text{SP}} \times L \quad (8)$$

where C_{WPP} is the water purification plant construction cost (million KRW), C_P is the pipeline cost (million KRW), C_{SP} is the cost of installing pipe by diameter and type (million KRW/km), L is the pipeline length (km) and WP_c is the capacity of water purification plant (m^3/d).

The capacity of the local water purification plant was applied as a constraint of the model, as shown in Eq. (9). In consideration of the scale of the study area, the minimum condition of water purification plant capacity was set at 900 m^3/d, which was the average capacity of the water purification plants in Korea whose capacities were smaller than 1,500 m^3/d; while the maximum condition was set at the maximum available quantity of water intake. The 'tolerable drought vulnerability level' pursued by water suppliers may vary according to their financial and environmental conditions. For this reason, in this research, a 'tolerable drought vulnerability level' that can satisfy the water supply service level was applied as a constraint, as shown in Eq. (10).

$$900 \le \text{WP}_c \le Q_{\text{WI}} \quad (9)$$

$$\text{DR} \le \text{Setting value} \quad (10)$$

where WP_c is the capacity of water purification plant (m^3/d), Q_{WI} is the available quantity of water intake (m^3/d) and DV is the drought vulnerability (m^3/year).

Population, generation, crossover rate and mutation rate—which are the genetic parameters of the genetic algorithm—were set at 200; 20,000; 0.80; and 0.20, respectively. Genetic operation was set to end upon the completion of calculation for the set generation. EVOLVER S/W, which operates within Microsoft Excel, was employed to apply a genetic algorithm.

3. Results and discussions

3.1. Result of drought simulation of dam

Fig. 3 shows the result of drought simulation of B dam, the sole water resource of the study area, by representative drought return periods that correspond to various probability of drought rainfalls. According to the result, the occurrence of probability of drought rainfalls with return periods of 10 years and under do not cause water supply damage, such as restricted water supply. However, occurrence of drought rainfall with a 15 years return period (717 mm/year) reduces dam water level in the flowing March and April below the red line specified in water supply adjustment guideline (K-water, 2016), causing restricted water supply for a total of 2 months during which only 20% of normal water supply amount is allowed. The result of drought simulation of B dam shows that the current status of the B dam is not capable of coping with droughts with return periods of 20~30 years as demanded by drought water supply safety. Also, it is anticipated that the occurrence of drought rainfalls with return periods of 15 years and over will cause greater water supply damage for longer periods, as presented in Table 7.

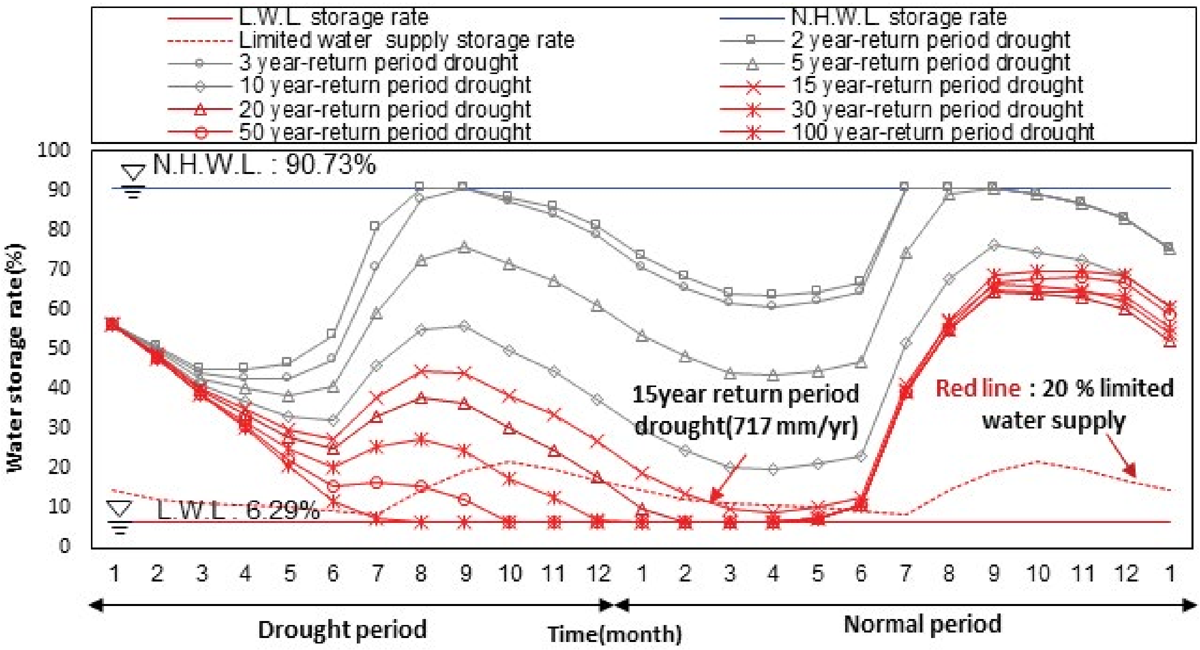


Fig. 3. Result of drought simulation of B dam.

Table 7
Consequence of drought by typical drought return periods

Drought return period (year)	Probability of drought rainfall (mm/year)	Consequence of drought (d/N)
2	1,257	0.0
3	1,132	0.0
5	992	0.0
10	816	0.0
15	717	6.1
20	648	50.7
30	551	72.3
50	429	112.1
100	266	142.7

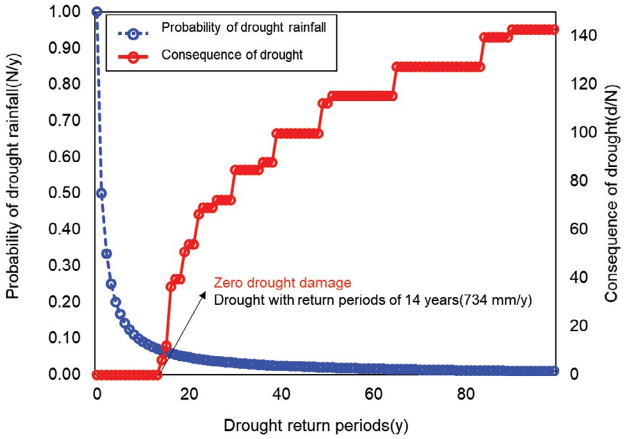


Fig. 4. Probability of drought rainfall and consequence of drought.

3.2. Drought vulnerability assessment

Fig. 4 shows the consequence of drought for the study area for drought return periods from 1 year up to 100 years, obtained by utilizing the probability of drought rainfall, as well as consequence of drought based on drought simulation of dam. It is judged that as the length of drought return period increases, the probability of drought rainfall decreases exponentially but the consequence of drought drastically increases.

Fig. 5 shows drought vulnerabilities to droughts with return periods from 1 year up to 100 years, to enable the simultaneous consideration of the probability of drought rainfall and consequence of drought. The result of drought vulnerability assessment for the study area based on drought simulation of the dam showed that droughts with return periods from 1 year to 14 years would not cause water supply damage. Therefore the study area's drought vulnerability to such a drought was assessed to be 0. As for droughts with return periods of 15 years and over, to which the study area showed drought vulnerability, the greatest drought vulnerability of 133,850.101 m^3/year (2.88 d/year) was to drought with a 24 years return period. This can be interpreted, in terms of probabilistic concept, that consecutive or intermittent water supply suspensions may occur for a total of 2.88 d/year. The current result of drought vulnerability assessment of study area shows that its water supply system is not capable of coping with droughts with return periods of 20–30 years, which is the length of drought return period specified in drought water supply safety and has been widely applied to water supply system operation. Accordingly, it is judged that the study area T city would need local water resource diversification as a countermeasure against drought.

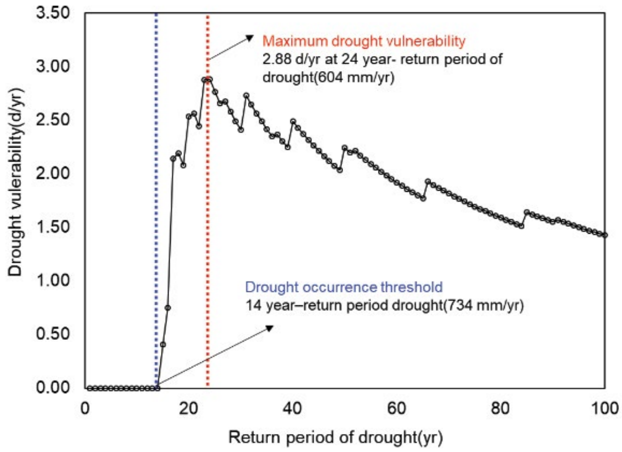


Fig. 5. Result of drought vulnerability by return periods.

3.3. Optimal diversification rate of local water resource

3.3.1. Optimal diversification rate for meeting drought water supply safety

The optimal local water resource diversification model was utilized to deduce a method for coping with drought with a 30 years return period, to satisfy drought water supply safety. Based on a genetic algorithm, an optimization method, the optimal local water resource diversification model suggested the location and capacity of new local water purification plants as well as the local water resource diversification rate. The result is shown in Figs. 5 and 6.

According to the result of utilizing the optimal local water resource diversification model to deduce a method for satisfying drought water supply safety, it is suggested to construct 3 new local water purification plants that can utilize local water resources at 3 locations, as shown in Fig. 7. In this case, the new system secures a local water resource diversification rate of 42.57% (18,830 m^3/d), so that it can cope with droughts with return periods up to 30 years without water supply suspension, as shown in Fig. 6, thus satisfying drought water supply safety. As the current system can cope with droughts with return periods only up to 14 years, the new system achieves a significant improvement effect. It was also shown that the new system can remarkably reduce drought vulnerability to droughts with return periods longer than 30 years. It is judged that such a reduction in drought vulnerability is due to reduction in water supply of B dam by the securing of T city's own local water resources for partial self-supply, which has the effect of reducing the

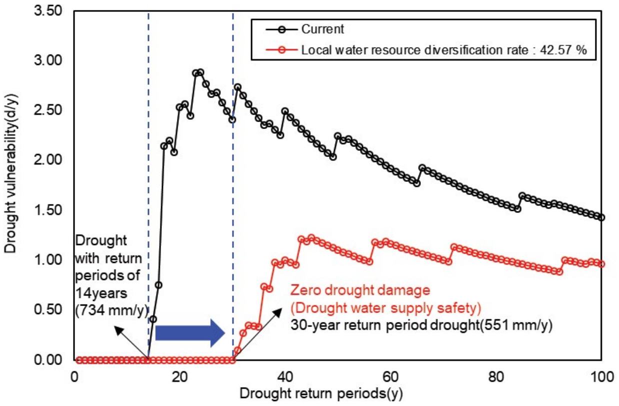


Fig. 6. Comparison of drought vulnerability between current and optimal design plan for meeting drought water supply safety.

drought vulnerability of B dam, as well as due to the local water resources' securing of extra amount of water that can reduce drought damage when drought occurs.

3.3.2. Maximum drought return period without damage

If the study area T city secures the maximum number of local water resources, its local water resource diversification rate will be 46.40% (20,960 m^3/d). In this case, it would be possible to cope with droughts with return periods up to 33 years without the damage of water supply suspension. However, from the fact that T city is only one of the cities receiving water from B dam and water supply amount of the local water resources is limited, it is judged impossible to completely prevent damage that can be caused by droughts with return periods longer than 33 years.

3.3.3. Optimal diversification rate for meeting tolerable drought vulnerability

Water supplier needs to establish a water supply system that can cope with drought with a 30 year return period as demanded by drought water supply safety. However, it is considered that some water suppliers cannot meet drought water supply safety because of their financial and environmental conditions or for some other reasons. In consideration of such situations, this research utilized the present drought vulnerability assessment result to set tolerable levels of drought vulnerability (2.0, 1.5, 1.0, 0.5, and 0.0 d/year) to drought with a 24 years return period, to which the target area showed the highest drought vulnerability; and then proposed a local water resource decentralization method that can satisfy those levels at minimum costs.

Fig. 8 shows the locations, capacities, and water supply reservoirs of the local water purification plants that need to be newly constructed based on the result of optimal local water resource diversifications by tolerable drought vulnerability levels. In the case of setting tolerable drought vulnerability level at 2.0 d/year, which is the probabilistic value of water supply suspension occurring for 2 d per year because of drought, the securing of 2 local water resources and the construction of local water purification plants will enable the self-supply of 10.78% (5,010 m^3/d) of the total water supply amount.

Fig. 9 and Table 8 present the result of drought vulnerability assessments by drought return periods for various drought vulnerability level scenarios. In the case of setting tolerable drought vulnerability level at 2.0 d/year, it was shown that the existing drought vulnerability of 2.88 d/year to drought with a 24 years return period could be reduced down to 1.99 d/year according to the varying tolerable drought vulnerability constraints, at minimum costs.

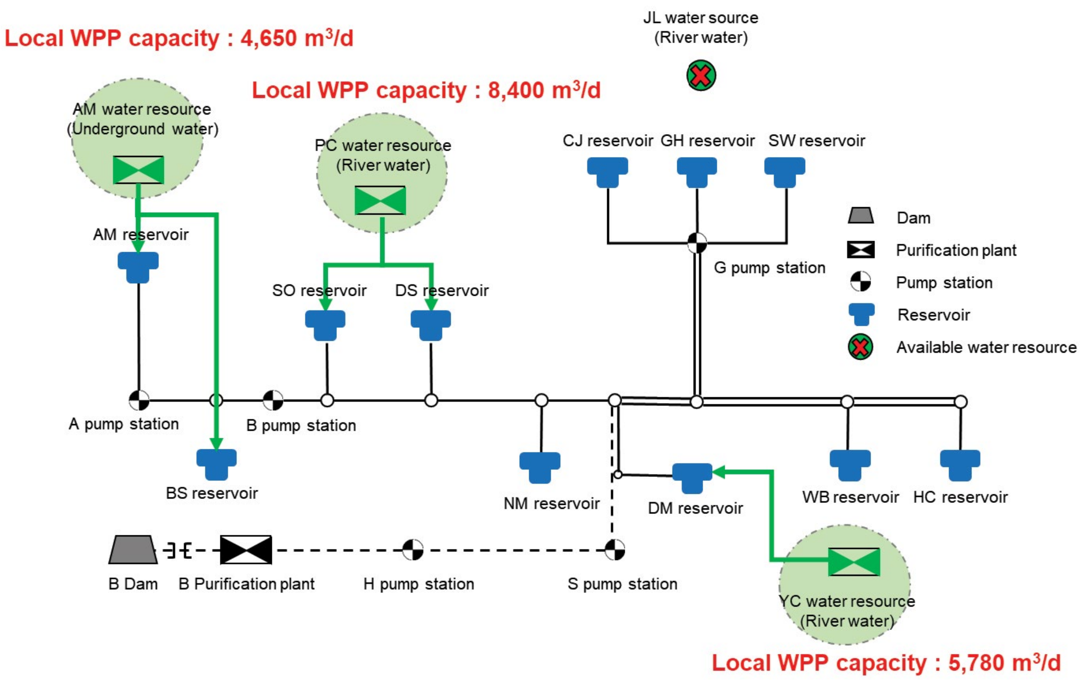
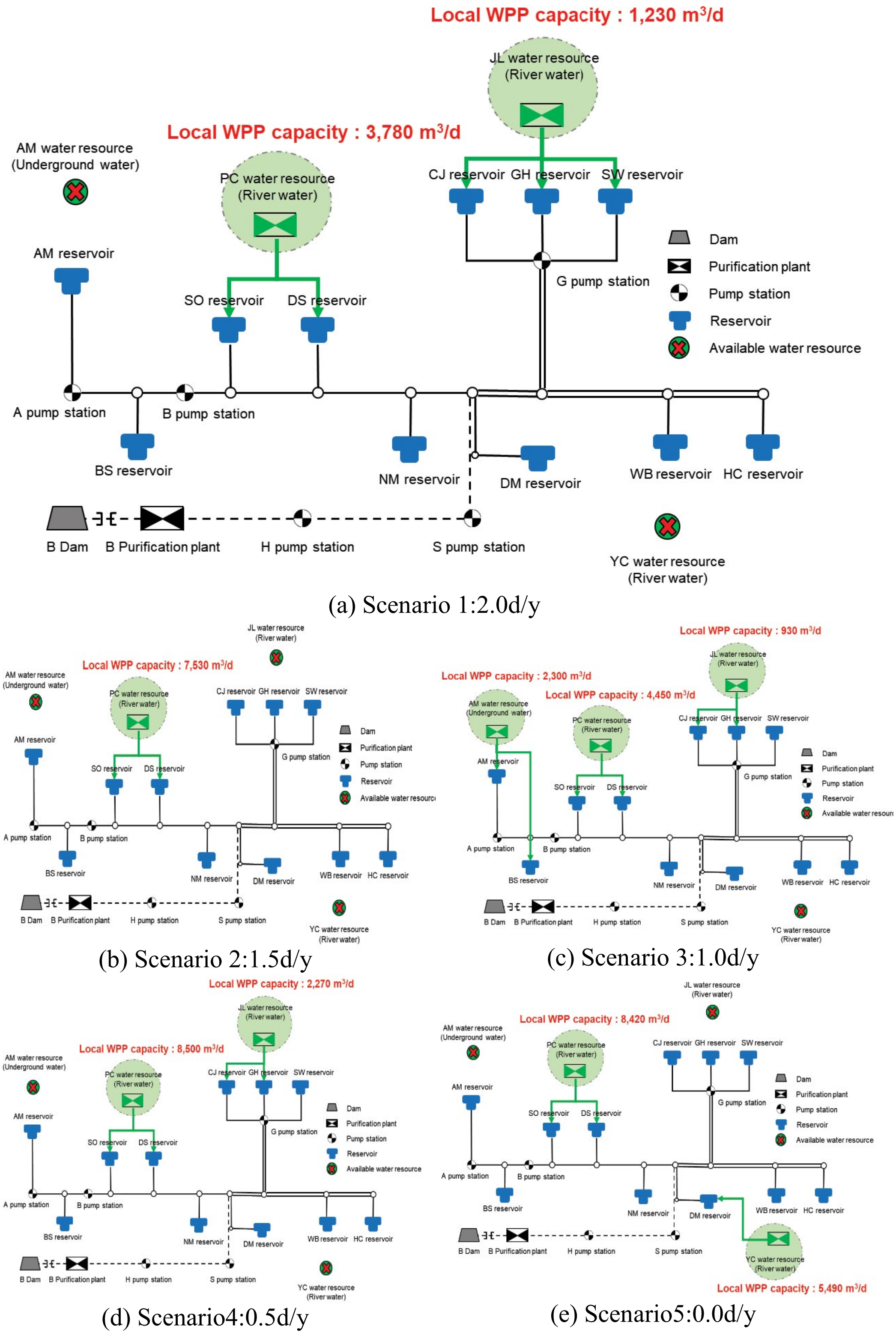


Fig. 7. Optimal design plan for meeting drought water supply safety.

It was also shown that water resource diversification by securing more local water resources and combining them with the current single water resource could not only reduce drought vulnerability for every drought return period but also increase tolerable drought return period from the current maximum of 14 years to a maximum of 24 years. However, the extent of drought vulnerability reduction showed a decreasing tendency as the length of the drought



(a) Scenario 1:2.0d/y

(b) Scenario 2:1.5d/y

(c) Scenario 3:1.0d/y

(d) Scenario4:0.5d/y

(e) Scenario5:0.0d/y

Fig. 8. Results of optimal design plan for meeting tolerable drought vulnerability scenario.

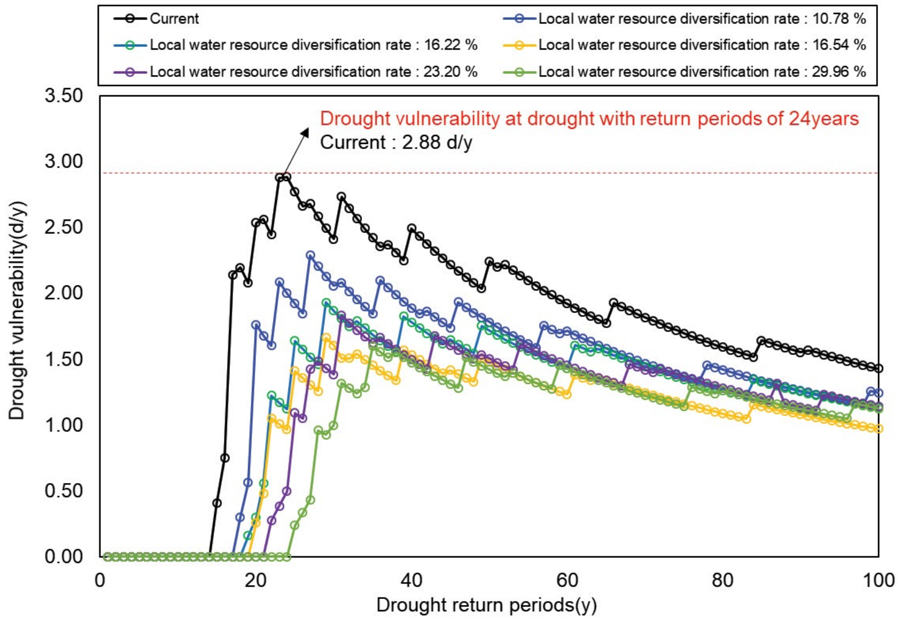


Fig. 9. Result of drought vulnerability assessments by drought return periods for various drought vulnerability level scenarios.

Table 8
Results of optimal local water resource diversification rate according to tolerable drought vulnerability

Category		Tolerable drought vulnerability (d/year)					
		Current	2.0	1.5	1.0	0.5	0.0
Local water resource diversification rate (%)		0	10.78	16.22	16.54	23.20	29.96
Drought return period of zero drought damage (year)		14	17	18	19	21	24
Drought vulnera-bility	m^3/year	133,850.101	92,843.109	52,097.528	44,829.584	23,043.793	0.000
	d/year	2.883	2.000	1.122	0.966	0.496	0.000
Water supply reservoirs (m3/d)	PC	–	SO, DS (3,780)	SO, DS (7,530)	SO, DS (4,450)	SO, DS (8,500)	SO, DS (8,420)
	JL	–	CJ, GH, SW (1,230)	–	CJ, GH (930)	CJ, GH (2,270)	–
	AM	–	–	–	AM, BS (2,300)	–	–
	YC	–	–	–	–	–	DM (5,490)

return period increased. It was judged that such a tendency is due to the limit on the available water supply amount of local water resource, as local water resource is also affected by drought occurring in watershed.

3.4. Cost-effectiveness analysis

To cope with droughts with a 30 years return period, it was judged desirable to secure a local water resource diversification rate of at least 42.57%. However, in case the water supplier has failed to secure sufficient local water resources because of financial or environmental condition, it is proper to choose an efficient method by comparing the ratio of expected effect to investment cost, that is, by comparing drought vulnerability reduction amount. For this reason, this research carried out a cost-effectiveness analysis, and the result is shown in Table 9.

According to the result of the cost-effectiveness analysis, the highest effect compared to investment cost (3.782 m^3/year/million KRW) was shown by scenario 2, which is the achieving of a local water resource diversification rate of 16.22% by securing local water resources and combining them with the existing single water resource that supplies water through B dam. This scenario can eliminate water supply damage from droughts with return periods up to 18 years and can reduce drought vulnerability to drought with a 24 year return period by 1.761 d/year at a cost of 21,615 million KRW. Therefore, in case water supplier has a problem in satisfying drought water supply safety because of financial or environmental limit, the best decision for coping with drought with the

Table 9
Results of cost-effectiveness analysis

Category		Tolerable drought vulnerability (d/year)					
		Current	2.0	1.5	1.0	0.5	0.0
Local water resource diversification rate (%)		0	10.78	16.22	16.54	23.20	29.96
Drought vulnerability reduction	m^3/y	0	41,007	81,753	89,021	110,806	133,850
	d/y	0	0.883	1.761	1.918	2.387	2.883
Cost (million KRW)		0.000	20,903	21,615	31,567	33,492	40,906
Cost-effectiveness (m^3/y/million KRW)		0.000	1.962	3.782	2.820	3.308	3.272

highest cost-effectiveness is judged to be the construction of a new local water purification plant with a facility capacity of 3,780 m^3/d at PC local water resource, having the new local facility secure 16.22% of total water supply amount and supply water to SO and DS distribution areas.

4. Conclusions

This research suggested the model to assess drought vulnerability through drought simulation of dam. In addition, the optimal local water resource diversification model was developed to propose the optimal location, capacity, water supply reservoir and water resource diversification rate of local water purification plants that are appropriate for coping with drought at minimum cost. The developed model verified the applicability of the model through a case study of a city in Korea that is vulnerable to drought.

It is possible to judge that the current status of the study area's water supply system is not capable of satisfying drought water supply safety that requires the ability to cope with droughts with return periods of 20–30 years. It was shown that to cope with droughts with a 30 year return period as specified in drought water supply safety, new local water purification plants need to be constructed that can self supply water using 3 local water resources, achieving the self-supply of 42.57% (18,830 m^3/d) of total water supply amount. In addition, cost-effectiveness analysis has been proposed to make effective decision-making by comparing the ratio of expected effect to investment cost—that is, by comparing drought vulnerability reduction amount.

It is expected that the drought vulnerability assessment method and optimal local water resource diversification model proposed in this research could be used in the design of the water supply system to cope with severe drought occurring under the influence of recent abnormal climate in other regions through actual data.

Acknowledgment

This subject is supported by the Korean Ministry of Environment as Global Top Project (2016002120006).

References

[1] D.A. Wilhite, M.H. Glantz, Understanding the drought phenomenon: the role of definitions, Water Int., 10 (1985) 111–120.
[2] F.N. Kogan, Global drought watch from space, Bull. Am. Meteorol. Soc., 78 (1997) 621–636.
[3] WEF (World Economic Forum), The Global Risk Report 2019, 14th ed., WEF, Geneva, Switzerland, 2019, pp. 1–107.
[4] O.V. Wilhelmi, D.A. Wilhit, Assessing vulnerability to agricultural drought: a Nebraska case study, Nat. Hazards, 25 (2002) 37–58.
[5] H.J. Kim, H.S. Kang, A.Y. Jeong, A Study on Adaptive Drought Management Policy to Drought Stages: Focused on the Non-structural Measures at Local Scale, KEI (Korea Environment Institute), Sejong, South Korea, 2016, pp. 1–125.
[6] K. Jinno, Risk assessment of a waste supply system during drought, Int. J. Water Resour. Dev., 11 (1995) 185–204.
[7] H.J. Fowler, C.G. Kilsby, P.E. O'Connell, Modeling the impacts of climatic change and variability on the reliability, resilience, and vulnerability of a water resource system, Water Resour. Res., 39 (2003) 1222–1232.
[8] J.Y. Yoo, H.H. Kwon, T.W. Kim, J.H. Ahn, Drought frequency analysis using cluster analysis and bivariate probability distribution, J. Hydrol., 420 (2012) 102–111.
[9] J.R. Santos, S.T. Pagsuyoin, L.C. Herrera, R.R. Tan, K.D. Yu, Analysis of drought risk management strategies using dynamic inoperability input–output modeling and event tree analysis, Environ. Syst. Decis., 34 (2014) 492–506.
[10] P. Amarasinghe, A. Liu, P. Egodawatta, P. Barnes, J. McGree, A. Goonetilleke, System under rainfall reduction due to climate change, J. Hydrol., 540 (2016) 1043–1052.
[11] G. Zhao, H. Gao, S.C. Kao, N. Voisin, B.S. Naz, A modeling framework for evaluating the drought resilience of a surface water supply system under non-stationarity, J. Hydrol., 563 (2018) 22–32.
[12] H.G. Bohle, T.E. Downing, M.J. Watts, Climate change and social vulnerability. Toward a sociology and geography of food insecurity, Global Environ. Change, 4 (1994) 37–48.
[13] MOE (Ministry of Environment), Standard for Waterworks Facilities, KWWA (Korea Water and Wastewater Association), Seoul, South Korea, 2017, pp. 1–213.
[14] MOLIT (Ministry of Land, Infrastructure, and Transport), Water Vision 2001~2020, MOLIT, Sejong, South Korea, 2016, pp. 1–131.
[15] MOLIT (Ministry of Land, Infrastructure, and Transport), Probability of Rainfall Improvement and Complementary, MOLIT, Sejong, South Korea, 2011, pp. 1–237.
[16] G.C. Dandy, M.C. Connarty, D.P. Loucks, Comparison of methods for yield assessment of multiple reservoir systems, J. Water Res. Plann. Manage., 123 (1997) 350–358.
[17] MOLIT (Ministry of Land, Infrastructure, and Transport), Existing Water Resources Utilization Report, MOLIT, Sejong, South Korea, 2016, pp. 1–472.
[18] K-water, Water Supply Adjustment Guidelines, K-water, Daejeon, South Korea, 2016, pp. 1–32.
[19] MOE (Ministry of Environment), Standards for Estimating the Operating Cost and Construction Cost of Waterworks, MOE, Sejong, South Korea, 2016, pp. 1–20.