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Evaluation of water shortage problems in the Han River basin, Korea and desalination as a countermeasure

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Abstract. This study evaluates the role of additional constant water resources to the variable water resources. The variable water resources indicate dam reservoirs, whereas the constant water resources indicate desalination. This study focuses on the water supply system in the Han River basin, Korea, particularly on the increasing failure frequency of water supply. As a first step, this study evaluates the changing trends in water supply failures over the last 50 years. Frequency analysis of both shortage frequency and shortage volume is conducted. Also, the same analysis is repeated while considering the addition of constant water resources. The difference between the two is then quantified as the effect of additional constant water resources. The results are summarized as follows. Frequency analyses result show that the water shortage problem has significantly worsened recently. For example, the occurrence probability of 20 or more water shortages over the 30-year period was almost zero in the 1980s; however, it has now approached one. Similarly, the return period for the shortage ratio of 0.2 was more than 400 years in the 1980s; but has now decreased to less than 30 years. The effect of additional constant water resources is found to be significant. With an additional constant water resources of 1.0×10^6 m^3/day, the occurrence probability of 20 or more water shortages decreases from nearly 1.0 to around 0.6, which can also increase the return period for the shortage ratio of 0.1 from 10 years to about 20 years.

Keywords: Beta distribution; constant water resources; failure in water supply; frequency analysis; Poisson distribution; variable water resources

1. Introduction

Most domestic and industrial water supply is from dam reservoirs (Altinbilek 2002, Agodzo *et al*. 2014, Kim *et al*. 2018, Schmitt and Rosa 2024). In addition, agricultural water supply from dam reservoirs is also important in many countries (Gohari *et al*. 2013, Di Baldassarre *et al*. 2021, Sang *et al*. 2023). Dam or reservoir constructions have been done continuously historically for those purposes along with flood control and river maintenance (Billington *et al*. 2005, Lempérière 2017, Angelakis *et al*. 2024), Especially, after the industrial revolution, more dam constructions have been continued worldwide for securing water resources and producing electric power in many countries (Leknes and Modalsli 2018, Zhang and Gu 2023).

Korea also relies most domestic and industrial water supply on multi-purpose dams (LTMA 2011, MLTMA 2012). Especially, in the 1970s and 1980s, several large multi-purpose dams were constructed mostly for satisfying the water demand satisfying the government's economic development plan (Jeon 1981, K-water 1998, K-water 1999, Lee 2013). The Soyanggang Dam and Chungju Dam were among the large dams constructed in that period. The reservoir capacity secured at that time was far beyond the water demand at that time. Interestingly, they could plan those large dams for the possible water demand in the future but is almost impossible now. At present, the reservoir capacity of dams is limited to the that satisfying the already confirmed water demand. This change seems to minimize the environmental impact and to avoid the political conflict due to a new dam construction.

Since 1990, dam construction has been strictly restricted mainly due to the rising environmental movement (Go 2006). The environmental movement was politically much stronger than the needs of water supply and flood control. Just a few small dams could be constructed since 1990, which were also mostly single-purposed such as domestic water supply (Kim 2022). Most domestic and industrial water supply was still done from the dams constructed in the 1970s and 1980s.

Global warming and the resulting climate change have become the most imminent issue since 2000. In addition, unprecedented floods and droughts have occurred frequently over the Korean Peninsula (Park 2009). At the same time, new industries such as semiconductor, AI, and data centers, have become important sectors in Korea's industries. As a result, a large amount of additional water supply is required. Both flood control and water supply issues seemed to be more dominant over the environmental issues, however, this situation did not guarantee the easy

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securement of additional water resources (Kim 2015). This was because the conventional way of securing water resources was still not free of various environmental and political issues. The government's management policy of the dam basins was also controversial to the public living within the dam basin (NARS 2015). Most development and economic activities are strongly prohibited within the dam basin, simply to secure clean water.

Another problem of this conventional way of securing water resources based on dams and dam reservoirs is that these water resources are variable. This means that most of the water supply from dam reservoirs in a basin can be affected by the same drought event. In case a dam reservoir is empty, it is more likely that the other dam reservoir is in the same situation. To overcome this problem, the dam reservoir should be bigger. In Korea, the size of dam reservoirs is generally determined as the level to permit the failure of water supply once in 20 years (MOCT 1998, Jang and Kim 2016). If considering that the 20-year drought, which denotes a drought with a 20-year return period, corresponds to just one half of the mean annual rainfall amount (MLTMA 2009), the size of the dam reservoir should be twice that required under the mean annual rainfall condition.

Instead, the constant water resources, which are independent of climate variability and typically represented by desalination, can be free of those adverse issues. It does not require large basin area. It can also pass most environmental issues. However, the economic issues still exist. Interestingly, this issue can be alleviated by considering the variability issue of the conventional water resources. That is, the constant water resources can be a more effective measure to overcome the drought. Also, under a drought situation, the economic issue must be minor, as the planned water supply can easily be satisfied regardless of any situation. Simply, the constant water resources can have more meaning as an important mixture to compensate the conventional variable water resources, which rely on climate-dependent sources such as dam reservoirs.

The objective of this study is to evaluate the role of constant water resources as additional water resources to the conventional variable water resources. This study considers the water supply system in the Han River basin, Korea. The Han River basin is the largest basin in Korea, and is in charge of water supply to the Seoul metropolitan city area with a population of more than 25 million. This study especially focuses on the failure of the water supply in the Han River basin. Both the shortage frequency of the planned water supply and the shortage volume are of concern in this study. As a first step, this study evaluates the changing trends of shortage frequency over the last 50 years since the systematic water supply from multi-purpose dams began. Frequency analysis of both the annual shortage frequency (i.e., the annual number of water shortage days) and the annual shortage volume (i.e., the annual total amount of water supply shortage compared to the planned demand) will be done. Also, the same analysis will be done with additionally considering the constant water resources based on desalination. The difference between the two is nothing but the effect of additional water resources on the water supply system of the Han River basin.

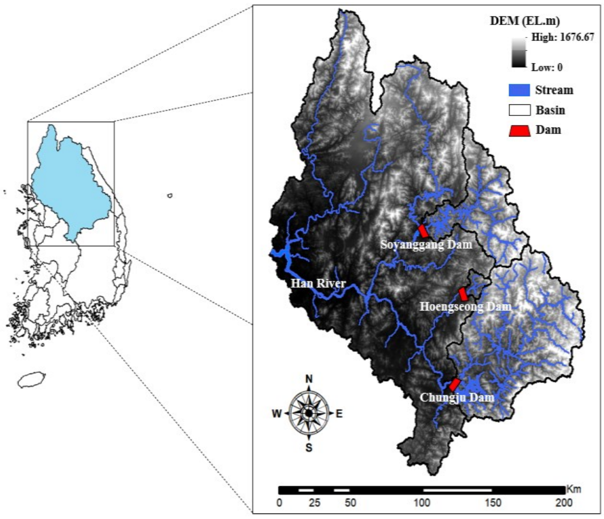


Fig. 1 Han River basin, its channel network and the locations of the three multi-purpose dams

2. Study sites and data

2.1 Change of water supply capacity in the Han River Basin

This study considered multi-purpose dams in the Han River basin, which are in charge of supplying most the domestic and industrial water demand. Agricultural water demand is mostly concentrated in the growing season of paddy from May to August. The Soyanggang Dam, Chungju Dam and Hoengseong Dam are the multi-purpose dams in the Han River basin. The Soyanggang Dam, built in 1973, was the first multi-purpose dam in the Han River basin, The Chungju Dam was built in 1985, and the Hoengseong Dam was built in 2000. These dams are also in charge of flood control in the Han River and water supply to the Seoul metropolitan area. These dams are all located in the middle of the Han River basin (Fig. 1), and the upstream part of the basin is mostly mountainous, and the downstream part is rather flat with farmland and urban. As can be seen in Fig. 1, these dams are located between the steep mountain and flat farmland area to make both roles of flood control and water collection effective.

Table 1 summarizes the major specifications of the dams, dam basins and dam reservoirs. The basin area of the Chungju Dam is the largest to be 6,648 km^2, that of the Soyanggang Dam is 2,703 km^2, and that of the Hoengseong Dam is the smallest to be just 209 km^2. The basin area of the Chungju Dam is about twice that of the Soyanggang Dam, but their dam and reservoir sizes are similar. That is, the total reservoir storage of the Chungju Dam is 2,750 × 10^6 m^3 and that of the Soyanggang Dam is 2,900 × 10^6 m^3. However, due to the large basin area, the planned water supply of the Chungju Dam is much more to be almost three times of the Soyanggang Dam (see Table 1). The

Table 1 Major specifications of the dams in the Han River Basin

Dam		Soyyanggang Dam	Chungju Dam	Hoengseong Dam
Dam Body	Dam Type	Rock Fill	Concrete Gravity	Rock Fill
	Height (m)	123.0	97.5	48.5
	Length (m)	530.0	447.0	205.0
	Crest (EL. m)	203.0	147.5	184.0
Reservoir	Flood Water Level (EL. m)	198.0	145.0	180.0
	Height Water Level (EL. m)	193.5	141.0	180.0
	Low Water Level (EL. m)	150.0	110.0	160.0
	Total Storage Capacity (× 10^6 m^3)	2,900.0	2750.0	86.9
	Effect Storage Capacity (× 10^6 m^3)	1,900.0	1789.0	73.4
	Flood Control Volume (× 10^6 m^3)	500.0	616.0	9.5

Table 2 Monthly planned water supply of Soyanggang Dam, Chungju Dam and Hoengseong Dam.

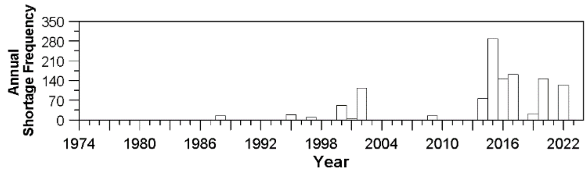
Month	Soyyanggang Dam (× 10^6 m^3)	Chungju Dam (× 10^6 m^3)	Hoengseong Dam (× 10^6 m^3)
Jan	102.0	260.3	11.0
Feb	92.2	235.1	9.2
Mar	103.7	260.3	8.6
Apr	101.3	275.5	8.3
May	104.7	318.7	13.9
Jun	101.3	324.5	14.3
Jul	104.7	308.6	9.1
Aug	104.7	323.8	9.1
Sep	101.3	279.4	9.1
Oct	103.7	281.8	7.5
Nov	98.8	251.9	9.6
Dec	102.0	260.3	9.6
Annual	1,220.5	3,380.4	119.2

Hoengseong Dam is much smaller than these two dams and has a total reservoir storage of just 86.9 × 10^6 m^3.

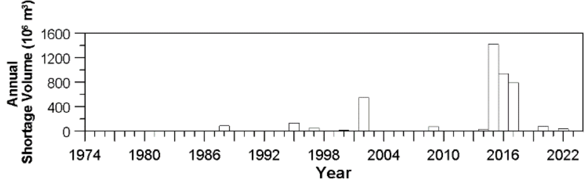
The planned water supply is generally composed of domestic, industrial, and agricultural water supply. The water supply for river management is also important. This planned water supply in Korea varies monthly because of the agricultural water supply to mostly paddy. In particular, the agricultural water supply is assigned to the Chungju dam, as can be seen in Table 2. The planned water supply per year from the Chungju Dam is largest to be 3,380.4 × 10^6 m^3 and that from the Soyanggang Dam basin is second to be 1,220.5 × 10^6 m^3. The planned water supply per year from the Hoengseong Dam is just 119.2 × 10^6 m^3.

2.2 Data

The data analyzed in this study are shown in Fig. 2. These data include the time series of the annual number of water shortage days and the time series of the annual volumes of water shortage. The data period of the Soyanggang Dam is from 1974 to 2023, and that of the Chungju Dam is from 1986 to 2023. The data period of the Hoengseong Dam is shortest from 2000 to 2023. The overall water supply capacity from the Han River basin increased much when the water supply from the Chungju Dam began, and also a little when the Hoengseong Dam was constructed in 2000.



(a) Annual number of shortages (days)



(b) Annual shortage volume

Fig. 2 Time series plots of the annual number of shortages (top) and annual shortage volume (bottom)

The water shortage in this study was defined as a situation in which the planned water supply was not satisfied. This judgment was done on a daily basis, and the

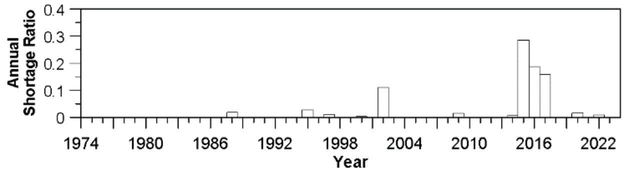


Fig. 3 Time series plot of the annual shortage ratio (i.e., the annual shortage volume divided by the annual planned water supply)

number of those water shortage days (i.e., annual shortage frequency) and the volume of those water shortages were counted. In fact, water shortage in Fig. 2 is estimated by subtracting the actual water supply volume from the planned water supply volume. The water demand is estimated when a new dam reservoir is planned. The size of dam reservoir is also determined to satisfy this water demand. The planned water supply is simply the volume to satisfy this water demand. This planned water supply is thus a fixed value given for each dam reservoir.

Fig. 2 shows these two times series. As can be seen in this figure, the water supply condition has become worsened recently. However, it must be normal, as the water demand is increasing due to the population increase and industrial development in the Han River basin. During the last 30 years, the population in the Seoul metropolitan area has been increased by about 30%. The recent climate change has also been pointed out as an important cause of water shortage in the Han River basin. A possible change in the rainfall pattern due to global warming works against the collection of water resources in large natural basins (Trenberth 2005, Dai 2011). The decreasing pattern of the runoff ratio in the Chungju Dam basin has also caused concern about securing water resources in the future (Jung *et al.* 2019).

This study normalized the water shortage volume data to consider the change in the planned water supply in the Han River basin. That is, the annual water shortage volume was divided by the annual planned water supply to obtain the shortage ratio. This water shortage is defined simply as follows.

$$Shortage\ Ratio = \frac{SV}{PS} \tag{1}$$

In the above equation, SV indicates the annual volume of water shortage, and PS the annual planned water supply. This shortage ratio moves from zero to one.

Basically, the shortage ratio is used to represent the severity of water shortage problems. A normalized index like this shortage ratio can also be helpful to guess qualitatively how the water shortage problem is. Additionally, in this study, it was important to statistically analyse the water shortage problem quantitatively by the frequency analysis.

The shortage ratio time series derived for the Han River basin is given in Fig. 3. As can be seen in this figure, the shortage ratio is increasing recently. Before 2000, the shortage ratio remained below 0.1, but increased much higher up to 0.3 after 2000. Frequency The frequency of a higher shortage ratio has also increased much recently indicating that the water shortage problem has become significantly worsened recently.

3. Frequency analysis and assessment of the water supply ability in the Han River Basin

3.1 Probability density functions and parameter estimation

The time series data to be analyzed in this study are obviously nonstationary. Both the frequency and volume of water shortages show an increasing trend. As the conventional frequency analysis is based on the assumption of stationarity or at least covariance stationarity, it was impossible to apply this conventional frequency analysis method to the entire data. Instead, this study considered the 30-year moving interval for the frequency analysis. The data length of 30 years was selected as the minimum length for the frequency analysis. That is, the first analysis was done for the 30-year data from 1974 to 2003, and the last one from 1994 to 2023. As the interval moves one year at a time, 21 intervals were considered for the frequency analysis. The 30-year data of each moving interval was assumed to be stationary; thus, the conventional frequency analysis could be performed. Each frequency analysis result could be assumed independent. as the analysis was done independently. The derived result just represents the corresponding moving window.

A goodness-of-fit test was also conducted to support the covariance stationary assumption. This approach was simply to use the conventional frequency analysis method for the stationary time series, but to investigate the non-stationarity in the results of the frequency analysis. The derived results will also constitute a time series.

Table 3 shows some interesting statistics derived for each moving interval (30-year period). This table provides both the mean and standard deviation of the annual shortage frequencies and annual shortage ratios. The sum of the entire shortages during the given 30-year period is also provided. The highest value for the given moving interval is also provided for the annual shortage ratio. As can be found in the change of the mean values, both the shortage frequency and the shortage ratio are increasing steadily, which is faster recently. Also, their standard deviations are increasing to indicate that the variability is much higher recently. On the other hand, the maximum shortage ratio does not seem to be changed much. It has just been updated just once. However, higher shortage ratios have also been recorded recently, which will be considered in the frequency analysis.

In this study, the Poisson distribution was used for the shortage frequency and the Beta distribution was used for the frequency analysis of the shortage ratio. First, the Poisson distribution explains the number of occurrences of an event for a given time duration (Poisson 1837). The probability density function of the Poisson distribution is as follows.

$$P_i = \frac{\lambda^i e^{-\lambda}}{i!},\ \ i = 0, 1, 2, 3 \ldots \tag{2}$$

Table 4 Parameter estimation and the results of the chi-squire goodness-of-fit test (p-value) derived for each time interval

Interval No.	Poisson		Beta		
	λ	p-value	α	β	p-value
1	6.967	0.606	0.060	15.918	0.935
2	6.967	0.606	0.060	15.918	0.935
3	6.967	0.606	0.060	15.918	0.935
4	6.967	0.606	0.060	15.918	0.935
5	6.967	0.606	0.060	15.918	0.935
6	6.967	0.606	0.060	15.918	0.935
7	6.967	0.606	0.060	15.918	0.935
8	7.433	0.914	0.060	15.918	0.935
9	7.433	0.914	0.060	15.918	0.935
10	7.433	0.914	0.060	15.918	0.935
11	7.433	0.914	0.060	15.918	0.935
12	9.967	0.982	0.062	16.197	0.597
13	19.567	0.960	0.061	5.667	0.878
14	24.467	0.766	0.064	3.910	0.880
15	29.867	0.659	0.064	3.316	0.885
16	29.400	0.766	0.064	3.282	0.873
17	30.167	0.766	0.064	3.373	0.873
18	35.033	0.884	0.064	3.373	0.873
19	35.033	0.884	0.064	3.373	0.873
20	39.167	0.789	0.066	3.472	0.880
21	39.167	0.789	0.066	3.472	0.880

Here, i is the number of occurrences of a specific event, Pi the occurrence probability that the specific event occurs i times, and λ the mean occurrence of the specific event. That, the larger Pi indicates the higher occurrence possibility of the specific event.

The Beta distribution was derived by Pearson (1934). By combining the two Gamma distributions, he could derive the Beta distribution with both lower and upper bounds. Similar to the Gamma distribution, this the Beta distribution is very flexible within the lower and upper bounds. The probability density function of the Beta distribution is as follows.

$$f(x) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{B(\alpha,\beta)}, 0 < x < 1 \tag{3}$$

Here, α and β are both the shape parameters, originated from their the Gamma distributions. Also, B represents the Beta function, which is defined as follows.

$$B(\alpha,\beta) = \int_0^1 u^{\alpha-1}\,(1-u)^{\beta-1}du \tag{4}$$

This Beta function is also expressed with the same two parameters α and β. The parameter estimation of these two parameters can be done by applying the maximum likelihood estimation method (MLE), which was also used in this study.

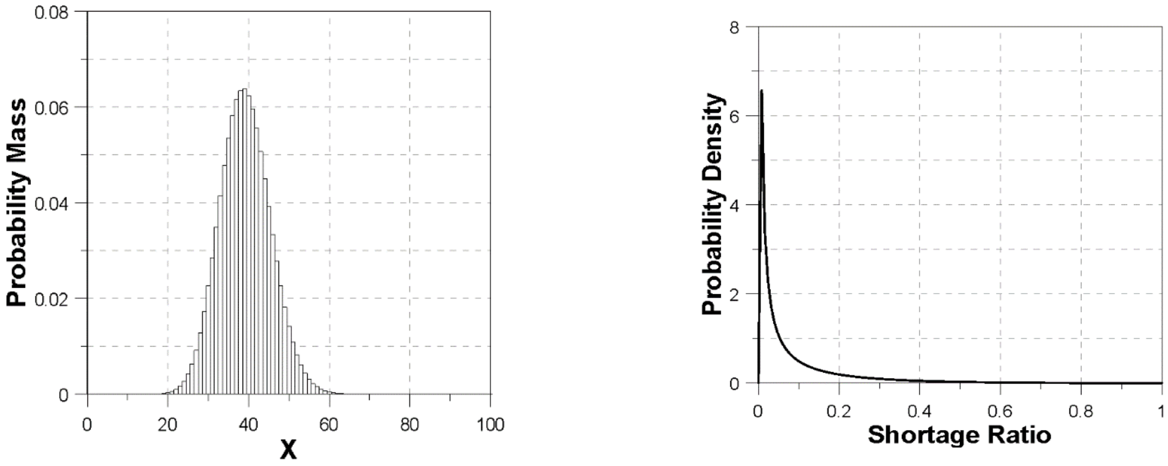
In this study, a goodness-of-fit test was conducted using the chi-square test. The chi-square test is a basic method that evaluates the difference between the observed frequency and the expected frequency (Tallarida *et al.* 1987). This test allows us to assess how well a particular probability distribution explains the data being used. The chi-square value can be calculated using the formula below.

$$x^2 = \sum \frac{(O_i - E_i)^2}{E_i} \tag{5}$$

Here, O_i represents the observed frequency, and E_i represents the expected frequency. In this study, the p-value was calculated using the obtained chi-square value. The p-values for those probability distributions used in this study were found to be greater than 0.05 for all moving intervals, indicating that the fit was appropriate (see Table 4).

The probability density functions derived for the last interval in this study are presented in Fig. 4 as an example. The derived Poisson distribution is rather symmetric around the mean frequency 40 and looks like a Gaussian distribution. This symmetric shape also indicates that the probability of 40 or higher frequency is almost 0.5 to show that the possibility of much extreme water shortage problem can occur easily and frequently.

The shape of the Beta distribution was found to be like the exponential distribution. This means that most water shortages are not so severe as to indicate a small shortage volume. On the other hand, the probability of a large shortage volume is small. This extreme case can happen rarely with the long return period. As a result, the parameter



(a) Poisson Distribution (b) Beta Distribution

Fig. 4 Determined Poisson and Beta distributions for annual number of shortages and annual shortage ratio, respectively, for the interval 21 (from 1994 to 2023)

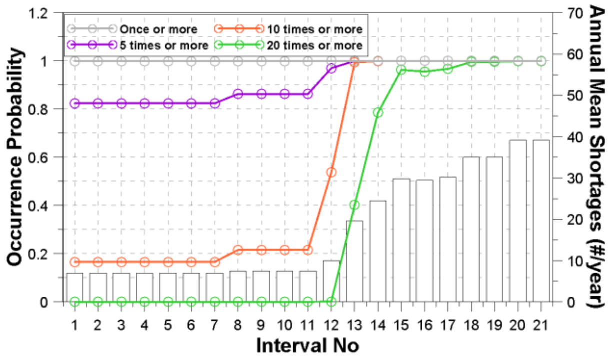


Fig. 5 Comparison of actual annual mean shortages and occurrence probabilities of water shortages once or more, 5 times or more, 10 times or more, and 20 times or more based on the determined Poisson distribution for each moving interval

α was estimated smaller than the parameter β, which leads the shape of the probability density function be positively skewed. In all cases of moving intervals, the estimation of the parameter α was to be smaller than the estimation of parameter β

Additionally, all the parameters estimated for each moving interval are compared in Table 4. In this table, the behavior of the parameter λ of the Poisson distribution and the parameters α and β of the Beta distribution can easily be understood. First, the parameter λ is increasing recently. The estimate of the last moving interval was almost six times larger than that of the first moving interval. This result indicates that the water shortage event occurred more frequently recently. Interestingly, the behavior of parameter α is opposite to the parameter β. That is, the parameter α becomes larger recently, but the parameter β becomes smaller. The change of parameter β is more extreme. The parameter α has been increased by about 10%, on the other hand, the parameter β has been decreased by about 80%. This dramatic change has also changed the shape of the probability density function and accordingly the return period for a given ratio of water shortage.

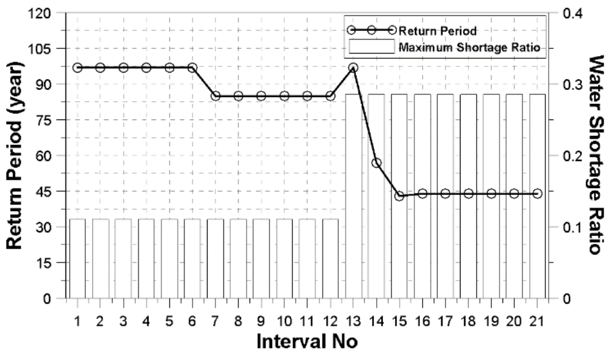


Fig. 6 Change of maximum water shortage volume within the given moving interval and its return period

3.2 Evaluation of the water shortage problem based on the frequency analysis results

The probability density functions determined for each moving interval can be used to evaluate the changes in the water shortage problem in the Han River basin. First, the frequency analysis result based on the Poisson distribution shows the changing trend of water shortages. Fig. 5 summarizes the changes in the return periods for the cases with the number of water shortages 1, 5, 10, and 20 times or more over the 30-year period. The result is also compared with the actual occurrence frequency of water shortages. This figure shows that the trend in the frequency analysis results is well matched with that of the actual occurrences. In the 1980s, the occurrence probability of 20 or more water shortages over the 30-year period was almost zero, but recently the probability has become very close to one. At present, it is not very strange to have water shortages in the Han River basin.

The frequency analysis result on the shortage ratio was first evaluated with the maximum water shortage ratio and its return period (Fig. 6). As the frequency analysis was done for the moving 30-year interval, the maximum water shortage ratio was not frequently changed. Simply, the maximum ratio could remain unchanged for a long time.

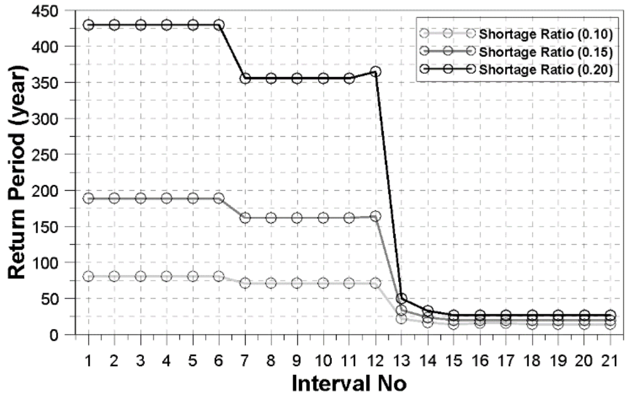


Fig. 7 Change in the maximum water shortage volume within the given moving interval and its return period

However, its return period was different. Depending on the newly added shortage ration, the parameters of the probability density function can be changed a lot and, as a result, the return period for the same maximum ratio could be changed significantly.

The overall trend shows that the return period for the maximum ratio in the 1970s was very long, but, recently, it has been shortened significantly. This trend is also in line with the frequency of water shortages. More in detail, the return period for the maximum shortage ratio up to 1990 was approximately around 100 years, but, recently, it has become just around 40 years. The return period of 40 years may not be short, but it is about the maximum event that occurred during the last 30 years.

To evaluate more objectively, it is necessary to consider some specific shortage ratios, not simply the maximum one. This study considered the shortage ratios of 0.1, 0.15 and 0.2. Fig. 7 compares the behavior of the return periods for those three shortage ratios. As can be seen in this figure, the over trends are similar to the previous case with the maximum ratio. At the beginning in the 1980s, the estimated return period was quite long, in the middle of the period, it was shortened a bit, and then recently, the return period has become much shorter to be less than 30 years in all three cases. For example, the return period for the shortage ratio 0.2 was more than 400 years in the 1980s, and that of the shortage ratio 0.1 was around 80 years. However, recently, the return period for the shortage ratio 0.2 was estimated to be less than 30 years, and that for the shortage ratio 0.1 was just less than 15 years. Simply, it can happen once every 14 years that the water supply is in short by 10% or more.

4. Consideration of additional constant water resources based on desalination

4.1 Desalination as a constant water resource~~s~~

This study considered desalination as an alternative water resource. Desalination is a process to transform the saltwater into the fresh one. Reverse osmosis, the electro-dialysis method, and the evaporation method are among those generally used, and, among them, the reverse osmosis is most frequently used. Desalination is expensive, but advantageous in the aspect that the desalination can produce fresh water constantly independent of the climate condition. Obviously, this alternative water resource~~s~~ is different from those like the water resources secured by the dam reservoir. We call these alternative water resources based on desalination the constant water resources. The conventional one based on dam reservoirs may be called the variable water resources.

This study assumed that this constant water resource~~s~~ was provided from the year 2000. This year is when the last multi-purpose dam, the Hoengseong Dam, was constructed and started the water supply. Consideration of this constant water resources was simple to provide the constant amount of water to the system. It was also considered the primary source of water supply, and the remaining portion of the planned water supply was supplied from the existing dam reservoirs. Reservoir operation was also done in the same way and the resulting water shortages were evaluated, in the same way based on the frequency analysis. The simulation result showed that this constant water resource was used mostly to fill the gap from the Chungju Dam reservoir.

4.2 Effect of additional constant water resources on the occurrence of water shortage

This study evaluated the effect of adding constant water resources on the frequency and volume of water shortages in the Han River basin. The effect was also quantified by the return period or occurrence probability based on the frequency analysis. In this study, 0.5×10^6 m^3/day, 1.0×10^6 m^3/day, 1.5×10^6 m^3/day, and 2.0×10^6 m^3/day were considered as the additional water supply through the desalination. In fact, the desalination capacities considered in this study were determined rather arbitrarily to consider the range of water shortage volumes recently. The additional water needs for the new semi-conductor plants in the Han River basin were also considered. The maximum water needed for those plants was estimated to be about 1.0×10^6 m^3/day. 1.0×10^6 m^3/day is about 10% of the total domestic and industrial water supply to the Seoul metropolitan area.

Table 5 summarizes the result of reservoir operation considering the additional water resources. Overall, most of the additional water resources is used effectively. The annual variation of the use of these additional water resources was not so high to make the range between the highest use and lowest use be within about ±15%. On average, about 90% of the additional water resources were used. This statistic was almost the same in all four cases of additional water resources. This result was due to the face that during the Monsoon season lasting about one month, the dam inflow was too much in the Han River basin and a large portion of it was discharged. So, during this period, it might be possible to stop the desalination plant to save the energy. Even though this monsoon period has become irregular recently, due to the climate change, it may be possible to stop the plant for about a month or so. During this period, the dam reservoirs are generally full.

Table 5 Annual maximum, annual minimum and annual mean use of additional water resources depending on the planned additional water resources depending on the planned additional water resources 0.5 × 10^6 m^3/day, 1.0 × 10^6 m^3/day, 1.5 × 10^6 m^3/day, and 2.0 × 10^6 m^3/day

Planned Additional Water Resources	0.5 × 10^6 m^3/day	1.0 × 10^6 m^3/day	1.5 × 10^6 m^3/day	2.0 × 10^6 m^3/day
Annual Max	183.0 × 10^6 m^3/day (100%)	366.0 × 10^6 m^3/day (100%)	549.0 × 10^6 m^3/day (100%)	732.0 × 10^6 m^3/day (100%)
Annual Min	141.0 × 10^6 m^3/day (77.3%)	281.0 × 10^6 m^3/day (77.0%)	429.0 × 10^6 m^3/day (78.4%)	568.0 × 10^6 m^3/day (80.3%)
Annual Mean	167.5 × 10^6 m^3/day (91.8%)	332.7 × 10^6 m^3/day (91.2%)	502.4 × 10^6 m^3/day (91.8%)	665.7 × 10^6 m^3/day (91.2%)

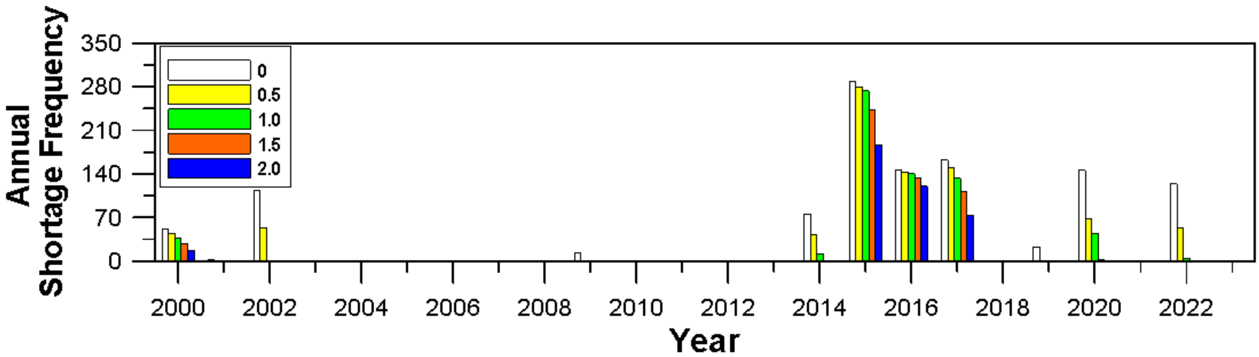
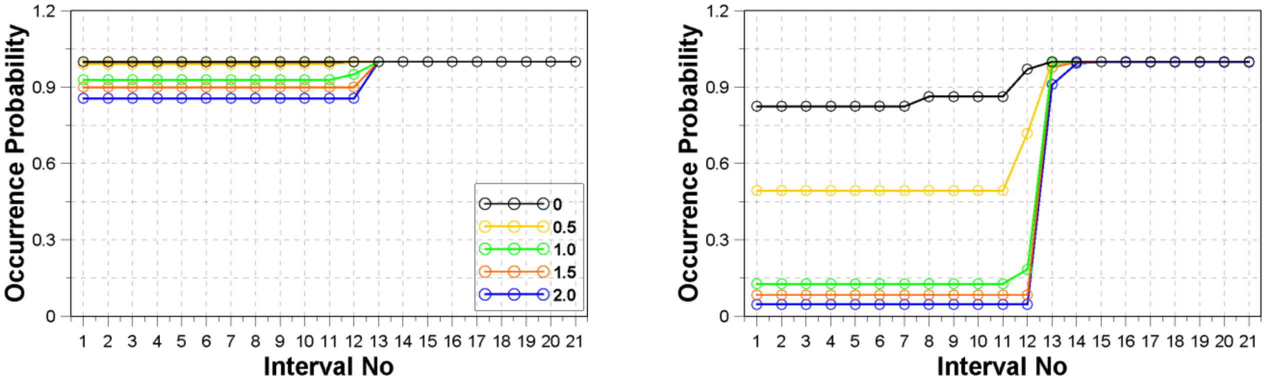
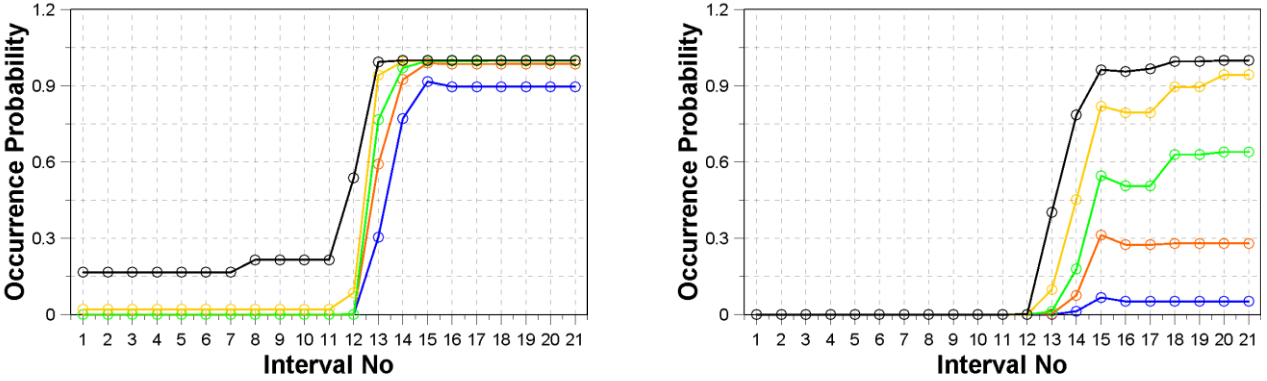


Fig. 8 Change of annual water shortage frequencies depending on the planned additional water resources 0.5 × 10^6 m^3/day, 1.0 × 10^6 m^3/day, 1.5 × 10^6 m^3/day, and 2.0 × 10^6 m^3/day



(a) Once or more

(b) 5 times or more



(c) 10 times or more

(d) 20 times or more

Fig. 9 Change of annual water shortage frequencies depending on the planned additional water resources 0.5 × 10^6 m^3/day, 1.0 × 10^6 m^3/day, 1.5 × 10^6 m^3/day, and 2.0 × 10^6 m^3/day

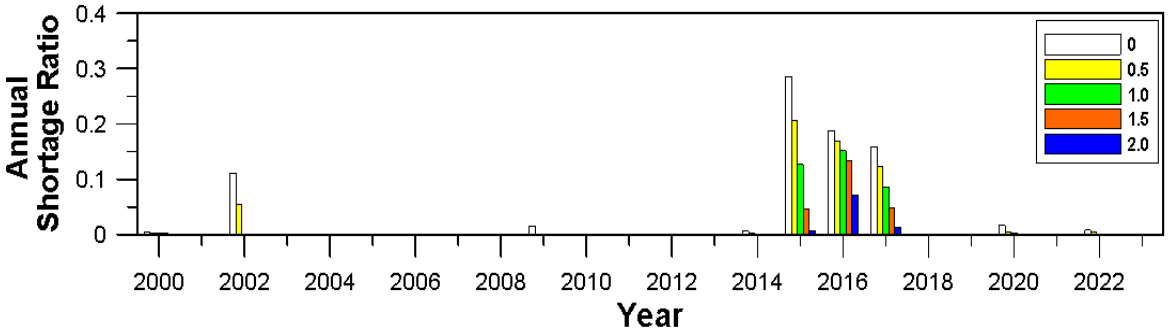


Fig. 10 Change of the annual water shortage ratios depending on the planned additional water resources 0.5 × 10^6

Table 6 Annual maximum shortage ratio (SR) for each moving interval and its return period (T) depending on the planned additional water resources 0.5 × 10^6 m^3/day, 1.0 × 10^6 m^3/day, 1.5 × 10^6 m^3/day, and 2.0 × 10^6 m^3/day

Interval No.	Additional Water Resources (× 10^6 m^3/day)									
	0.0		0.5		1.0		1.5		2.0	
	SR	T	SR	T	SR	T	SR	T	SR	T
11	0.1105	85	0.0545	57	0.0279	56	0.0279	57	0.0279	58
12	0.1105	85	0.0545	57	0.0279	56	0.0279	57	0.0279	58
13	0.2856	92	0.2062	98	0.1262	108	0.0451	50	0.0279	49
14	0.2856	54	0.2062	50	0.1513	54	0.1330	76	0.0713	67
15	0.2856	41	0.2062	37	0.1513	40	0.1330	57	0.0713	63
16	0.2856	41	0.2062	38	0.1513	42	0.1330	62	0.0713	76
17	0.2856	42	0.2062	38	0.1513	42	0.1330	62	0.0713	76
18	0.2856	41	0.2062	38	0.1513	42	0.1330	63	0.0713	76
19	0.2856	41	0.2062	38	0.1513	42	0.1330	63	0.0713	76
20	0.2856	41	0.2062	38	0.1513	42	0.1330	63	0.0713	76
21	0.2856	41	0.2062	38	0.1513	42	0.1330	63	0.0713	76

Additionally, it should be mentioned that the inter-annual variation of rainfall has a significant effect on the use of additional water resources. During dry years, the role of additional water resources must be very important, but during the wet year, its usage becomes lower. However, even during wet years, the use of additional water resources was more than 80%, with the lowest use of additional water resources being more than 77%. This result shows that additional water resources are imperatively necessary, and even the additional water resources of 2.0 million m^3 per day do not exceed the demand.

The same frequency analysis was repeated with the new data considering the additional water resources. The Poisson distribution and the Beta distribution were also applied to this frequency analysis. Before presenting the frequency analysis result, it is also good to see the time series of water shortage occurrences (Fig. 8). As can be seen in this figure, the frequency of water shortage was decreased significantly by adding this constant water resources.

Especially, the year 2022 when the drought was severe, the frequency of water shortage was decreased to be just one half simply by adding the 0.5 × 10^6 m^3/day. When adding 1.0 × 10^6 m^3/day, the water shortage almost disappeared. However, the effect of additional water resources was not very big when the drought lasted longer for several years such as in the period from 2014 to 2017. Even in the case of considering 2.0 × 10^6 m^3/day, the occurrence of water shortages could not be clearly removed.

The frequency analysis results with the Poisson distribution are summarized in Fig. 9. This figure compares the occurrence probabilities of water shortages 1, 5, 10 and 20 times a year or more. First to be noticed is that the occurrence probability of 1 or more water shortages did not change much regardless of the additional water resources. The occurrence probability was all higher than 0.85. It seemed that the additional water resources were a bit helpful in the early 2000 when the volume of water shortage was small. However, from the late 2000, its effect seemed not very significant at all. In fact, it was because of the long-lasting drought. Under the condition that the water demand exceeded the available water resources. Just one day of water shortage could happen every year recently regardless of adding this constant water resources of 2.0 × 10^6 m^3/day. As a result, no significant decrease in this occurrence probability could be expected.

However, the effect of additional water resources could be confirmed in the case of 5 or more water shortages. The effect was also highest in the early 2000 when the water demand was rather small. Excluding the case with the

Table 7 Change of return period (T, year) of annual shortage ratios (SR) of 0.1, 0.15 and 0.2 for each moving interval depending on the planned additional water resources 0.5 × 10^6 m^3/day, 1.0 × 10^6 m^3/day, 1.5 × 10^6 m^3/day, and 2.0 × 10^6 m^3/day

SR	Interval No.	Additional Water Resources (× 10^6 m^3/day)				
		0.0	0.5	1.0	1.5	2.0
0.1	11	71	186	1,000+	1,000+	1,000+
	12	71	187	1,000+	1,000+	1,000+
	13	22	32	70	238	1,000+
	14	17	21	31	48	128
	15	14	17	24	38	119
	16	16	18	25	41	150
	17	16	18	25	41	150
	18	14	18	25	41	150
	19	14	18	25	41	150
	20	14	17	25	41	150
	21	14	17	25	41	150
0.15	11	162	613	613	1,000+	1,000+
	12	162	613	626	1,000+	1,000+
	13	164	626	55	159	877
	14	24	32	53	95	370
	15	20	25	40	71	337
	16	20	26	41	77	463
	17	20	26	41	77	463
	18	20	26	41	78	463
	19	20	26	41	78	463
	20	20	26	42	78	463
	21	20	26	42	78	463
0.20	11	356	1,000+	1,000+	1,000+	1,000+
	12	365	1,000+	1,000+	1,000+	1,000+
	13	50	92	355	1,000+	1,000+
	14	33	47	89	183	1,000+
	15	27	36	62	127	935
	16	27	37	65	139	1,000+
	17	27	37	65	139	1,000+
	18	27	37	66	143	1,000+
	19	27	37	66	143	1,000+
	20	27	37	67	143	1,000+
	21	27	37	67	143	1,000+

additional water resources 0.5 × 10^6 m^3/day, the occurrence probability of water shortages decreased to less than 0.15. However, this effect has become weakened from the 12th moving interval (1985 – 2014). The occurrence probability has returned to near 1.0 again. A similar pattern was also noticed when considering 10 or more water shortages.

The effect of additional water resources could be clearly confirmed when considering 20 or more water shortages. Different from the other cases, the effect of additional water resources was noticeable even after the year 2010. When considering the additional water resources of 1.0 × 10^6 m^3/day, the occurrence probability of 20 or more water shortages decreased to about 0.6. It has been decreased to be around 0.3 with an additional constant water resources of 1.5 × 10^6 m^3/day, and less than 0.1 with an additional constant water resources of 2.0 × 10^6 m^3/day. These results correspond to the decrease of 20%, 70% and 90% in the occurrence of those severe water shortages. Obviously, additional water resources are especially effective reducing the risk of water shortage under severe or more extreme drought conditions.

The effect of additional water resources could also be evaluated from the point of the volume of water shortage. The analysis was also done based on the frequency analysis with the Beta distribution. First, the shortage ratio was recalculated by considering the additional water resources (Fig. 10). As can be seen in this figure, the shortage ratio has decreased significantly due to the additional water

resources. The decrease in shortage ratio seems to be proportional to the amount of additional water resources. For example, with an additional constant water resources of 0.5×10^6 m^3/day (yellow box in the figure), the shortage ratio was about 70% of that without the additional water resources. It has become about 50% with an additional constant water resources of 1.0×10^6 m^3/day (green), and about 30% with an additional constant water resources of 1.5×10^6 m^3/day (orange). With an additional constant water resources of 2.0×10^6 m^3/day (blue), the shortage ratio decreased to less than 10% level. In this case, the shortage ratio also remained less than 0.1 during the entire simulation period. Overall, it was found that the additional water resources of more than 1.0×10^6 m^3/day could significantly decrease the water shortage ratio.

Table 6 compares the above-mentioned results using the maximum shortage ratio and its return period. It is natural that the maximum shortage ratio decreases in proportional to the amount of additional water resources. Compared with the original condition, the additional water resources decreased the maximum shortage ratio by about 40% ~ 50%, 60% ~ 70%, 60% ~ 80%, and 70% ~ 90%, respectively, depending on the amount of additional water resources. The change in the return period for the maximum shortage ratio is more interesting. In case the amount of additional water resources is rather small like 0.5×10^6 m^3/day, the return period for this maximum shortage was estimated to be higher than that in the original condition. In fact, it is normal as the maximum shortage ratio has also become smaller. However, when considering additional water resources like 1.0×10^6 m^3/day, even though the maximum shortage ratio was much smaller, its return period was estimated to be longer. This trend were clearer when larger additional water resources was considered. That is, when considering enough additional water resources, a very positive result, smaller maximum shortage ratio and longer return period could be secured.

This study also repeated the same analysis for several shortage ratios, including 0.1, 0.15 and 0.2. The result derived in this part of the study may be more objective than the case considering the maximum shortage ratio. Table 7 compares these cases with the original one without the additional water resources. This table also focused on the moving intervals from 11 to 21, when the effect of the additional water resources is more vivid. As can be found in this table, the effect of the additional water resources is very clear. For example, additional water resources of 1.0×10^6 m^3/day could increase the return period for the shortage ratio 0.1 from around 10 years to 20 years. In the same case, the return period for the shortage ratio 0.15 could be increased from around 20 years to 40 years, and the return period for the shortage ratio 0.2 could be increased from less than 30 years to 700 years.

The effect of additional water resources was much higher when the water shortage volume was greater. For example, additional water resources of 1.0×10^6 m^3/day could increase the return period for the shortage ratio 0.1 from around 10 years to 20 years. A greater change was also observed when considering more addition water resources.

That is, the additional water resources of 1.5×10^6 m^3/day could increase the return period to about 40 years, and the additional water resources of 2.0×10^6 m^3/day could increase the return period to more than 100 years. That is, a significant stability of water supply could be secured by adding the constant water resources.

5. Conclusions

This study evaluated the role of additional but constant water resources to the conventional variable water resources. The variable water resources in this study indicate the conventional water resources like those from dam reservoirs, which are highly dependent on the climate variability. In contrast, the constant water resources are assumed to be independent of the climate variability, and the desalination may be a typical example. This study considered the water supply system in the Han River basin, Korea. The Han River basin is the largest basin in Korea, which is responsible for most water supply to the Seoul metropolitan city with the population of more than 25 million. This study especially focused on the increasing failure frequency of water supply in the Han River basin. Both shortage frequency (i.e., the annual number of shortage days) and shortage volume were of concern in this study. As a first step, this study evaluated the changing trends in water supply failures over the last 50 years since the systematic water supply from multi-purpose dams began. Frequency analysis of both shortage frequency and shortage volume was conducted. Also, the same analysis was repeated while additionally considering the constant water resources. The difference between the two was then quantified as the effect of additional constant water resources. The results are summarized is as follows.

The Poisson distribution was applied to analyse the annual shortage frequency (i.e., annual number of water shortages), and the Beta distribution to analyse the annual shortage volume. The derived Poisson distributions showed that it was originally positively skewed but has recently become symmetric. The shape of Beta distribution remained almost unchanged and continued to resemble the exponential distribution. This exponential shape indicates that most water shortages are not so severe. However, as the mean shortage volume has also increased recently, the probability of extreme shortage volume has increased significantly.

The result of the frequency analysis using the Poisson distribution shows that the water shortage problem has become much worse recently. For example, the occurrence probability of 20 or more water shortages over the 30-year period was almost zero in the 1980s; however, it has now approached one. At present, it is not very strange to have water shortages every year in the Han River basin. The result based on the Beta distribution also showed a similar trend. For example, the return period for the shortage ratio of 0.2 (the shortage volume is 20% of the planned water supply) was more than 400 years in the 1980s, but, recently, it has become less than 30 years. Similarly, the return period for the shortage ratio 0.1 was around 80 years in the 1980s, but has become just less than 15 years recently.

The effect of additional constant water resources was found to be so significant. For example, in the year 2022 when the drought was severe, the frequency of water shortage was decreased to just one half, simply by adding the 0.5×10^6 m^3/day. If adding 1.0×10^6 m^3/day, the water shortage almost disappeared. This effect was also confirmed in the frequency analysis results. For example, adding 1.0×10^6 m^3/day reduced the occurrence probability of 20 or more water shortages from near 1.0 to around 0.6. It decreased to about 0.3 with an additional constant water resources of 1.5×10^6 m^3/day, and less than 0.1 with an additional constant water resources of 2.0×10^6 m^3/day. These results correspond to the decrease of 20%, 70%, and 90% in the occurrence of those severe water shortages.

A similar result could also be derived in the application of the Beta distribution. For example, additional water resources of 1.5×10^6 m^3/day could increase the return period for the shortage ratio 0.1 from about 20 years to about 40 years. Similarly, for shortage ratios of 0.15 and 0.2, adding 1.5×10^6 m^3/day increased the return periods from less than 20 years to over 80 years and from less than 30 years to over 100 years, respectively. That is, a significant stability of water supply could be secured by adding the constant water resources.

Above results clearly confirm the effect of additional constant water resources. However, this additional water resources cannot remove all the shortage cases, especially small occurrences like once or five times per year. On the other hand, the effect of additional water resources was especially vivid when considering more extreme cases with large number of shortage frequencies like 15 or 20 times per year. Additionally, it was also found that the effect of additional water resources becomes smaller when the drought lasted longer for several years or more. This could be noticed in this study in the period from 2014 to 2017, when the drought was so severe in the Han River basin. Even in the case of considering 2.0×10^6 m^3/day, the occurrence of water shortages could not be clearly removed.

Despite the above effects, it may not be easy to determine the promotion of seawater desalination in Korea. Another obstacle seems to be that the construction cost is more than twice that of dam construction. If considering an emergency situation such as a drought, it is absurd to simply compare the methods with the same water supply capacity. A relatively smaller environmental impact of desalination could also improve its economic feasibility. Those assumed amounts of additional water resources are also sufficiently realistic, as the capacity of the main seawater desalination plant currently in operation exceeds 1 million tons per day (i.e., 1.0×10^6 m^3/day). Not only countries in the Middle East but also countries such as Taiwan and Australia, which were also relied on dam reservoirs in the past, consider seawater desalination as a major additional water supply method at present. This could serve as a good indicator of the availability of seawater desalination plants.

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