Adaptive Reservoir Management by Reforming the Zone-based Hedging Rules against Multi-year Droughts

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Abstract

In this study, the zone-based hedging rule, which is the main operating policy adopted from multipurpose reservoirs in Korea is adjusted to reflect the multi-year droughts caused by climate change. Annual synthetic inflow series with different magnitudes of long memory were generated using the autoregressive fractional integrated moving average (ARFIMA) model. The generated inflow series were then disaggregated into 10-day series and utilized as input variables to derive the alternative hedging rules. The alternative hedging rules from this study were used in adaptive reservoir management by newly updated information. Finally, the performance of the suggested policy is measured in terms of frequency and magnitude under the historical inflow series. As a result, adaptive reservoir management demonstrated improvements in the following terms of the frequency of critical failures (water deficit ratio greater than 30%): 6.14% of the simulation period in the status quo (SQ) policy, and 2.99% in the adaptive management. However, the overall reliability of the reservoir during the simulation horizon was better when operated with the SQ policy (41.19%) than the results from adaptive management (26.42%). Because this result is in a good agreement with the original objective of the hedging rules, the adaptive policy suggested in this study holds promise and may be utilized in further reservoir management under drought conditions.

1. Introduction

Reservoirs have been widely adopted as the principal source of freshwater for various purposes including irrigation, municipal, industrial, hydropower generation, and flood mitigation (Labadie 2004). Nevertheless, the recent surge in the frequency and magnitude of abnormal hydro-climatic variabilities and their consequences (Loucks 2000; Salazar et al. 2016; Kim et al. 2021) have forced the traditional reservoir management strategies to be reformed. The primary factor that complicates the advancement in operating policies is the inherently sophisticated nature of water management problems caused by conflicting interests and distinctive attitudes toward the risk of involving stakeholder groups (Castelletti et al. 2008; Quinn et al. 2019). Furthermore, the global increase in unpredictable severe meteorological multi-year droughts and their consequences have also contributed to the intricacy of water resources management schemes.

To date, the development of reservoir operating policies has been led by either optimization models based on optimization algorithms or simulation-based models based on predefined rules (Stedinger 1984). A few optimization algorithms that have been adapted for solving reservoir operation problems include: nonlinear programming (Birhanu et al. 2014), dynamic programming (Stedinger et al. 1984), and genetic algorithms (Cheng et al. 2008). Therefore, since numerous applications have been made regarding the optimization algorithms in reservoir operation problems, the reader is referred to the prominent review papers by Yeh (1985) and Labadie (2004) for more details. So, this paper intends to focus on the noted shortcomings of these optimization models in actual applications that primarily arise because of the discrepancies between academia and onsite end users.

In contrast to the optimization models, actual operations in multipurpose reservoirs rely more heavily on simulation-based predefined operation rules. Two notable types that are affiliated with the rule-based predefined policies are the standard operating policy (SOP) (Klemeš 1977) (the S-shaped curve of operation) and various types of hedging rules (Shih and ReVelle 1994; Kim and Kim 2021). Because the SOP targets meeting the demand on all possible occasions and spills only when the capacity is exceeded, the practical application of SOP is largely limited and is only adapted in theoretical simulations (Shih and ReVelle 1994). Contrastingly, hedging rules focus on preventing damage to the target reservoir from potential droughts and consequential water deficits by demand reductions before water shortages (Neelakantan and Pundarikanthan 1999). Among the various candidate types of hedging rules, onsite reservoir operators prefer to manage their reservoirs with relatively straightforward policies (Mohammad Ashrafi 2021), which are implementable under wide circumstances.

Other than the aforementioned inherently complex nature of the field of water resources management, another key decisive component, climate change, is forcing the review of conventional water resources management strategies. The firm linkage between climate change and water resources management has been proven in multiple past studies (Frederick and Major 1997; Sowers et al. 2011). As such, this study aims to focus on the two distinctive characteristics of climate change: non-stationarity (Milly et al. 2008) and Knightian uncertainty. While the non-stationarity refers to the change in historical statistics, Knightian uncertainty refers to the property of climate change in which even the distribution of future variables is unknown. Therefore, due to these two attributes, climate change has induced a rapid surge in irregular hydro-climate events such as extreme floods and droughts that last for multiple years. In response, measures that aim to minimize the damage from hydro-climate disasters have been developed including robust (Kim et al. 2021) and adaptive (dynamic) decision making strategies (Herman et al. 2020). Among the two strategies, this study focuses on the adaptive approach, in which the decisions are updated with the introduction of new information, and aims to apply adaptive reservoir management based on multiple status quo (SQ) rule curves generated considering multi-year droughts. The novelty of this study is both in the consideration of long memory during hedging rule generation process and the utilization of adaptive decision making scheme during the operation.

In this study, the rule curve of the reservoir which is adapted as the primary operating strategy is reformed by considering the multi-year drought during the rule generation process. The reformation procedure is conducted by utilizing the identical algorithm that actual reservoir managers onsite have developed to generate policies that are applicable during actual operations under drought conditions. The alternative policies are then adaptively applied with the rule curve that is actually being dynamically adapted in the target reservoir by updating information based on the standardized runoff index (SRI). For evaluation, a simulation using historical inflow series was conducted, and the results from the simulation are compared with the results from the SQ policy.

2. Methodology

2.1 Reservoir Management based on Hedging Rules

The fundamental concept behind diverse types of hedging rules in reservoir operations lies in reducing the risk of water deficits in the future in the expanse of shortage in the current release (You and Cai 2008a). This action is possible by utilizing only partial release, although all or at least more of the target demand could be provided (Hashimoto et al. 1982). The specifics of hedging policy, such as the portion to be deducted and the timing of reduction, are determined according to predefined hedging rules of various types (Kim and Kim 2021). Chiefly, hedging rules are a type of simulation model-based decision support tool commonly adopted in onsite reservoir management problems (Bayazit and Ünal 1990; You and Cai 2008b). Owing to their applicability and effectiveness, numerous studies on hedging rules linked with optimization models in reservoir operations (Neelakantan and Pundarikanthan 1999; Tu et al. 2008; Taghian et al. 2014; Eum et al. 2011) have been conducted. The results from the previous studies proved that optimally derived hedging rules enhanced the efficiency of reservoir performance under both normal and drought conditions.

Depending on the shape and the specifics of the hedging policy, hedging rules developed in previous studies can be classified into one of the following: one-point (SOP), two-point (Bayazit and Ünal 1990), continuous (Hashimoto et al. 1982), and zone-based (Shih and ReVelle 1994, 1995). Starting from the simplest one-point hedging rule, which is a slight variation from the SOP, other alternative hedging rules were suggested that all aim to prevent failures with greater magnitude in future operations. More specifically, to determine the timing and amount of demand reduction, available storage and demand at the time step are often selected as the trigger (Taghian et al. 2014).

Among the various types of hedging rules previously introduced, this study aims to focus on the specific type of hedging known as zone-based (discrete) hedging rules. This is because all the multipurpose reservoirs in the Republic of Korea have adopted this policy as their main reservoir management technique. The fundamental concept behind zone-based hedging rules is adopted in multipurpose reservoir management with the term, water supply adjustment standards (WSAS). Figure 1 displays the zones of the Boryeong multipurpose reservoir, in which the standards of the sequential reduction in water supply that is proportional to the demand at each time step is based on. This dissertation aims to modify the current on-site hedging rule by taking the recent multi-year drought into consideration.

2.2 Time Series Models with Long Memory

The concept of long persistence, the existence of significant dependence between observations separated by a long time span (Hosking 1984), initially started from Hurst (1951), in which the hydrological and geophysical data (annual minimum series of the Nile River) were heuristically identified. This long-range dependence of hydroclimatic variables is often linked with the concept of non-stationarity (Koutsoyiannis 2006), which is identified as a key characteristic of climate change. Particularly, Montanari et al. (1997) identified two main reasons behind long persistence, also referred to the Hurst phenomenon in the literature: (1) inherent long-term dependence (or long memory) in the time series itself and (2) the non-stationarity of the time series. Although the principle behind the Hurst phenomenon is yet to be completely determined, multiple studies have discovered the existence of long memory in hydrological data (Koutsoyiannis 2002, 2003).

A widely known, heuristic approach often utilized in detecting long memory from time series data is often conducted using the Hurst exponent $H (0 < H < 1)$ (Montanari et al. 1997). Specifically, a series with H less than or equal to 0.5 indicates no long-term persistence; moreover a series with exponent H greater than 0.5 indicates strong long persistence. Multiple models including the Hurst exponent have been developed and utilized so that the series generated from the model includes long memory, primarily because of the relative simplicity of the heuristic estimation methods of the Hurst exponent (Montanari et al. 1997). As an example, the fractional autoregressive integrated moving average (FARIMA) model (Hosking 1984) was designed to include long-term persistence in the series with fractional differencing. This model is often referred to the autoregressive fractional integrated moving average (ARFIMA) model.

With a time series X_t with zero mean, the ARFIMA(p, d, q) model can be generally expressed using the following equation (Montanari et al. 1997):

$$\Phi_p(\mathrm{B})(1-B)^d X_t = \Theta_q(\mathrm{B})\epsilon_t \Phi \ (1)$$

where B = backward shift operator ($BX_t = X_{t-1}$); $\Phi_p(\mathrm{B})$ = p-order autoregressive polynomial; $\Theta_q(\mathrm{B})$ = q-order moving average polynomial; ϵ_t = independent, zero mean white noise; and d = order of differencing, not limited to integers but can include fractional values.

Specifically, the order term d in Eq. 1 is closely related to the Hurst exponent $H$with the following relationship:

$$d = H - 0.5\Phi(2)$$

Compared to other models, ARFIMA models have been widely adopted during the generation of long memory series primarily because of their strengths which allow the inclusion of both short- and long-term persistence. For instance, Mudelsee (2007) utilized the Hurst exponent during the spatial aggregation process across various rivers. More recently, Yang and Bowling (2014) applied the ARFIMA model to identify and estimate the daily streamflow series which were later analyzed for the effect of urbanization in the Great Lakes region. In this study, multiple ARFIMA models with different H values were used to generate inflow series which were used to create the standards for the hedging rules in reservoir operations. The alternative rule curves containing long memory were then utilized with adaptive manners, which is to be thoroughly explained in subsection 4.3.

3. Application On The Boryeong Multipurpose Reservoir

3.1 Study Site

Boryeong multipurpose reservoir (Fig. 2) located on the western coast of the Korean Peninsula was selected as the test case in which the proposed methodology was applied. Because the Boryeong Dam is responsible for suppling municipal and industrial (M&I), agricultural (A), and environmental (E) water to the nearby eight districts, adequate reservoir management schemes in case of droughts is required.

Moreover, due to the recent multi-year drought which lasted for 6 years (2015–2019), both structural and non-structural measures to enhance water supply were conducted to the Boryeong Dam. This study aims to modify the current zone-based SQ rule by including the effect of the multi-year drought with long memory time series with adaptive measures in which the decisions are iteratively updated.

3.2. Application Overview

To derive alternative hedging rules with the consideration of multi-year droughts with long-term persistence time series models, this study first generated an annual inflow series while preserving the statistics from the historical inflow series (average and standard deviation) using the ARFIMA model. Then, a non-parametric disaggregation method based on the k-nearest neighbor (k-NN) resampling approach proposed by Nowak et al. (2010) was applied to transform the annual inflow series into a 10-day series. This disaggregation procedure was conducted because the "DrResOPT" software, a program utilized to derive the standards for the hedging rule used by onsite reservoir operators (K-water) is based on a time step of 10 days. While preserving other input variables such as monthly demand, reservoir capacity, and reliability, only the inflow series were assumed to vary so that the alternative rule curves were generated with inflow series with different magnitudes of long memory. A total of seven cases of alternative hedging rules (Cases 1 through 7) were generated with the inflow series with H from 0.6 to 0.9. After creating alternative rule curves, this study applied adaptive reservoir management, in which the alternative rule curves were selectively utilized according to updating information.

Ultimately, this study advances the previous work by Seo et al. (2019) in the following manner: (1) utilizes the synthetic inflow series during the zone-based hedging rule generation, (2) includes 100 sets of a 500-year series of synthetic inflow during the zone derivation process, and finally (3) applies an adaptive reservoir management scheme to cope with climate change-induced long-lasting droughts. Moreover, whereas the previous study from Kim et al. (2021) only utilized the hedging rule by combining with optimization models, this study endeavors to reform the SQ policy against multi-year droughts and adaptively apply the alternatives with newly updated information according to each time step.

3.3 Procedures for Hedging Rule Generation

Disaggregation

Because the generated inflow series from the ARFIMA model is composed of an annual time step and the algorithm for hedging rule generation requires an inflow series with time steps of 10 days, a step for disaggregation is necessary. Among multiple candidates of disaggregation methods, a nonparametric stochastic approach based on the k-NN resampling method (Nowak et al. 2010) was selected in this study. Briefly, the disaggregation method adopted in this study identifies the vector of annual aggregate flows among the historical inflow series that is most identical to the inflow to be disaggregated. Then, the annual aggregate flow to be disaggregated is resampled according to the weight function shown in Eq. 3:

$$W(i) = \left(\frac{1}{i}\right) \Big/ \left(\sum_{i=1}^{K} \frac{1}{i}\right) \quad (3)$$

In this study, K, the number of nearest neighbors is selected according to the heuristic equation ($K = \sqrt{n} = 5$, where n is the number of years of observed data). Consequently, the outcome of this procedure, the disaggregated inflow series, can preserve the basic statistics (mean, variance, coefficient of skew, maximum, and minimum values) of the historical inflow series (Nowak et al. 2010). For detailed explanations regarding the disaggregation method adopted in this study, the reader is referred to Nowak et al. (2010).

Rule Curve Generation

After the annual inflow series are disaggregated into a 10-day series, the rule curve of the reservoir, which is utilized as the standard for zone-based hedging rules, is determined according to the algorithm used onsite. Accordingly, three out of the four rule curves were established according to the results from the iterative reservoir simulation for 500 years, and one of them was calculated from the previous computation results. Figure 3 summarizes the algorithm used for the rule curve generation process.

For illustration, the sequence for deriving the rule curve for the caution stage among the four stages corresponding to attention, caution, alert, and critical zones is explained. First, the demand corresponding to each time step was determined. The demand for the caution stage is D_3, which is the aggregate sum of M&I, A, and E water uses corresponding to each time step. Then, starting from the storage at the normal high water level, an iterative calculation of the reservoir using the continuity equation is conducted until the probability of success falls below 95% during the 500 years of simulation. During the simulation, a synthetically generated inflow series with long-term persistence was utilized along with the drought response measures available at the Boryeong reservoir. The lowest value of the storage level that meets 95% reliability is selected as the storage level corresponding to each stage. The rule curve for the attention stage is inferred from the rule curve for the caution stage by adding the amount of water corresponding to the 15-day demand in practice. In this study, the procedures for the rule curve generation were improved as the follows: (1) by including multi-year drought in the rules by simulation using the synthetically generated inflow series with long memory, and (2) by generating multiple rule curves corresponding to each case to reduce the uncertainty during the synthetic inflow generations.

4. Results And Discussion

4.1 Inflow Series Generation

To remove the potential uncertainty arising from the synthetic inflow generation, this study utilized 100 cases of a 500-year series of synthetic inflow for each case with different Hurst coefficients ($H = 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9$). The statistics of the selected cases, which were utilized to derive the storage of the zones in the next step of the study, are shown in Fig. 5.3. During generation, the average and standard deviation of the annual series aimed to replicate the values from the observed statistics. The Hurst coefficient, H, indicates the extent of the long memory incorporated into the generated time series. A time series with higher H indicates stronger long-term persistence, and consequently, a higher chance in containing a multi-year drought in the generated time series model.

4.2 Alternative Hedging Rule Generation

After the selection of 100 cases among the generated time series with different long-term persistence, the selected annual series were then disaggregated into 10-day intervals. Then, the 10-day time series were used during the hedging rule generation, with the algorithm that is currently being used in actual rule generation adapted onsite. Consequently, the rules generated in this study advance the SQ zone-based hedging rule with regard to the following points: (1) includes the effect of multi-year drought during the generation process, and (2) provides a range of zones by using 100 cases. Among the 100 cases, the median values were selected as representative values and utilized during adaptive reservoir operations. The generated rules are shown in Fig. 5.

Inclusion of the inflow series with long-term persistence during hedging rule generation yielded divergent policy outcomes. In general, the rule curves generated from the long memory inflow series resulted in higher rule curves than the SQ hedging rules. Higher values of rule curves indicate that the water supply reduction should take place earlier, even when there is enough water stock when operated under the SQ rules. Moreover, as shown in Fig. 5, among the alternative rule curves, policies established using the inflow series with stronger long-term persistence yielded even higher rule curves. Given that the alternative rule curves aimed to cope with recent multi-year droughts, higher rule curves or preemptive actions against potential future droughts appear to be legitimate results.

4.3 Adaptive Reservoir Operations with Alternative Hedging Rules

Until this point of the study, alternative zone-based hedging rules were created by reflecting the multi-year drought through the generation of a time series with long persistence. However, as the procedures were utilized, the novel policies were created by only considering the reliability of the reservoir, and direct adoption of the alternative policy is hardly feasible. Thus, this study aims to dynamically employ the generated alternatives during reservoir operation under drought conditions with adaptive actions (Pahl-Wostl 2007). Particularly, adaptive strategies primarily utilize new information when updating decisions in response to new states. To trigger the alternative rule curve, the standard runoff index accumulated over 12 months (SRI12) was selected. The probability distribution employed during the fitting process for the SRI calculation was selected as the three-parameter log-logistic distribution.

Among the SRI values with different lengths, SRI12 was selected for the following two reasons. Firstly, since the primary motivation behind this study was in deriving alternative reservoir operating policy based on adaptive decision making against multi-year droughts, including the information accumulated for 12 months is more reasonable than shorter periods. The second reason behind the selection of SRI12 was in considering policy inertia (Giuliani et al. 2014), which refers to low flexibility of water resources policy especially in laws related to water resources infrastructure unless either a dramatic failure or water conflict takes place. For comparison, this study performed simulations with SRI3, SRI6, SRI12, and SRI24 selected as triggers for adaptive operations. The simulation resulted in the change of policy for 47.10%, 42.39%, 26.09%, and 22.83% of the simulation period, respectively. Furthermore, the overall vulnerability of the reservoir, measured in terms of the average magnitude of failure during the simulation horizon, hardly improved when the system was operated with SRI6 as the trigger. Since the change of the operating policy for more than 40% may lead to extreme stress to the target system and the enhancement of the vulnerability can be considered insignificant, this study selected SRI12 as the trigger for adaptive reservoir management.

Ultimately, the results from the adaptive operations were analyzed, focusing on the trade-off relationship between supply and demand. The standards adopted in this study for adaptive reservoir operations are listed in Table 1.

Table 1
SRI triggers utilized in adaptive reservoir operation of the Boryeong multipurpose reservoir

SRI Trigger Value	Cumulative Probability	Interval Probability	Utilized Policy
$0 < SRI$	100%	50%	K-water SQ Rule (Fig. 1)
$-0.180 < SRI \leq 0$	50.00%	7.14%	Case 1 ($H = 0.6$)
$-0.366 < SRI \leq -0.180$	42.86%	7.14%	Case 2 ($H = 0.65$)
$-0.566 < SRI \leq -0.366$	35.71%	7.14%	Case 3 ($H = 0.7$)
$-0.792 < SRI \leq -0.566$	28.57%	7.14%	Case 4 ($H = 0.75$)
$-1.068 < SRI \leq -0.792$	21.43%	7.14%	Case 5 ($H = 0.8$)
$-1.465 < SRI \leq -1.068$	14.29%	7.14%	Case 6 ($H = 0.85$)
$SRI \leq -1.465$	7.14%	7.14%	Case 7 ($H = 0.9$)

To evaluate the proposed methodology, a reservoir simulation model based on a 10-day time period was developed, and the historical inflow series of 23 years after the construction of the reservoir (January 1998 through December 2020) was utilized. The starting storage for the simulation was observed storage at the beginning of 1998 (35.342 MCM). Finally, for the simulation to reflect the conditions of actual operations, the Boryeong conduit, an alternative operated in the case of extreme droughts was also included in the model according to its operating policies. The simulation results were finally evaluated using the reliability and vulnerability concept from Hashimoto et al. (1982) by focusing on the trade-off relationship between the reservoir operators and water users.

Release Rule Comparison

The first advantage arising from the adaptive operations proposed in this study compared to the operations based solely on the SQ policy is the more flexible release decisions through the introduction of the SRI as the trigger. For instance, whereas the release decisions made from the SQ policy (Fig. 6a) only considers the storage, the adaptive policy includes both the information from the storage and the SRI when making decisions. This indicates that even under the same storage value, the decision may vary according to the value of the SRI. The extensive range of decisions made from the adaptive policy is demonstrated in the contour plots drawn from the release decisions from the adaptive operations proposed in this study (Fig. 6b). In addition to the improvements in adaptive operations in terms of reliability and vulnerability, the extension of the range of release decisions also presents another advantage over the SQ policy.

Simulation Results Evaluation

Moreover, the simulation results of both operations were comparatively analyzed from the widely known concept of risk and vulnerability suggested by Hashimoto et al. (1982) both from the reservoir operators and the endwater users. Before the evaluation process, the criteria for evaluation were selected in the following manners: (1) the percentage of the reservoir storage for the supply side, and (2) water deficit ratio (i.e., $max\left(\frac{D_t - R_t}{D_t}, 0\right)$) for the demand side. Figure 7 shows the distribution of either the storage (Fig. 7a) or water deficit (Fig. 7b) over the drought period (Jun-2014 through Sep-2019), and Fig. 8 shows the same during normal periods. Darker bars in Fig. 7 and Fig. 8 indicate lower storage and greater magnitude of water deficit, and consequently, there are undesirable outcomes from the supply and demand, respectively.

Overall, the performance of the reservoir showed a trade-off relationship between supply and demand as initially expected. From the supply side, operating the reservoir with the alternative policies in an adaptive manner resulted in improved performance in terms of both magnitude and frequency in both normal and drought conditions. Because the reservoir storage below 20% conventionally indicates critical failure in terms of supply, the threshold of critical failure for the supply was selected as 20%. In terms of critical failure during the entire simulation horizon, the SQ policy yielded in average frequency, magnitude, and duration of 26.45%, 12.95%, and 12.88 10-day periods, respectively. Contrarily, adaptive operations suggested in this study resulted in 15.10%, 13.69%, and 13.89 10-day periods, respectively. The results indicate that the adaptive operations enhance the frequency of critical failures at the expense of magnitude and duration in terms of reservoir storage.

Contrastingly, the performance of the simulation measured from the water users in terms of water deficit ratio showed relatively similar, yet disparate results from the performance from the supply side. Figure 5.6b shows the distribution of the magnitude of the water deficit ratio during historical drought periods, whereas Fig. 5.7b shows the same during normal periods (Jan-1998 through May-2014 and Oct-2019 through Dec-2020). In terms of overall reliability, SQ policy especially yielded in better results (41.19%) than adaptive operations (26.42%) under normal periods. Operation of the reservoir with the adaptive operating method proposed in this study largely improved the frequency of critical failures in terms of demand (incidents with water deficit ratio greater than 30%) during the drought period. Whereas the adaptive operations failed to improve the frequency of water deficit ratio greater than 50% than the SQ policy, adaptive operations were able to improve the frequency of the second worst failure (incidents with water deficit ratio greater than 30% and less than 50%) by 17.7%. Finally, given that the fundamental objective of general hedging rules is to reduce the frequency of critical failures at the expense of overall performance (Eum 2007), adaptive operations proposed in this study better achieve this specific objective, and also hold promise under extreme multi-year drought incidents.

5. Conclusions

Because multiple reservoirs utilize various types of hedging rules as their main operating policy, this study first proposed seven alternative rule curves by considering the long-term persistence proven in historical multi-year droughts. To derive alternative rule curves against multi-year droughts, the inflow series reflecting long-term persistence were generated with ARFIMA models with diverse strengths of long memory and disaggregated using the nonparametric stochastic approach based on the k-NN resampling method. The synthetic inflow series were then used to derive alternative hedging rules, which were finally used in adaptive reservoir operations. The SQ policy and adaptive operations with alternative rule curves were simulated under the historical inflow series, which were ultimately evaluated in terms of risk and vulnerability.

The key findings of this study are organized and analyzed comparatively. First, the alternative rule curves created with inflow series containing long-term persistence yielded higher rule curve standards compared to the SQ policy. Thus, operating the reservoir according to the alternative rule curves suggests that water supply reduction occurs earlier. Given that the consequences of multi-year droughts may be detrimental and lead to severe water deficits, the alternative policies derived from this study can be concluded to yield reasonable results against multi-year droughts. Moreover, the results from the simulation using historical inflow series indicate that the adaptive operations reduce the frequency of most water deficit incidents at the expense of overall reliability. Because this result is the intention of the hedging rules, the results support the adaptive reservoir operations proposed in this study especially during the drought periods.

Despite the key findings from the results of this study, few possible improvements remain for future research. Primarily, this study utilized the algorithm for hedging rule derivation which was utilized onsite (Fig. 3) so that the alternative policies are not so distant from the SQ policy. However, a further analysis of the reliability of the algorithm should be conducted. Specifically, a sensitivity analysis with the input variables used in deriving hedging rules such as demand, synthetic inflow series, drought response measures, and the probability of success. Moreover, because many reservoir systems are complex and involve multiple water resources infrastructures, consideration of the system and expanding the model to include related structures also hold promise.

Declarations

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Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material

The datasets generated during and analyzed during the current study are available on Mendeley Data (https://data.mendeley.com/datasets/b54wd2gtdx/1).

Code availability

All codes that support the findings of this study are available on Github (https://github.com/gijoo-kim/watersupply_standard_update).

Authors' contributions

Gi Joo Kim, Young-Oh Kim, and Seung Beom Seo contributed to the study conception and design. Material preparation, data collection and analysis were performed by Gi Joo Kim. The first draft of the manuscript was written by Gi Joo Kim. Young-Oh Kim and Seung Beom Seo commented on previous versions of the manuscript. Gi Joo Kim, Young-Oh Kim, and Seung Beom Seo read and approved the final manuscript.

Ethics approval

Not applicable, because this article does not contain any studies with human or animal subjects.

Consent to participate

Not applicable, because this article does not contain any studies with human or animal subjects.

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Figures

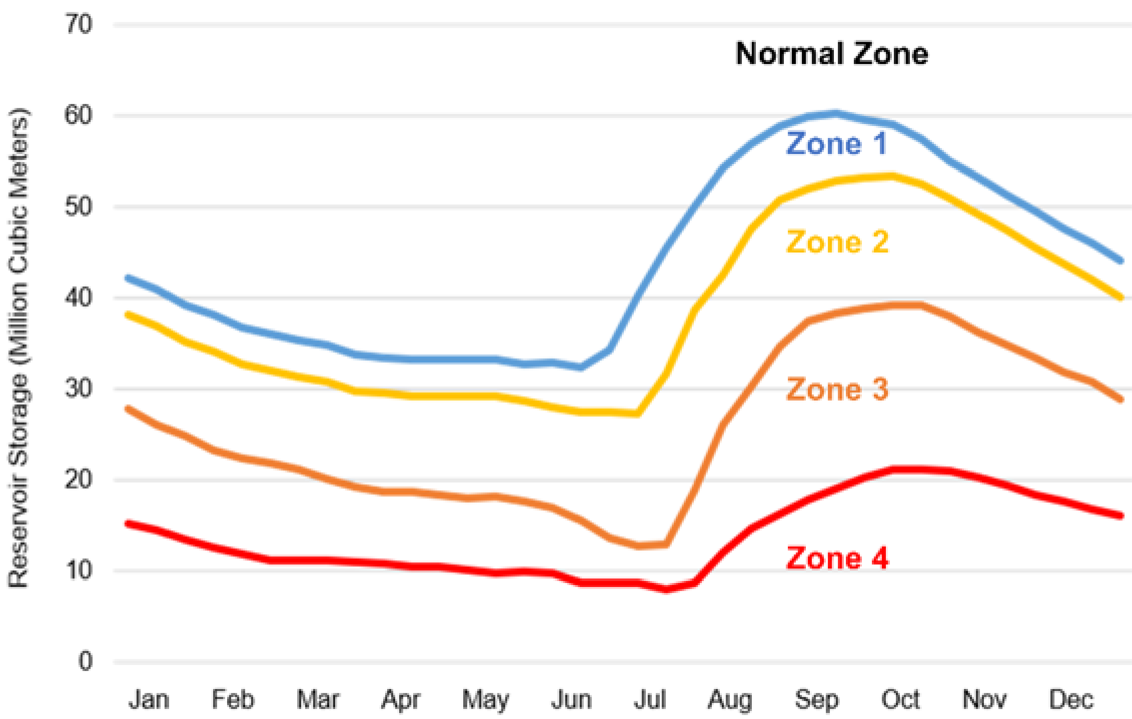

Figure 1

Actual rule curves of the Boryeong multipurpose reservoir in Korea. The storage of the reservoir is divided into five zones according to the four curves in the figure

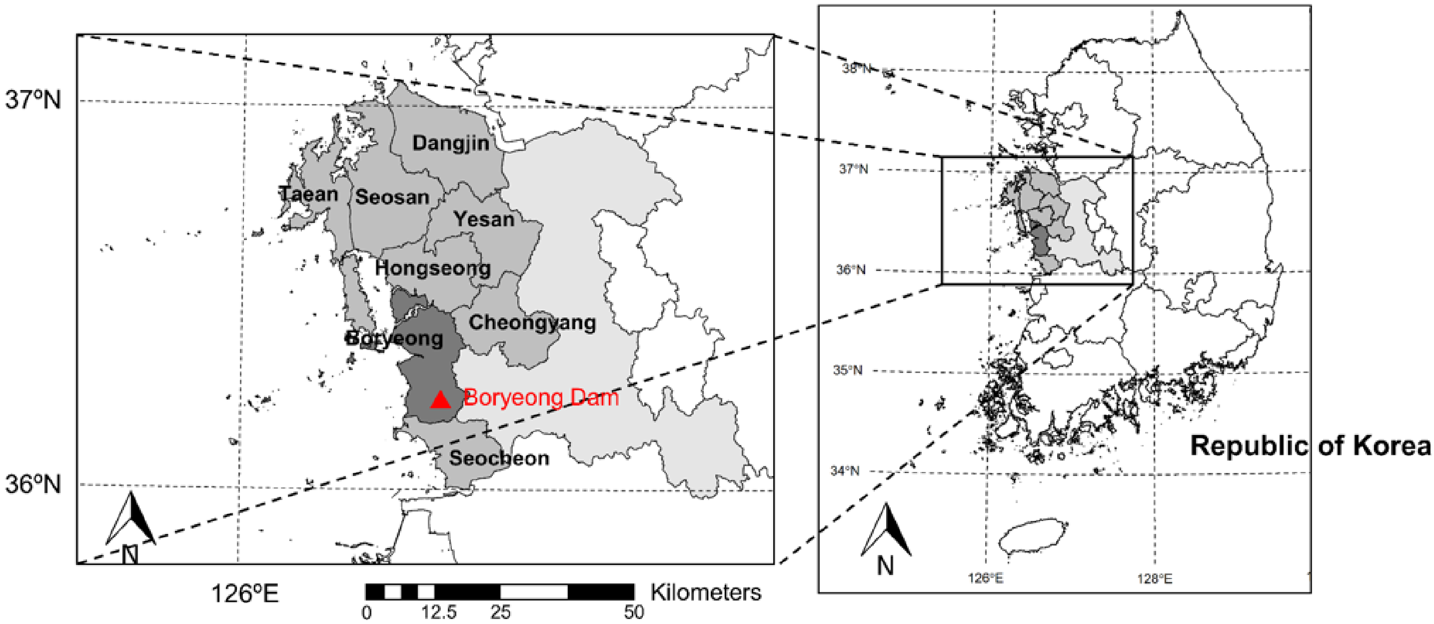

Figure 2

Map of the target reservoir: Boryeong Multipurpose Reservoir and eight administrative districts depending on the Boryeong Dam of their water uses

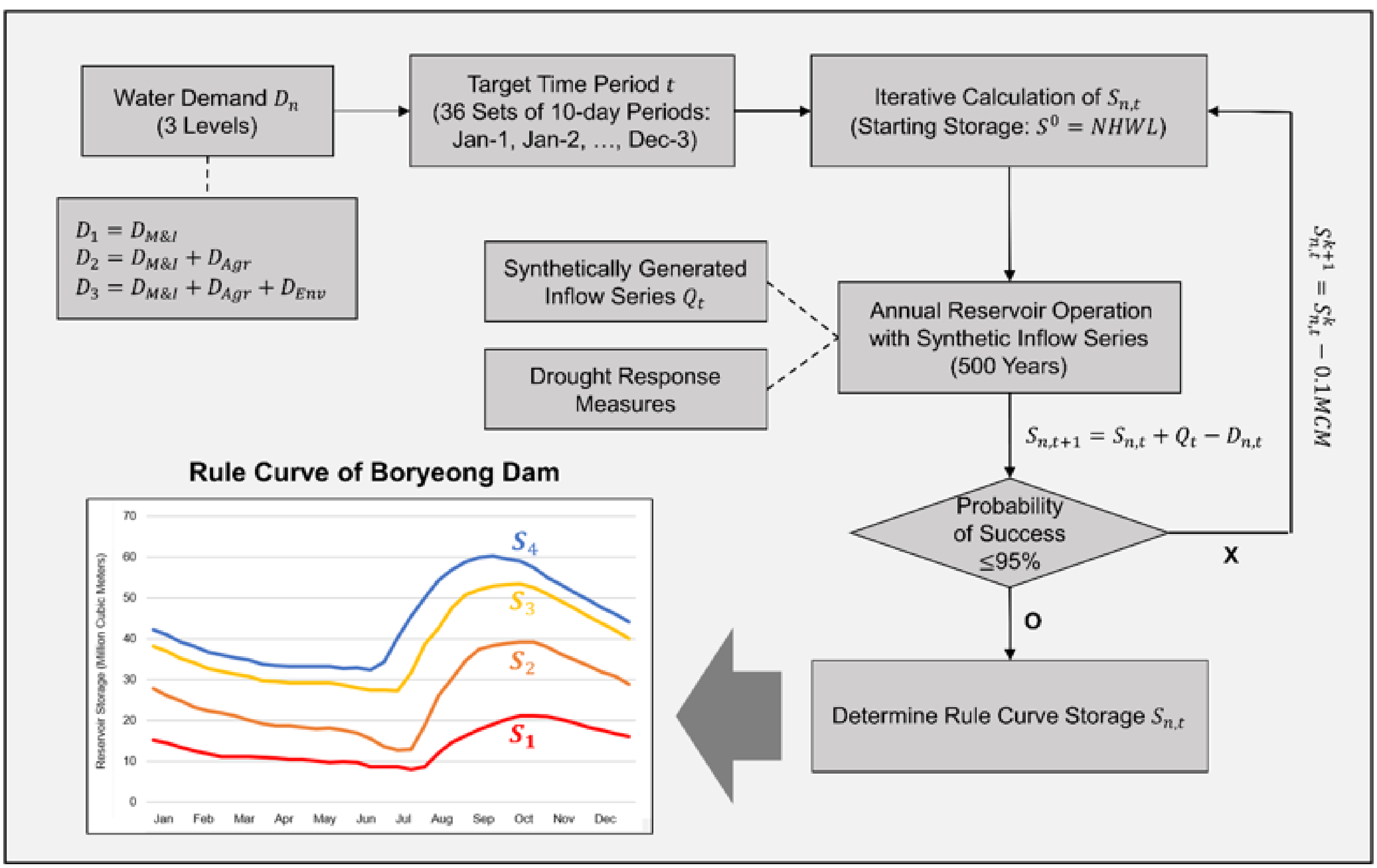

Figure 3

Procedures utilized to derive rule curves in hedging rules. The flow chart displays an example of the Boryeong multipurpose reservoir

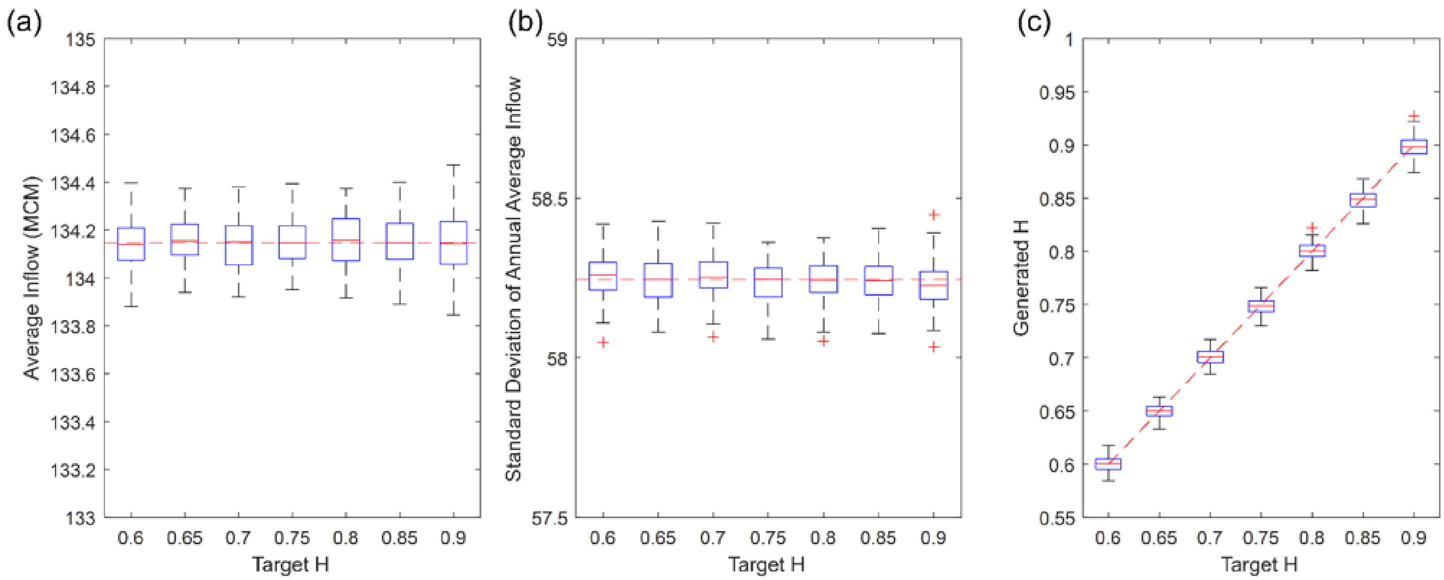

Figure 4

The statistics of the selected 100 cases of generated time series: (a) annual average (b) standard deviation, and (c) Hurst coefficient

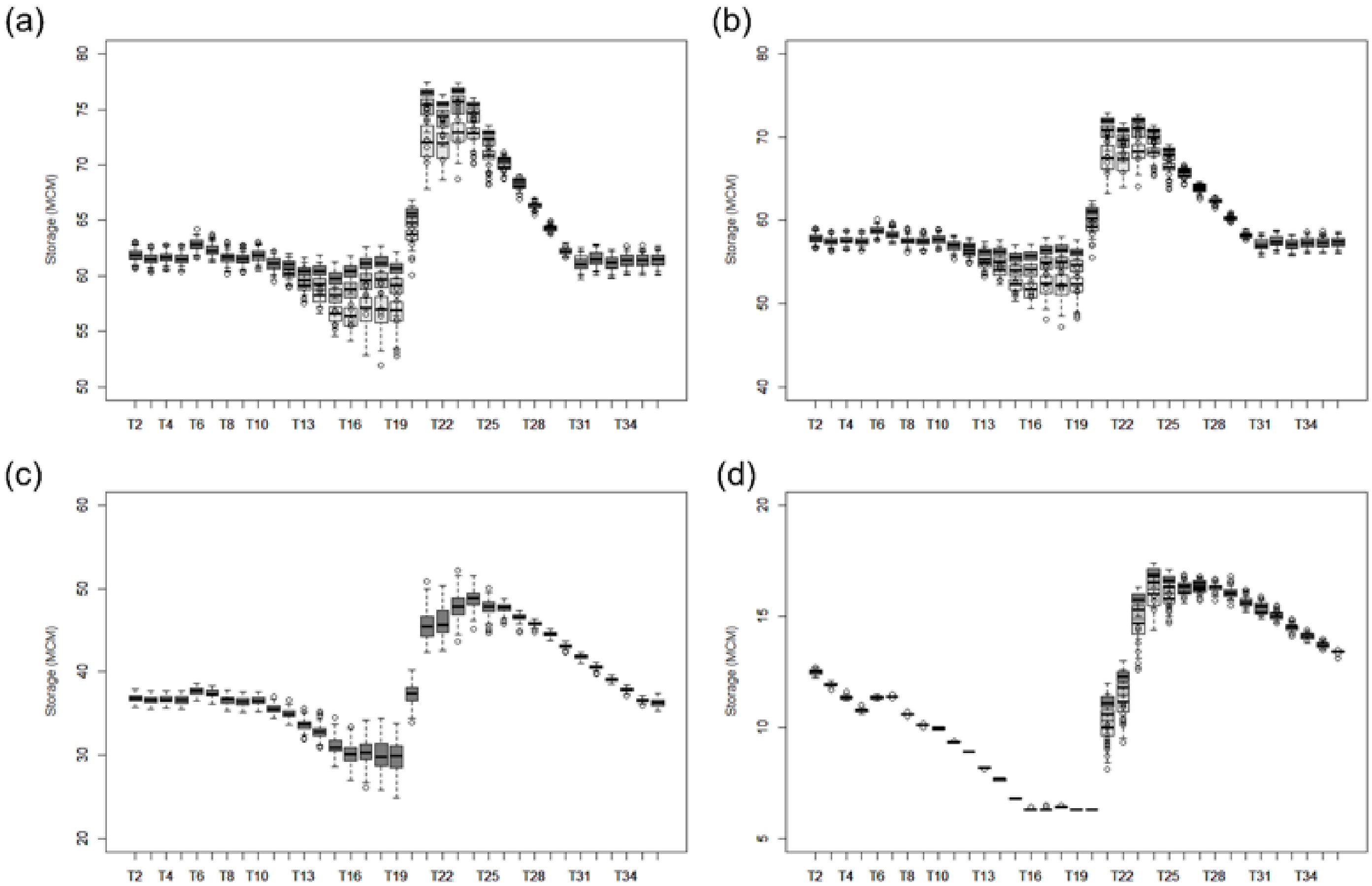

Figure 5

Alternative rule curves of the Boryeong Dam derived from synthetic inflow series with long memory (Cases 1, 4, and 7 or = 0.6, 0.75, and 0.9): (a) zone 1 (b) zone 2 (c) zone 3, and (d) zone 4. Darker boxplots indicate rules derived using inflow series with stronger long-term persistence

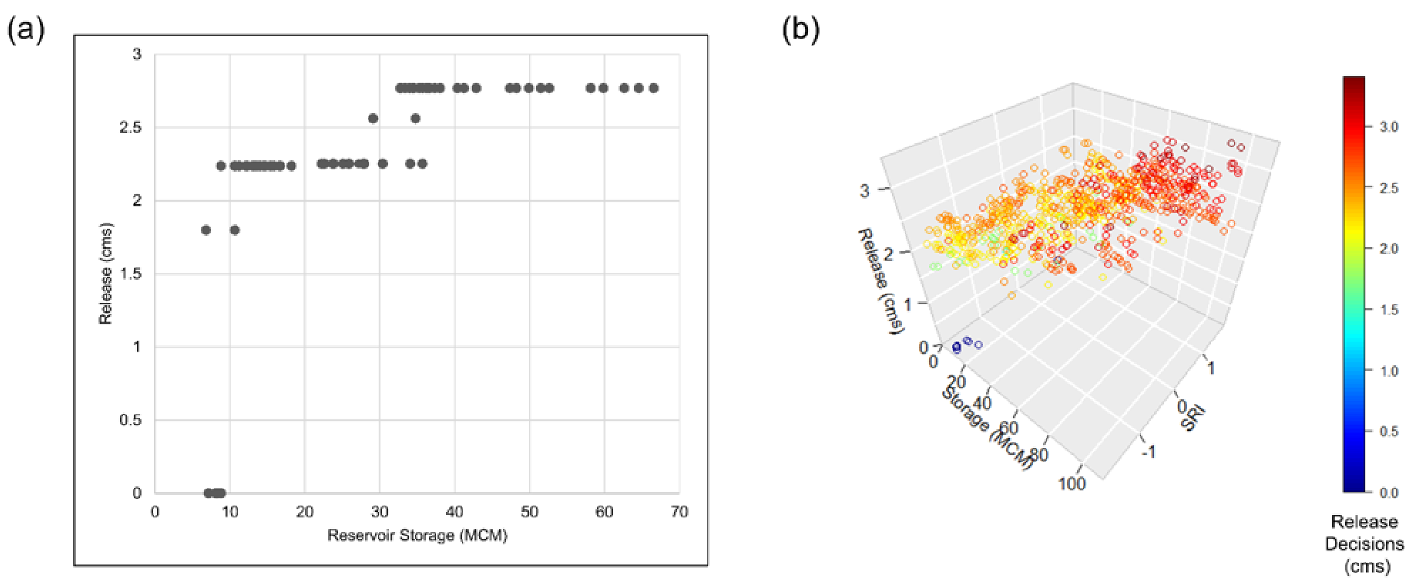

Figure 6

Release decisions from (a) SQ policy operations in April and (b) adaptive operations during all time periods proposed from this study. While the SQ policy only allows stepwise release decisions mainly based on the storage, adaptive operations enable a wider range of release decisions over time

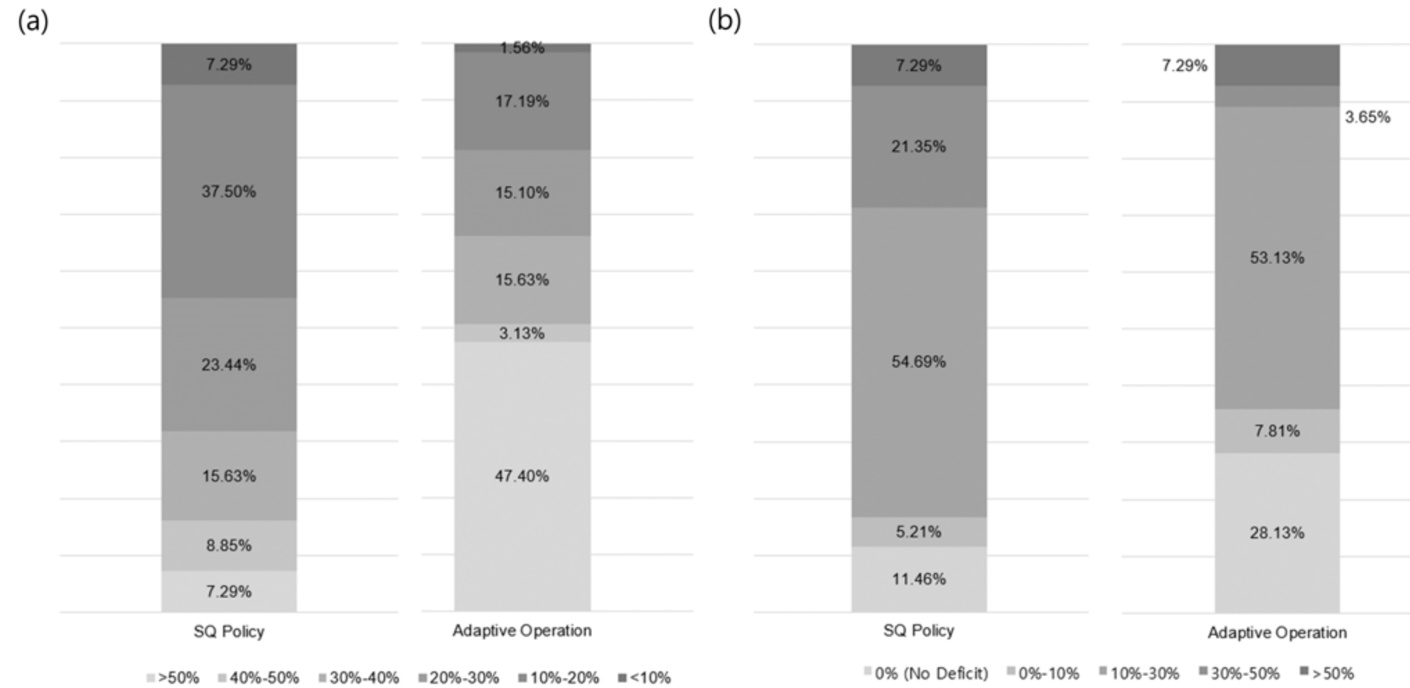

Figure 7

Frequency and magnitude (a) supply side (in terms of storage) and (b) the demand side (in terms of water deficit) during drought periods (Jun-2014 through Sep-2019)

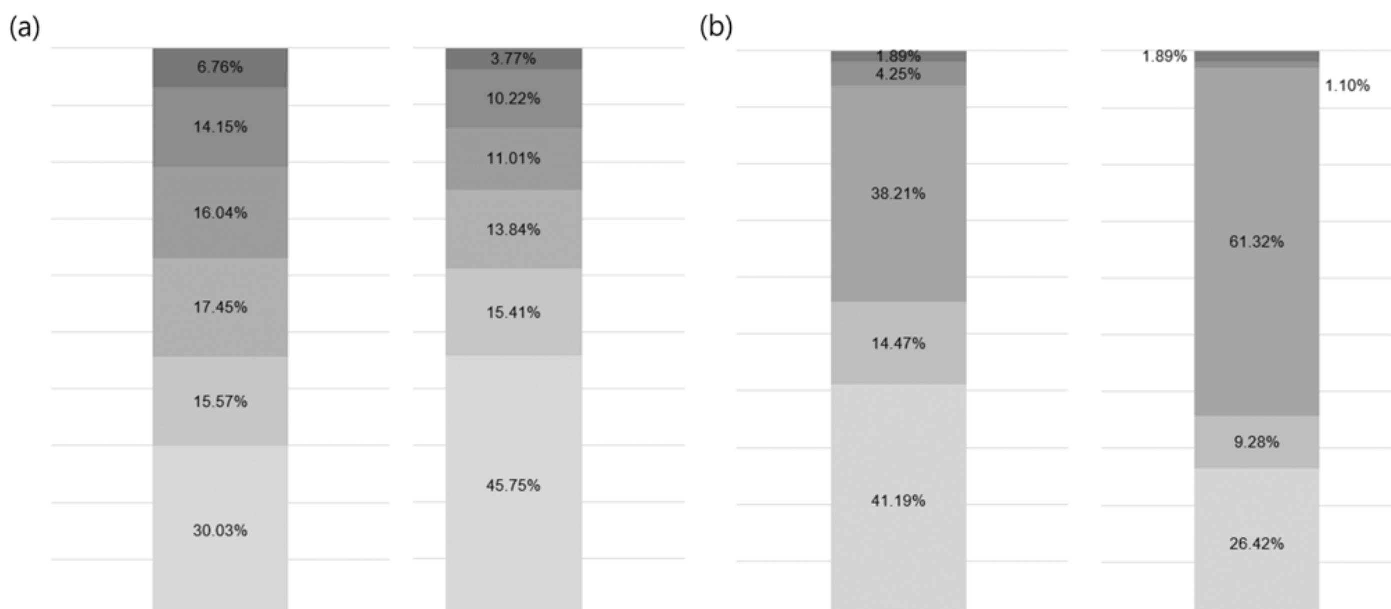

Figure 8

Frequency and magnitude (a) supply side (in terms of storage) and (b) the demand side (in terms of water deficit), during normal periods (Jan-1998 through May-2014 and Oct-2019 through Dec-2020)