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Conjunctive Operation of Sand Dam and Groundwater Well for Reliable Water Supply during Drought Conditions

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Abstract: Some mountainous regions without water service facilities are among the areas most vulnerable to drought. In these locations, it is particularly essential to establish practical alternatives to cope with the increase in the intensity and duration of droughts caused by climate change. This study proposes a methodology for the conjunctive use of a sand dam and groundwater well under various drought conditions. The method has been applied to a small mountainous area in South Korea. Owing to the scarcity of observational data, it is crucial to properly estimate the hydrological components necessary for judging the feasibility and reliability of conjunctive operations. The step-by-step procedures for performing the tasks are presented in this study. For the inflow of the sand dam, which is a portion of the basin runoff, two different approaches were employed and compared: the Kajiyama formula and a simple two-parameter monthly water balance model (TPM). Water budget analysis allowed for the determination of whether the current and increased water demand could be met under various drought conditions. Preliminary analysis revealed that a sand dam alone could not reliably meet the demand for 10-year or more severe drought conditions. Various water allocation scenarios between surface water (i.e., sand dam) and groundwater were tested. Conjunctive use of a sand dam and groundwater well turned out to increase the reliability of the water supply. As water demand increases and droughts become more severe, the role of groundwater increases. With appropriate resource allocation, 100% water supply reliability could be achieved, even for one year-lasting 50-year drought. We demonstrated how a system could be flexibly operated to meet the target demands monthly, given the system reliability level.

Keywords: conjunctive use; sand dam; groundwater well; water budget analysis; runoff estimation; water balance model; Kajiyama formula

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1. Introduction

Climate change is projected to increase the intensity and frequency of droughts by increasing temperature and evapotranspiration [1–4]. Moreover, water shortages are expected to intensify in drought-prone areas, where water service facilities are not provided. Although the water supply rate in Korea reached 97.4% in 2020, some mountainous areas remain vulnerable to drought, and people living in these areas chronically suffer from water shortages. For areas with difficulties in developing water service facilities due to economic or environmental limitations, it is essential to develop alternatives for a stable water supply with maximum utilization of available water resources.

Sand dam installation can increase the water supply capability without significantly damaging the natural environment. As shown in Figure 1, a sand dam can be constructed on impervious bedrock, storing water in the pores of sand depositions. Various types can be designed and built, depending on the field conditions, as illustrated in Figure 2. A standalone sand dam can serve as an intake source with an erosion control function. However, it may require periodic maintenance, incurring high costs. A multistage sand dam can steadily supply water by separating the erosion control function. A by-pass sand dam induces flow into a specially designed structure, causing less disturbance to the streamflow and making the system less susceptible to contamination.

Sand dams are widely used in Africa, as well as in North/South America, Asia, and the Middle East [5–13]. They are mainly used for supplying domestic or agricultural water and their ability to reduce evaporation and pollution makes them favorable, especially in arid and semi-arid regions.

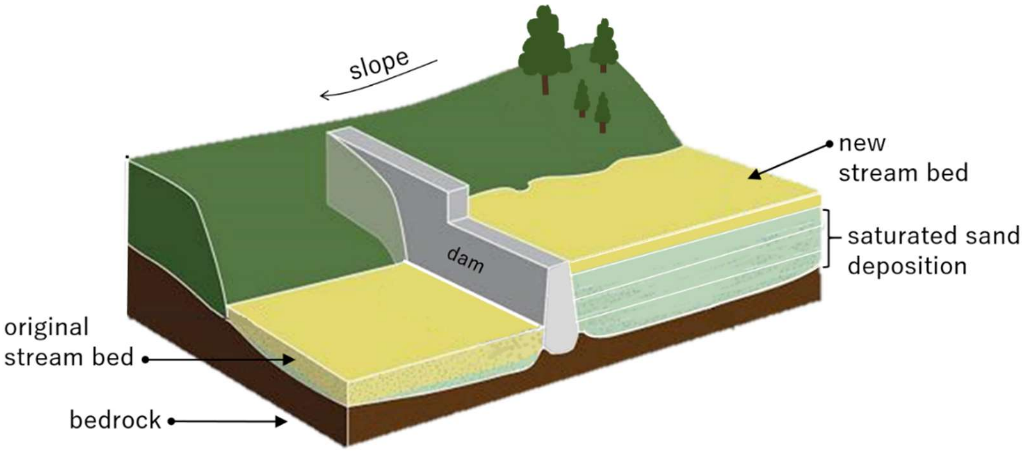


Figure 1. Configuration of sand dam (modified from [14]).

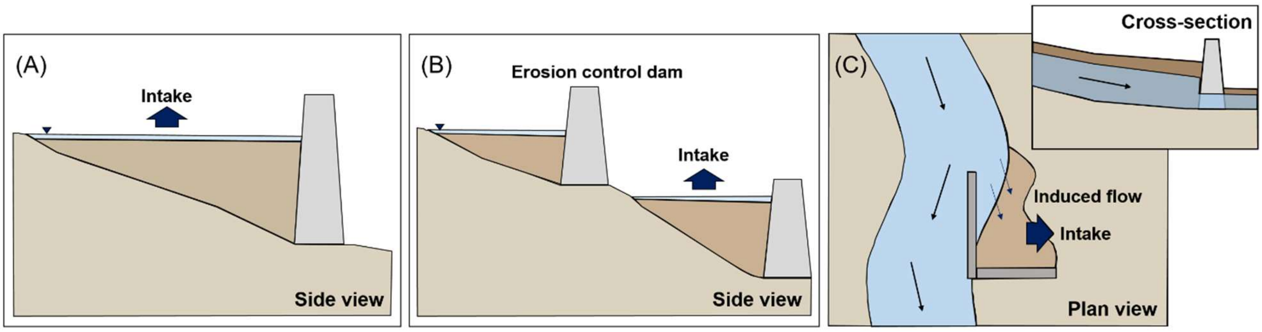


Figure 2. Types of sand dams: (**A**) Stand-alone, (**B**) Multi-stage, (**C**) By-pass (modified from Kim et al. [15]).

The conjunctive use of available water resources can contribute to the alleviation of dependence on a single source and provide resilience to the water supply system from various adverse situations, such as temporary interruption of water intake for maintenance or system failure. Conjunctive use does not imply the simple addition of water amount. Rather, it pursues efficient allocation of water resources. Conjunctive use has been widely employed to solve water resource management issues such as securing domestic/agricultural water, managing water quality, and preventing saltwater intrusion. Rafipour-Langeroudi et al. [16] proposed an operating rule for the conjunctive use of rivers and canals in the Tehran Plain, India. Tabari and Yazdi [17] developed an optimal water supply allocation ratio between the surface water and groundwater of the Urmia Lake Basin, Iran. Dai et al. [18] suggested a cost-effective surface and subsurface water allocation scheme for the Yunnan Province, China. Barlow et al. [19] simulated a management model for the stream/aquifer system of Rhode Island, USA. Khare et al. [20] evaluated the possibility of optimal conjunctive use of surface water and groundwater for canal operations in Andra Pradesh, India. Kim and Lee [21] provided a more extensive review of this subject.

The main objective of this study is to propose a methodology for the conjunctive operation of a sand dam and a nearby groundwater well, which has rarely been investigated elsewhere. We aim to provide useful guidelines for effective water supply under drought conditions by demonstrating how the methodology works. Information on the study site is presented in Section 2. Section 3 presents the step-by-step methodology. The results of the methodology applied to the study area are presented in Section 4. In Section 5, we conclude our study and provide suggestions for future work.

2. Study Site

The study area, Mullo-ri, is in the mountainous region of Chuncheon-si, Gangwon-do, South Korea (Figure 3). The catchment basin has a 2.1 km^2 area and 2.2 km stream length. Topographical characteristics of the 1708 m high Taebaek Mountains make the slope of the basin quite steep, causing rapid surface outflow. According to the 1992–2021 30-year rainfall data from the Chuncheon meteorological station (37.90262° N and 127.7357° E), July and August account for 53% of the total annual rainfall, June to September for 72%, and May to October for 83% [22]. With no modern facilities, seasonal fluctuations of streamflow and low yields of groundwater well make the water supply problem of this small village difficult. Overall, the precipitation pattern and the characteristics of the location lead to the low water supply potential especially during the dry season.

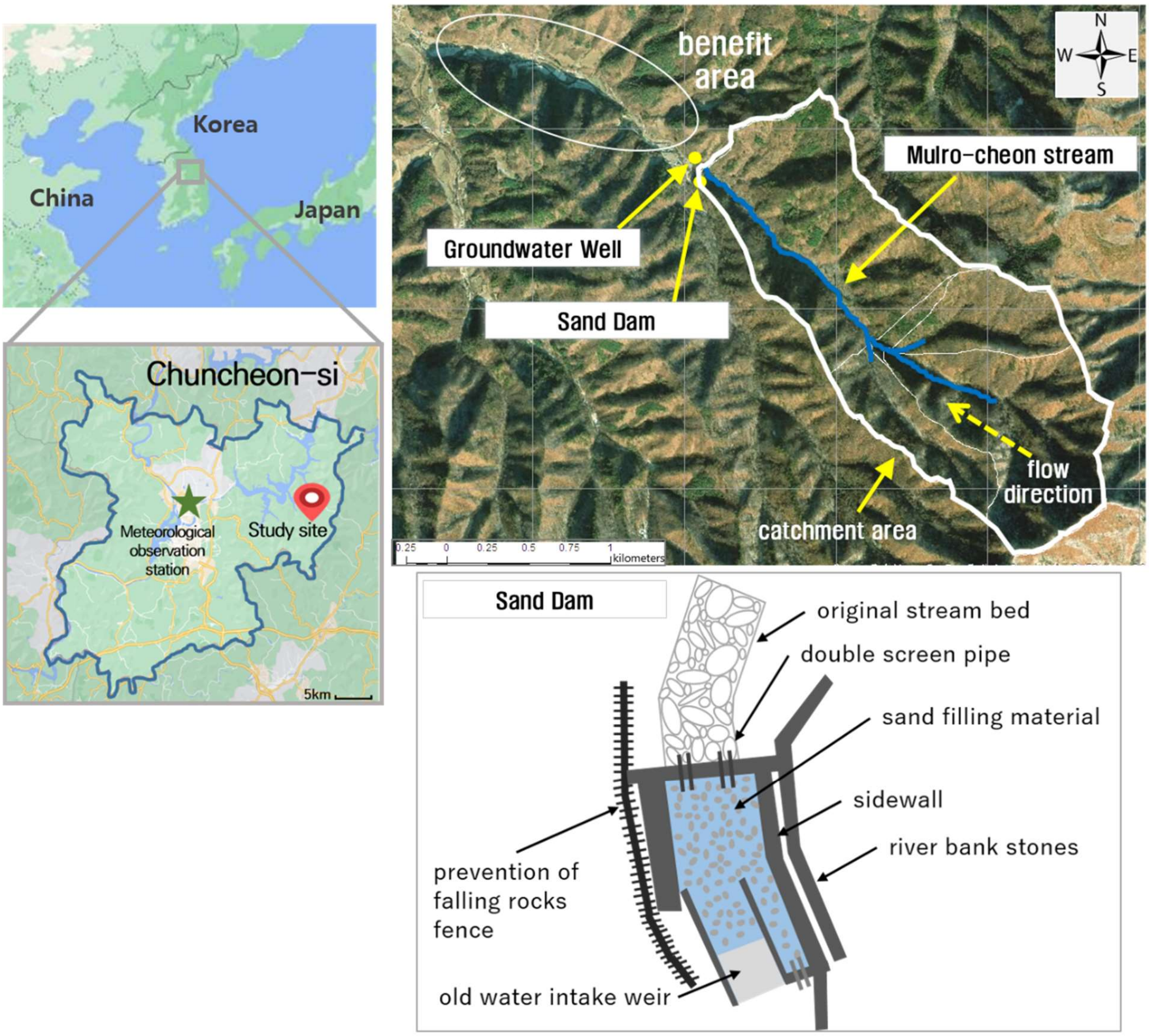


Figure 3. Study site and sand dam schematics (modified from [23]).

Figure 4 shows the standard precipitation index (SPI) plots for the data observed at the Chuncheon meteorological station. The SPI is a drought index based on the probability of precipitation at any time scale [24]. For example, a 3-month SPI at the end of March compares the January–February–March precipitation total in that particular year with the same period precipitation totals of all years. SPI plots with time scales of 3–12 months revealed frequent episodes of precipitation lower than in other years. The blue dotted lines indicate that major droughts caused significant damage to people living in the region, creating social issues.

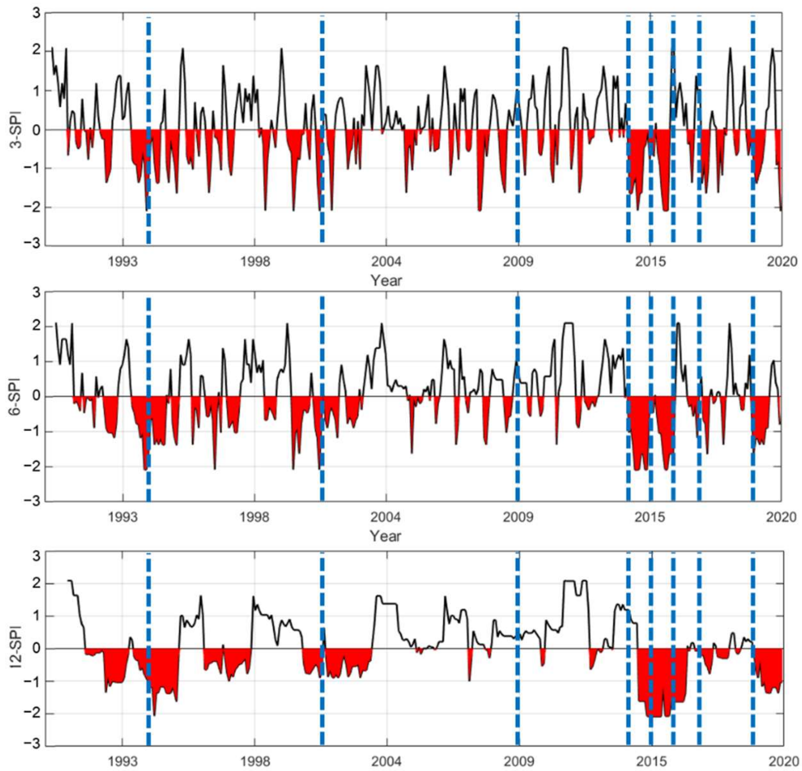


Figure 4. Standard precipitation index (SPI) for study site. The blue dotted lines indicate major droughts caused significant damage.

Originally, Mullo-ri utilized an old water intake weir (5 × 10 m) for water supply. As the entire village depended on a small facility, residents (population size of 50) frequently suffered from water shortages. In 2021, a by-pass type sand dam was built downstream of the old water-intake weir. In addition, a groundwater well was installed 470 m downstream from the sand dam. Table 1 lists the characteristics of the two water resources in this region [23]. Figure 5 shows the configuration of the well.

Table 1. Characteristics of the sand dam and groundwater well.

Sand Dam		**Groundwater Well**	
Top width (m)	13	Type of rock	Sedimentary rock
Bottom width (m)	13	Excavation depth (m)	120
Height (m)	1.9	Discharge pipe diameter (mm)	20
Design rainfall (mm/h)	109	Pumping capacity (m^3/day)	23
Runoff coefficient	0.8	Pump power (hp)	1
Maximum discharge (m^3/s)	3.18	Depth to pump (m)	100

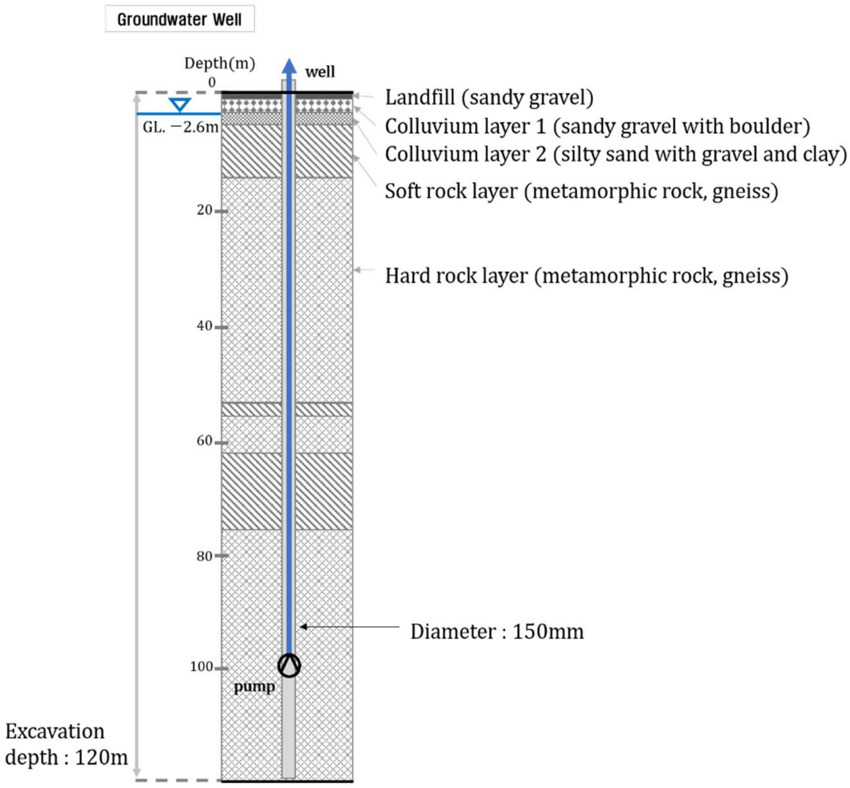


Figure 5. Cross-sectional view of the well configuration.

3. Methodology

Conjunctive use of the effective water supply from multiple sources requires a systematic approach. We proposed a six-step procedure, as indicated in Figure 6. The details are explained in the following sections.

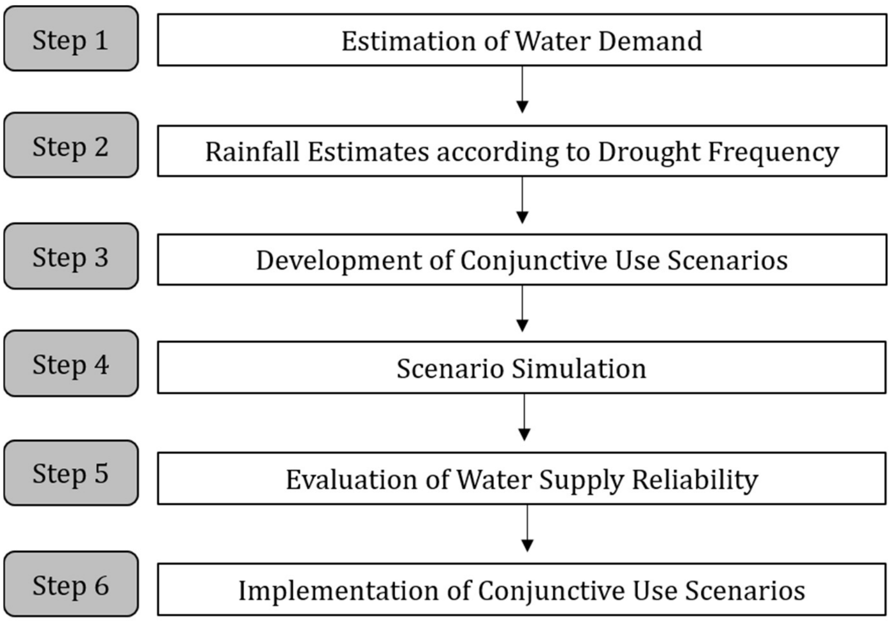


Figure 6. Procedure for conjunctive use of multiple water sources.

3.1. Estimation of Water Demand

The first step included the prediction of water demand. The water demand can be defined as the total amount of domestic water supplied through the conjunctive use of water sources. When there are no officially recognized data sources on daily water consumption in areas such as the study site, water demand can be calculated as the product of daily water consumption per person (lpcd) and population. The target water demand can be estimated by considering the following characteristics: location (a mountainous village in this study), age structure, and water usage. Future demand, along with the current amount of water use, can be obtained and used for scenario simulation (Step 4).

3.2. Rainfall Estimates According to Drought Frequency

Drought is a natural stochastic phenomenon caused by a severe shortage of precipitation. Although drought gradually progresses, it can exhibit longer-lasting effects than other meteorological hazards. To properly understand the impact of drought on the conjunctively operated system, rainfall data is a prerequisite. Probable rainfalls according to drought frequency are estimated in the second step. They were used as the input data for the water budget analysis (Step 4). Typical rainfall-frequency analysis methods can also be used. We employed the NDIC-FAT software program for this purpose [25]. The NDIC-FAT was developed by the K-water Institute and can facilitate drought frequency analysis. In this study, probable rainfalls for various drought frequencies (normal, 5-year, 10-year, 20-year, and 50-year) were estimated.

3.3. Development of Conjunctive Use Scenarios

The third step included the development of water supply scenarios that allocate water supply amounts to each water source under drought conditions. Furthermore, water supply scenarios for a sand dam and groundwater well are developed according to the frequency of drought. As the sand dam can be more vulnerable to drought than groundwater well, this requires consideration. In a normal year, the sand dam solely covers the demands without placing a burden on groundwater. As the drought intensifies, the role of groundwater in each scenario increases. However, the maximum groundwater allocation must be less than the pumping capacity, as excessive pumping can increase the risk of groundwater depletion or land subsidence [26].

3.4. Scenario Simulation

In the next step, the feasibility of the water supply was investigated through a simulation based on the developed scenarios. With the target water demand preset, the monthly water budget was analyzed according to a scenario (i.e., the ratio allocated to each water source).

Even for a scenario in which groundwater allocation is at its maximum, supplying groundwater will have no problem because the allocated water is less than the pumping capacity. This means that the feasibility of the water supply depends entirely on the success of sand dam operation.

The sand dam can be considered a reservoir, and the water budget equation (Δ Storage = inputs − outputs) is applied to it. To simulate time-varying storage levels, the water budget equation is formulated as follows:

$$\begin{aligned} RS_{i,j} &= RS_{i-1,12} + I_{i,j} - WD_{i,j} - EV_{i,j} - OF_{i,j} \quad && \text{when } j = 1 \\ RS_{i,j} &= RS_{i,j-1} + I_{i,j} - WD_{i,j} - EV_{i,j} - OF_{i,j} \quad && \text{otherwise} \end{aligned} \tag{1}$$

where $RS_{i,j}$ is the reservoir storage in year i and month j, $I_{i,j}$ is the inflow to the reservoir, $WD_{i,j}$ is the water demand, $EV_{i,j}$ is evaporation, and $OF_{i,j}$ is overflow. The water level was estimated and the water supply was considered feasible when the level was higher than the dead storage level.

It is not uncommon for inflow data ($I_{i,j}$) to be unavailable in rural areas. Depending on the type of sand dam, the entire amount or some portion of the runoff from the watershed would become inflow. Among the many ways to estimate watershed runoff, we utilized two approaches: the Kajiyama formula and a simple two-parameter monthly water balance model (TPM).

The Kajiyama formula has been widely used in practice in Korea [27,28]. It was developed based on relatively old data (1916–1927) but has been considered useful, especially when there is not much available data. The mathematical expression is as follows:

$$Q(t) = \sqrt{P(t)^2 + (138.6f + 10.2)^2} - 138.6f + \epsilon \quad (2)$$

where $Q(t)$ is the monthly runoff depth (mm), $P(t)$ is the monthly rainfall (mm), f is the runoff characteristic coefficient, and ϵ is the monthly correction factor (mm). Details of the runoff characteristic coefficient (f) and monthly correction factor (ϵ) can be found in the literature [27].

A simple two-parameter monthly water balance model (TPM) was proposed by Xiong and Guo [29]. It has been widely used because of its high accuracy and applicability. Given the observed monthly precipitation $P(t)$ and pan evaporation $EP(t)$, the actual monthly evapotranspiration $E(t)$ can be determined by the following:

$$E(t) = c \times EP(t) \times \tanh\left[\frac{P(t)}{EP(t)}\right] \quad (3)$$

where c is the first model parameter to consider the effect of the change in time scale, that is, from year to month. The monthly runoff $Q(t)$ is also assumed to be a hyperbolic tangent function of the soil water content $S(t)$, which is given by the following:

$$Q(t) = [S(t-1) + P(t) - E(t)] \times \tanh[\{S(t-1) + P(t) - E(t)\}/SC] \quad (4)$$

Here, the second parameter SC is the field capacity of the catchment (mm). The water content at the end of the t-th month can be calculated according to the water conservation law as follows:

$$S(t) = S(t-1) + P(t) - E(t) - Q(t) \quad (5)$$

3.5. Evaluation of Water Supply Reliability

Once the water supply scenarios are simulated, the reliability of the water supply system can be quantified [30]. This can be defined as the ratio of the period of continuous water supply to the total simulation period.

$$\text{water supply reliability} = \left(1 - \frac{\text{water shortage period}}{\text{total simulation period}}\right) \times 100 \quad (6)$$

A 100% water supply reliability means that a continuous water supply is possible throughout the year under certain drought conditions. The reliabilities of 91.7% and 83.3% corresponded to 11 and 10 months of continuous water supply, respectively. If a sand dam is designed to achieve a water supply reliability of, for example, 95% for a 20-year drought, one can expect higher reliability when groundwater well is added for conjunctive use.

3.6. Implementation of Conjunctive Use Scenarios

The last step was to implement conjunctive use scenarios for monthly operations based on real precipitation data. The drought conditions (i.e., frequency and duration) can be determined regularly at a certain time of a month by comparing the observed rainfall with the probable drought rainfall. Subsequently, an appropriate scenario was selected and applied to meet the target demand and reliability. To avoid excessive dependence on a certain water source and its resultant depletion, changing the scenarios is recommended if other options are available.

4. Results and Discussion

4.1. Water Demand

Two water demands were considered as the target supply amounts: the current amount of water use (Demand 1) and 150% of the current amount of water use (Demand 2). Demand 1 (9.16 m^3/day) corresponds to 187 L per capita per day (lpcd), which is the water consumption of typical small villages in South Korea. Demand 2 (13.7 m^3/day) accounts for 280.5 lpcd, which assumes future lifestyle changes, including water consumption patterns. It is the median value between 187 lpcd for small villages and 362 lpcd for the nearby city of Chuncheon [31].

There are various population projection methods [21] and the estimation of water demand based on such projection is feasible. Here, we did not follow the procedure due to the small size of the population (<50). Two water demands were devised by taking into account the local circumstances.

4.2. Probable Rainfall for Drought

Probable rainfall for drought was calculated according to the procedure described in Section 3.2. Rainfall data from the last 30 years were used, and the Gumble type was chosen for the probability distribution [23]. The calculated annual rainfall for the 5-year, 10-year, 20-year, and 50-year droughts was 1074.2, 986.2, 921.5, and 855.9 mm, respectively. These annual rainfall events were disaggregated into months according to the characteristics of past data. The estimated monthly rainfall according to drought frequencies is shown in Table 2. Considering the precipitation pattern of the monsoon watershed, four typical drought periods were assumed for the scenario simulation. They were (i) two months (July–August), (ii) four months (June–September), (iii) six months (May–October), and (iv) twelve months (January–December).

Table 2. Estimated monthly rainfall according to the drought frequency (unit: mm).

Drought Frequency	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Normal	18.6	26.5	35.9	73.9	102.2	122.6	383.0	322.3	125.3	50.6	49.3	22.8
5-year	15.0	21.4	28.9	59.6	82.4	98.8	308.6	259.7	101.0	40.8	39.8	18.3
10-year	13.8	19.6	26.6	54.7	75.6	90.7	283.3	238.4	92.7	37.4	36.5	16.8
20-year	12.9	18.3	24.8	51.1	70.7	84.7	264.7	222.8	86.6	35.0	34.1	15.7
50-year	11.9	17.0	23.1	47.4	65.6	78.7	245.9	206.9	80.5	32.5	31.7	14.6

4.3. Conjunctive Use Scenarios

Scenarios were developed to allocate the water supply to each water source under drought conditions (Table 3). In each scenario, the amounts of water supplied to the sand dam and groundwater well were assigned to meet the target demands. Each scenario with a different allocation ratio was tested through a simulation to determine whether the designated supplies would meet the target demand. For all scenarios, the sand dam supplies the entire demand with no help from the groundwater well during normal years. As drought becomes more severe, groundwater supply increases. The scenarios were designed to examine the effect of the increased role of groundwater in the context of conjunctive use. The maximum groundwater allocation can reach 40% of the total supply (S4, 50-year drought) but remains under the pumping capacity.

According to the Korean groundwater regulations, if the pumping rate exceeds 100 m^3/day, a groundwater impact assessment must be conducted before the development of a groundwater well. If it is below 100 m^3/day, it is regarded that no environmental problems are expected and the impact assessment is exempted. In our study, the maximum groundwater allocation (S4 with 50-year drought frequency) is 5.5 m^3/day, which is lower than 100 m^3/day and way below the pump capacity of 23 m^3/day. Pumping of such amount for several months would create little environmental problems. Of course, rigorous simulations may be needed for accurate environmental impact assessment.

Table 3. Scenarios for water allocation ratio (%) and supply (m^3/day) under various drought conditions.

Scenario	Frequency	Sand Dam %, Supply 1, Supply 2	Groundwater Well %, Supply 1, Supply 2
S0 (Base Scenario)	Normal	100, 9.16, 13.74	0, 0.00, 0.00
	5-year	100, 9.16, 13.74	0, 0.00, 0.00
	10-year	90, 8.25, 12.37	10, 0.92, 1.37
	20-year	90, 8.25, 12.37	10, 0.92, 1.37
	50-year	85, 7.79, 11.68	15, 1.37, 2.06
S1	Normal	100, 9.16, 13.74	0, 0.00, 0.00
	5-year	95, 8.70, 13.06	5, 0.46, 0.69
	10-year	90, 8.25, 12.37	10, 0.92, 1.37
	20-year	90, 8.25, 12.37	10, 0.92, 1.37
	50-year	85, 7.79, 11.68	15, 1.37, 2.06
S2	Normal	100, 9.16, 13.74	0, 0.00, 0.00
	5-year	95, 8.70, 13.06	5, 0.46, 0.69
	10-year	90, 8.25, 12.37	10, 0.92, 1.37
	20-year	85, 7.79, 11.68	15, 1.37, 2.06
	50-year	80, 7.33, 11.0	20, 1.83, 2.75
S3	Normal	100, 9.16, 13.74	0, 0.00, 0.00
	5-year	95, 8.70, 13.06	5, 0.46, 0.69
	10-year	90, 8.25, 12.37	10, 0.92, 1.37
	20-year	85, 7.79, 11.68	15, 1.37, 2.06
	50-year	70, 6.41, 9.62	30, 2.75, 4.12
S4	Normal	100, 9.16, 13.74	0, 0.00, 0.00
	5-year	95, 8.70, 13.06	5, 0.46, 0.69
	10-year	90, 8.25, 12.37	10, 0.92, 1.37
	20-year	80, 7.33, 11.0	20, 1.37, 2.06
	50-year	60, 5.50, 8.25	40, 3.67, 5.50

4.4. Simulation of Conjunctive Use Scenarios

The scenarios in Table 3 were applied to simulate the sand dam/well operation. The purpose was to determine whether the target water demand could be met under drought conditions. As the scenarios were designed such that even the maximum groundwater allocation (S4 with 50-year drought frequency) would not cause any environmental problems, the pumping operation according to all scenarios would always be possible. This implies that the judgment depends only on the simulation results of the sand dam.

The sand dam can be considered as a rectangular box with a dimension of 7.5 m × 13 m × 2.0 m with three layers of filling material (Figure 7). The porosities of the coarse, medium, and fine sands were 45, 35, and 25%, respectively, resulting in a total pore volume of 82.5 m^3. The water surface area was 97.5 m^2, the high water level was 1.9 m from the bottom, and the dead water level was 0.2 m due to the diameter of the drainage pipe. The surface evaporation was calculated using the daily pan evaporation dataset from 2017 to 2020. Evaporation from the sand-fill volume was not considered.

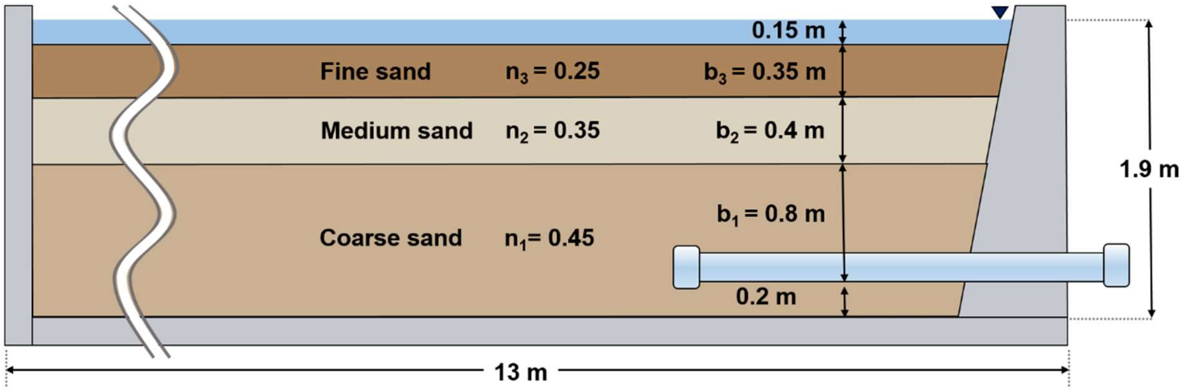


Figure 7. Sand dam with three layers of sand-fill material.

4.4.1. Inflow Estimation

When the water budget was analyzed using Equation (1), the inflows to the sand dam were used from the two runoff models described in Section 3.4. For the Kajiyama formula, Equation (2), $\mathrm{P}(t)$ corresponds to the monthly rainfall for different drought frequencies in Table 2. The value of f was 0.8, owing to the steep slope of the study area, and ϵ was determined according to monthly rainfall [27].

Regarding TPM, Equation (3), locally observed data were used for the soil water content and evaporation [32]. Parameters from a study of the Hongchun sub-basin, 4 km from the study site, were adopted [33].

References [33–35] compared the Kajiyama formula and TPM in terms of the accuracy of runoff estimation. They analyzed the performance of the models against the observed data. However, the study area was ungagged and lacked runoff data. Therefore, we intend to compare the two models from the aspect of conjunctive use, not to determine which model is more accurate.

In 2021, observations were made to determine the amount of water directed through the by-pass structure. The ratio between the stream and inflow to the sand dam was 9:1, indicating that 10% of the watershed runoff was the inflow to the sand dam. The estimated runoff depth (Q) multiplied by the watershed area provided the total runoff and 10% was used as the inflow to the sand dam.

Figure 8 shows the inflow to the sand dam estimated using the Kajiyama formula and TPM. The first subplot compares the estimated values with observed ones made in 2020. Frequency analysis indicated that the precipitation corresponded to a normal year. Overall, the TPM resulted in a lower inflow than that of the Kajiyama formula, apart from the fall/winter season when precipitation was not high. The Kajiyama formula, an empirical equation originally developed to relate the rainfall and runoff for relatively larger rivers than ours, may have difficulties in reflecting characteristics such as slope or vegetation of the mountainous watershed.

In contrast, TPM considers various hydrologic components, such as monthly precipitation, evapotranspiration, and soil water content. As a result, the peak flows were much lower than those of the Kajiyama formula and shifted accordingly. On a more scientific basis, TPM was considered suitable for scenario analysis.

As it is common for observed runoff data to be scarce for small mountainous watersheds, the estimation of runoff is crucial to water budget analysis. The Kajiyama formula, which is commonly used in practice, is easy to use but tends to result in higher runoff than the TPM. A large amount of inflow to the sand dam overwhelmed the water demand and did not make any difference between the scenarios. TPM is recommended based on its scientific background and credibility.

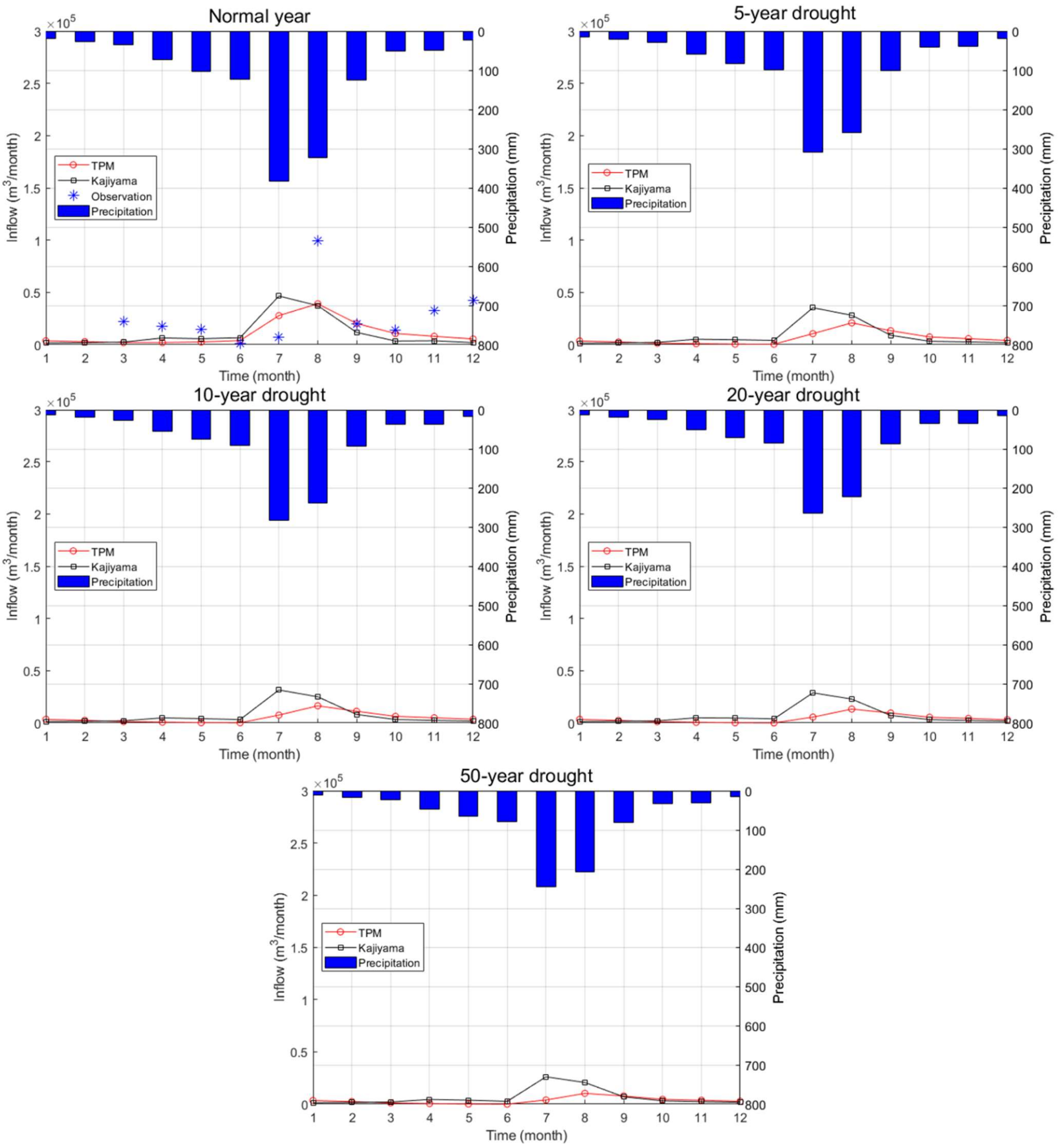


Figure 8. Precipitation and inflow to sand dam for various drought conditions (normal, 5-, 10-, 20-, and 50-year frequency). Data observed in a normal year are shown along with model estimates.

4.4.2. Water Supply Reliability

Before simulating the conjunctive use scenarios, one must test whether meeting the two target demands would be feasible with only the sand dam. If it fails, its conjunctive use with the aid of groundwater would be justified. As shown in Table 4, the water demand was satisfied for all cases when the inflow was estimated using the Kajiyama formula. As for the TPM, the water supply would cause no problems for normal years, and it would be the same for drought situations of 5-year frequency. The water supply started to fail in more severe droughts, showing the reliability of 91.7% for 10-year droughts and 83.3% for worse cases. These results call for measures to ensure a reliable water supply.

Table 4. Water supply reliability when only the sand dam is operated. A year-round drought is assumed.

Inflow Estimation	Water Demand (m^3/day)	Drought Frequency				
		Normal	5-Year	10-Year	20-Year	50-Year
Kajiyama formula	Demand 1 (9.16)	100	100	100	100	100
	Demand 2 (13.7)					
TPM	Demand 1 (9.16)	100	100	91.7	83.3	83.3
	Demand 2 (13.7)	100	100	83.3	83.3	83.3

Table 5 presents the comprehensive simulation results for the conjunctive operation. Scenario-wise outcomes of the possibility and reliability of a continuous water supply are tabulated. Black circles indicate that the conjunctive operation succeeds in meeting the demand, whereas the white circles correspond to the water shortage. Outcomes for both Demand 1 (current amount) and Demand 2 (increased amount) are shown. When a water shortage occurs, system reliability is given in parentheses.

When the Kajiyama formula was used for the inflow estimation, continuous water supply was possible for all cases, regardless of water demand and drought conditions. Sufficient inflow was believed to make the water supply system robust, even for a 50-year drought lasting 12 months. However, when the TPM was used for inflow estimation, this may not be the case. Water could be supplied to meet the demands of drought episodes of any return period lasting up to four months. Yet, when a drought lasted for six months, the water supply failed (S0, S1, S2). Failure could occur under the most severe conditions, that is a 50-year drought frequency with increased demand (Demand 2). The reliability dropped to 91.7%, implying that water shortages may have occurred for a month. Even though groundwater covered 15–20% of the target demand (see Table 3), the water storage in the sand dam could fall below the dead water level. Such water shortage problems can be solved by increasing the groundwater supply to 30% or more (S3 and S4).

When the drought period was extended to 12 months (last column in Table 5), the water supply capability weakened. Unlike the six-month drought, in which no problems occurred for droughts of the 20-year return period, the system could not meet Demand 2 even for the precipitation of the 10-year return period (S0). Not to mention, more severe drought. The water supply became infeasible for both demands, and the reliability could fall to 83.3% depending on the cases (S1 and S2). The input from the groundwater well, accounting for 30% of the total, could not completely solve the water shortage problem (S3). The water supply was made possible throughout the year only when the ratio between the sand dam and groundwater well became 6:4 (S4).

In this study, we presented the reliability of a water supply system. At a later stage, it would be meaningful to consider similar but different features as well: resiliency and vulnerability may be the candidates. The former refers to how rapidly a system will likely return from a failure state, and the latter describes the degree to which a system is susceptible to adverse effects of failure.

Table 5. Possibility and reliability of continuous water supply with conjunctive operation.

Inflow Estimation	Scenario	Drought Frequency	Duration			
			2 Months (July–Aug.)	4 Months (June–Sept.)	6 Months (May–Oct.)	12 Months (Jan.–Dec.)
Kajiyama formula	All	All	●/●	●/●	●/●	●/●
TPM	S0	Normal	●/●	●/●	●/●	●/●
		5-year	●/●	●/●	●/●	●/●
		10-year	●/●	●/●	●/●	●/○ (91.7)
		20-year	●/●	●/●	●/●	○/○ (91.7/83.3)
		50-year	●/●	●/●	●/○ (91.7)	○/○ (83.3/83.3)
	S1	Normal	●/●	●/●	●/●	●/●
		5-year	●/●	●/●	●/●	●/●
		10-year	●/●	●/●	●/●	●/○ (91.7)
		20-year	●/●	●/●	●/●	○/○ (91.7/83.3)
		50-year	●/●	●/●	●/○ (91.7)	○/○ (83.3/83.3)
	S2	Normal	●/●	●/●	●/●	●/●
		5-year	●/●	●/●	●/●	●/●
		10-year	●/●	●/●	●/●	●/○ (91.7)
		20-year	●/●	●/●	●/●	○/○ (91.7/83.3)
		50-year	●/●	●/●	●/○ (91.7)	○/○ (83.3/83.3)
	S3	Normal	●/●	●/●	●/●	●/●
		5-year	●/●	●/●	●/●	●/●
		10-year	●/●	●/●	●/●	●/○ (91.7)
		20-year	●/●	●/●	●/●	○/○ (91.7/83.3)
		50-year	●/●	●/●	●/●	○/○ (83.3/83.3)
	S4	Normal	●/●	●/●	●/●	●/●
		5-year	●/●	●/●	●/●	●/●
		10-year	●/●	●/●	●/●	●/●
		20-year	●/●	●/●	●/●	●/●
		50-year	●/●	●/●	●/●	●/●

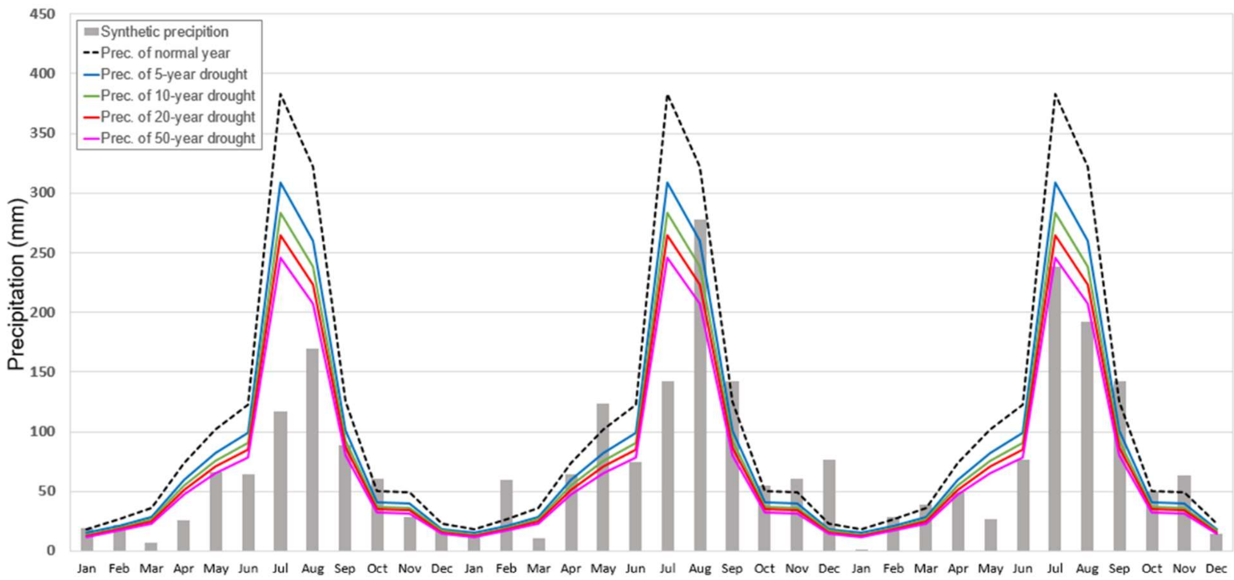
Note: ●/●: Possible for Demand 1 and 2. ●/○: Possible for Demand 1, but a water shortage for Demand 2. The number (%) in parentheses indicates reliability. ○/○: Water shortages for Demands 1 and 2.

4.5. Operation with Conjunctive Use Scenarios

In the previous section, we saw that droughts of six to twelve months could result in water shortages and that such a situation could be resolved by increasing the allocation of water supply from groundwater. Given the simulation results, system operators or managers must make decisions to supply water in a sustainable manner. It is common for such a decision to be made monthly, even in a multi-purpose dam. In this section, we demonstrate the practical implementation of conjunctive use scenarios.

For instance, if a drought is at the end of a month and the target amount of water supply and reliability provided, the first step in determining the scenario for the next month's operation is to compare the precipitation of that month with the probable precipitation. With the frequency of drought known, the duration of drought can be determined by referring to the records of the previous months. The applicable scenarios were identified based on the simulation results shown in Table 5. Special attention must be paid when sudden changes in precipitation occur. A 'critical month' concept may be useful for developing some operational guidelines. A month when a severe drought starts abruptly is an example of a critical month. In such a case, scenarios with high groundwater allocation could be considered. Another example of a critical month is a transitional case, in which a long and severe drought is interrupted by normal precipitation. Since there is always a possibility that drought conditions will resume again, a sudden change to a surface water source might not be ideal. Concurrently, as there is a high chance of using groundwater for a long time, a policy change to a surface water source (i.e., sand dam) might be desirable. The final decision must be made considering various aspects such as water availability and environmental impacts.

Figure 9 illustrates an example of the operation of the sand dam and groundwater well in the study area, with conjunctive use scenarios. Precipitation sequences (hypothetical for demonstration purposes) are displayed, along with probable rainfall with various drought frequencies. The target was to meet Demand 2, and the design reliability of the system was set to 100%. Each month, the drought frequency is decided (third row in the table), and inapplicable/applicable scenarios are classified using simulation results, as shown in Table 5 (fourth and fifth rows). Critical months are identified (sixth row), and the final determination of the applicable scenario is made based on the guidelines mentioned above (seventh row).



Target	150% of the current water demand, 100% of water supply reliability																	
Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Drought frequency [year]	Normal	5	50	50	50	50	50	50	10	Normal	50	10	10	Normal	50	5	Normal	50
Inapplicable scenario	S0 S1 S2	-	-	-	-	-	-	S0 S1 S2	-	-	-	-	-	-	-	-	-	-
Operational scenario	S3 S4	All	All	All	All	All	All	S3 S4	All	All	All	All	All	All	All	All	All	All
Critical month	ⓐ						ⓑ		ⓒ						ⓓ			
Application	S3 S4	S0	S0	S0	S0	S0	S4	S4	S0	S0	S0	S0	S0	S0	S3	S0	S0	S0

Month	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Drought frequency [year]	50	5	Normal	Normal	Normal	Normal	50	Normal	Normal	50	50	50	50	50	Normal	Normal	Normal	50
Inapplicable scenario	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Operational scenario	All	All	All	All	All	All	All	All	All	All	All	All	All	All	All	All	All	All
Critical month																		
Application	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S0	S3	S0	S0	S0	S0

Figure 9. Illustrative operation with conjunctive use scenarios.

An additional explanation may be helpful for a better understanding of the final decision-making process. In this illustration, it is assumed that a 50-year drought lasted for six months prior to month 1. Since it is the first month experiencing an abrupt change, it is transitional (critical month ⓐ). Normal precipitation might be temporary, and drought can resume. Therefore, scenarios with high dependency on surface water (S0, S1, S2) are not recommended, and S3 or S4 can be applied. As for month 7 (ⓑ), it is the fifth month of a 50-year drought and one more month of drought would see a water shortage. The simulation results proved that S0 could not be maintained (Table 5). The adoption of S4 is in order. At ⓒ, a 50-year drought that lasted for a relatively short period (two months) ended. A return to the base scenario (S0) appears to be a reasonable decision. In month 15 (ⓓ), S3 might be reasonable for the preparation of a possible drought owing to the significant reduction in rainfall. The rationale for the change to S3 in month 32 (ⓔ) is similar to ⓑ.

As operational records accumulate, the methodology presented here can be adjusted and modified. Such issues will be dealt with elsewhere. Last but not least, it is worth mentioning that our approach is suitable for application to data-scarce regions, since sand dams are typically built in rural or ungaged areas.

5. Conclusions

In the era of climate change, drought-prone areas, such as mountain regions where modern water facilities are not available, could suffer from chronic water shortages. To establish practical alternatives to overcome water shortage problems, this study proposed a methodology for the conjunctive use of a sand dam and groundwater well under various drought conditions. It employed a scenario-based approach in which the water allocation ratios between sources varied with the drought frequency. Simulations were carried out to determine whether the target water demand could be met under various drought conditions. The results revealed that the effect of the conjunctive operation began to appear in droughts for more than 5-year frequency in terms of water supply reliability. With detailed simulation results for various scenarios, decisions can be made for the monthly operation of the combined surface/subsurface water supply system.

According to our analysis, the system could achieve 83.3–100% water supply reliability through conjunctive use, even in the extreme case of a 50-year drought lasting an entire year. A higher water demand generally led to lower reliability, and the increased supply from the groundwater made the system more robust. Through an illustrative operation, it was shown that flexible application of scenarios can be achieved based on simulation results and practical guidelines concerning environmental impacts.

The methodology proposed here is not limited to a combination of a sand dam and a groundwater well. Other types of water resources can be conjunctively used by adopting this drought scenario-based method. As hydrologic and operational data accumulate, the system can evolve towards real-time operation. Fluctuations in demand, inflow, or groundwater level can be considered, which will make the use of valuable water resources more flexible.

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