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A Strategy to Quantify Water Supply of an Agricultural Reservoir for Integrated Water Management Policy

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Abstract: A data-driven approach is required to scientifically manage agricultural water resources in accordance with the integrated water management policy of South Korea. In this study, a quantification strategy is presented to calculate reservoir supply by comparing the results with the actual reservoir water storage. Strategies considering current calculation methods were divided into canal flow measurement (S1), theoretical flow rate (S2), water storage decrease in field practice (S3), and water demand in design practice (S4), utilizing water levels of the reservoir and its canal and the level–flow rate curve obtained from surveying the canal flow. Each strategy was assessed through hydrological verification of reservoir water balance modeling. Based on the determination coefficient (R^2), Nash–Sutcliffe efficiency (NSE), and relative error (RE) values, the S1 method was found to be the most suitable. S2 had lower reliability than S1, while S3 and S4 satisfied neither R^2 nor NSE and had a larger RE than S1 and S2. To accurately quantify agricultural water supplies, the importance of directly measuring reservoir canal flows must be emphasized using automatic water level and flow gauges in canals. This study provides insights into more scientific management of agricultural reservoir water supplies and more effective monitoring of agricultural water usage.

Keywords: agricultural water reservoir management; agricultural water monitoring; irrigation facility; data-driven water supply; water quantification strategy

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1. Introduction

On a global scale, agricultural water accounts for 70% of the total water withdrawal and more than 90% of total consumption [1,2]. The Water Environment Federation (WEF) [3] predicts that the demand for agricultural water in 2030 will increase by more than 40% over that in 2011, considering current population trends. It has been predicted that the shortage of water resources will intensify in the future, owing to spatiotemporal fluctuations in the available water resources resulting from climate change. Therefore, accurate monitoring of agricultural water supplies is essential for effective resource management.

Flow monitoring is crucial in the design, operation, management, and modeling of water infrastructure [4]. Currently, there are more than 13,000 monitors in the USA and 817 in South Korean rivers. Other countries, including Japan, Germany, and China, are utilizing real-time monitoring to automate flow measurements [5]; automatic alarm systems are being used to monitor river water levels [6]. This flow data can provide useful insights for regulating water use as well as enable sustainable water management in local watersheds [7].

The agricultural water supply in South Korea is highly dependent on reservoir systems [8]. In South Korea, agricultural, agricultural water accounts for 61% of the total water resources of 25.1 billion m^3 (BCM), excluding river maintenance water at 12.1 BCM [9]. Notably, 17,401 agricultural reservoirs are included in the water supply infrastructure of the country, supplying 75% of the total agricultural water, with a total effective storage capacity of 3.1 BCM [10,11]. However, most reservoir systems do not monitor the amounts of water supplied; the importance of such quantification has not been recognized because agricultural water in South Korea is a free public resource. However, water usage data play an important role in water resource management at the watershed scale. Therefore, to address future water scarcity, efficient plans must be established based on the latest accurate information [12].

Currently, information regarding agricultural water usage in South Korea is lacking. Although previous studies have analyzed it in a few areas, those that have quantified agricultural water in the context of reservoir management are limited. Lee et al. [13] analyzed the water supply for the irrigation of rice paddies and estimated the demand for rice-growing seasons using a demand calculation method. Kim et al. [14] reviewed the adequacy of evapotranspiration calculations by comparing methods used to calculate the water demand and supply. Shin et al. [15] evaluated the water supply efficiency in downstream irrigation areas based on onsite supply records but used simulations to estimate the reservoir supply. The Korea Water Resources Corporation [16] analyzed problems in calculating the demand for agricultural water and suggested an improvement plan. Notably, the amount supplied by agricultural reservoirs is markedly different from the amount required for each rice-growing season. In a study conducted by Kim et al. [17], the factors related to agricultural water resources depended on the model estimates rather than on direct observations. Reportedly, the amounts of agricultural water supplied have been estimated using calculation methods and not actual quantities supplied. Owing to the differences in the calculation methods used by the design and field departments, it is difficult to accurately verify reservoir supplies, presenting formidable challenges to completing water management tasks.

With the implementation of a national integrated water management policy for South Korea, interest in the water usage of the agricultural sector, which is known to constitute a large fraction of total water usage, is growing. To date, only reservoir level data have been used for water management. In the past, water managers have directly observed and recorded water levels on site. However, currently, automatic level gauges are used to monitor agricultural reservoirs [18]. This system was introduced to assess real-time reservoir supplies and is being used nationwide to inform water management [19,20]. However, there are limitations to this practice. Conventional calculation methods have been used that assume that the supply of agricultural water is consistent with the demand for planning at the national level. Another management practice among in the field involves calculating water storage using reservoir level data. However, the results of the demand formula and the indirect methods used to calculate reservoir storage reductions differ from actual supplies, leading to confusion regarding which information should be used for sustainable management.

To respond to changes in the water management environment due to the fact of climate change, scientific and informatic analyses of the agricultural water supplies are being developed [21]. As an integrated water management policy is implemented, data-driven approaches are required to assess the reliability of the current calculations of supplies through comparison with actual supplies. However, owing to a lack of measurements of the agricultural water supply in South Korea, an official calculation method has yet to be established for the reservoir system. The purpose of this study was to assess the reliability of four current calculation methods by comparing changes in the reservoir storage between the calculated and the observed values, based on a reservoir water balance analysis. The current calculation strategies are canal flow measurement (S1), theoretical flow rate (S2), water storage decreases in field practice (S3), and water demand in design practice (S4).

2. Materials and Methods

2.1. Study Area

This study focused on a reservoir with a simple supply system: Jangan Reservoir, located in Jangan-dong, Seo-gu, Daejeon Metropolitan City, in central South Korea (127°07′ E, 35°00′ N). Figure 1 shows a satellite photo of the reservoir and irrigation canal. The reservoir was built in 1993 to supply downstream agricultural water.

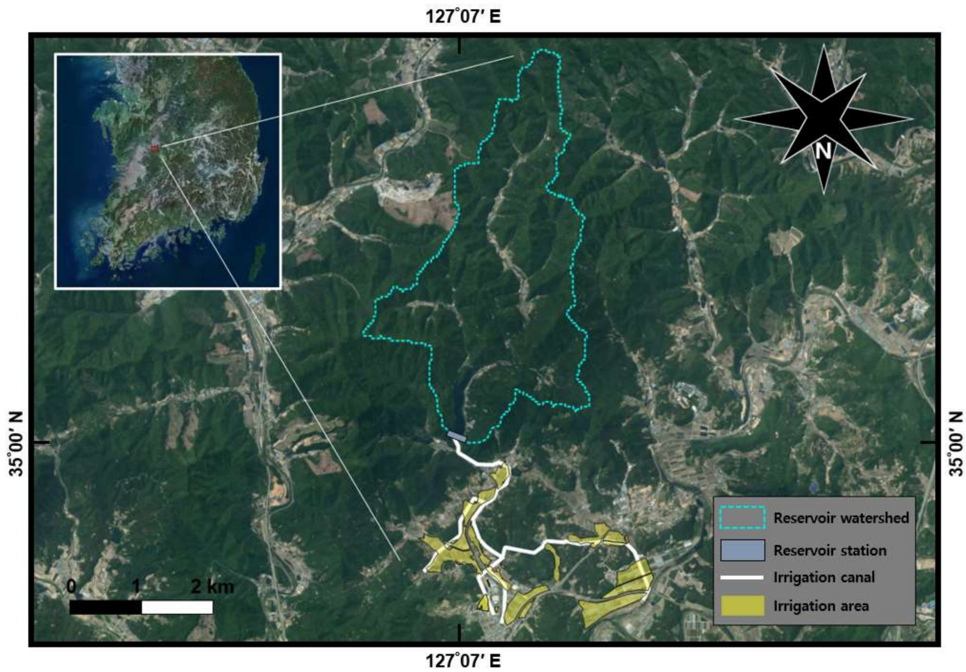

Figure 1. Jangan Reservoir study area showing the irrigation area and watershed.

Jangan Reservoir has a storage capacity of 1015 thousand m^3, with the watershed area being 8.8 times larger than the irrigation area. The reservoir's water is supplied through a single canal that supplies to the downstream irrigation area of 88.7 ha. Its water level is continuously and automatically monitored using a gauge installed at the starting point of the irrigation canal. Therefore, there are high-quality hydrological data available for evaluating the reservoir supply. For the 30 year period 1991–2020, the average annual rainfall was 1351.2 mm, with annual rainfall of 55%–60% concentrated in summer. The average annual temperature was 13.1 °C, average high temperature was 18.5 °C, average low temperature was 8.4 °C, average annual humidity was 67.9%, and the average annual wind speed was 1.7 m/s.

2.2. Hydrological Data and Flow Monitoring

Hydrological and meteorological data along with field instrumentation were used to estimate the agricultural water supply via the four methods described above. The water level data included that of the reservoir and irrigation canal; both types were obtained in real time from an automatic gauge measuring at 10 min intervals. The irrigation canal is an open concrete channel connected to the reservoir. and an ultrasonic water level gauge is present at the starting point of the canal to monitor the water discharged from the reservoir. The canal water level was monitored starting in 2018, providing data from the Korea Rural Community Corporation for a 3 year period from 2018 to 2020.

To evaluate the reliability of the reservoir supply calculations, a hydrological analysis was carried out using meteorological data collected from the Weather Data Opening Portal [22] at the Daejeon weather station, the closest station to the study area. The elevation–storage curve for converting water level data into the stored water amount, as well as the inflow information, were provided by the Korea Rural Community Corporation [23]. Figure 2 shows a flow chart and field imagery of the agricultural reservoir embankment, including the water level station, water supply control station, and water level in the irrigation canal station. The reservoir level gauge is located upstream of the reservoir embankment, and the irrigation canal level gauge is located downstream of the reservoir embankment. The supply control system is located directly below the reservoir embankment. The flow monitoring point is located between the water supply control station and the irrigation canal water level station. A flow survey was performed on the water supply of the reservoir at the starting point of the irrigation canal. In this process, field surveys were conducted in compliance with the guidelines presented by the United States Geological Survey [24]. From April 2019 to October 2020, a total 16 measurements of canal flow were acquired for calculating the actual water supply.

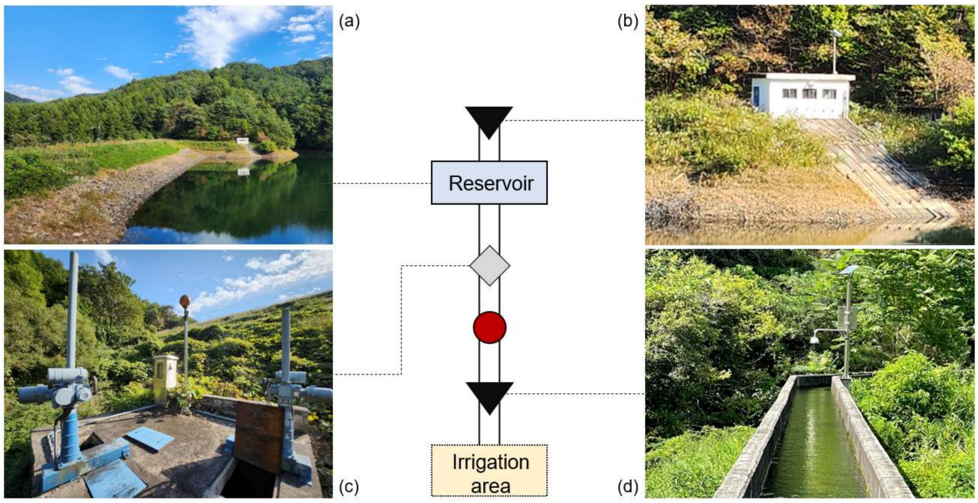

Figure 2. Flow chart and field photographs showing the (**a**) reservoir embankment; (**b**) reservoir water level station; (**c**) water supply control station; (**d**) irrigation canal water level station. The red circle indicates the flow monitoring point; The black triangle indicates the water level monitoring point.

2.3. Strategies for Quantification of the Reservoir Water Supply

As shown in Table 1, the reservoir supply calculations were divided into four strategies (S1–S4) based on the presence or absence of reservoir and irrigation canal monitoring data. Strategy 1 (S1) is applied to the reservoir's condition and secures the water level data of the reservoir, level data, and the flow monitoring of the canal. It tends to be used when both reservoir level and flow data are available. Both reservoir and canal level gauges have been installed, and canal flow monitoring is being performed. Strategy 2 (S2) is used when water level gauges in reservoirs and canals have been installed but flow rate monitoring is not available. It tends to be used when only reservoir and canal water level data are available. For a station where the flow is not measured, flows are estimated by a theoretical velocity formula. Strategy 3 (S3) is applied to reservoir conditions in which only reservoir level gauges are present, whereas canal level monitoring is not available. This is usually employed in the field to quickly calculate current or past water supplies. Strategy 4 (S4) is applied when neither water level nor flow data are available. This is typically only employed by designers because there can be no historical data. Using this strategy, agricultural reservoirs in Korea are designed for the purpose of supplying water for rice paddies, and the calculated demand is used as the supply.

Table 1. Strategies for quantification of reservoir supplies as a function of reservoir and canal data availability.

Strategy	Reservoir	Canal	
	Water Level	Water Level	Flow
S1	O	O	O
S2	O	O	X
S3	O	X	X
S4	X	X	X

O, available; X, unavailable data.

In S1, both the level and flow data were measured at the canal to allow analysis of the water level–flow relationship in the canal [25]. For the reservoir supply, the level–flow relationship was calculated (Equation (1)) using an exponential relationship:

$$Q_{s1} = a(H - z)^b \times 86{,}400, \quad (1)$$

where Q_{s1} is the water supply for strategy 1 (m^3/day); H is the level in the canal (m); z is the water level when the flow is zero (m); and a and b are local constants.

In S2, the canal flow was estimated using a theoretical flow rate formula, suitable for cases in which level data are available but canal flow data are not. The flow was calculated using the Manning formula (Equation (2)) [26]; a roughness coefficient of 0.017 was applied for the concrete canal (rough wood formwork) based on the agricultural infrastructure improvement project plan [27]. The height and width of the canal were reflected as 70 cm and 80 cm, respectively. In addition, the canal slope was 1/1000 based on a field survey. The cross-sectional area and hydraulic radius were calculated by considering water level data of the canal:

$$Q_{s2} = A \times V \times 86{,}400 = A \times \left({}^{1}\!/_{n} \times R^{2/3} \times S^{1/2} \right) \times 86{,}400, \quad (2)$$

where Q_{s2} is water supply for strategy 2 (m^3/day); A is the cross-sectional area in canal flow (m^2); V is the average velocity (m/s); n is the roughness coefficient, R is the hydraulic radius (m); and S is the canal slope (m/m).

In S3, reservoir water level data were used without using the level or flow data of the canal. The decrease in the amount of water stored in the reservoir, or the difference in the water level between the previous and present days, was used as the supply and calculated by Equation (3). Notably, if this difference in storage had a negative value, it assumed no supply:

$$Q_{s3} = WS_{t-1} - WS_t, \quad (3)$$

where Q_{s3} is water supply for strategy 3 (m^3/day); WS_t and WS_{t-1} are the water storage in the reservoir (m^3) on days t and $t-1$, respectively.

In S4, the water demand of the reservoir was estimated from the design criteria and past meteorological data; this value was used as the supply. This strategy is used for reservoirs and associated canals for which monitoring data are not available. In this method, the required quantity for the irrigation of rice paddies was calculated by applying values of evapotranspiration, infiltration, and rainfall calculated using Equation (4) [14,28]. Here, the parameters at the time of the reservoir's design were used. The infiltration depth was 6.5 mm, and the ponding depth was 80 mm:

$$Q_{s4} = IA \times IW_t/100 = IA \times (PD_t - PD_{t-1} + I_t + ET_t - PR_t)/100, \quad (4)$$

where Q_{s4} is water supply for strategy 4 (m^3/day); IA is the irrigation area (m^2); IW_t is the required irrigation depth (mm); PD_t and PD_{t-1} are the ponding depths in the paddy field on days t and $t-1$ (mm), respectively; I is infiltration (mm); ET is evapotranspiration (mm); and PR is rainfall in the paddy field (mm).

2.4. Assessment Using Hydrological Verification Methods

The reservoir supply is the quantity supplied from the reservoir to the irrigation area through canals. In this study, a hydrological analysis of the reservoir was performed by calculating its supply using methods S1–S4, then the differences between reservoir water storage were analyzed. The hydrological factors of the reservoir were calculated by simplifying Equation (5) [29,30]:

$$\frac{dS}{dt} = RI + P - E - Q, \quad (5)$$

where dS/dt is the variation of the water storage in the reservoir on day t; RI is the reservoir inflow; P and E are the rainfall and evaporation in the reservoir, respectively; and Q is the reservoir outflow estimated by four supply calculation strategies. All units were in m^3/day.

Next, the supply calculated using the hydrological method, based on the water balance of the reservoir, was compared with the observed values. The reliability of the method used to estimate the agricultural water supply for each strategy was also assessed. The coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), and relative error (RE) were used as indicators to evaluate the comparisons [31]. Ramanarayanan et al. [32] suggested that a model simulates the natural phenomenon being modeled more accurately when $R^2 \geq 0.5$ and NSE ≥ 0.4 [33–35]. An RE closer to 0 indicates a satisfactory agreement. Each water supply calculation strategy was assessed, as shown in Equations (6)–(8):

$$R^2 = \left(\frac{\sum(O - \overline{O})(S - \overline{S})}{\sqrt{\sum(O - \overline{O})^2} \sqrt{\sum(S - \overline{S})^2}} \right)^2, \quad (6)$$

$$NSE = 1 - \frac{\sum(O - S)^2}{\sum(O - \overline{O})^2}, \quad (7)$$

$$RE(\%) = \frac{(\overline{O} - \overline{S})}{\overline{O}} \times 100, \quad (8)$$

where O and S are the observed and estimated reservoir storage values, respectively; $\overline{O}$ and $\overline{S}$ are the average observed and estimated reservoir storage values, respectively.

3. Results

3.1. Characteristics of the Water Level Monitoring in Reservoirs and Canals

Real-time level data for the reservoir and canal were used to analyze the water supply characteristics of the reservoir. Figure 3 shows water level data for the reservoir and canal levels from April to October for the years 2018–2020. The start and end periods of the supply were estimated from the reservoir level data. The initial time of the supply was the beginning of the decrease in the reservoir level: 16 May 2018, 9 May 2019, and 6 May 2020. The ending time of the supply was the point at which the reservoir level increased after the irrigation period: 26 August 2018, 20 September 2019, and 2 September 2020. A general pattern was identified in which the levels decreased between May and September but were restored during other periods. It was inferred that the water was being supplied when the reservoir water level decreases, and the water supply is stopped when the reservoir water level increases during the irrigation period.

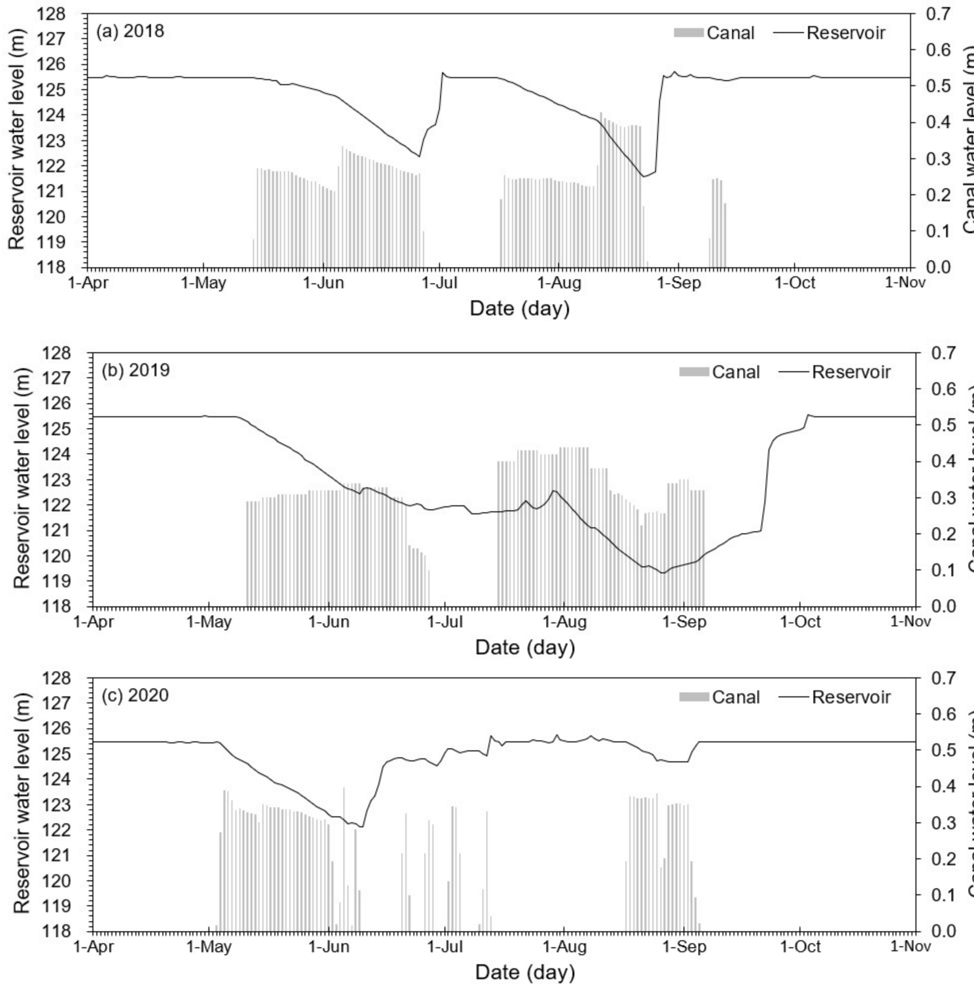

Figure 3. Water levels in the reservoir and canal for (**a**) 2018; (**b**) 2019; and (**c**) 2020.

From the canal data, the supply began on 14 May 2018, 11 May 2019, and 3 May 2020. The supply ended on 13 August 2018, 6 August 2019, and 5 September 2020. During these periods, water was supplied while maintaining the level data between 37.5%–53.8% of the canal height. The reservoir supply was controlled between two and six times based on the canal levels data. The number of days of the water supply was 89 in 2018, 102 in 2019, and 72 in 2020. Using the reservoir level data during irrigation, it can be estimated whether the water supply was consistent by the decrease in the reservoir level. There were limitations in determining whether the water was supplied from the reservoir using only reservoir level data. In contrast, the canal level data provided useful information regarding the reservoir supply.

3.2. Comparison of Water Level–Flow Relationships Based on Canal Flow Surveys

A canal flow survey was conducted 16 times from 2018 to 2019, at the point in the canal where the water level was measured automatically. Table 2 shows observations from the canal flow survey and the flow estimates calculated using Equation (2) in the absence of a canal flow survey. The flow survey was conducted in the section where the water level in the canal was 0.06–0.34 m, and the observed value was 0.003–0.173 m^3/s. At the same water level, the average error between the observed value and that estimated value was 0.019 m^3/s. Notably, the estimated flow value was at least 0.9 times and up to 4.0 times larger than the observed values, with the average value being 1.6 times larger than the observed value.

Table 2. Observed values by surveying the canal flow and the flow estimates calculated using the Manning formula.

No.	Water Level (m)	Observed Flow (m^3/s)	Estimated Flow (m^3/s)	Difference	No.	Water Level (m)	Observed Flow (m^3/s)	Estimated Flow (m^3/s)	Difference
1	0.180	0.033	0.067	−0.034	9	0.300	0.124	0.138	−0.014
2	0.210	0.046	0.083	−0.037	10	0.310	0.134	0.144	−0.010
3	0.220	0.055	0.089	−0.034	11	0.320	0.150	0.151	−0.001
4	0.230	0.055	0.095	−0.040	12	0.330	0.169	0.157	0.012
5	0.240	0.064	0.101	−0.037	13	0.340	0.173	0.164	0.009
6	0.265	0.092	0.116	−0.024	14	0.310	0.128	0.144	−0.016
7	0.280	0.104	0.125	−0.021	15	0.130	0.015	0.041	−0.026
8	0.290	0.112	0.131	−0.019	16	0.060	0.003	0.012	−0.009

Figure 4 illustrates a comparison of the observed and estimated flow values, based on whether the flow was measured in the canal. The white circles denote the actual flow values; the water level–flow relationship equation was calculated using the following equation:

$$Q = 2.1043 \times \mathrm{H}^{\,2.3814}. \tag{9}$$

The black points denote the unmeasured flow values calculated using Equation (2); the water level–flow relationship was calculated using the following equation:

$$Q = 0.8198 \times \mathrm{H}^{1.4764}. \tag{10}$$

In the water level–flow relationship, when the water level was below 0.35 m, the estimated flow value was higher than the observed flow value; above 0.35 m, the converse trend was apparent. At a water level of 0.15 m, the observed and the estimated value showed the greatest disparity.

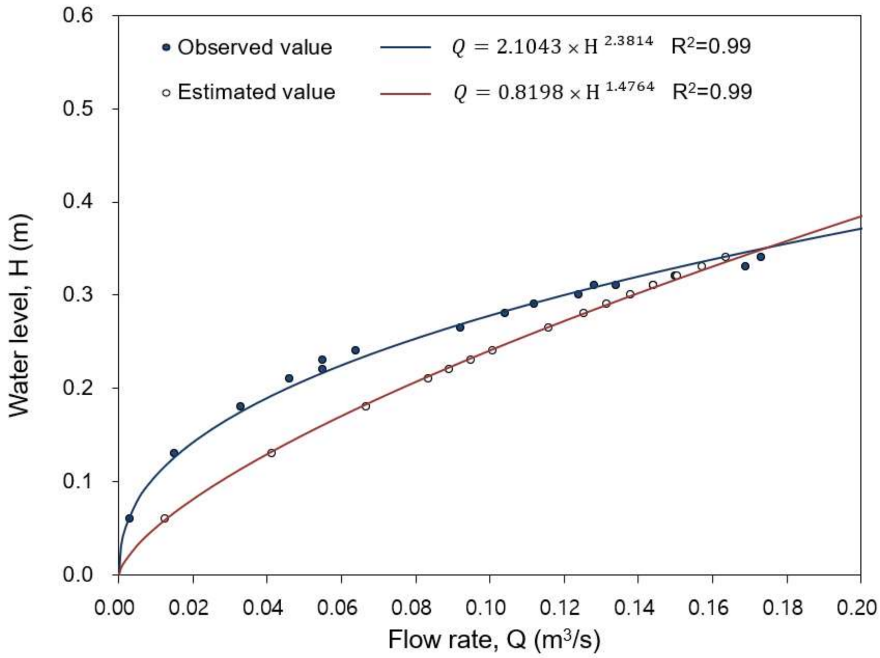

Figure 4. Comparison of observed and estimated flow values based on whether the flow was measured in the canal.

3.3. Comparison of Reservoir Supply Calculation Methods

The four supply calculation strategies were analyzed to determine the reservoir supply: canal flow measurement (S1), theoretical flow rate (S2), water storage decrease method (S3), and water demand design method (S4). Table 3 provides a comparison of the monthly agricultural water supply calculated for the three years 2018–2020. For S1, the reservoir supply, calculated using the canal flow measurement, was 758,000 m^3 in 2018; 1,425,000 m^3 in 2019; and 753,000 m^3 in 2020. For S2, the amount of the reservoir supply calculated using the theoretical flow rate increased 35.0% in 2018, 11.2% in 2019, and 19.6% in 2020; compared with the flow measurement values derived using S1, all of the values by S2 were overestimated. It was noted that the estimated flow rate was higher than the observed flow at the same water level, indicating that the overall supply was high. For S3, the value calculated using the decreased information on the reservoir level was 2.3% in 2018, −43.7% in 2019, and 6.0% in 2020; thus, all were overestimated except for the 2019 value. When the fluctuation of the reservoir level due to the fact of rainfall was not large in 2019, supplies calculated using only the reservoir water level data were small. For S4, the values determined based on the design method was 27.4% in 2018, −42.2% in 2019, and −36.3% in 2020; compared to the results obtained using S1, the value for 2018 was overestimated. In this case, since the required quantity was calculated based on meteorological data, a relatively large error occurred compared to other strategies.

Table 3. Monthly agricultural water supply calculated for 2018–2020.

Year	Strategy	Agricultural Water Supply (10^3 m^3)								Difference from S1 (%)
		April	May	June	July	August	September	October	Sum	
2018	S1	0	123	230	93	290	22	0	758	-
	S2	0	187	319	150	330	39	0	1024	+35.0
	S3	18	123	230	93	290	22	0	776	+2.3
	S4	10	61	313	239	338	5	0	965	+27.4
2019	S1	0	229	270	390	458	78	0	1425	-
	S2	0	292	342	360	497	92	0	1584	+11.2
	S3	6	239	188	63	279	0	27	802	−43.7
	S4	9	63	282	159	269	43	0	824	−42.2
2020	S1	0	372	89	49	208	34	0	753	-
	S2	0	435	124	65	232	43	0	900	+19.6
	S3	22	303	114	134	198	26	0	798	+6.0
	S4	11	80	220	42	122	4	0	480	−36.3

Figure 5 depicts a time-series comparison of the daily agricultural water supply determined according to each reservoir supply calculation strategy. The results obtained by the measured (S1) and theoretical flow rate (S2) methods showed significant differences, but with similar patterns. For S3, there were several issues in the estimation of water supply by field water managers. First, it was estimated that water supply occurred even though the actual water supply was stopped. In addition, for 2020, the estimated supply was double the actual value. For S4, the calculated amount based on the water demand design value was smaller than that determined by measurement (S1), except for part of 2018. Further, with S4, it was estimated that the water supply existed even during the midsummer drainage or when the water supply did not occur.

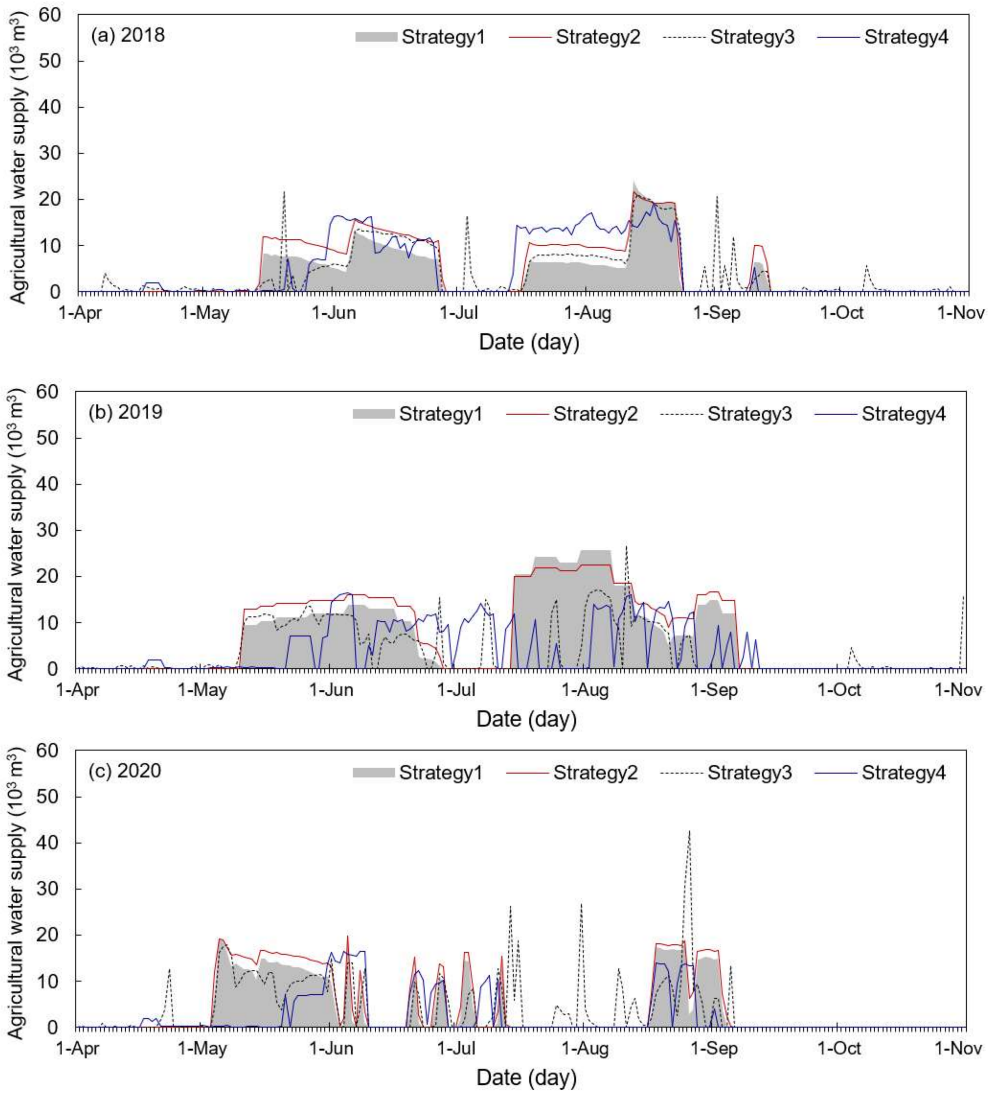

Figure 5. Time-series comparison of flow values determined using strategies S1–S4 for (**a**) 2018; (**b**) 2019; and (**c**) 2020.

3.4. Reliability of Reservoir Supply Calculation Strategies

Based on reservoir storage behavior analysis, the reliability was estimated by applying the supply calculation strategy. Figure 6 depicts the changes in the amount of water stored in Jangan Reservoir from 2018 to 2020, calculated by applying methods S1–S4. Among these, the canal flow measurement strategy (S1) had the best agreement with the actual reservoir storage behavior. The S3 (storage reduction) and S4 (water demand) strategies tended to overestimate the actual water storage in 2019 and 2020, whereas the S2 (theoretical flow rate) strategy underestimated the actual water storage. Based on the observed values, the average of annual maximum errors was calculated as 159,400 m^3 for S1, 239,800 m^3 for S2, 326,500 m^3 for S3, and 408,400 m^3 for S4. S1 and S2 showed different changes in reservoir behavior according to the level–flow relationship between the observed and estimated values in the canal. In the case of 2019, with low water storage, S3 and S4 showed a similar trend from mid-July. However, in the case of 2020, with high water storage, the error only increased in the case of S4.

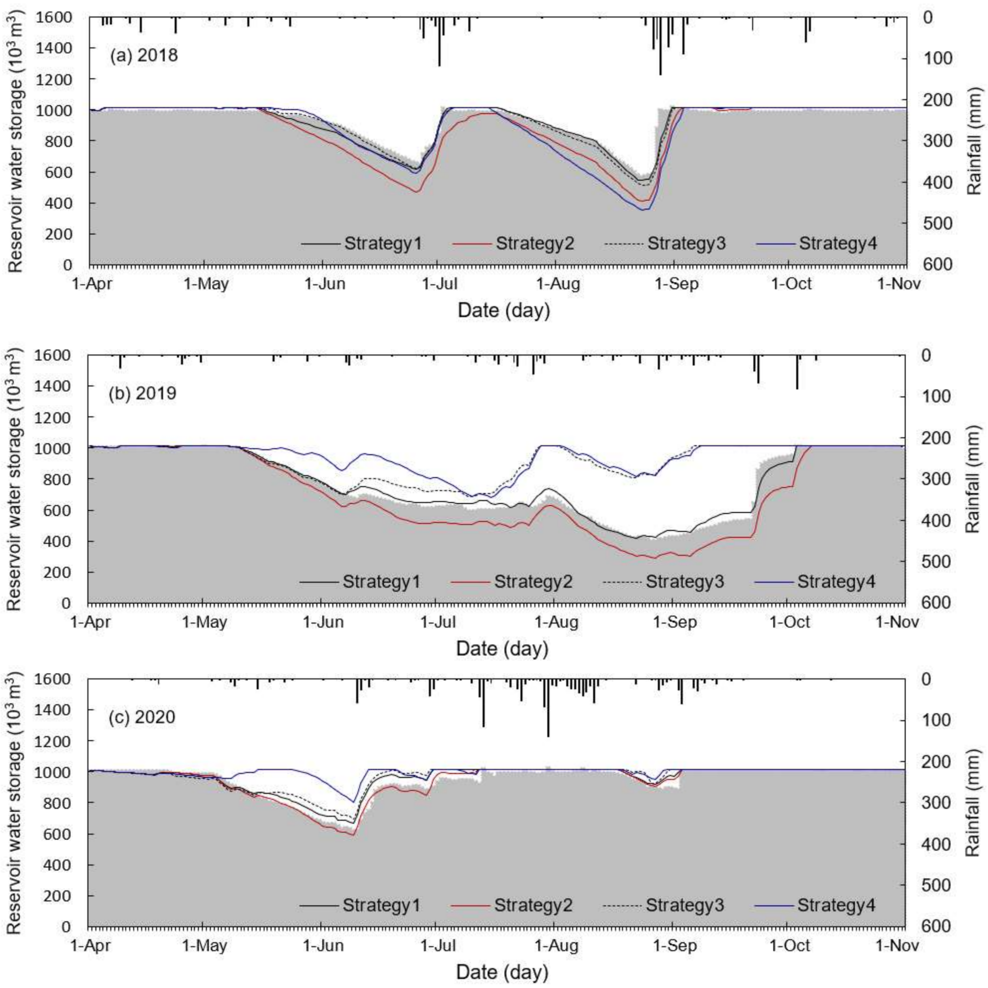

Figure 6. Changes in the reservoir water storage using strategies S1–S4 for (**a**) 2018; (**b**) 2019; and (**c**) 2020. The gray shading indicates the observed storage volumes.

Table 4 lists the quantitative assessment indicators for the four strategies (S1–S4). Each calculation method compared the results of the quantitative assessment indicator calculations by year; for S1, R^2 = 0.95, NSE = 0.91, and RE = −1.21%. For S2, R^2 = 0.95, NSE = 0.86, and RE = 4.52%. For S3, R^2 = 0.68, NSE = 0.32, and RE = −7.48%. For S4, R^2 = 0.55, NSE = −0.03, and RE = −8.47%. For the R2 index, it was determined that both S1 and S2 were satisfied according to the evaluation criteria presented by Ramanarayanan et al. [32]. However, the strategies (S1 and S2) using the available information on the canal were more reliable than the strategies (S3 and S4) using the unavailable information on the canal; thus, they were considered to be suitable for estimating the reservoir supply. In the case of the NSE indicator, both of the evaluation criteria for S1 and S2 were satisfied, but S3 and S4 were not satisfied. Strategy S1, which uses both water level and flow in the canal, showed the greatest difference relative to strategy S4, without data available. With respect to the RE index, that for S1 had the least deviation, those for S2, S3, and S4 had increasingly larger deviations, in that order. A major challenge for quantifying reservoir supplies is to simultaneously measure water flows and levels in associated canals.

Table 4. Quantitative assessment indicators for the four calculation strategies.

Strategy	Period	R^2	NSE	RE (%)
S1	2018	0.94	0.93	0.07
	2019	0.99	0.98	−1.50
	2020	0.91	0.82	−2.20
	Average:	0.95	0.91	−1.21
S2	2018	0.91	0.74	5.41
	2019	0.97	0.89	8.51
	2020	0.96	0.96	−0.37
	Average:	0.95	0.86	4.52
S3	2018	0.95	0.93	−0.11
	2019	0.26	−0.57	−19.48
	2020	0.84	0.61	−2.86
	Average:	0.68	0.32	−7.48
S4	2018	0.87	0.25	3.67
	2019	0.34	−0.39	−23.5
	2020	0.43	0.06	−5.59
	Average:	0.55	−0.03	−8.47

4. Discussion

In this study, when only reservoir level data were used, it could not be ascertained whether the water supply was originating from the reservoir itself. However, using canal level data with flow survey (strategy S1) was the most effective for quantifying the reservoir supply. Nhu et al. [36] evaluated the causes of decreased reservoir levels using satellite imaging and a global-positioning-based method. Water resource management using imaging is effective for understanding long-term trends; however, it has limitations when used for quantifying water supplies in real time. Therefore, automatic water level monitoring is important. Choi et al. [37] examined the efficient use of agricultural water by analyzing the actual water supply characteristics of main canals. In particular, monitoring canal levels plays an important role in confirming whether the water has been supplied to the reservoir. The canal level data provided more useful information than reservoir level data. However, there may be uncertainties in the evaluations of supplies based on the water balance of the reservoir using reservoir and canal data. Reservoir water storage was affected by sedimentation, and the change in reservoir volume was causing uncertainty in supply evaluation results [38,39].

A major challenge in water management is monitoring water levels and flows [40]. In South Korea, agricultural water supplies are not necessarily monitored; therefore, data have only been reported in a few studies [41,42]. In this study, the actual supply in Jangan Reservoir was calculated based on canal flow measurement, which was compared with the calculations using the theoretical flow, S2. As S2 depends on the Manning formula, the calculation was based on the roughness coefficient, the resistance to flow in the canal; this is a function of the canal wall material in contact with the water affects the roughness coefficient [43,44]. Choi et al. [45] reported that the roughness coefficients varied for different canals. In this case, the canal material was concrete; therefore, the roughness coefficient applied was 0.017, from the canal design criteria [27]. However, the calculated supply was different from the actual supply. The average velocity formula for estimating the flow rate has often been used in the absence of measured flow data. This study revealed a limit to quantifying reservoir supplies using the Manning formula.

In practice, when calculating supply using the S3 method, based on the decrease in the reservoir level, water managers use the daily volume change information in storage from the previous day and the current day. Currently, this is the customary and simplest way to calculate reservoir supplies. Bonnema and Hossain [46] used satellite data to estimate reservoir volume changes and analyzed the reliability of its discharge volume. In contrast to this study, they compared modeled instead of measured values. Furthermore, it is known that reservoir water volumes continuously fluctuate as a function of inflow and outflow [47]. Additionally, the supply calculated as the reduction in the amount of stored water in the reservoir was smaller than that calculated from the canal flow measurement. This phenomenon is similar to that reported by Lee et al. in which the reservoir water supply followed while the water inflow to the reservoir continued [48].

With the establishment of a national water management plan for South Korea, the amount of agricultural water has been assumed to be equal to the demand for it. In this study, S4 was used for estimating the demand for paddy cultivation based on the design method; its output varied depending on meteorological data, cropping time, and amount of infiltration [49]. Park et al. [28] suggested a large disparity in calculation methods for the ponding depth and evapotranspiration used in most studies. Kang et al. [50] reported that supply varied with regional water management characteristics. Kim et al. [51] reported that irrigated areas were oversupplied based on the required water demand; their results were similar to those of this study. The design method artificially calculated the water supplied from the reservoir, considering rainfall. Therefore, it can be deduced that there were limitations arising from quantifying the reservoir water supply using the similar methods to calculate the water demand. There were limitations to applying the same value to estimate the agricultural water demand in the regions where agricultural water use had not been surveyed [52].

Water supplies are significantly affected by climate; however, in terms of managing the water demand, the use of policies are more important. Water usage information is important for decision makers to develop viable and effective future water management plans. Currently, agricultural water supplies are calculated using multiple methods, making scientific management difficult. Here, supply calculation based on canal flow survey (S1) best reflected observed changes in reservoir storage; this suggests that water management policies based on canal level and/or flow monitoring should be expanded to improve agricultural reservoir water management.

5. Conclusions

As an integrated water management policy is being implemented in Korea, it is attracting attention in the context of developing data-driven, sustainable agricultural water management. However, agricultural water supplies from reservoirs are calculated by multiple methods in terms of field and design, which can cause distortion in quantifying both used and available water. In this study, according to the use of the available data on the reservoir and the canal, four supply calculation strategies were assessed. Each was evaluated through hydrological verification of the water balance of the reservoir, utilizing the water levels of the reservoir and its canal and the water level flow curve obtained from canal flow data. Upon comparison with the findings of the reservoir water balance analysis based on measurement data, the analysis suggested that using the rating curve obtained through the flow survey of the canal (S1) was the most suitable, comparing the results of the condition without water level and flow. The supply estimate calculated using the Manning formula for unmeasured canal flow (S2) was less reliable than that obtained using the actual water level–flow relationship derived from the canal flow data. Moreover, the water storage decrease method used by field water manager (S3) had limitations in that the inflow was continuously reflected, even in situations in which reservoir water was being supplied. The method used to estimate the water demand by applying a design value (S4) did not reflect midsummer drainage accurately. These findings support the necessity of incorporating real-time canal flow measurements; they also suggest that it is desirable to install and use automatic water level and flow gauges in canals supplied from reservoirs to improve the reliability of reservoir supplies. This study verified the usefulness and limitations of the current reservoir supply calculation methods applied in South Korea from multiple aspects. The results of this study can be used not only for basic data for the scientific water management of agricultural water following the national integrated water management policy but also for planning more effective monitoring of agricultural water usage.

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