

A NOVEL APPROACH TO WATERSHED WATER BALANCE USING ADVANCED PADDY WATER METRICS

UNE NOUVELLE APPROCHE DU BILAN HYDRIQUE À L'ÉCHELLE DU BASSIN VERSANT AU MOYEN DE MÉTRIQUES HYDRIQUES AVANCÉES DES RIZIÈRES

Dong-Hyun Yoon¹, and Won-Ho Nam²

ABSTRACT

Quantifying agricultural water balance is essential for effective irrigation management and water policy design. In South Korea, however, national-scale assessments are often constrained by simplified assumptions, including fixed return-flow ratios, integrated treatment of reservoirs and river facilities, and omission of river water balance processes. This study presents a watershed-scale agricultural water balance framework that integrates individual hydraulic structures with river systems in rural water districts and applies updated paddy water requirements reflecting current cultivation practices. The framework was applied to the Anseongcheon mid-watershed and validated using 5-day streamflow observations at eight gauging sites, showing satisfactory performance ($R^2 \geq 0.81$, $NSE \geq 0.65$). Water balance components including supply rate, shortage characteristics, and return-flow ratio were evaluated across ten rural water districts over a 50-year simulation period (1975–2024). The estimated return-flow ratio ranged from approximately 20% to 60%, indicating substantial seasonal and inter-annual variability beyond conventional fixed-ratio assumptions. Results further showed that both facility-level supply-network representation and paddy water demand assumptions significantly influence watershed water balance outcomes. These findings suggest that incorporating distributed hydraulic structures and river-network connectivity can improve agricultural water balance assessment in managed irrigation systems. The proposed framework provides a practical and transferable approach for watershed-scale agricultural water management and may support improved drought response and irrigation planning under changing hydroclimatic conditions.

Keywords: Agricultural water balance; Paddy water requirement; Return-flow ratio; Rural water district; Watershed hydrology; Irrigation water management.

RÉSUMÉ

La quantification du bilan hydrique agricole est essentielle à une gestion efficace de l'irrigation et à la conception des politiques de l'eau. En Corée du Sud, toutefois, les évaluations à l'échelle nationale sont souvent limitées par des hypothèses simplificatrices, notamment l'emploi de rapports fixes de retour d'eau, le traitement intégré des réservoirs et des ouvrages fluviaux, ainsi que l'omission des processus de bilan hydrique des cours d'eau. Cette étude présente un cadre de bilan hydrique agricole à l'échelle du bassin versant qui intègre les ouvrages hydrauliques individuels aux réseaux fluviaux dans les districts hydrauliques ruraux et applique des besoins en eau des rizières actualisés afin de refléter les pratiques culturelles actuelles. Le cadre a été appliqué au sous-bassin versant d'Anseongcheon et validé à l'aide d'observations du débit à pas de cinq jours sur huit stations de jaugeage, avec des performances satisfaisantes ($R^2 \geq 0,81$; $NSE \geq 0,65$). Les composantes du bilan hydrique, notamment le taux d'approvisionnement, les caractéristiques des pénuries et le rapport de retour d'eau, ont été évaluées dans dix districts hydrauliques ruraux sur une période de simulation de 50 ans (1975–2024). Le rapport de retour d'eau estimé variait d'environ 20 % à 60 %, révélant une

1 Senior Researcher, National Agricultural Water Research Center, Hankyong National University, Republic of Korea, donghyun.yoon@hknu.ac.kr

2 Professor, School of Social Safety and Systems Engineering, National Agricultural Water Research Center, Hankyong National University, Republic of Korea, wonho.nam@hknu.ac.kr

variabilité saisonnière et interannuelle importante qui dépasse les hypothèses conventionnelles fondées sur un rapport fixe. Les résultats montrent également que la représentation du réseau d'approvisionnement à l'échelle des ouvrages et les hypothèses relatives à la demande en eau des rizières influent fortement sur les résultats du bilan hydrique du bassin versant. Ces constatations indiquent que la prise en compte des ouvrages hydrauliques distribués et de la connectivité du réseau fluvial peut améliorer l'évaluation du bilan hydrique agricole dans les systèmes d'irrigation aménagés. Le cadre proposé constitue une approche pratique et transférable de la gestion de l'eau agricole à l'échelle du bassin versant et peut contribuer à améliorer la réponse aux sécheresses et la planification de l'irrigation dans un contexte d'évolution des conditions hydroclimatiques.

Mots-clés : Bilan hydrique agricole; Besoins en eau des rizières; Rapport retour-débit; Périmètre hydraulique rural; Hydrologie des bassins versants; Gestion de l'eau d'irrigation.

INTRODUCTION

Agricultural water plays a critical role in maintaining food production and rural water security in South Korea. Approximately 42% of total national water consumption is used for agriculture, and nearly 80–85% of agricultural water demand is associated with paddy rice cultivation (Korea Ministry of Environment, 2021). Because paddy irrigation systems require continuous and seasonally concentrated water supply, accurate estimation of agricultural water balance is essential for irrigation planning, drought response, reservoir operation, and long-term water management policy. Despite its importance, quantifying agricultural water balance at the watershed scale remains difficult due to the structural complexity of agricultural irrigation systems. In South Korea, agricultural water is supplied through interconnected systems consisting of reservoirs, pumping stations, diversion weirs, canals, and river networks. In many rural watersheds, water is repeatedly reused through irrigation return flow and river recirculation processes, creating complex interactions between supply, demand, and downstream flow conditions. In addition, open-channel irrigation systems, limited field-scale measurement data, and spatially distributed water withdrawals introduce substantial uncertainty into agricultural water balance estimation (Nam et al., 2014).

Existing national-scale agricultural water balance analyses have commonly relied on simplified assumptions to address these limitations. For example, water balance assessments conducted under South Korea's National Water Management Master Plan using the MODSIM model have generally treated reservoirs and river facilities as a single integrated water source, excluded explicit river water balance processes, and applied a uniform irrigation return-flow ratio of 35% across all facilities (Kang et al., 2022). Although these simplifications improve computational efficiency at large scales, they may reduce the representativeness of watershed-scale agricultural water circulation. In particular, fixed return-flow assumptions may not adequately capture seasonal variability, watershed heterogeneity, or differences in irrigation-system operation among rural water districts.

Previous studies have attempted to improve components of agricultural water balance analysis through reservoir-network modeling, irrigation return-flow estimation, and watershed-scale agricultural water simulation (Kang and Park, 2014; Yoon et al., 2024). Kang and Park (2014) evaluated water flow dynamics in serial irrigation reservoir systems considering irrigation return flow and reservoir operation, while Song et al. (2020) investigated uncertainty in irrigation return-flow estimation using conceptual and physically based approaches. More recently, Yoon et al. (2024) developed an agricultural water balance analysis model for watershed applications. However, an integrated framework that simultaneously connects individual hydraulic facilities, distributed irrigation supply networks, and river water balance processes across a full mid-watershed system remains limited. Another important source of uncertainty involves irrigation water demand estimation itself. Conventional paddy water requirement calculations often rely on simplified assumptions regarding irrigation efficiency, conveyance losses, and cultivation practices. However, changes in rice cultivation methods, irrigation scheduling, and field management conditions may significantly influence actual agricultural water demand. Therefore, both supply-network representation and updated paddy water demand estimation should be considered simultaneously in watershed-scale water balance analysis.

This study presents a watershed-scale agricultural water balance analysis framework that integrates individual hydraulic structures with river systems within rural water districts. The framework constructs facility-level supply networks based on sub-watershed topology and incorporates updated paddy water requirements reflecting contemporary cultivation practices. The proposed approach was applied to the Anseongcheon mid-watershed in South Korea and evaluated using long-term streamflow observations. Through watershed-scale simulation and validation, this study aims to examine the influence of supply-network representation and irrigation demand assumptions on agricultural water balance estimation and to provide a more realistic framework for agricultural water management in complex irrigation watersheds.

DATA AND METHODS

Study Area and Datasets

The Anseongcheon mid-watershed covers approximately 1,659 km² across Gyeonggi and South Chungcheong provinces, encompassing ten rural water districts, four national rivers, and 99 local rivers. The watershed includes a mix of reservoir-dominated upper reaches and river-facility-dependent lower reaches, making it a suitable case study for an integrated analysis framework. A total of 158 reservoirs, 145 pump stations, and 91 weirs supply irrigation water to a field-survey-corrected irrigated area of 20,185 ha. Input data included spatial data such as DEM, land cover maps, and facility locations, along with daily meteorological records from three ASOS stations (Suwon, Icheon, Cheonan) covering 1975–2024, and facility specification data from the RAWRIS and RIMS national databases. Irrigated area data were refined through field surveys cross-referenced against aerial imagery and farm map records, yielding an adjusted total that differed from statistical records. Streamflow observations at eight gauging stations were used for model validation.

Spatial Framework and Network Construction

The model uses sub-watersheds delineated from the Korean Reach File (KRF) as the minimum spatial unit, resulting in 331 sub-watersheds across the study area. Within each sub-watershed, a node-based topological network is constructed linking reservoir nodes, river facility nodes, sub-watershed nodes, and outlet nodes. Facilities are classified as primary water sources (reservoirs) or secondary water sources (pump stations and weirs), reflecting the supplementary supply role of river facilities in Korean irrigation systems. The overall model structure is shown in Figure 1.

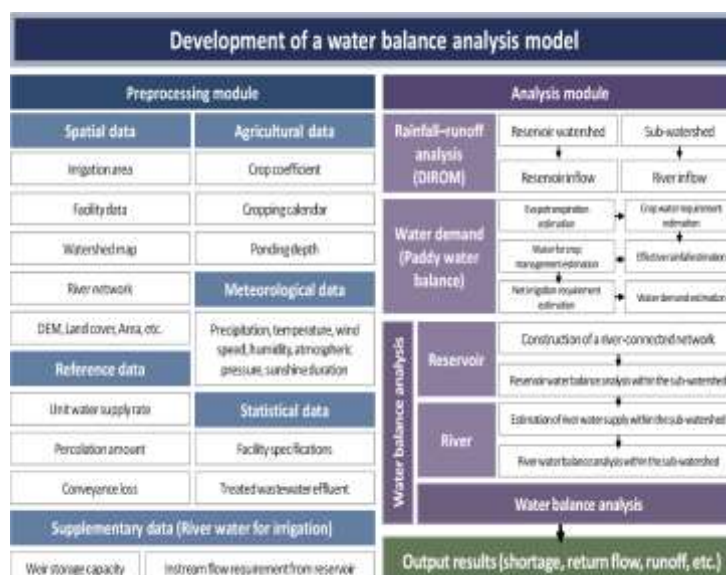


Figure 1. Integrated framework for watershed-scale agricultural water balance analysis

Water Demand and Inflow Estimation

Daily irrigation demand is estimated using a crop-calendar-based approach for transplanting cultivation, applying the Modified Penman equation for reference evapotranspiration and stage-specific crop coefficients. Effective rainfall is computed using the daily ponding depth tracking method ($D_{max} = 80$ mm, $D_{min} = 20$ mm). The nationally measured average unit water supply rate (1,618 mm/ha) is used as the total annual demand basis, distributed daily according to the net irrigation requirement pattern. This approach is intended to better reflect actual irrigation practice compared with theoretically derived demand formulations.

Sub-watershed inflow is simulated using the DIROM three-tank model (Figure 2), with parameters estimated from regression equations based on land-use ratios and watershed area (Table 1) (Lee et al., 2024; Yoon et al., 2024). This allows application to ungauged sub-watersheds without individual calibration, which is a practical requirement given the number of facilities involved.

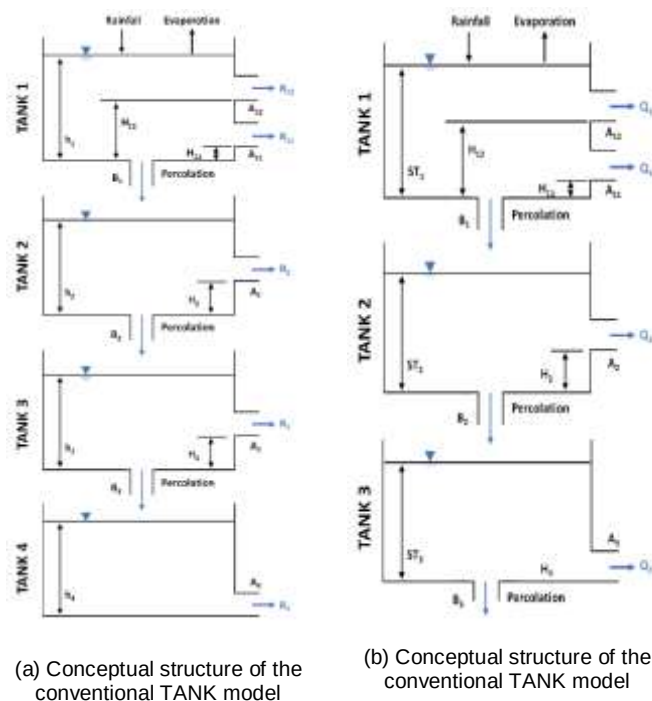


Figure 2. Comparison of the conventional TANK model and the modified DIROM structure

Table 1. DIROM parameter estimation equations and hydrological interpretations

Parameter	Estimation equation	Hydrological interpretation
A11	$-0.00414P + 0.169$	Surface runoff coefficient
A12	$-0.00175F + 0.333$	Subsurface runoff coefficient
A2	$0.00657U + 0.163$	Intermediate flow coefficient
A3	$-0.000267U + 0.00912$	Baseflow coefficient
B1	$-0.07(\ln A) + 0.470$	First-tank percolation coefficient
H12	$16.68(\ln A) + 24.20$	Upper outlet threshold height

*P = paddy field ratio (%); U = upland field ratio (%); F = forest ratio (%); A = watershed area (km²).

Two-Stage Water Balance Algorithm

A two-stage sequential water balance is performed within each sub-watershed (Figure 3). Stage 1 conducts reservoir-centric water balance: effective storage is compared against daily demand to determine supply, shortage, return flow, and overflow. Stage 2 conducts river facility water balance: all river water components (return flow, overflow, instream release, natural runoff, wastewater discharge, and weir storage) are aggregated and allocated sequentially to river facilities from upstream to downstream. When a secondary river facility cannot meet demand from river water alone, supplementary supply from the associated primary reservoir is triggered. Results are aggregated through the topological network to rural water district and mid-watershed scales. The sub-watershed water balance concept is illustrated in Figure 4.

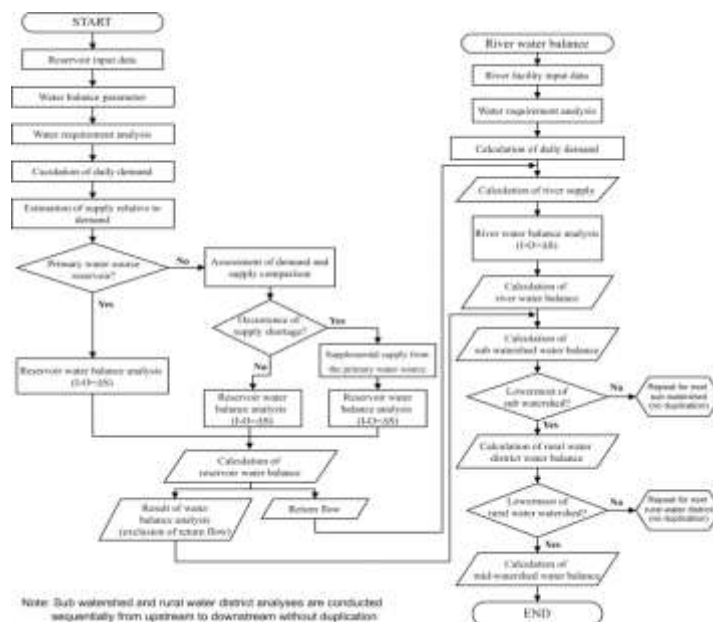


Figure 3. Flowchart of the two-stage agricultural water balance analysis framework within rural water districts

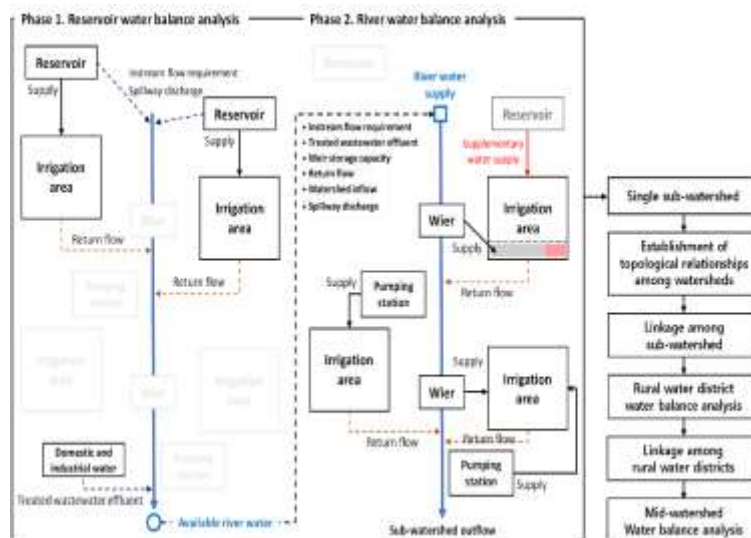


Figure 4. Conceptual framework linking reservoir and river water balance analyses within interconnected sub-watersheds

RESULTS AND DISCUSSION

Model Validation

Model performance was evaluated at eight streamflow gauging stations using 5-day aggregated time series. Statistical indicators included R^2 , NSE, RSR, and PBIAS. Scatter plots of simulated versus observed discharge are shown in Figure 5. All eight sites achieved $NSE \geq 0.65$ and $R^2 \geq 0.81$, meeting the Good performance threshold (Moriassi et al., 2007). Three sites reached $NSE \geq 0.76$. PBIAS remained within $\pm 10\%$ at most sites, indicating reasonable long-term volume reproduction. The results suggest that the model captures the general pattern of streamflow dynamics at the operational time step used for water balance analysis, though some uncertainty remains at downstream sites where river facility withdrawals are difficult to quantify directly.

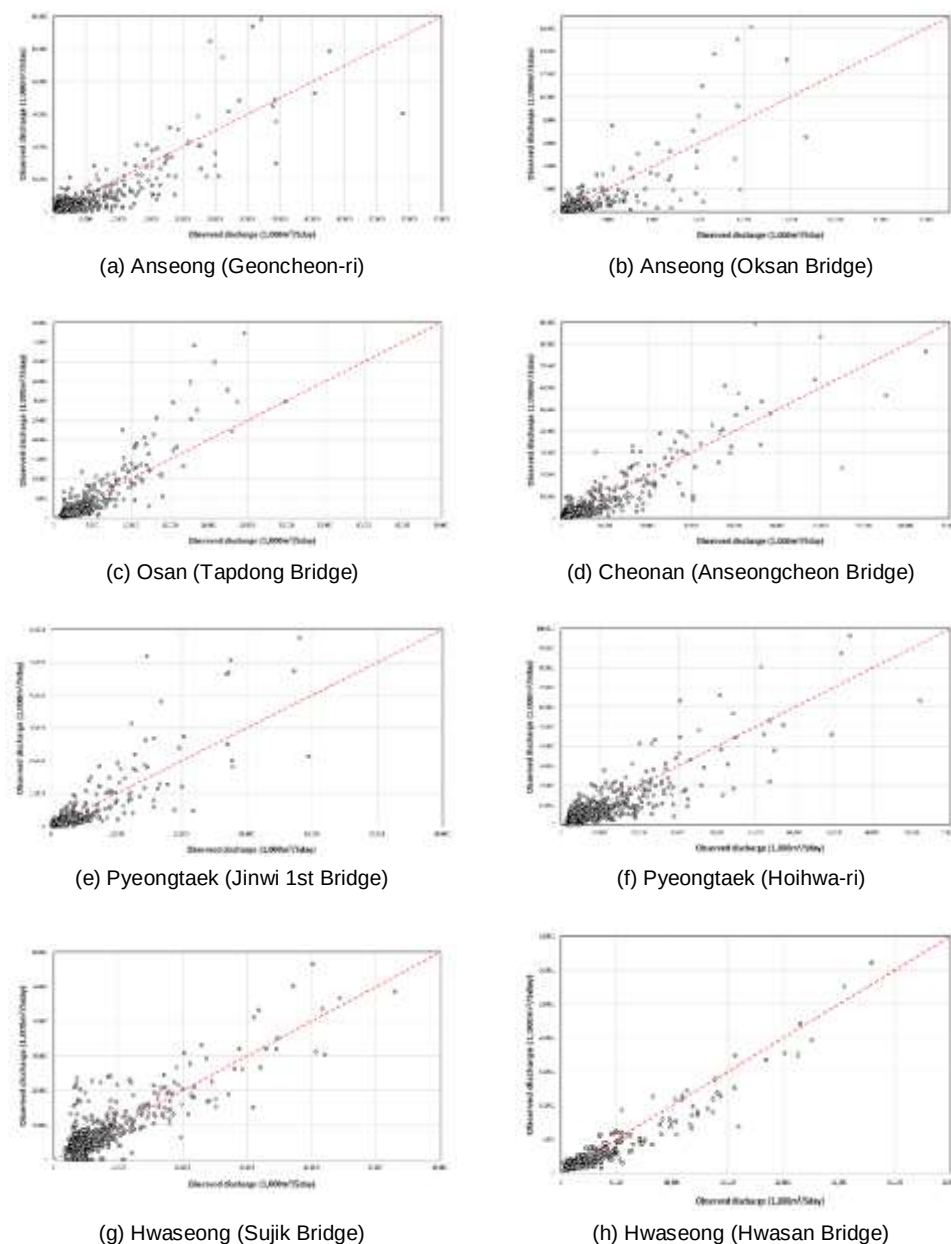


Figure 5. Scatter plots comparing simulated and observed streamflow at eight gauging stations

Table 2. Model performance statistics for streamflow simulation at eight gauging stations

Validation site	R ²	NSE	RSR	PBIAS (%)	Performance rating
Anseong (Geoncheon-ri)	0.72	0.71	0.54	4.5	Good
Anseong (Oksan Bridge)	0.66	0.65	0.59	9.0	Good
Osan (Tapdong Bridge)	0.81	0.73	0.52	17.3	Good
Cheonan (Anseongcheon Bridge)	0.83	0.82	0.42	2.2	Very Good
Pyeongtaek (Jinwi 1st Bridge)	0.74	0.70	0.55	-8.5	Good
Pyeongtaek (Hoihwa-ri)	0.74	0.73	0.52	8.2	Good
Hwaseong (Sujik Bridge)	0.76	0.76	0.49	-1.0	Very Good
Hwaseong (Hwasan Bridge)	0.92	0.90	0.31	1.9	Very Good

*Performance ratings based on Moriasi et al. (2007): $NSE \geq 0.75$ = Very Good; $0.65 \leq NSE < 0.75$ = Good.

Watershed Water Balance Characteristics

Water balance simulations over 1975–2024 yielded annual supply rates, shortage volumes, and return-flow ratios by rural water district. The 50-year average supply rates and water balance components by district are summarized in Figure 6. To illustrate the range of observed patterns, annual supply rate time series for four representative districts—selected to reflect different supply configurations (reservoir-dominant: Yongnam; river-dominant: Pyeonggo; mixed supply: Cheonjik; high-deficit: Yonggi)—are shown in Figure 7. Averaged over the simulation period, supply rates ranged from approximately 81% to 94% across the ten districts. Districts relying primarily on river facilities showed greater inter-annual variability in supply rates compared with reservoir-dominated districts, reflecting the higher sensitivity of river water availability to seasonal meteorological conditions. A general tendency toward lower supply rates in the more recent 15-year period (2010–2024) relative to earlier periods was observed in most districts, though the magnitude of this trend varied.

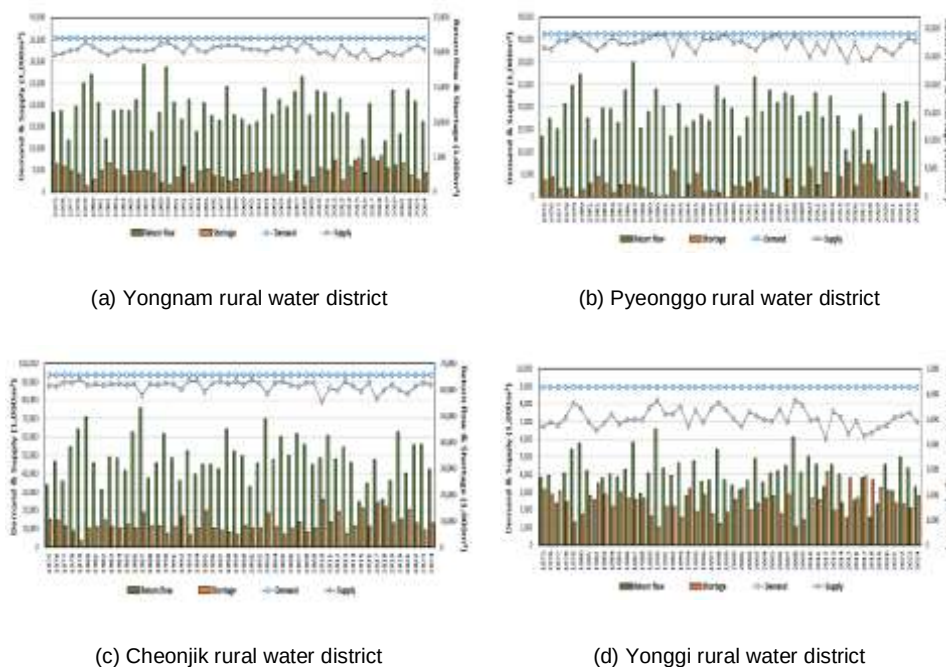


Figure 6. Long-term water balance components in representative rural water districts (1975–2024)

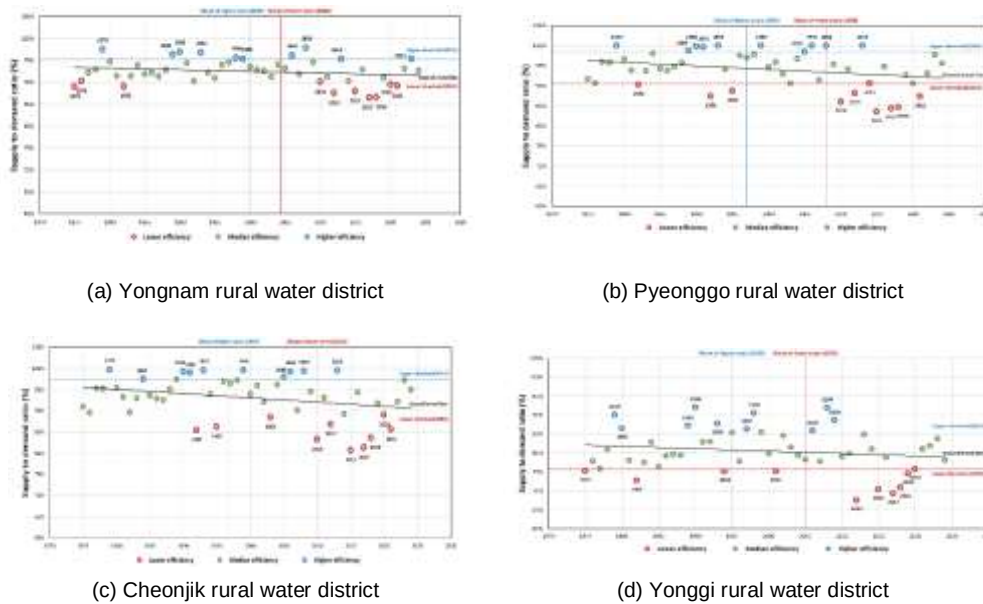


Figure 7. Inter-annual variability and efficiency classification of supply rates in representative rural water districts (1975–2024)

Water Shortage Characteristics by Supply Source

Disaggregating shortage volumes by water source type (reservoirs vs. river facilities) revealed different patterns across districts. Figure 8 presents results for the same four representative districts. Yongnam (reservoir-dominant) showed shortages concentrated in reservoir depletion events, while Pyeonggo (river-dominant) showed shortages primarily during mid-to-late irrigation season when river water availability declined. Cheonjik exhibited a mixed pattern, and Yonggi—despite a balanced supply structure—generated most shortages from river facilities, suggesting that watershed-specific hydrological characteristics also influence shortage distribution. These results are exploratory in nature and would benefit from further validation against observed shortage records.

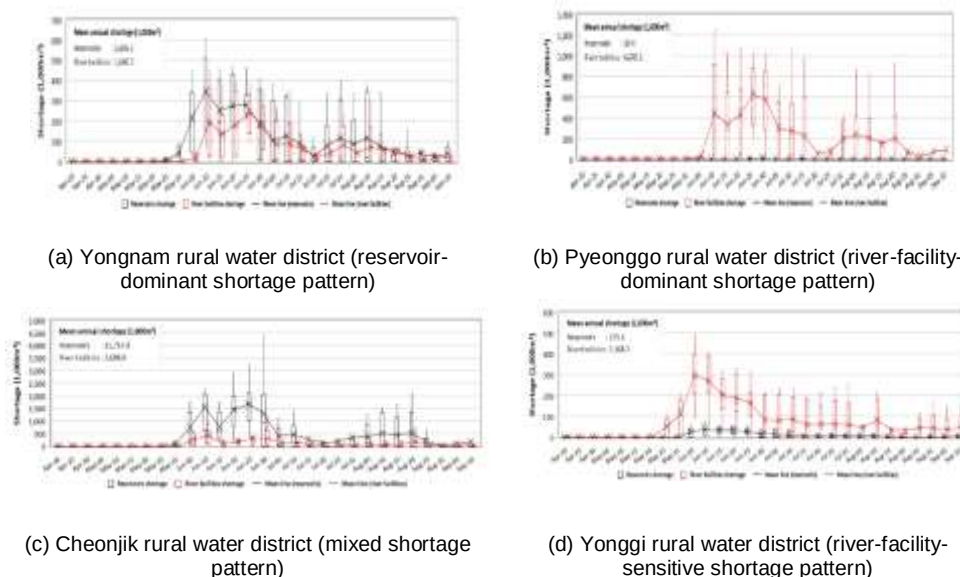


Figure 8. Temporal variation of water shortage by supply source type in four representative rural water districts

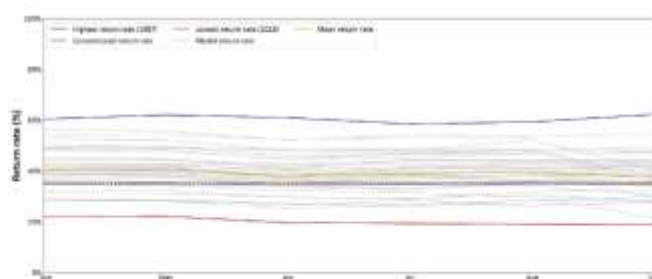
Implications of Return-Flow Variability and Demand Assumptions

Annual return-flow ratios estimated by the model ranged from approximately 20% to 60% over the 50-year period, with a mean of approximately 40% (Figure 9). The conventional fixed ratio of 35% applied in existing national models was within the range of estimated values, but individual years showed substantial deviations—particularly during drought years, when the ratio dropped considerably below 35%, and during wet years, when it exceeded 50%. The implications of this variability for downstream water availability estimates are discussed in the following section.

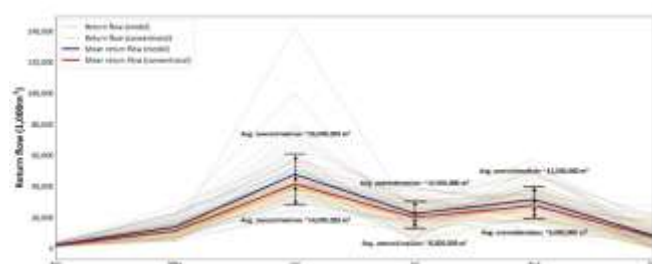
The validation results indicate that the proposed framework reproduces observed streamflow dynamics within a range considered acceptable for long-term water balance analysis. However, some uncertainty remains, particularly at sites influenced by large river facility withdrawals and regulated flow contributions from the Asan estuarine reservoir. These uncertainties suggest caution in directly comparing simulated shortage estimates with planning figures without additional field-based verification.

The observed inter-annual variability in return-flow ratios (20–60%) raises questions about the adequacy of applying a uniform fixed ratio in national-scale analyses. While the mean estimated ratio (~40%) is not far from the conventional 35% assumption, individual years diverge considerably, and systematic underestimation of return flow during wet years and overestimation during drought years could propagate into downstream supply availability estimates. Whether this variability is consistent across other watersheds in South Korea remains to be examined.

The demand input—using a nationally measured average unit supply rate rather than a theoretically derived drought-frequency requirement—also influences water balance outcomes. The approach used here produces demand estimates that appear more consistent with observed operational data, but further evaluation against field-measured supply records across multiple watersheds would be needed to confirm the appropriateness of this assumption under different conditions.



(a) Inter-annual variability of estimated return-flow ratios



(b) Comparison of simulated and conventional irrigation return-flow volumes

Figure 9. Inter-annual variability of irrigation returns flow and comparison with the conventional 35% assumption in the Anseongcheon mid-watershed (1975–2024)

CONCLUSIONS

This study presented a watershed-scale agricultural water balance analysis framework integrating hydraulic structures and river systems in rural water districts, and applied it to the Anseongcheon mid-watershed as a case study. The main findings are as follows:

- The proposed two-stage water balance algorithm, which sequentially performs reservoir and river facility analysis within sub-watersheds, provides a structured approach for estimating facility-level supply and shortage disaggregated by water source type. Validation against streamflow observations at eight sites yielded NSE of 0.65–0.90, indicating acceptable model performance for long-term water balance purposes.
- The 50-year simulation results suggest that river-facility-dependent districts exhibit greater inter-annual supply rate variability than reservoir-dominated districts, and that supply rates have generally declined in the most recent 15-year period. These patterns warrant further investigation, particularly regarding the influence of climate variability and changes in irrigated area.
- Estimated annual return-flow ratios ranged from 20% to 60%, with considerable deviation from the conventional fixed 35% assumption in individual years. This variability may have practical implications for downstream water availability assessment, though the extent to which these findings generalize to other watersheds remains an open question.

The framework is intended as a contribution toward more detailed watershed-scale agricultural water balance analysis in data-limited settings. Additional testing across different watershed types and operational conditions would be needed to assess its broader applicability.

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