

Article

Optimizing Multi-Well Operation in Riverbank Filtration Systems Using Long-Term Field Monitoring and Groundwater Modeling

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Abstract

Riverbank filtration (RBF) is a sustainable technology for securing drinking water resources; however, many existing systems operate below their design capacities due to lack of optimization for site-specific hydrogeological conditions. Improving the performance of existing facilities is therefore an important challenge for sustainable groundwater management. This study proposes an operational management framework for improving the performance of a multi-well RBF system using long-term field monitoring data and groundwater modeling. A collector-well system located along the Nakdong River, South Korea, was selected as a case study. A MODFLOW groundwater model was calibrated using observed groundwater levels and single-well pumping tests and applied to evaluate hydraulic interference among wells and alternative pumping scenarios under multi-well operating conditions. The calibrated model reproduced the measured pumping rates from single-well pumping tests with relative errors ranging from 1.34% to 7.25%. Simulation results showed that simultaneous operation of multiple wells reduced individual pumping performance because of hydraulic interference, whereas appropriate grouping of productive wells mitigated the loss of pumping performance. The optimal 2 + 4 and 3 + 3 well-grouping strategies yielded combined modeled abstraction capacity indicators of 94,217 and 93,902 m³ day⁻¹, respectively, demonstrating substantial differences in the potential abstraction performance among alternative well-grouping strategies. Integrating long-term operational monitoring with groundwater modeling provides a practical decision-support approach for improving the operational performance of existing multi-well RBF systems.



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1. Introduction

Riverbank filtration (RBF) is a managed aquifer recharge technique in which surface water is induced to infiltrate through riverbed and aquifer materials toward pumping wells installed adjacent to a river. During subsurface passage, filtration, sorption, biodegradation, and mixing processes improve raw-water quality while providing a relatively stable source of water for municipal supply [1–4]. The effectiveness of RBF depends strongly

on the hydraulic connection between the river and adjacent aquifer, aquifer properties, river-stage fluctuations, pumping conditions, and travel pathways between the river and production wells [5–7]. Consequently, understanding groundwater–surface water interactions and the hydraulic response of RBF well fields is essential for maintaining reliable long-term abstraction.

The hydraulic performance of RBF systems has been investigated using field observations, pumping tests, and numerical groundwater-flow models. Numerical modeling is particularly valuable for estimating induced river infiltration, groundwater flow paths, drawdown, and pumping capacity under different hydrogeological and operational conditions [8–10]. Radial and horizontal collector wells are widely used at large RBF facilities because their laterals can distribute abstraction over a relatively large aquifer volume while limiting excessive drawdown near the central caisson [8]. However, collector-well performance is sensitive to pumping rate, aquifer heterogeneity, river–aquifer connectivity, and hydraulic interactions among neighboring wells. When multiple wells are operated simultaneously, overlapping drawdown reduces individual well productivity and causes the effective abstraction capacity of the well field to differ substantially from its installed design capacity. More broadly, numerical modeling of subsurface well and reservoir systems has demonstrated the importance of considering interactions among well configuration, hydraulic conditions, and subsurface properties when evaluating system performance [11].

Long-term operation introduces additional challenges. Riverbed and aquifer clogging can reduce hydraulic conductivity and induce infiltration, thereby progressively affecting RBF performance [12,13]. Field-scale studies have also demonstrated that RBF performance varies over time in response to changes in river conditions, groundwater levels, pumping intensity, and individual well characteristics [14,15]. These observations indicate that design capacity alone may not adequately represent the actual production potential of a mature RBF facility. Consequently, operational records collected after commissioning provide important information for diagnosing changes in individual well performance and for evaluating whether the existing pumping strategy remains hydraulically efficient.

Several studies conducted along the Nakdong River in South Korea provide an important basis for understanding the hydraulic and operational characteristics of RBF systems under local hydrogeological conditions. Lee et al. [8] numerically analyzed a radial collector well near the Nakdong River and demonstrated that groundwater abstraction could induce a substantial proportion of river water into the collector well, highlighting the importance of collector-well configuration and river–aquifer connectivity. Time-series analysis at a lower Nakdong River RBF facility further demonstrated that groundwater levels respond to both river-stage fluctuations and pumping rates [16]. At Ddanseom Island (referred to as Ttansum Island in Lee et al. [17]), which corresponds to the study area investigated herein, Lee et al. [17] evaluated the productivity of radial collector wells using groundwater-flow modeling under several design-stage well configurations and estimated pumping capacities for the planned RBF system. Additional studies along the Nakdong River have investigated the feasibility, hydrogeological characteristics, and water-quality performance of RBF and horizontal collector-well systems [18–20]. Together, these studies established the hydrogeological feasibility and potential production capacity of RBF systems in the region.

Despite these advances, an important gap remains between design-stage evaluation and long-term operational management of multi-well RBF systems. Most previous studies have focused on hydrogeological characterization, induced infiltration, water-quality improvement, clogging processes, or potential abstraction capacity under prescribed pumping conditions [8–10,12–20]. Relatively few studies have examined how long-term operational records can be integrated with groundwater-flow modeling to evaluate alternative combinations of existing collector wells after years of actual facility operation. This issue is

particularly important where individual wells exhibit unequal productivity and where hydraulic interference varies with the number and spatial combination of simultaneously operating wells. Groundwater-management studies outside the RBF domain have demonstrated that numerical models and pumping-allocation strategies can support more efficient wellfield operation [21–23]; however, practical application of such approaches to existing multi-well RBF facilities remains limited.

The increasing availability of long-term operational data provides an opportunity to move from design-oriented assessment toward data-informed operational management of existing RBF facilities. Accordingly, this study investigates the long-term performance of the Gimhae RBF system using daily operational records from 2018 to 2022 combined with a MODFLOW groundwater-flow model [24]. The objectives are to (1) characterize long-term groundwater abstraction and individual well contributions, (2) evaluate the effects of alternative multi-well operating combinations on groundwater production and hydraulic interaction, and (3) develop a practical operating strategy for improving the utilization of the existing well field. Unlike previous design-stage studies at the site, the present study focuses on the actual post-construction performance of the RBF facility and uses observed long-term operational behavior to define and evaluate alternative pumping scenarios. Beyond the presented case study, the proposed approach provides a transferable framework for improving the operational management of existing multi-well RBF systems and supporting more efficient use of existing water-supply infrastructure.

2. Materials and Methods

2.1. Study Area and Operational History

The study site is located at the Ddanseom riverbank filtration (RBF) facility along the lower Nakdong River in Gimhae, South Korea (Figure 1). The Nakdong River is the longest in South Korea and one of the country's most important drinking water sources. To enhance water supply reliability and reduce dependence on direct river-water abstraction, a large-scale riverbank filtration system was constructed on the alluvial deposits adjacent to the river. The hydrogeological setting consists of highly permeable alluvial sediments hydraulically connected to the Nakdong River, providing favorable conditions for induced riverbank infiltration and groundwater abstraction.

The subsurface profile at the study site consists of five principal hydrogeological units, comprising fill sand, marine sand, gravelly sand, sandy gravel, and weathered rock from the ground surface downward. The hydraulic conductivity of these units varies considerably, with the gravelly sand layer exhibiting the highest hydraulic conductivity among the identified units. The horizontal laterals of the radial collector wells are installed within this gravelly sand layer. The mean water level of the Nakdong River in the study area is approximately EL. 1.65 m, whereas the mean groundwater level is approximately EL. −8.10 m. The minimum riverbed elevation near the study site is approximately EL. −10.0 m.

The nine original collector wells (W1–W9) were constructed using the same radial collector-well design. Each well consists of a vertical caisson with a depth of 42.3 m and a diameter of 6.0 m, from which ten horizontal laterals extend into the surrounding aquifer. Each lateral is 30 m long and 0.20 m in diameter. As noted above, the horizontal laterals are installed within the gravelly sand layer.

The RBF facility was originally designed to produce 180,000 m³ day^{−1} using nine radial collector wells (W1–W9). During subsequent construction and commissioning, three additional collector wells (W10–W12) were installed to improve production flexibility and operational reliability. W10–W12 were in operation during the study period (2018–2022) and remain in operation. However, these wells are spatially separated from the original

W1–W9 well field considered in this study and belong to different operational areas; in particular, W11 and W12 are located outside Ddanseom. Accordingly, the present analysis focused on the original W1–W9 collector-well field at Ddanseom, and W10–W12 were excluded from the operational scenario analysis and evaluation of inter-well hydraulic interactions. Their potential hydraulic influence was therefore outside the spatial and operational scope of the present study. However, because W5, W7, and W8 exhibited persistently low abstraction performance, the operational scenario analysis was restricted to the six productive wells (W1, W2, W3, W4, W6, and W9). Based on the original design capacity of $20,000 \text{ m}^3 \text{ day}^{-1}$ per well, the combined nominal design capacity of these six wells is $120,000 \text{ m}^3 \text{ day}^{-1}$. This value was used solely as a reference capacity for the analyzed well group and does not represent a revision of the original nine-well facility design capacity. The facility has been operated as one of the major municipal water supply systems in the region since 2018, with groundwater production being controlled through various combinations of collector wells according to operational requirements. However, long-term operational records indicate that groundwater production during routine operation was substantially lower than the design abstraction capacity. Under normal operating conditions, the combined production of the original W1–W9 well field ranged from approximately $46,000$ to $63,000 \text{ m}^3 \text{ day}^{-1}$, equivalent to approximately 26–35% of the original nine-well design capacity of $180,000 \text{ m}^3 \text{ day}^{-1}$.

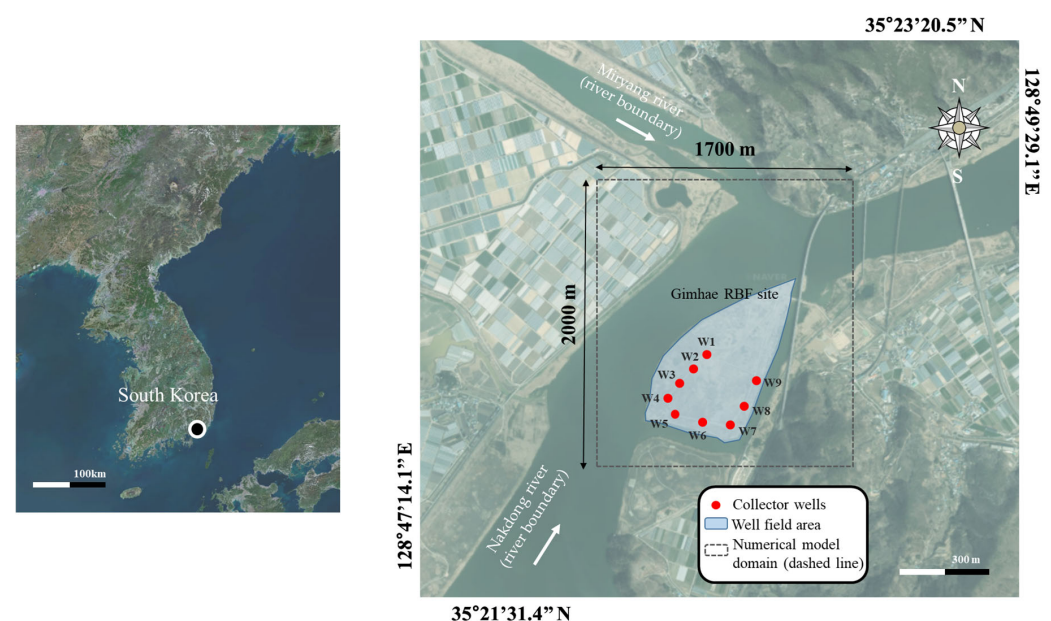


Figure 1. Study site and numerical model domain of the Gimhae riverbank filtration system. The collector-well layout, well field area, and groundwater-flow model domain used in this study are superimposed on a satellite image of the study area.

To investigate the factors behind this discrepancy, we analyzed long-term operational records collected between 2018 and 2022, along with groundwater monitoring data and numerical groundwater modeling. The operational dataset includes daily pumping records, groundwater abstraction volumes, and well operation histories, providing a unique opportunity to evaluate hydraulic interference among collector wells under actual operating conditions. The availability of long-term operational records together with comprehensive hydrogeological information makes this site particularly suitable for evaluating operation strategies and developing a practical framework for improving the performance of existing multi-well riverbank filtration systems.

2.2. Operational Data and Processing

The long-term operational dataset summarized in Table 1 was analyzed to characterize the operational behavior of the collector-well system and to establish representative pumping scenarios for numerical simulation. The dataset includes daily groundwater abstraction, operating well combinations, groundwater levels, and river stage observations collected during routine operation of the RBF facility.

Table 1. Summary of datasets used in this study.

Category	Data	Temporal Resolution	Purpose in This Study
Operation	Pumping volume	Daily	Operational history analysis
Operation	Operating wells	Daily	Scenario development
Monitoring	Groundwater level	Daily	Model calibration
Monitoring	River stage	Daily	Boundary condition
Design	Well specifications	Static	Model construction

Historical operating records were analyzed to identify the pumping frequency of individual collector wells, total groundwater abstraction, and typical operating well combinations. The RBF facility was operated continuously over a 24-h daily cycle, while individual collector wells and well combinations could be switched within a day according to water-supply requirements. Accordingly, the collector wells were operated either individually or simultaneously in various combinations, and the operating configuration could change during the same day. Because the operating combinations were adjusted according to daily water-supply requirements, fixed operating durations were not assigned to individual wells or well combinations. The six productive collector wells considered in the subsequent scenario analysis (W1, W2, W3, W4, W6, and W9) were not operated simultaneously during the historical operating period. However, all six productive wells could contribute to the total daily abstraction through sequential operation of different well combinations within the same 24-h period. These operational records provide valuable information for evaluating hydraulic interference among wells and changes in groundwater production under actual operating conditions.

The historical operational records were subsequently used to support the development of representative multi-well pumping scenarios and the evaluation of alternative operating strategies, as described in Section 2.5.

2.3. Groundwater Flow Model

A three-dimensional groundwater-flow model was developed using Visual MODFLOW (version 3.1.0, Waterloo Hydrogeologic Inc., Waterloo, On, Canada), which is based on the MODFLOW code developed by the U.S. Geological Survey [24]. The model was constructed to simulate groundwater flow within the Gimhae riverbank filtration (RBF) system and to evaluate the hydraulic response of the collector-well system under alternative multi-well pumping scenarios. Although groundwater-flow models are commonly used for aquifer characterization and wellfield design, the model developed in this study was intended to evaluate operational strategies to improve groundwater pumping performance in an existing multi-well RBF system. In this study, the steady-state model was used primarily to compare the relative hydraulic performance of alternative well combinations under a consistent hydraulic framework rather than to reproduce time-dependent field operation. Accordingly, the scenario simulations were interpreted in terms of differences in groundwater abstraction and hydraulic interaction among operating well combinations under comparable hydraulic conditions.

The conceptual groundwater-flow model is illustrated in Figure 2. The study site is characterized by a layered alluvial aquifer hydraulically connected to the Nakdong River, where groundwater abstraction from the collector wells induces riverbank infiltration toward the well field. Figure 2a illustrates the conceptual hydrogeological cross-section, including the principal hydrogeological units, river and groundwater levels, and the general direction of induced riverbank infiltration and groundwater flow toward the collector wells. Figure 2b presents the configuration of a representative radial collector well, consisting of a vertical caisson and horizontal laterals extending into the surrounding aquifer. The horizontal laterals are installed within the gravelly sand layer, which has relatively high hydraulic conductivity compared with the other hydrogeological units at the site. In the numerical model, the Nakdong River was represented using the River (RIV) Package, whereas groundwater abstraction by the collector wells was simulated using the Well (WEL) Package.

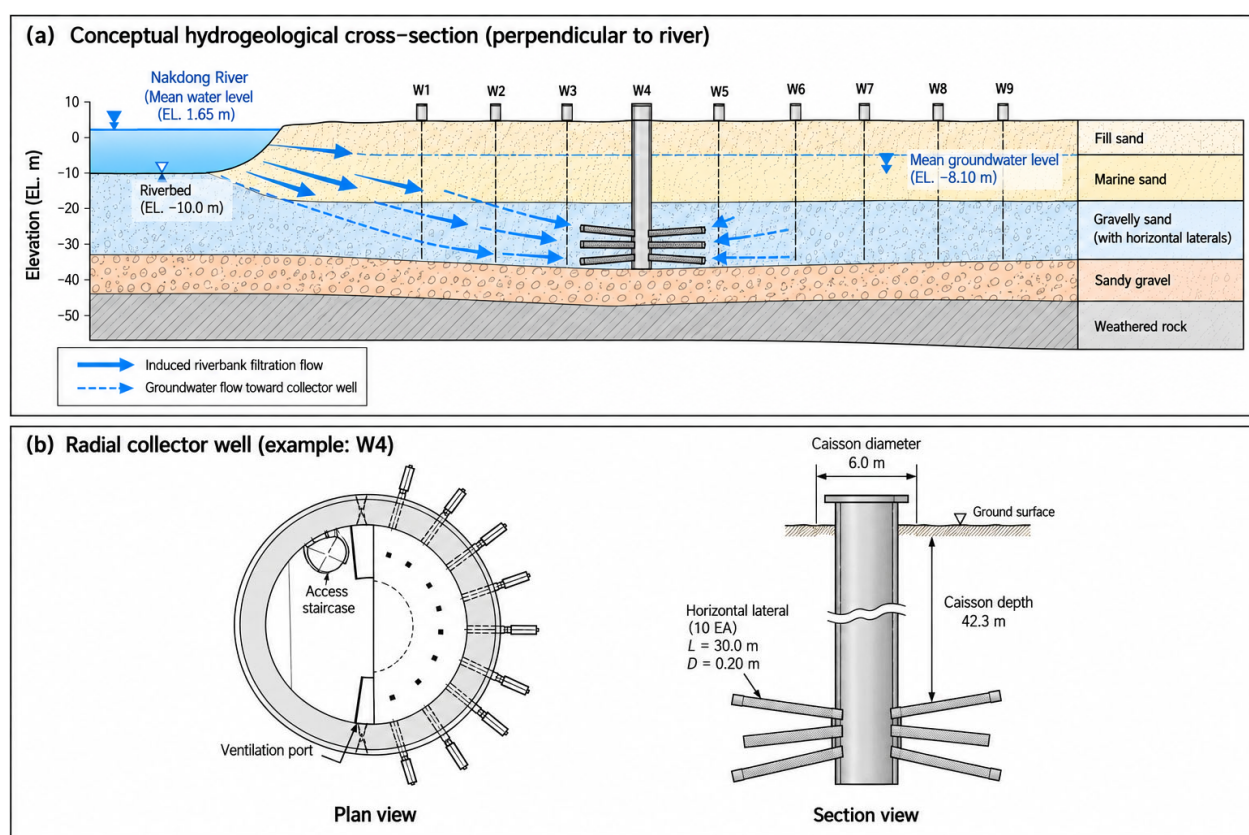


Figure 2. Conceptual representation of the Gimhae riverbank filtration system: (a) hydrogeological cross-section illustrating the relative positions of the Nakdong River, alluvial aquifer, underlying weathered rock, and collector wells, together with the river–aquifer connection and groundwater-flow directions toward the collector wells, and (b) plan and cross-sectional views of a representative radial collector well showing the vertical caisson and horizontal laterals.

The numerical model domain covered an area of $1700 \text{ m} \times 2000 \text{ m}$ and was discretized into 170 columns and 200 rows, resulting in a uniform horizontal grid resolution of $10 \text{ m} \times 10 \text{ m}$. Vertically, the model was discretized into seven numerical layers to represent the subsurface structure of the study area.

Hydraulic conductivity was assigned according to the hydrogeological units identified at the study site. The hydraulic conductivity values used in the calibrated model were $3.4 \times 10^{-6} \text{ m/s}$ for fill sand, $1.3 \times 10^{-6} \text{ m/s}$ for marine sand, $1.4 \times 10^{-4} \text{ m/s}$ for gravelly sand, $3.9 \times 10^{-5} \text{ m/s}$ for sandy gravel, and $4.2 \times 10^{-6} \text{ m/s}$ for weathered rock. Hydraulic

conductivity was assumed to be isotropic within each hydrogeological unit, and the same conductivity was therefore assigned in the horizontal and vertical directions. Groundwater recharge was specified as 140 mm/year, corresponding to a recharge rate of approximately 12.9%. The hydraulic properties assigned to the hydrogeological units are summarized in Table 2.

Table 2. Hydrogeological parameters used in the groundwater-flow model.

Hydrogeological Unit	Hydraulic Conductivity (m/s)
Fill sand	3.4×10^{-6}
Marine sand	1.3×10^{-6}
Gravelly sand	1.4×10^{-4}
Sandy gravel	3.9×10^{-5}
Weathered rock	4.2×10^{-6}

Note: Hydraulic conductivity was assumed to be isotropic; therefore, identical values were assigned in the horizontal and vertical directions.

The hydrogeological parameters were assigned based on the available site investigation and design data. Hydraulic conductivity was subsequently adjusted within physically reasonable ranges during model calibration, as described in Section 2.4.

2.4. Model Calibration

The groundwater-flow model was calibrated to ensure its applicability for evaluating alternative collector-well operating strategies. To improve the model's applicability to operational scenario analysis, calibration incorporated both groundwater level observations and measured groundwater abstraction from single-well pumping tests. This approach improved the model's ability to reproduce not only regional groundwater-flow conditions but also the pumping performance of individual collector wells.

Model calibration was performed primarily through iterative adjustment of hydraulic conductivity within physically reasonable ranges based on the available site investigation and design data. Groundwater level observations obtained from the long-term monitoring program were used to reproduce the regional hydraulic conditions of the study area, while the measured abstraction rates from the single-well pumping tests were used to evaluate the model's ability to reproduce the pumping performance of individual collector wells.

The calibrated model was evaluated by comparing the simulated groundwater abstraction with the measured pumping rates obtained from the single-well pumping tests. The calibration errors reported in this study were calculated from the measured and simulated pumping rates obtained for the individual single-well pumping tests and were not derived from the long-term average operational data. Model performance for each well was quantified using the relative error (RE), calculated as

$$RE(\%) = |Q_{sim} - Q_{obs}| / Q_{obs} \times 100$$

where Q_{sim} is the simulated pumping rate and Q_{obs} is the measured pumping rate obtained from the corresponding single-well pumping test. The relative errors reported herein refer specifically to differences between the measured and simulated pumping rates and do not represent groundwater-level calibration errors. Table 3 summarizes the comparison of measured and simulated pumping rates and the corresponding relative errors for the six operating collector wells. The calibrated model was subsequently used to evaluate the effects of alternative multi-well operating scenarios on groundwater abstraction and hydraulic interference.

Table 3. Comparison of measured and simulated groundwater abstraction for individual collector wells used in model calibration.

Well	Measured Pumping Rate (m ³ Day ^{−1})	Simulated Pumping Rate (m ³ Day ^{−1})	Relative Error * (%)
W1	21,072	22,600	7.25
W2	22,272	21,267	4.51
W3	23,400	21,757	7.02
W4	21,984	22,839	3.89
W6	13,560	13,742	1.34
W9	10,968	10,728	2.19

* Note: $RE(\%) = |Q_{sim} - Q_{obs}| / Q_{obs} \times 100$.

2.5. Operation Scenario Simulation and Performance Evaluation

To evaluate the operational performance of the Gimhae riverbank filtration (RBF) system, a series of multi-well pumping scenarios was developed using the calibrated groundwater-flow model. The scenarios were designed to quantify the effects of different collector-well operating combinations on groundwater abstraction and hydraulic interference, identifying practical well-operating strategies with the potential to improve groundwater abstraction performance under existing field conditions. For the numerical scenario analysis, each well combination was evaluated independently on a common 24-h operating basis. Accordingly, the simulated abstraction rate for each scenario represents the modeled daily abstraction assuming continuous operation of the corresponding well combination for 24 h, rather than the actual operating duration of that combination in the historical field records.

As described in Section 2.1, the operational scenario analysis was restricted to the original W1–W9 well field. Among the nine original collector wells, W5, W7, and W8 exhibited persistently negligible groundwater abstraction in the long-term operational records and made only marginal contributions to the total production. Because the objective of the scenario analysis was to evaluate alternative operating combinations among wells that remained functionally productive under existing field conditions, these three poorly performing wells were excluded from the scenario analysis. Accordingly, operational scenarios were developed using the six productive collector wells that remained in routine operation (W1, W2, W3, W4, W6, and W9). The specific causes of the reduced performance of W5, W7, and W8 were not directly investigated in this study; therefore, potential mechanisms such as clogging are considered only as possible explanations rather than confirmed causes.

Representative pumping scenarios were established by considering all possible combinations of one-, two-, three-, and four-well operations among the six productive collector wells. A total of 56 operational scenarios were evaluated, consisting of 6 single-well, 15 two-well, 20 three-well, and 15 four-well combinations.

To develop combined operating strategies, the six productive collector wells were partitioned into complementary operating groups such that all six wells were included once in each combined configuration. Three general partitioning schemes are theoretically possible for the six wells: 1 + 5, 2 + 4, and 3 + 3. In this study, the combined-operation analysis focused on the 2 + 4 and 3 + 3 configurations. The four-well configuration therefore does not represent a physical or operational limit on the number of collector wells that can be operated simultaneously, but rather reflects the maximum group size considered within the selected complementary operating strategies. The 1 + 5 configuration was not evaluated because it represents a highly unbalanced distribution of operating wells and would

require simultaneous operation of five wells in one group, which was outside the range of multi-well scenarios considered in the present analysis. For the 2 + 4 configuration, each two-well combination was paired with its complementary four-well combination, resulting in 15 complementary pairs. For the 3 + 3 configuration, each three-well combination was paired with the remaining three wells; after eliminating reciprocal duplicates, 10 unique complementary pairs were obtained.

The grouping was not predetermined solely on the basis of geographic distance, well depth, a prescribed hydraulic interference radius, or a specific aquifer-property threshold. Instead, all complementary pairs within the selected partitioning schemes were systematically compared using the abstraction rates simulated by the calibrated groundwater-flow model, which represents the spatial configuration of the wells and the hydraulic characteristics of the aquifer. Table S1 provides the complete set of operational scenarios and their simulated groundwater abstraction rates. The procedure used to establish and evaluate the operational scenarios is illustrated in Figure 3. For each complementary pair, a combined modeled abstraction capacity was calculated as the sum of the 24-h modeled abstraction rates of the two constituent scenarios. This value was used as a comparative indicator of the abstraction capacity associated with alternative well-grouping strategies and does not represent a time-weighted estimate of realized daily production under an actual sequential pumping schedule.

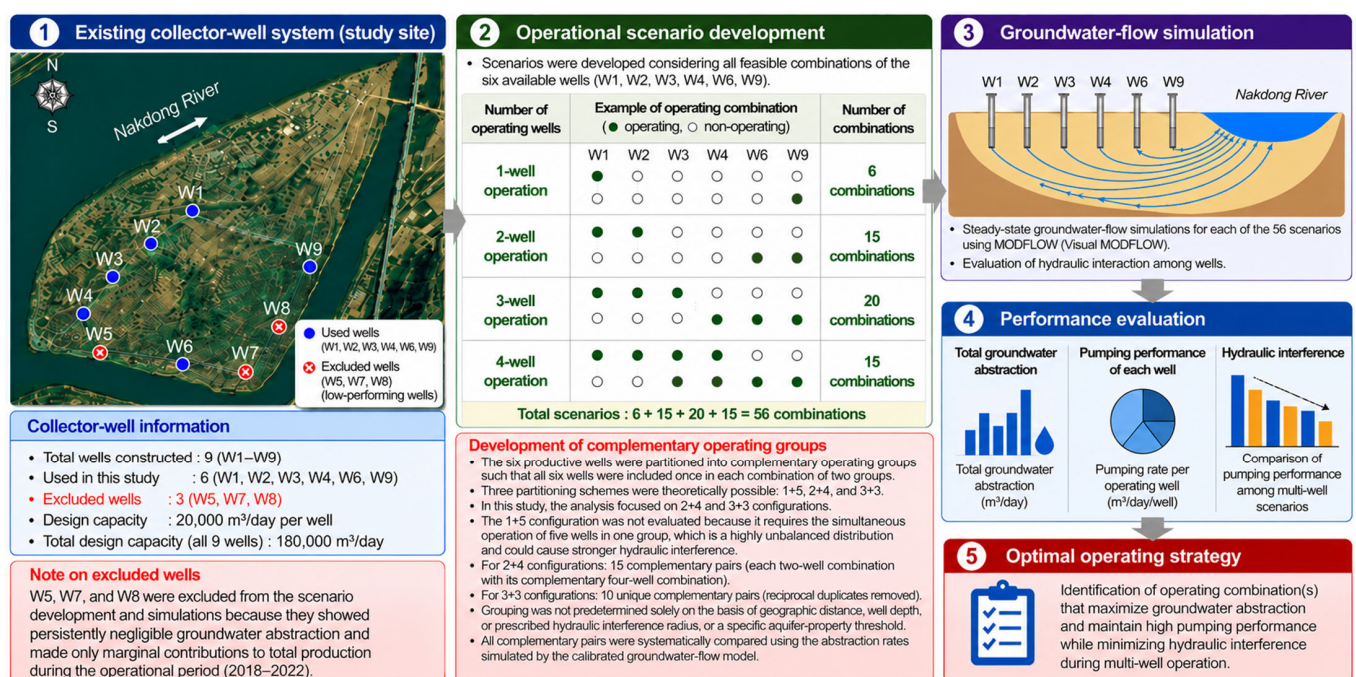


Figure 3. Framework for developing and evaluating multi-well operational scenarios for the Gimhae RBF system.

For each operational scenario, steady-state groundwater-flow simulations were performed using the calibrated model described in Sections 2.3 and 2.4. The simulation results were evaluated in terms of total groundwater abstraction and pumping performance under different numbers and combinations of simultaneously operating wells. Hydraulic interference was assessed by comparing changes in pumping performance among the simulated multi-well operating scenarios rather than by calculating a separate interference index. These comparisons were subsequently used to identify well combinations capable of maintaining relatively high groundwater abstraction while limiting the adverse effects of hydraulic interference.

3. Results

3.1. Long-Term Operational Characteristics

The long-term operational records collected between 2018 and 2022 were analyzed to characterize the operating conditions of the Gimhae riverbank filtration (RBF) system. Figure 4 summarizes the annual groundwater abstraction of individual collector wells together with their contribution to the total groundwater production during the study period. The operational records provide valuable insight into the actual performance of the collector-well system under routine field conditions and form the basis for developing representative operational scenarios.

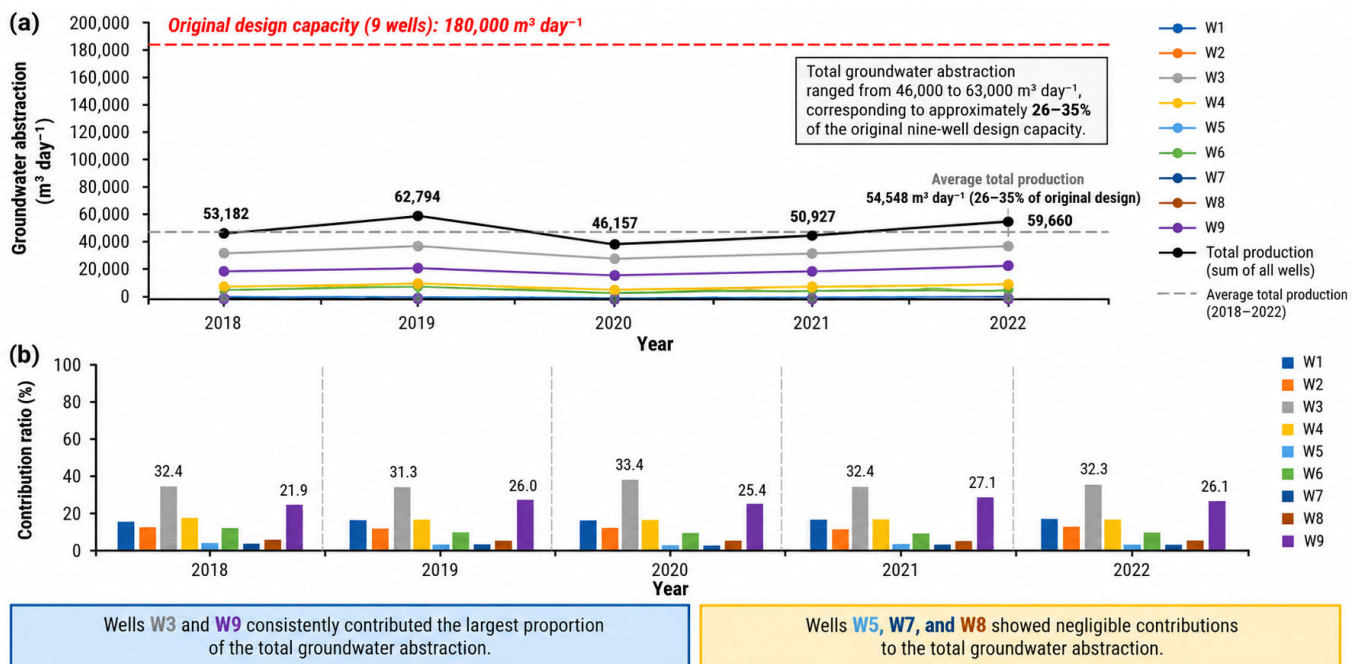


Figure 4. Long-term operational characteristics of the Gimhae riverbank filtration system during 2018–2022: (a) annual groundwater abstraction of individual collector wells and (b) annual contribution ratio of each collector well to the total groundwater production.

As shown in Figure 4a, considerable differences in groundwater abstraction were observed among the collector wells throughout the operating period. Under normal operating conditions, the combined production of the original W1–W9 well field ranged from approximately 46,000 to 63,000 m³ day⁻¹, equivalent to approximately 26–35% of the original nine-well design capacity of 180,000 m³ day⁻¹. For reference, these total well-field abstraction rates correspond to approximately 38–53% of the combined nominal design capacity of the six productive wells (120,000 m³ day⁻¹). This comparison is provided only as a reference and should not be interpreted as the actual capacity utilization of the six productive wells. Annual groundwater production remained relatively stable over the five years, indicating that the reduced production was not a temporary operational issue but a persistent characteristic of the existing collector-well system.

Distinct differences were also observed in the operating performance of individual collector wells. Wells W3 and W9 consistently produced the largest groundwater abstraction throughout the monitoring period, whereas W5, W7, and W8 exhibited negligible production after the initial operation period (Figure 4a). After 2020, each of these three collector wells individually contributed less than 1% of the total groundwater production (Figure 4b), indicating their limited contribution to the overall abstraction performance of the well field. Given their persistently low productivity during long-term operation,

W5, W7, and W8 were classified as poorly performing wells and were excluded from the operational scenario analysis.

The contribution ratio in Figure 4b further shows that groundwater production gradually concentrated in a limited number of collector wells, particularly W3 and W9, while the contribution of the remaining productive wells remained relatively consistent throughout the monitoring period. These long-term operational characteristics indicate that the reduced system performance cannot be explained solely by the installed abstraction capacity but is strongly influenced by the operational status and productivity of individual collector wells. Consequently, alternative operating combinations of the six productive collector wells (W1, W2, W3, W4, W6, and W9) were evaluated in the subsequent scenario analysis to identify practical operating strategies that improve groundwater abstraction while minimizing hydraulic interference.

3.2. Multi-Well Operational Scenarios

The performance of the multi-well operational scenarios was evaluated using the six productive collector wells (W1, W2, W3, W4, W6, and W9). The simulation results showed that groundwater abstraction was influenced by both the number of simultaneously operating wells and the specific combination of wells. To examine these effects, pumping performance was first compared by the number of operating wells, followed by an assessment of variation in total abstraction among representative well combinations.

Figure 5 compares the minimum, average, and maximum pumping rates per well under the two-, three-, and four-well operational scenarios. The average pumping rate per well decreased progressively from 16,593 m³ day^{−1} per well for two-well operation to 14,984 m³ day^{−1} per well for three-well operation and 13,090 m³ day^{−1} per well for four-well operation. A similar trend was observed for the maximum pumping rate, which decreased from 20,872 m³ day^{−1} per well for two-well operation to 17,130 and 14,353 m³ day^{−1} per well for three- and four-well operations, respectively. The minimum pumping rates were 12,025, 13,756, and 11,090 m³ day^{−1} per well for the two-, three-, and four-well scenarios, respectively. These results indicate that the abstraction capacity of an individual collector well decreased as more wells were operated simultaneously, consistent with increasing hydraulic interaction among the operating wells.

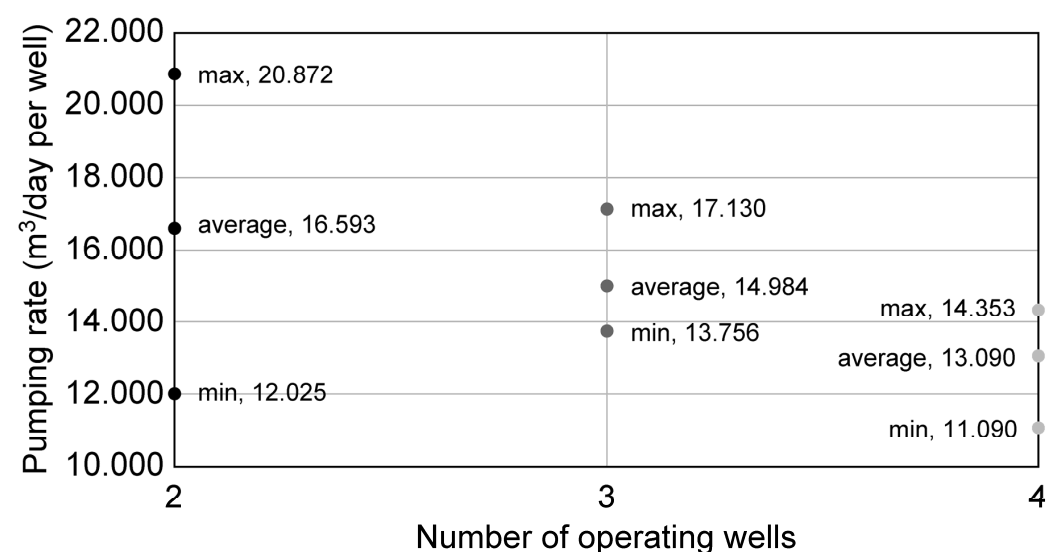


Figure 5. Minimum, average, and maximum pumping rates per well under two-, three-, and four-well operational scenarios.

The importance of the specific operating combination becomes more evident when the total groundwater abstraction is compared among representative scenarios (Figure 6). For two-well operation, the total abstraction ranged from 24,050 m³ day^{−1} in the worst-performing scenario (S2-15) to 41,743 m³ day^{−1} in the best-performing scenario (S2-3), while the median scenario (S2-1) produced 32,826 m³ day^{−1}. Similar differences were observed for three-well operation, with total abstraction increasing from 41,267 m³ day^{−1} (S3-13) to 51,389 m³ day^{−1} (S3-8). For four-well operation, the corresponding values ranged from 44,359 m³ day^{−1} (S4-13) to 57,411 m³ day^{−1} (S4-8), with the median scenario (S4-11) producing 51,804 m³ day^{−1}. These differences demonstrate that even when the same number of wells is operated, total groundwater production can vary substantially depending on the selected well combination.

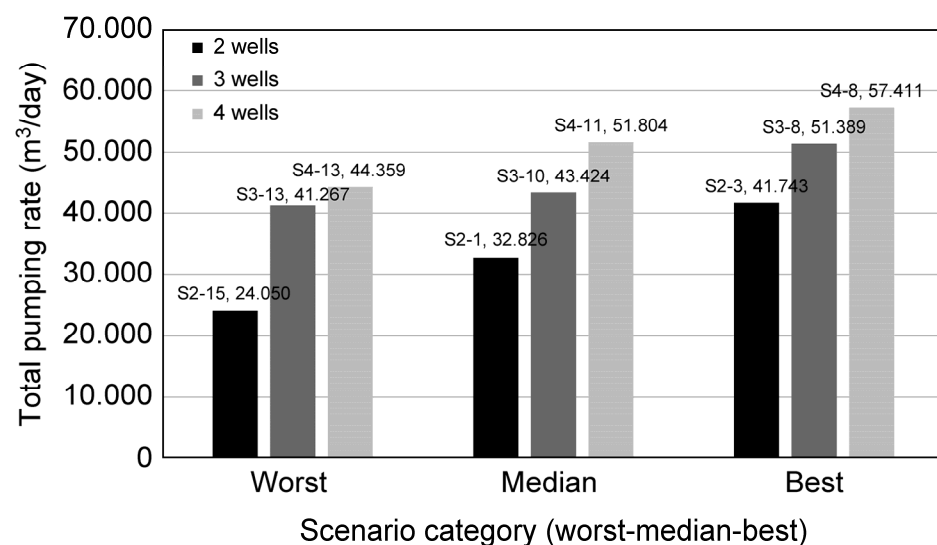


Figure 6. Comparison of total groundwater abstraction among representative multi-well operational scenarios classified as worst-, median-, and best-performing combinations.

Although increasing the number of operating wells generally increased total groundwater abstraction, the increase was not proportional to the number of wells in operation. For example, the best-performing two-well scenario produced 41,743 m³ day^{−1}, whereas the worst-performing four-well scenario produced only 44,359 m³ day^{−1}, despite operating twice as many wells. This relatively small increase in total abstraction shows that simply increasing the number of simultaneously operating wells does not proportionally improve system-level production. Instead, the spatial arrangement and hydraulic interaction of the selected wells play an important role in determining the overall performance of the collector-well system.

Overall, the multi-well scenario analysis shows that operational performance depends not only on the number of active collector wells but also on selecting an appropriate well combination. Therefore, an effective operating strategy should seek to maintain high total groundwater abstraction while avoiding combinations that result in excessive mutual hydraulic interference. Based on these findings, the following section evaluates the performance of the recommended operating strategies.

3.3. Recommended Operating Strategy

Based on the multi-well scenario results, alternative well-grouping strategies were evaluated to identify combinations with favorable modeled abstraction performance while reducing the effects of hydraulic interference among simultaneously operating collector wells. The six productive collector wells were partitioned into complementary groups. Two

grouping strategies were evaluated: a 2 + 4 configuration consisting of complementary two-well and four-well groups and a 3 + 3 configuration consisting of two complementary three-well groups. For each strategy, the combined modeled abstraction capacity was calculated as the sum of the 24-h modeled abstraction rates of the two complementary scenarios. The evaluated grouping strategies and corresponding combined modeled abstraction capacities are summarized in Table S2.

As shown in Figure 7, the arithmetic mean of the five annual average groundwater abstraction rates during 2018–2022 was $54,548 \text{ m}^3 \text{ day}^{-1}$. Under the common 24-h scenario framework used in the numerical analysis, the highest combined modeled abstraction capacity was $94,217 \text{ m}^3 \text{ day}^{-1}$ for the optimal 2 + 4 grouping, while the optimal 3 + 3 grouping yielded $93,902 \text{ m}^3 \text{ day}^{-1}$. These combined modeled capacities were derived by summing the 24-h abstraction rates of two complementary scenarios and therefore represent comparative model-based capacity indicators rather than time-weighted predictions of realized daily production under a specific field pumping schedule. Accordingly, the modeled capacities and the observed field abstraction are presented to illustrate the difference between current operational performance and the potential capacity identified through scenario-based grouping, rather than as a direct prediction of achievable daily production.

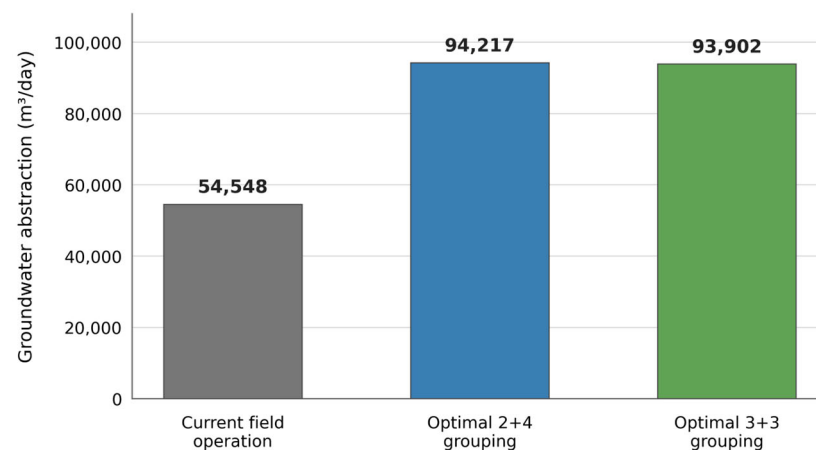


Figure 7. Comparison of the average field abstraction with the combined modeled abstraction capacity indicators of the optimal 2 + 4 and 3 + 3 well-grouping strategies. The modeled values represent the sums of the 24-h abstraction rates of two complementary scenarios and should not be interpreted as predictions of realized daily field production.

The differences among the evaluated well-grouping strategies can be explained by the hydraulic interactions identified in the multi-well scenario analysis. As demonstrated in Section 3.2, increasing the number of simultaneously operating wells reduced the average pumping rate per well, and substantial differences in total abstraction were observed among different well combinations. Partitioning the productive wells into favorable complementary groups can therefore reduce the loss of pumping performance associated with hydraulic interference within each modeled scenario. The comparable combined modeled capacities of the optimal 2 + 4 and 3 + 3 groupings further indicate that the selection and grouping of collector wells are important considerations in developing operational strategies.

These results demonstrate the potential value of reorganizing the existing productive wells without constructing additional collector wells or immediately expanding abstraction infrastructure. For the Gimhae RBF system, the scenario-based comparison identified complementary well groupings with favorable modeled abstraction capacities under the common 24-h scenario framework. These results provide a practical basis for developing improved field operating schedules, although the realized daily abstraction would

depend on the actual operating duration and sequencing of the selected well groups. The broader applicability and implications of this approach for sustainable RBF management are discussed in Section 4.

4. Discussion

4.1. Operational Implications for Existing RBF Systems

The results of this study demonstrate that the operational performance of a multi-well RBF system cannot be determined solely by the installed abstraction capacity or the number of collector wells in operation. Although operating additional wells simultaneously increased total groundwater abstraction, the average pumping rate per well decreased as the number of operating wells increased. Moreover, total abstraction differed substantially among well combinations even when the same number of wells was operated. These results indicate that hydraulic interaction among collector wells is an important factor controlling the effective production capacity of an existing RBF well field.

Previous studies conducted along the Nakdong River have investigated the hydraulic and hydrogeological characteristics of RBF systems, including river–aquifer connectivity, river-stage responses, and pumping behavior [8,16–19]. In particular, Lee et al. [17] evaluated the potential pumping capacity of radial collector wells at Ddanseom Island under design-stage conditions, providing an important basis for the development of the present RBF facility. The present study extends these previous investigations from design-stage assessment to post-construction operational management by evaluating the long-term performance of the well field using operational records collected during 2018–2022. The results demonstrate that the effective production capacity after several years of operation is strongly influenced by the productivity of individual wells and by the combinations in which these wells are operated. This distinction is important because the present study addresses operational decisions for an existing well field rather than the design or construction of additional abstraction facilities.

The importance of well configuration and hydraulic interaction has been demonstrated in previous multi-well studies. Li et al. [25] developed an analytical–numerical method for optimizing the extraction layout of a riverside well field along the Luan River, China, examining river–well distance, inter-well spacing, and alternative intake configurations. Whereas their study addressed the design of a well field, the present investigation evaluates operating combinations within an existing RBF facility without changing its physical configuration. Related studies in geothermal groundwater systems examined alternative multi-well production and reinjection configurations [26] and showed that neglecting simultaneously operating wells can bias interpretation of interference tests [27]. These geothermal findings provide methodological analogies rather than direct evidence of RBF pumping behavior. Here, the calibrated groundwater-flow model represents the combined hydraulic response of selected collector wells, but the resulting differences also reflect their individual productivity and should not be attributed exclusively to hydraulic interference.

The scenario analysis further indicates that increasing the number of simultaneously operating wells does not necessarily provide a proportional increase in groundwater production. The best-performing two-well scenario produced $41,743 \text{ m}^3 \text{ day}^{-1}$, whereas the worst-performing four-well scenario produced only $44,359 \text{ m}^3 \text{ day}^{-1}$. Thus, operating twice as many wells yielded only a marginal increase in abstraction when an unfavorable combination was selected. Conversely, selecting combinations that account for both individual well productivity and potential hydraulic interactions resulted in more favorable modeled pumping performance. This finding emphasizes that the spatial and hydraulic relationships among wells must be considered alongside individual well capacity when determining pumping schedules for multi-well RBF systems. Unlike studies optimizing

well-field layouts by changing spacing or infrastructure [25], the present analysis shows that operating combinations within an unchanged configuration can have markedly different modeled abstraction capacities. Because the combinations also differ in individual well productivity, the observed contrasts cannot be assigned solely to well-to-well interference.

This operational perspective is consistent with previous wellfield-management studies showing that groundwater production can be improved through appropriate allocation and scheduling of pumping rather than by simply maximizing simultaneous abstraction [23]. However, such approaches have been less frequently examined for existing RBF facilities using long-term operational records. In the Gimhae RBF system, analysis of the 2018–2022 records first identified substantial differences in the contribution and productivity of individual collector wells, after which the calibrated groundwater-flow model was used to evaluate alternative operating combinations. The resulting well-grouping strategies yielded combined modeled abstraction capacities of approximately $94,000 \text{ m}^3 \text{ day}^{-1}$ on the common 24-h scenario basis. These modeled values represent comparative capacity indicators derived from the sum of two complementary 24-h scenarios and are therefore not directly equivalent to the arithmetic mean of the five annual average field abstraction rates ($54,548 \text{ m}^3 \text{ day}^{-1}$), which reflects actual operation with varying well combinations and operating durations. Nevertheless, the scenario-based comparison demonstrates that the selection and grouping of productive wells can substantially influence the abstraction capacity of the existing well field and provides a basis for developing improved field operating schedules.

These findings have important implications for existing RBF facilities experiencing declining or insufficient production. When actual abstraction remains below design expectations, increasing pumping intensity or adding new production wells may not necessarily represent the first or most efficient management response. Evaluating the performance of existing wells and their hydraulic interactions can reveal opportunities to improve production through changes in well grouping and operating schedules. Accordingly, operational management should be considered an integral component of maintaining the long-term performance of multi-well RBF systems, particularly where infrastructure expansion is constrained or where more efficient use of existing abstraction facilities is desirable.

4.2. Practical Framework for Operation Management

The results of this study provide a practical basis for developing an operational management framework for existing multi-well RBF systems. Rather than treating the installed pumping capacity as a fixed measure of system performance, the proposed approach accounts for the actual productivity of individual wells and their hydraulic interactions under different operating conditions. Previous groundwater-management studies have demonstrated that numerical groundwater models can support pumping allocation and wellfield management by evaluating alternative operational strategies [21–23]. Building on this concept, the framework proposed in this study integrates long-term operational records with groundwater-flow modeling and scenario-based evaluation, allowing operational decisions to be based on observed well performance and simulated responses of the well field.

The proposed framework can be organized into four sequential stages. First, long-term operational records are used to diagnose the performance of individual collector wells. Pumping history, operating frequency, groundwater levels, and river stages can be examined to identify wells with persistent productivity declines or abnormal operating behavior. In the present study, this initial screening identified W5, W7, and W8 as poorly performing wells and allowed subsequent analyses to focus on the six productive wells. This step is particularly important for existing RBF facilities because the current production

capacity of individual wells may differ substantially from their original design capacity after prolonged operation.

Second, a calibrated groundwater-flow model is used to characterize the hydraulic response of the productive well field. Once the model adequately represents observed groundwater levels and abstraction behavior, alternative combinations of operating wells can be systematically evaluated without disrupting actual water-supply operations. This provides a practical means of examining hydraulic interactions that would otherwise require numerous field pumping tests with different combinations of collector wells. The numerical model therefore serves not only as a representation of groundwater flow but also as an operational assessment tool for existing well fields.

Third, alternative multi-well operational scenarios are evaluated using performance indicators such as total groundwater abstraction, pumping performance per well, and hydraulic interaction among simultaneously operating wells. The scenario results can then be used to distinguish favorable and unfavorable well combinations. As demonstrated in this study, the number of operating wells alone was insufficient to determine operational performance; combinations involving the same number of wells produced substantially different abstraction rates. Scenario-based assessment therefore enables operators to identify well groups that use the available production capacity more effectively while limiting losses associated with mutual hydraulic interference.

Finally, operators can incorporate the selected well combinations into practical operating schedules and periodically reassess them as field conditions change. RBF well performance is not necessarily stationary because long-term operation may alter individual well productivity through clogging, changes in river-aquifer connectivity, or variations in groundwater conditions. The proposed framework should therefore be treated as an adaptive management process rather than a one-time optimization procedure. Updating the operational dataset and periodically reevaluating well combinations would allow operating strategies to be adjusted as the hydraulic performance of the well field evolves.

This framework differs from approaches focused primarily on well-field design or expansion because it emphasizes better use of existing infrastructure. For RBF facilities where actual production has declined below design expectations, combining operational monitoring with scenario-based groundwater modeling can provide an intermediate management option before considering additional wells, rehabilitation, or major infrastructure expansion. The framework is therefore particularly applicable to mature RBF systems with sufficient operational records, where water-supply performance can be improved through better allocation of existing abstraction capacity. Although the specific operating combinations identified for the Gimhae RBF system are site-dependent, the overall procedure—performance diagnosis, model-based scenario evaluation, selection of favorable well combinations, and periodic reassessment—provides a transferable approach for supporting the operational management of existing multi-well RBF systems.

4.3. Limitations and Future Work

Several limitations should be considered when interpreting the results of this study. First, the groundwater-flow model necessarily simplifies the spatial heterogeneity of the alluvial aquifer and the complex hydraulic connection between the river and aquifer. Although the model was calibrated using observed groundwater levels and pumping data, local variations in hydraulic properties around individual collector wells may not be fully represented. In addition, the steady-state modeling approach does not explicitly represent temporal variations in river stage, transient drawdown and recovery, or dynamic start-stop pumping conditions. The model was therefore used primarily to compare the relative hydraulic performance of alternative well combinations under a consistent hydraulic

condition rather than to reproduce time-dependent field operation. Consequently, the simulated differences among operating scenarios should be interpreted primarily as a basis for comparing relative operational performance rather than as exact predictions of time-varying abstraction rates. Future studies incorporating transient river-stage conditions and dynamic pumping schedules would be valuable for extending the proposed framework toward real-time or seasonally adaptive operation. Studies of multi-depth soil moisture responses [28] and seasonal runoff variability [29] further illustrate the broader importance of temporally varying hydrological conditions, although neither directly examines RBF well-field operation.

Second, the persistently low abstraction observed at W5, W7, and W8 was identified from long-term operational records, but its causes were not directly investigated. In laboratory column experiments simulating RBF, Hu et al. [13] reported reductions in hydraulic conductivity of 39.6–88.2% associated with physical and chemical clogging of filtration media. Dubuis and De Cesare [30] reviewed physical processes of riverbed clogging and their implications for permeability. However, riverbed and aquifer-media clogging must be distinguished from clogging of well screens and horizontal collector laterals. Jeong et al. [31] reviewed clogging mechanisms and rehabilitation approaches in aquifer storage and recovery systems, emphasizing the need to diagnose deterioration mechanisms before selecting rehabilitation measures. Neither these studies nor the present operational records establish whether screen clogging, riverbed clogging, aquifer heterogeneity, mechanical problems, or other factors caused the low abstraction at W5, W7, and W8. Therefore, this study focused on the remaining productive wells; future investigations should include well-performance tests, direct assessments of screen and lateral conditions, and before-and-after rehabilitation evaluations.

Third, the present analysis focused on abstraction capacity and hydraulic performance without explicitly evaluating water-quality responses. At an RBF site in Embaba, Cairo, Abd-Elaty et al. [32] used flow and transport modeling to examine how hydrological and operational conditions influence bank-filtrate contribution and travel time. Hoang et al. [33] reported variation in the feasibility and river-water contribution of RBF wells in Vietnam, while Nguyen et al. [10] examined groundwater–surface water interaction and the influence of seasonal conditions at a Vietnamese RBF site. These studies show that changes in pumping conditions can alter flow paths, river-water contribution, and residence times, all of which are relevant to water-quality protection. However, these hydraulic indicators do not by themselves establish contaminant removal performance. Accordingly, the combinations identified here should be interpreted as hydraulically favorable scenarios rather than fully optimized water-supply strategies. Future assessments should evaluate abstraction capacity together with bank-filtrate contribution, travel time, and measured water-quality indicators.

Finally, the recommended operating combinations identified in this study are specific to the hydrogeological conditions, well configuration, and operational characteristics of the Gimhae RBF system. Direct application of the same combinations to other RBF facilities is therefore not appropriate without site-specific evaluation. Nevertheless, the overall approach of using long-term operational data to diagnose well performance, calibrating a groundwater-flow model, evaluating alternative operating scenarios, and periodically updating the resulting strategy can be transferred to other multi-well RBF systems. Future research should evaluate this framework at additional RBF sites and extend it toward an adaptive decision-support approach in which operating strategies are periodically updated in response to changes in well productivity, river stage, groundwater conditions, and water-supply requirements.

5. Conclusions

This study evaluated the operational performance of the Gimhae multi-well river-bank filtration (RBF) system using long-term operational records from 2018–2022 and groundwater-flow modeling. Based on the field observations and numerical scenario analysis, the main conclusions are summarized as follows:

(1) Long-term operational performance differed substantially among individual collector wells. The actual groundwater production of the RBF facility remained substantially below its design abstraction capacity during 2018–2022. Long-term operational records showed clear differences in the contribution and productivity of individual wells, and six productive wells (W1, W2, W3, W4, W6, and W9) were selected for subsequent multi-well scenario analysis.

(2) Groundwater abstraction was strongly influenced by both the number and combination of simultaneously operating wells. The average pumping rate per well decreased from 16,593 m³ day^{−1} per well under two-well operation to 14,984 and 13,090 m³ day^{−1} per well under three- and four-well operations, respectively. Moreover, the best-performing two-well scenario produced 41,743 m³ day^{−1}, whereas the worst-performing four-well scenario produced 44,359 m³ day^{−1}. These results demonstrate that increasing the number of operating wells alone does not necessarily result in a proportional increase in groundwater production because hydraulic interaction and well combination also affect pumping performance.

(3) Model-based evaluation identified well-grouping strategies with favorable combined abstraction capacities. Under the common 24-h scenario framework, the optimal 2 + 4 grouping yielded the highest combined modeled abstraction capacity of 94,217 m³ day^{−1}, while the optimal 3 + 3 grouping yielded a comparable value of 93,902 m³ day^{−1}. These results demonstrate the potential benefit of selecting favorable combinations of the existing productive wells without expanding the abstraction infrastructure. The combined modeled capacities represent comparative model-based indicators rather than time-weighted predictions of realized daily production under a specific field operating schedule.

(4) Integrating long-term operational monitoring with groundwater-flow modeling provides a practical framework for managing existing multi-well RBF systems. The results indicate that operational decisions should consider individual well productivity and hydraulic interaction rather than relying solely on installed capacity or the number of operating wells. Although the specific well combinations identified in this study are site-dependent, the proposed approach of diagnosing long-term well performance, evaluating alternative operating combinations, and reorganizing well operation provides a transferable framework for improving the use of existing RBF infrastructure.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su182010572/s1>, Table S1: Simulated groundwater abstraction for 56 operational scenarios; Table S2: Evaluation of combined operating well-grouping strategies based on combined 24-h modeled abstraction capacity.

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Abbreviations

The following abbreviations are used in this manuscript:

RBF	Riverbank filtration
MODFLOW	Modular Finite-Difference Groundwater Flow Model
RIV	River Package
WEL	Well Package
Q_{sim}	Simulated pumping rate
Q_{obs}	Measured pumping rate obtained from the corresponding single-well pumping test

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