

Hydraulic response of well-based artificial recharge in a stratified aquifer considering screen configuration and inter-well interference

Zhenjie Zhang

Shandong Provincial Geo-mineral Engineering Exploration Institute (801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources)

Di Wang

202420840@mail.sdu.edu.cn

School of Civil Engineering, Shandong University

Liang Gong

Shandong Provincial Geo-mineral Engineering Exploration Institute (801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources)

Shuai Gao

Shandong Provincial Geo-mineral Engineering Exploration Institute (801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources)

Shasha Wu

Shandong Provincial Geo-mineral Engineering Exploration Institute (801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources)

Research Article

Keywords: Artificial recharge, Stratified aquifer, Screen–aquifer connectivity, Injection pressure, Hydraulic interference

Posted Date: October 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10983061/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Hydraulic response of well-based artificial recharge in a stratified aquifer considering screen configuration and inter-well interference

Highlights

- Screen–aquifer connectivity governs recharge capacity and flow partitioning
- Injection pressure primarily strengthens the hydraulic driving force for recharge
- Overlapping head fields cause spacing-dependent interference between recharge wells

Abstract

Artificial recharge is widely used to mitigate groundwater-level decline caused by construction dewatering, yet its performance in vertically stratified aquifers is jointly controlled by hydrostratigraphic heterogeneity, well-screen configuration, injection pressure, and hydraulic interaction among neighbouring wells. This study investigates well-based artificial recharge in a vertically stratified aquifer by integrating staged field recharge tests with field-constrained three-dimensional groundwater-flow modeling. The model explicitly represents the principal permeable strata, lower-permeability interbeds, and hydraulically active screened intervals, and introduces a lumped pressure-transfer relationship to account for hydraulic losses between the wellhead and aquifer. Calibration and cross-well evaluation show that the model captures the main pressure-dependent recharge trend across the investigated wells, while retaining site-specific deviations associated with local well–aquifer conditions. Simulations reveal a distinctly three-dimensional and vertically non-uniform hydraulic pattern, characterized by near-well radial spreading, preferential lateral migration through permeable strata, and restricted vertical exchange across lower-permeability layers. Increasing screen length enhances recharge capacity nonlinearly because it alters screen–aquifer connectivity and redistributes flow among aquifer units, whereas injection pressure primarily strengthens the hydraulic driving force through the available recharge pathways. Multi-well simulations further show that overlapping recharge-induced head fields elevate the ambient groundwater head around adjacent

31 wells, reduce the effective recharge gradient, and suppress individual-well capacity,
32 while this interference weakens with increasing spacing. These results demonstrate that
33 recharge-system performance in stratified urban aquifers depends on the coordinated
34 effects of screen–stratigraphy connectivity, hydraulic driving, and inter-well
35 interference, providing a physically grounded basis for recharge-system design and
36 operation during deep-excavation groundwater control.

37 **Keywords:** Artificial recharge; Stratified aquifer; Screen–aquifer connectivity;
38 Injection pressure; Hydraulic interference.

39

1. Introduction

Groundwater is an important component of urban and regional water-resource systems, providing water supply, subsurface storage, and hydraulic support for the surrounding environment. However, long-term groundwater abstraction and engineering dewatering associated with deep excavations can substantially disturb natural groundwater conditions, leading to groundwater-level decline, redistribution of groundwater flow, loss of groundwater storage, and, under susceptible geological conditions, ground deformation. Artificial recharge is an important means of groundwater replenishment and regulation because it can restore groundwater levels, compensate for groundwater losses, and mitigate the hydraulic impacts of pumping (Bouwer 2002; Dillon et al. 2019). Among available recharge methods, well-based recharge can deliver water directly to target aquifers and is particularly suitable where the aquifers are relatively deep, overlying low-permeability strata restrict surface infiltration, or urban land availability is limited. In deep-excavation projects, peripheral recharge wells can therefore operate together with construction dewatering to compensate for groundwater losses and reduce groundwater-level decline and associated environmental impacts (Zhang et al. 2017a; Zhang et al. 2017b; Zheng et al. 2018; Guo et al. 2022; Liu et al. 2022). The hydraulic performance of such systems is consequently governed not only by recharge operation but also by the interaction between well configuration and the local hydrogeological setting.

Well-based artificial recharge has been investigated extensively through field tests, well-hydraulic analyses, and groundwater-flow modeling (Zhang et al. 2017b; Cao et al. 2022). Recent studies have further emphasized that the performance of managed aquifer recharge depends strongly on adequate hydrogeological characterization together with appropriate system design and operation (Meles et al. 2024; Seidl et al. 2024). Field pumping–recharge tests in deep confined and semiconfined aquifers have demonstrated that appropriately designed recharge can effectively recover groundwater head and mitigate the impacts of construction dewatering, while also revealing substantial differences in hydraulic response among wells and between pumping and recharge processes (Zhang et al. 2017b; Zheng et al. 2018; Zeng et al. 2019a; Zeng et

al. 2019b). At the system scale, three-dimensional numerical models have been used to examine recharge-induced head fields, pumping–recharge interactions, and the effects of well configuration and spacing. Zhang et al. (2017a), for example, showed that recharge performance in multi-well pumping–recharge systems is closely related to well spacing, whereas Mukhopadhyay et al. (2022) demonstrated that well spacing, well construction, aquifer conditions, and operating strategy jointly control multi-well recharge performance. Beyond these operational controls, combined physical experiments and numerical simulations have shown that geological heterogeneity and spatial variability in hydraulic conductivity can substantially modify recharge-induced groundwater-flow patterns across scales (Wu et al. 2021; Wu et al. 2023). More recent studies have further shown that heterogeneity can channel injected water along preferential pathways and that permissible recharge rates depend on both hydrogeological conditions and well-design parameters (Kumar et al. 2025; Zhu et al. 2026). Taken together, these studies show that system-scale recharge performance is governed by the combined effects of well configuration, operating conditions, and aquifer heterogeneity. This system-scale perspective, however, does not by itself reveal how recharge is partitioned among individual screened intervals and hydraulically contrasting aquifer units.

At the individual-well scale, recharge behaviour is further governed by how the screened interval interacts with the surrounding hydrostratigraphy. Classical well-hydraulic analyses established that partial penetration and hydraulic contrasts between aquifer layers can substantially modify the three-dimensional flow field around a well (Javandel and Witherspoon 1980; Bakker 2001). Consistent with this principle, field and scenario analyses have shown that locating partially penetrating recharge wells within more permeable strata can improve recharge performance in construction-dewatering systems (van Lopik et al. 2020), while partial penetration and local permeability reduction can markedly alter well response (Li et al. 2020). The vertical position of lower-permeability layers relative to the active screen interval is likewise important because it controls hydraulic access to individual aquifer units and thereby affects recharge efficiency (Patton et al. 2023). Inter-aquifer leakage can further modify

well-injection capacity by altering hydraulic communication and head redistribution among adjacent aquifer units (Shandilya et al. 2022). Direct field measurements provide particularly clear evidence of this effect: Martinez and Widdowson (2024) observed pronounced differences in flow distribution among individual screened intervals of a multiaquifer recharge well, demonstrating that injected water is not necessarily distributed uniformly along the well depth. At a broader spatial scale, variations in hydraulic conductivity also influence the suitability of recharge-well locations and the resulting groundwater response (Poursalehi et al. 2022), while simulation–optimization studies of complex urban aquifer systems indicate that spatially variable hydraulic connections among aquifer units should be considered when locating injection wells (Mok et al. 2024). Collectively, these findings indicate that individual-well recharge capacity cannot be interpreted solely in terms of injection pressure or a single geometric parameter; rather, it reflects the coupled effects of hydraulic driving, screen–stratigraphy connectivity, and the surrounding aquifer system.

Despite this progress, several hydraulic processes in vertically stratified aquifers still require further quantitative investigation. First, previous studies of excavation-related recharge have mainly focused on groundwater-level recovery, mitigation of dewatering impacts, and overall pumping–recharge performance (Zheng et al. 2018; Guo et al. 2022; Liu et al. 2022). Although previous studies have established the importance of well configuration and hydrostratigraphic heterogeneity, the redistribution of recharge among individual aquifer layers as screen configuration changes has been less systematically quantified in field-constrained excavation recharge systems (Patton et al. 2023; Martinez and Widdowson 2024; Kumar et al. 2025; Zhu et al. 2026). Second, increasing screen length and increasing injection pressure can both enhance recharge, but they represent different hydraulic controls. Screen configuration determines the degree of hydraulic connection between the well and individual aquifer layers, whereas pressurization primarily increases the hydraulic driving force acting through the available recharge pathways. In addition, the pressure applied at the wellhead may not be transferred completely to the aquifer because hydraulic losses can occur within the well, screen, gravel pack, and near-well formation

(Guttman et al. 2017; Cao et al. 2022). Directly equating wellhead pressure with the effective hydraulic head acting on the aquifer may therefore oversimplify field recharge conditions. Third, the performance of a multi-well recharge system cannot be obtained by simply multiplying the capacity of an isolated well. Previous field and numerical studies have shown that well spacing influences recharge performance and that simultaneous injection can reduce individual-well capacity through hydraulic interference (Zhang et al. 2017a; Mukhopadhyay et al. 2022; Choi and Kim 2023). However, spacing-dependent hydraulic interference has rarely been examined together with screen–stratigraphy connectivity and effective pressure transmission within a field-constrained stratified aquifer system. Overall, relatively few field-constrained studies have jointly resolved screen–stratigraphy connectivity, effective pressure transmission, layer-resolved recharge partitioning, and spacing-dependent hydraulic interference within a consistent three-dimensional modeling framework.

To address these issues, this study integrates staged field recharge tests with field-constrained three-dimensional groundwater-flow modeling to investigate the hydraulic controls on well-based artificial recharge in a vertically stratified urban aquifer. The modeling framework explicitly accounts for hydrostratigraphic heterogeneity, hydraulically active screened intervals, and the transfer of applied wellhead pressure to the effective hydraulic head governing aquifer recharge. On this basis, three interrelated processes are examined: the three-dimensional propagation and preferential redistribution of recharge-induced groundwater flow within a stratified aquifer; the coupled effects of screen configuration and injection pressure on recharge capacity and layer-resolved flow allocation; and hydraulic interference between neighbouring recharge wells as a function of well spacing. By linking field observations with process-oriented modeling, this study clarifies how hydraulic driving, screen–stratigraphy connectivity, and inter-well interaction jointly govern recharge performance, providing a physically grounded basis for the design and operation of well-based artificial recharge systems in stratified aquifers.

2. Field recharge tests

2.1 Site and hydrogeological conditions

The field investigation was conducted at Yujiazhuang Station of Jinan Metro Line 6, China, where a deep excavation was constructed using the cut-and-cover method. The excavation depth was approximately 17.3–18.9 m, requiring continuous groundwater control during construction. Dewatering within the excavation lowers the local groundwater head and induces a hydraulic disturbance in the surrounding aquifer system. To compensate for groundwater loss and limit dewatering-induced groundwater-level decline, a peripheral well-based artificial recharge system was installed outside the excavation. The study area is located in Jinan, Shandong Province, China, as shown in Fig. 1(a).

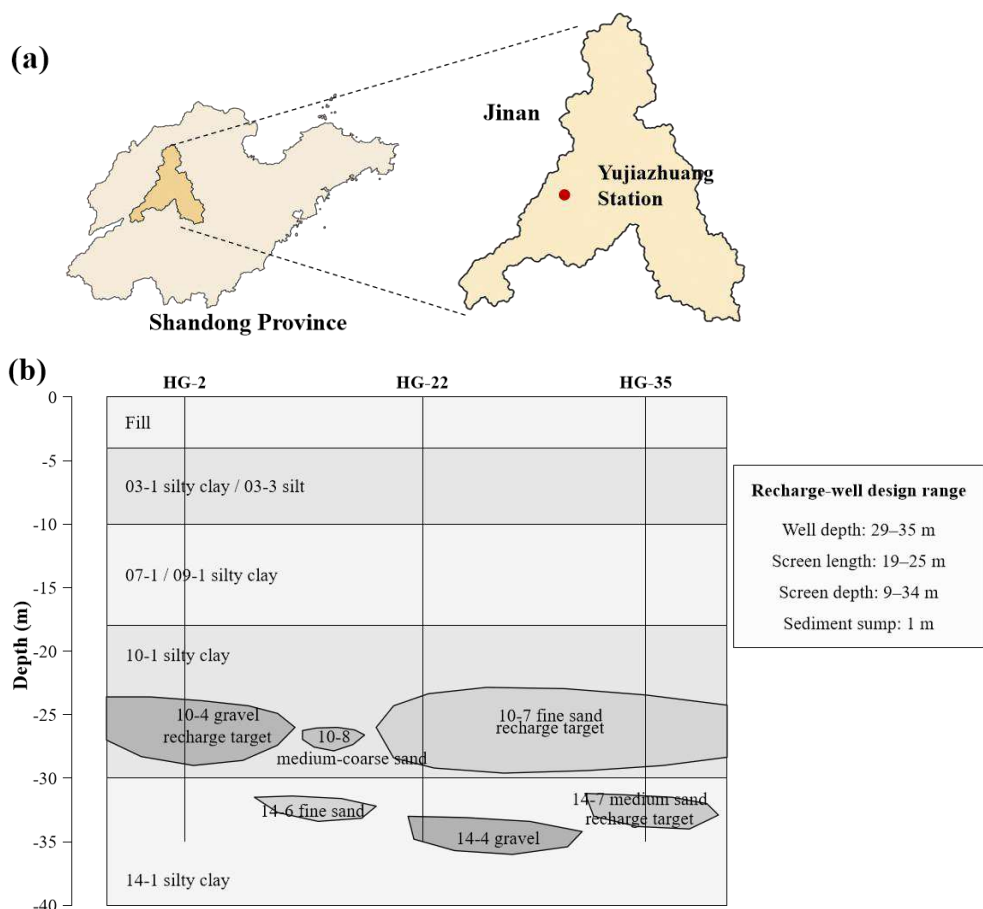


Fig. 1. Study location and hydrogeological conditions: (a) location of the study area in Jinan, Shandong Province, China; (b) representative hydrogeological profile showing the principal recharge-bearing strata, target layers, and recharge-well design range. The base map and administrative boundaries in (a) were redrawn from the Standard Map Service System of the Ministry of Natural Resources of the People's Republic of China; the administrative boundaries are shown for location reference only.

The Quaternary deposits at the site exhibit pronounced vertical stratification and lithological heterogeneity, as illustrated by the representative hydrogeological profile

in Fig. 1(b). The upper sequence is dominated by fill, silty clay, and silt, whereas several sand and gravel units occur at greater depths. These relatively permeable units are interbedded with lower-permeability fine-grained deposits and vary in thickness and lateral continuity, producing marked hydraulic contrasts along the well depth. The 10-4 gravel, 10-7 fine sand, and 14-7 medium sand layers were identified as the principal recharge target units, while the 10-8 medium-coarse sand, 14-6 fine sand, and 14-4 gravel layers constitute additional permeable strata within the screened depth range. The recharge wells are approximately 29–35 m deep, with screened intervals extending over depths of about 9–34 m, individual screen lengths of approximately 19–25 m, and a 1-m sediment sump at the well bottom. Because a single screened interval may intersect several hydraulically contrasting strata, the field configuration allows injected water to enter multiple aquifer units rather than a hydraulically uniform formation.

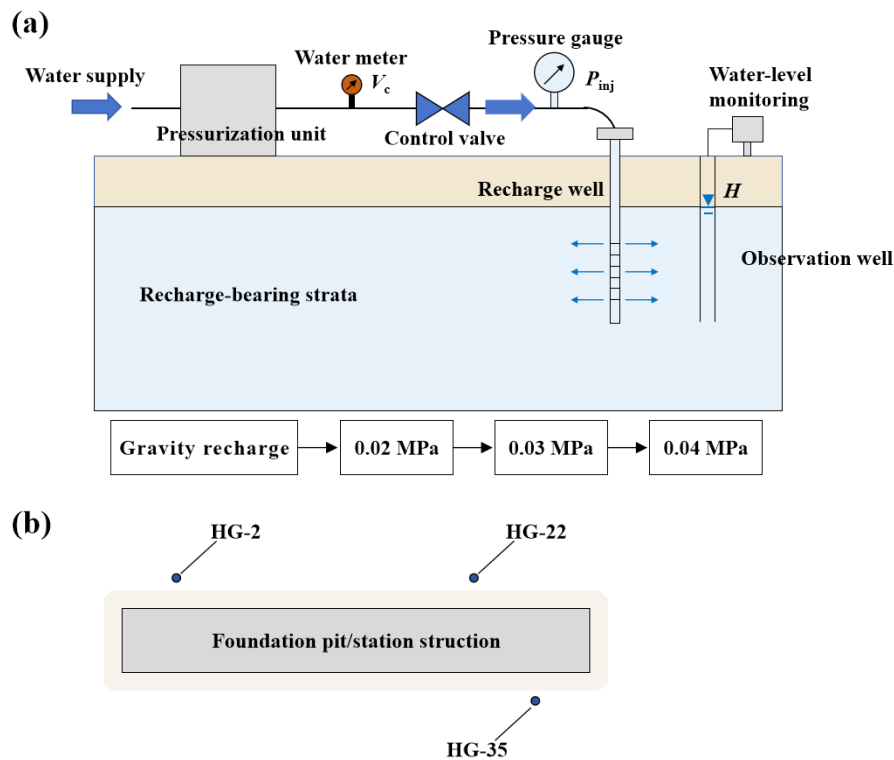


Fig. 2. Field recharge-test configuration: (a) schematic of the recharge-test system and staged loading procedure; (b) relative locations of the representative recharge wells with respect to the station excavation.

Staged single-well recharge tests were conducted at three representative recharge wells, HG-2, HG-22, and HG-35, with adjacent wells used for groundwater-level monitoring. The field recharge-test system and staged loading procedure are illustrated

schematically in Fig. 2(a), while the relative locations of the three representative recharge wells with respect to the station excavation are shown in Fig. 2(b). Each test began under gravity recharge and was subsequently conducted at applied wellhead pressures of 0.02, 0.03, and 0.04 MPa, with each pressure stage initiated after the preceding recharge response had approached a relatively stable condition. Cumulative recharge volume, applied wellhead pressure, and groundwater level in the corresponding observation well were recorded continuously throughout the tests. For each stage, a representative recharge rate was determined from the stabilized portion of the cumulative recharge-volume record. The same staged-loading sequence and data-processing procedure were adopted for all three recharge wells, providing a consistent field basis for comparing pressure-dependent recharge behaviour at different locations.

2.2 Observed recharge responses

The field measurements show a clear pressure-dependent increase in recharge capacity at all three representative wells, together with a measurable groundwater-head response in the adjacent observation wells. As shown in Fig. 3(a–c), cumulative recharge volume V_c increased continuously during each test, while the slope of the V_c -time curve increased as the applied pressure was raised, indicating progressively greater well intake rates under stronger hydraulic driving. Under gravity recharge, the mean recharge rates of HG-2, HG-22, and HG-35 were 20.82, 19.65, and 20.70 $\text{m}^3 \cdot \text{h}^{-1}$, respectively. At an applied pressure of 0.04 MPa, the corresponding rates increased to 36.65, 38.08, and 47.51 $\text{m}^3 \cdot \text{h}^{-1}$, representing increases of approximately 76–130 % relative to the gravity-recharge condition. The groundwater level in each adjacent observation well also responded after recharge commenced, with a comparatively rapid initial change followed by a more gradual evolution as the local hydraulic disturbance developed. These observations demonstrate that increasing wellhead pressure enhances recharge capacity while simultaneously modifying the surrounding groundwater-head field.

A comparison among the three representative wells further reveals marked spatial variability in the magnitude of the recharge response, as summarized in Fig. 3(d). The

three wells exhibited broadly similar recharge rates under gravity conditions, whereas their responses became increasingly differentiated as the applied pressure increased. In particular, HG-35 showed the strongest pressure-induced increase in recharge rate at the higher pressure stages, while HG-2 and HG-22 exhibited comparatively more moderate responses. Thus, comparable increases in applied wellhead pressure did not produce identical increments in recharge capacity at different well locations. This spatial variability indicates that the hydraulic effect of pressurization is conditioned by local well–aquifer characteristics, including the hydraulic connection between the active screen and the surrounding permeable strata. The field observations therefore provide both the pressure-dependent recharge characteristics and the cross-well variability required for subsequent evaluation and interpretation using the three-dimensional groundwater-flow model.

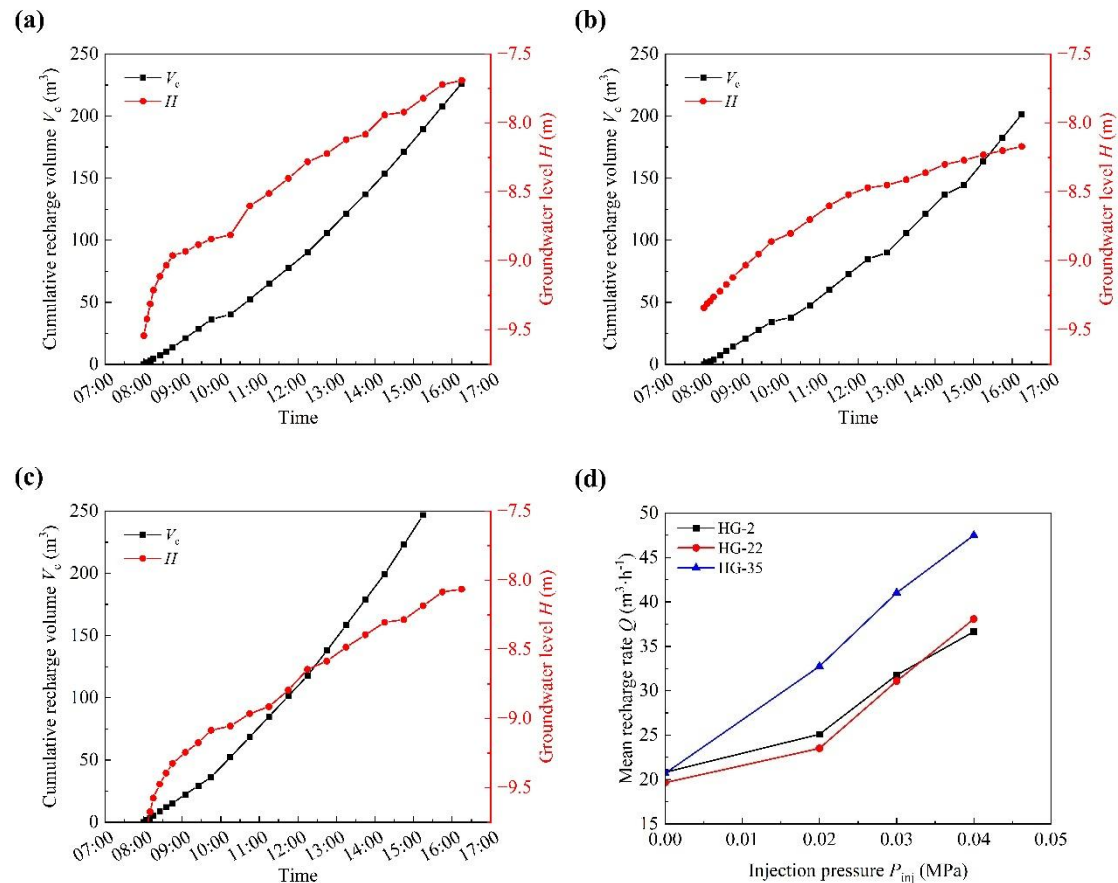


Fig. 3. Field responses during staged single-well recharge tests: (a) HG-2; (b) HG-22; (c) HG-35; and (d) comparison of mean recharge rates among the three representative wells under different injection pressures.

3. Three-dimensional numerical modeling of artificial recharge

3.1 Model geometry and hydrostratigraphic representation

A three-dimensional groundwater-flow model was established based on the site hydrogeology and recharge-well layout to simulate recharge-induced flow and head redistribution within the stratified aquifer system. The model geometry and principal hydrostratigraphic units are illustrated in Fig. 4. The computational domain has a horizontal extent of 120 m $\times$ 100 m and a vertical thickness of 50 m. In plan view, the model encompasses the representative recharge-well area and the surrounding groundwater-affected domain, while the vertical extent incorporates the principal aquifers involved in artificial recharge together with the adjacent low-permeability strata. Rather than representing the site as a single homogeneous aquifer, the model preserves the dominant vertical hydraulic stratification observed in the field so that recharge water can migrate differently through units with contrasting transmissive capacities. The lateral extent of the computational domain was selected to minimize the influence of the artificial outer boundaries on the hydraulic response around the recharge wells.

The complex Quaternary succession was hydrostratigraphically simplified according to lithology, hydraulic characteristics, and functional relevance to the recharge process. Sand and gravel strata were explicitly represented as the principal transmissive units. In particular, the main recharge target layers identified in the field—the 10-4 gravel, 10-7 fine sand, and 14-7 medium sand units—were incorporated into the simplified hydrostratigraphic representation according to their depth, hydraulic characteristics, and relevance to recharge. The intervening fine-grained strata were incorporated as comparatively less transmissive units that restrict vertical hydraulic exchange between the principal recharge-bearing intervals. This representation avoids a direct layer-by-layer reproduction of all geotechnical subdivisions while retaining the hydraulic contrasts most relevant to artificial recharge, namely preferential lateral migration through permeable sand and gravel layers and cross-layer exchange constrained by less permeable interbeds. Explicit representation of these hydraulic contrasts is consistent with previous recharge studies showing that aquifer stratification and the relative position of hydraulically active well intervals can substantially affect

recharge-induced groundwater response and well intake capacity (Zhang et al. 2017b; Kumar et al. 2025). The hydraulic parameters assigned to the individual hydrostratigraphic units were determined from site-investigation and field-test information and are summarized in Table 1. These parameters were retained unchanged during subsequent model evaluation rather than being adjusted independently for individual recharge tests.

Table 1. Hydrostratigraphic representation and hydraulic properties used in the numerical model.

Model layer	Depth range (m)	Hydrostratigraphic representation	Hydraulic conductivity K ($\text{m}\cdot\text{d}^{-1}$)
Layer I	0 to -4	Near-surface equivalent unit	5
Layer II	-4 to -20	Upper fine-grained-dominated unit	6.59
Layer III	-20 to -30	Principal recharge-bearing unit	14
Layer IV	-30 to -34	Lower recharge-bearing/interbedded unit	12
Layer V	-34 to -46	Deeper transmissive unit	14
Layer VI	-46 to -50	Basal lower-transmissivity unit	4

Note: Each model layer represents a hydrostratigraphically simplified interval rather than an individual geotechnical stratum; hydraulic conductivity was assumed isotropic within each model layer. The listed hydraulic conductivities are field-scale equivalent values assigned to the simplified hydrostratigraphic intervals and should not be interpreted as intrinsic conductivities of individual lithological sublayers.

The field recharge system comprised a total of 39 recharge wells installed along the northern and southern sides of the excavation, with well spacing ranging from approximately 7 to 16.5 m. Depending on the burial depths of the target aquifers, five well depths of 29, 30, 31, 32, and 35 m were adopted in the field. The screened intervals extended over depths of approximately 9–34 m, with individual screen lengths ranging from 19 to 25 m. The recharge wells were constructed with a borehole diameter of 650 mm and a steel casing and bridge-screen diameter of 273 mm, with a 1-m-long sediment sump at the well bottom. In the numerical model, the representative recharge well was

explicitly represented according to this field geometry. Hydraulic exchange with the surrounding formation was permitted only along the screened interval, whereas the unscreened casing was treated as hydraulically inactive with respect to recharge. This representation enables injected water to enter different hydrostratigraphic units according to the overlap between the screen and the permeable layers. Such treatment is essential because the subsequent analyses address not only the total recharge capacity but also the redistribution of recharge among aquifer layers caused by changes in screen configuration and the spatial superposition of recharge-induced head fields during multi-well operation. The resulting model therefore preserves the principal geometric and hydrostratigraphic controls observed at the site while simplifying local details that do not materially affect the recharge process.

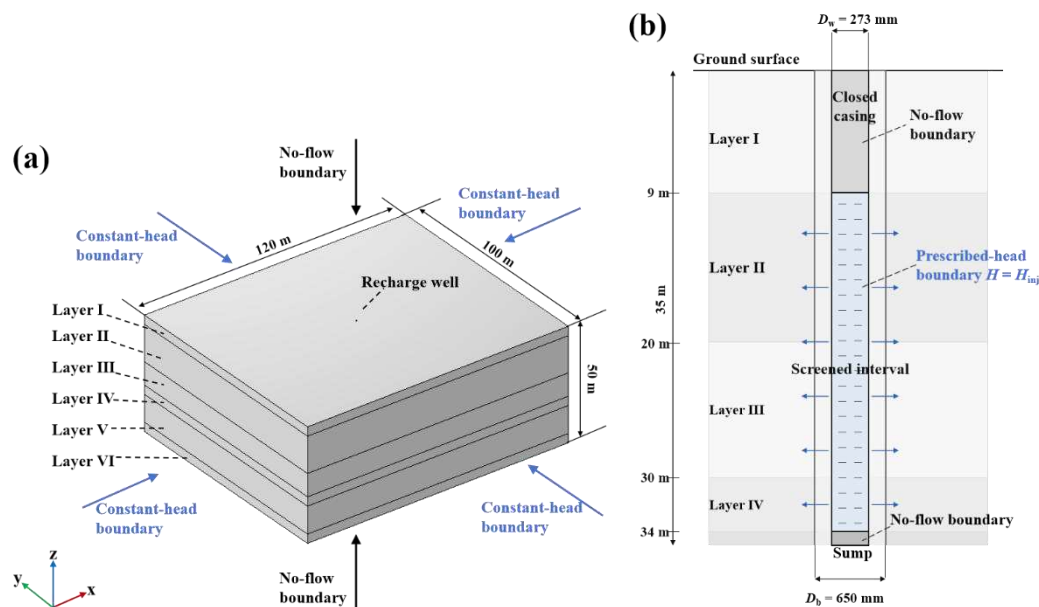


Fig. 4. Numerical model configuration and recharge-well boundary conditions: (a) overall three-dimensional model domain and constant-head boundaries; (b) local recharge-well structure and hydraulic boundary conditions.

3.2 Hydraulic formulation and boundary conditions

Groundwater flow within the model domain was described as three-dimensional saturated flow through porous media. The numerical analyses focused on the stabilized hydraulic response attained under each recharge condition; therefore, the groundwater-flow field was treated as steady state. According to Darcy's law, the Darcy flux is expressed as

$$\mathbf{q} = -\mathbf{K}\nabla H \quad (1)$$

where $\mathbf{q}$ is the Darcy-flux vector, $\mathbf{K}$ is the hydraulic conductivity, and H is the hydraulic head. Combining Darcy's law with mass conservation gives the governing equation

$$\nabla \cdot (\mathbf{K}\nabla H) = 0 \quad (2)$$

The hydraulic parameters listed in Table 1 were kept unchanged among all recharge simulations. Consequently, differences among the simulated hydraulic responses were attributed to changes in recharge conditions and well configuration rather than to case-specific adjustment of formation properties. This treatment is consistent with the hydrostratigraphic representation described in Section 3.1, in which the principal permeable sand and gravel units provide preferential pathways for recharge-water migration, whereas the intervening fine-grained strata restrict hydraulic exchange between adjacent aquifers.

The external hydraulic boundaries were specified according to the local groundwater setting and the dimensions of the computational domain shown in Fig. 4(a). Constant-head conditions were imposed on the four lateral boundaries to represent the far-field groundwater environment, whereas the upper and lower boundaries were treated as no-flow boundaries. Excavation dewatering was not represented as a separate pumping boundary in the present recharge-focused simulations. Instead, the model was formulated in terms of hydraulic-head differences relative to the prescribed far-field condition, while the well-specific gravity-recharge stages were used to define the corresponding baseline screen heads. The horizontal dimensions of the computational domain were selected to maintain sufficient separation between the recharge well and the artificial lateral boundaries, thereby limiting their influence on the near-well hydraulic response. Within the recharge well, hydraulic exchange with the surrounding formation was permitted only along the screened interval. The closed casing above the screen and the lower sump section were treated as hydraulically inactive and were therefore assigned no-flow conditions. Under this representation, recharge water can enter the formation only through the active screen, and its subsequent distribution is governed by the imposed screen head together with the hydraulic properties and vertical

positions of the hydrostratigraphic units intersected by the screen.

A prescribed-head boundary was applied along the screened interval to represent both gravity and pressurized recharge, as illustrated in Fig. 4(b). The pressure measured at the wellhead was not transferred directly to the screen boundary because part of the applied pressure is dissipated through the well, screen, gravel pack, and near-well flow zone before being transmitted to the surrounding formation. Such head losses are affected by well-screen geometry, discharge rate, filter-pack hydraulic properties, and near-well flow conditions, and can therefore cause the hydraulic head acting on the aquifer to differ appreciably from the pressure measured at the wellhead (van Lopik et al. 2021; Bayer - Raich et al. 2022; Cao et al. 2022). A lumped pressure-transfer coefficient, η_p , was therefore introduced to represent the effective transfer of the applied wellhead pressure to the hydraulic head acting along the screened interval. For recharge well j , the prescribed screen head was expressed as

$$H_{inj,j} = H_{g,j} + \eta_p \frac{P_{inj}}{\rho_w g} \quad (3)$$

where $H_{inj,j}$ is the prescribed hydraulic head along the screened interval of well j , $H_{g,j}$ is the corresponding baseline screen head under gravity recharge, P_{inj} is the applied wellhead pressure, ρ_w is the density of water, and g is gravitational acceleration. The gravity-recharge term is retained because measurable recharge occurs even when no external pressure is applied. Accordingly, $P_{inj} = 0$ represents gravity recharge rather than a zero-recharge condition. The second term in Eq. (3) represents the additional effective hydraulic head transmitted to the screened interval during pressurization. The coefficient η_p is therefore an equivalent parameter for the combined hydraulic losses of the well–screen–near-well system rather than an intrinsic hydraulic property of an individual aquifer layer.

The gravity-recharge stage of each field test was first used to determine the well-specific baseline screen head $H_{g,j}$ by matching the simulated recharge rate to the corresponding measured gravity-recharge rate. The subsequent pressurized stages of HG-2 were then used to calibrate the common pressure-transfer coefficient η_p . After

calibration, the same pressure-transfer coefficient and formation hydraulic properties were applied to HG-22 and HG-35 without further adjustment to their pressurized stages; only the well-specific $H_{g,j}$ was determined from the corresponding gravity-recharge condition. This procedure accounts for differences in the local baseline hydraulic conditions among the three wells while retaining a common pressure-transfer relationship across the site. The resulting cross-well comparison therefore evaluates whether the calibrated pressure-response relationship can be transferred to other well locations without independently fitting their pressurized responses. The four lateral boundaries were prescribed with a reference far-field head of $H_{\text{far}} = 0$ m. Here, $H_{\text{far}} = 0$ m defines the hydraulic-head datum used in the model and should not be interpreted as the absolute groundwater elevation measured in the field. The resulting gravity-recharge baseline screen heads were $H_{g,j} = 2.536, 2.394$, and 2.521 m for HG-2, HG-22, and HG-35, respectively.

For each simulation, the total recharge rate was calculated by integrating the Darcy flux over the complete hydraulically active screen surface,

$$Q = -\int_{\Gamma_{\text{scr}}} \mathbf{q} \cdot \mathbf{n} dA \quad (4)$$

where Γ_{scr} denotes the screened surface and $\mathbf{n}$ is the outward unit normal vector of the groundwater-flow domain. With this sign convention, positive Q represents water entering the formation from the recharge well. To resolve the vertical redistribution of recharge among the stratified aquifers, the flux through the portion of the screen intersecting each hydrostratigraphic unit was also integrated separately. The recharge contribution of layer k can therefore be expressed as

$$Q_k = -\int_{\Gamma_{\text{scr},k}} \mathbf{q} \cdot \mathbf{n} dA \quad (5)$$

$$Q = \sum_k Q_k \quad (6)$$

where $\Gamma_{\text{scr},k}$ is the part of the screened surface hydraulically connected to layer k . This layer-resolved flux calculation provides the quantitative basis for distinguishing an increase in total recharge capacity from a redistribution of flow among different aquifer units when the screen configuration is changed.

Model performance was evaluated by comparing simulated and field-measured

recharge rates under the staged recharge conditions. The mean absolute percentage error (MAPE) was used as the quantitative evaluation metric,

$$\text{MAPE} = \frac{100}{N} \sum_{i=1}^N \left| \frac{Q_{\text{sim},i} - Q_{\text{obs},i}}{Q_{\text{obs},i}} \right| \quad (7)$$

where $Q_{\text{sim},i}$ and $Q_{\text{obs},i}$ are the simulated and observed recharge rates under the i -th recharge condition, respectively, and N is the number of compared conditions. The calibration and cross-well evaluation were completed before the subsequent parametric analyses, and the calibrated hydraulic representation was retained unchanged thereafter. In this way, the analyses of screen configuration, injection pressure, and well spacing were conducted using a common model basis rather than through separate parameter fitting for individual simulation cases. Unless otherwise stated, the subsequent mechanistic and parametric analyses used the calibrated HG-2 configuration as the reference case.

Following model evaluation, the calibrated model was first used to characterize the three-dimensional hydraulic response under the representative pressurized-recharge condition of $P_{\text{inj}} = 0.04$ MPa. Recharge-induced head rise was defined as $\Delta H = H - H_0$, where H_0 denotes the background hydraulic head before artificial recharge under the same external boundary conditions. Hydraulic-head distributions and Darcy-velocity fields were then extracted from vertical and horizontal sections to examine the spatial propagation of the recharge disturbance, preferential migration through the more permeable strata, and restricted vertical exchange across the lower-permeability units. These simulations were intended to establish the spatial hydraulic mechanism underlying the subsequent parameter analyses rather than to evaluate recharge capacity solely from the integrated well flow.

The influence of screen configuration was then investigated by varying the total screen length while keeping the screen centre fixed at $z_c = -21.5$ m. Four screen lengths, $L_{\text{scr}} = 10, 15, 20$, and 25 m, were considered. The 10 and 15 m cases were introduced as controlled shorter-screen scenarios for sensitivity analysis, whereas the 20 and 25 m cases fall within the field design range. The screen was extended symmetrically upward and downward about the fixed centre so that the effect of screen length could be

examined without simultaneously changing its central elevation. Because the surrounding formation is vertically stratified, each increase in L_{scr} changes not only the total active screen area but also the degree of hydraulic connection between the recharge well and individual aquifer layers. For this reason, both the total recharge rate and the layer-resolved recharge contributions defined by Eq. (5) were evaluated. This simulation design allows the hydraulic effect of screen extension to be interpreted in terms of screen–aquifer connectivity and vertical flow partitioning rather than simply as an increase in infiltration area.

The combined effects of screen configuration and injection pressure were subsequently examined using injection pressures of $P_{inj} = 0, 0.02, 0.03, \text{ and } 0.04 \text{ MPa}$ for each investigated screen length. All formation properties and external hydraulic boundaries were kept unchanged. This set of simulations was designed to distinguish the two hydraulic roles of the investigated variables: screen length modifies the effective hydraulic connection and flow-transmission capacity between the well and the layered aquifer system, whereas injection pressure modifies the hydraulic driving force acting through the available recharge pathways. Comparison among the resulting pressure–recharge relationships therefore provides a basis for determining whether pressure and screen length act primarily as complementary controls or produce a pronounced nonlinear interaction within the investigated range.

Finally, the calibrated single-well model was extended to a two-well configuration to quantify hydraulic interference between neighbouring recharge wells. The two wells were assigned the same geometry and operating condition, and their centre-to-centre spacing was varied as $S = 7, 10, 12, 15, 16.5, 20, 25, \text{ and } 30 \text{ m}$. For all spacing cases, the midpoint of the well pair was fixed at the model centre, with the two wells positioned symmetrically along the x direction. The formation properties, screen configuration, recharge pressure, and external hydraulic boundaries were otherwise kept unchanged. This arrangement isolates the influence of spacing on the overlap of the recharge-induced head fields. When the two wells are sufficiently close, the head rise generated by one well increases the ambient hydraulic head around the neighbouring screen and thereby reduces the effective hydraulic gradient available for

recharge. To quantify the reduction in pair recharge capacity relative to two hydraulically isolated wells, the retained recharge capacity was defined as

$$R_Q = \frac{Q_{\text{pair}}}{2Q_{\text{single}}} \times 100\% \quad (8)$$

where Q_{pair} is the combined recharge rate of the two simultaneously operating wells and Q_{single} is the recharge rate of an isolated well under the same hydraulic and geometric conditions. A value of $R_Q = 100\%$ therefore represents hydraulically independent operation, whereas $R_Q < 100\%$ indicates a reduction in recharge capacity caused by inter-well interference. The resulting simulations provide a common numerical basis for examining recharge-induced groundwater redistribution, screen–aquifer connectivity, pressure-controlled hydraulic driving, and spacing-dependent well interference within the stratified aquifer system.

4. Results and discussion

4.1 Model calibration and cross-well evaluation

The HG-2 field test was used to calibrate the pressure-transfer coefficient, with the gravity-recharge condition defining the well-specific baseline head and the pressurized stages constraining the incremental pressure response. The resulting coefficient was $\eta_p = 0.4315$. As shown in Fig. 5(a), the calibrated model reproduces both the non-zero recharge capacity under gravity recharge and the overall increase in recharge rate with injection pressure, with a MAPE of 3.98 %.

The calibrated pressure-transfer coefficient and formation hydraulic properties were subsequently applied to HG-22 and HG-35 without further adjustment to the pressurized stages; only the local baseline head was determined from the corresponding gravity-recharge condition. As shown in Fig. 5(b), the model captures the pressure-dependent response of HG-22 reasonably well, yielding a MAPE of 6.69 %. A larger discrepancy is observed for HG-35, as shown in Fig. 5(c), for which the measured recharge capacity increases more rapidly with pressure and the unified model tends to underpredict the high-pressure response, resulting in a MAPE of 15.99 %.

The deviation observed for HG-35 indicates that the unified pressure-transfer representation can reproduce the dominant site-scale pressure–recharge behaviour but

cannot fully resolve local hydraulic differences among individual wells. Such differences may arise from variations in the actual overlap between the screened interval and highly permeable sand–gravel layers, local aquifer heterogeneity, and near-well hydraulic connectivity (Cao et al. 2022; Martinez and Widdowson 2024). Accordingly, the comparisons in Fig. 5(a–c) are used to assess the cross-well transferability and associated uncertainty of the calibrated pressure-response representation rather than to demonstrate point-by-point agreement for every individual well. The evaluated model is therefore used in the following analyses to investigate recharge-induced groundwater redistribution, screen-configuration effects, pressure–screen interactions, and multi-well hydraulic interference.

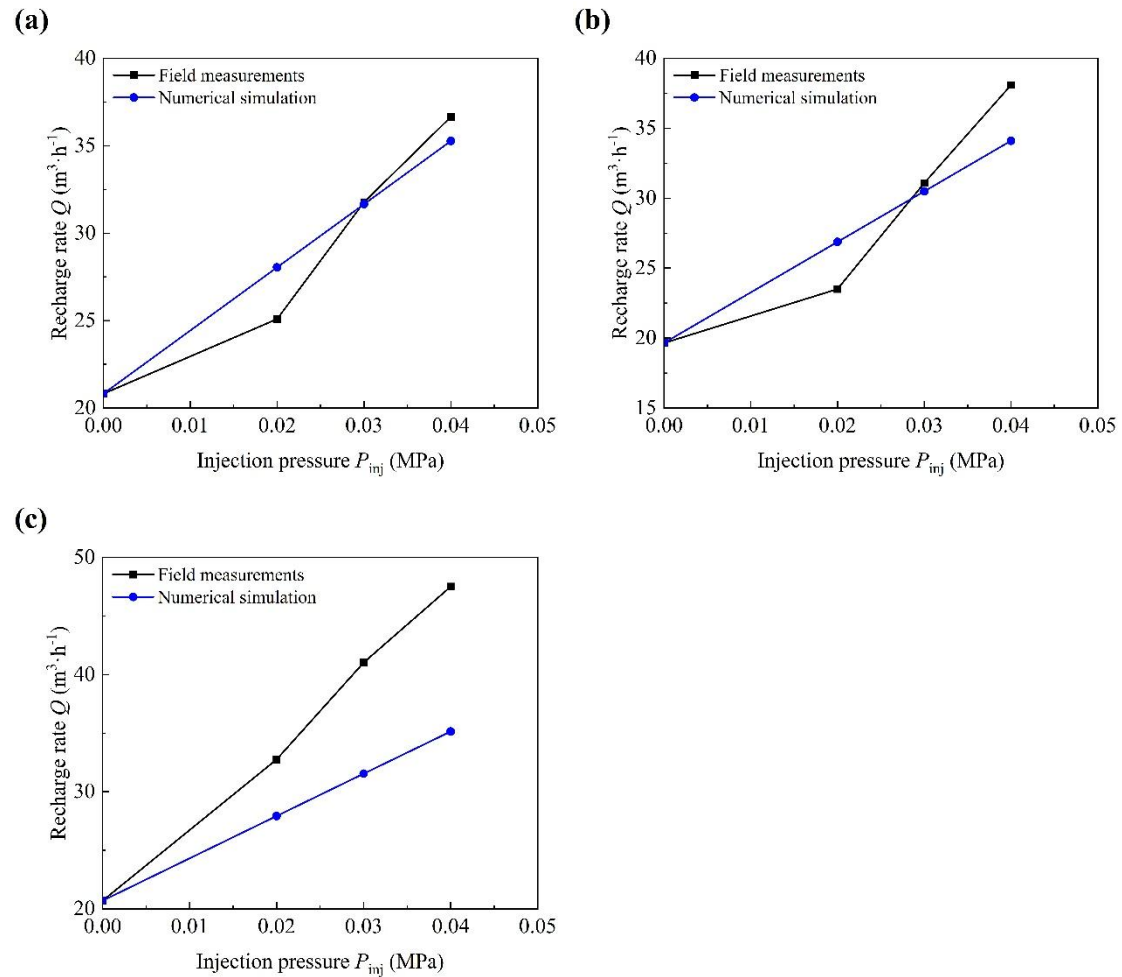


Fig. 5. Comparison between measured and simulated single-well recharge rates under different injection pressures: (a) HG-2; (b) HG-22; and (c) HG-35.

4.2 Spatial redistribution of recharge-induced groundwater head and flow

The evaluated numerical model was used to examine the spatial redistribution of

groundwater head and flow under the representative pressurized-recharge condition of $P_{inj} = 0.04$ MPa. As shown in Fig. 6(a), the vertical section through the recharge well exhibits a strongly non-uniform response controlled jointly by the screened interval and the hydrostratigraphic structure. A narrow high-head zone develops immediately adjacent to the screen because the prescribed well head creates a strong local hydraulic gradient, while the head rise decreases rapidly with distance from the well. The Darcy-velocity vectors indicate that injected water is transmitted predominantly outward from the screened interval and spreads mainly laterally through the surrounding formation. The strongest flow occurs where the screen intersects the more permeable units, whereas vertical exchange across the intervening lower-permeability layers is comparatively restricted. Below the lower end of the screen, part of the injected water is redistributed downward before spreading laterally within the deeper formation, producing a broader but substantially weaker response. These features show that recharge water does not migrate uniformly along the well depth. Instead, the resulting flow field reflects the combined effects of local radial spreading near the screen and preferential transmission through hydraulically favourable strata. This preferential hydraulic response is consistent with observations and modeling studies showing that recharge through a screened well can be strongly redistributed among aquifer intervals according to their hydraulic properties and connection with the active screen (Kumar et al. 2025).

In Fig. 6(b), the horizontal section at $z = -25$ m provides a complementary view of the lateral propagation of the recharge disturbance. The largest head rise remains concentrated around the well, while successive contours expand outward and decrease continuously in magnitude. In the near-well region, the approximately concentric contours indicate a quasi-radial response within the aquifer plane. With increasing distance, the hydraulic gradient progressively decreases, and the localized high-head disturbance develops into a broader zone of relatively weak head rise. No pronounced directional distortion is observed within the main recharge-affected region, suggesting that the near-well response is dominated by recharge-induced spreading rather than by the rectangular far-field boundaries. Compared with the vertical section, the head

perturbation extends substantially farther within the permeable aquifer plane than across the vertically layered sequence, reflecting the contrasting roles of transmissive aquifer units and lower-permeability interbeds in controlling lateral and vertical hydraulic propagation (Cihan et al. 2011).

Taken together, Figs. 6(a) and 6(b) demonstrate that the hydraulic influence of artificial recharge is controlled not only by the magnitude of the near-well head rise but also by the spatial extent over which the disturbance is transmitted through hydraulically connected strata. The high-head response remains concentrated near the active screen, whereas a lower-amplitude perturbation propagates over a much wider lateral area within the principal permeable layers. This distinction is important for recharge-system design because the broader lateral disturbance determines the range over which neighbouring wells may begin to interact hydraulically. The spatial response identified here therefore provides the physical basis for the subsequent analyses of screen configuration, pressure effects, and inter-well interference.

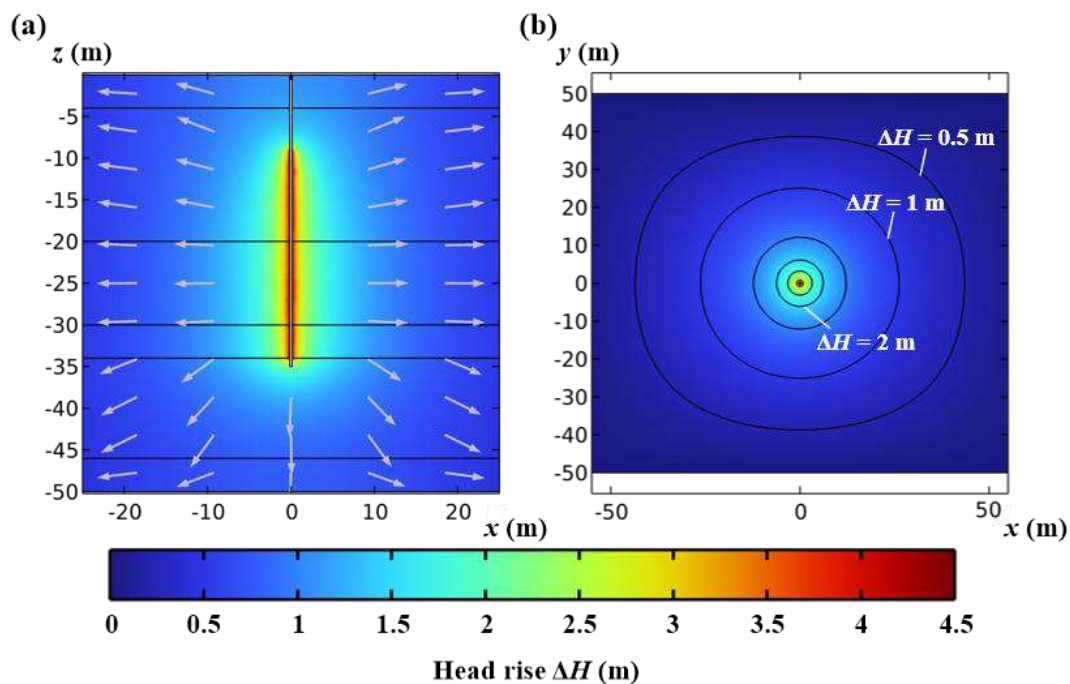


Fig. 6. Simulated groundwater response under the representative pressurized recharge condition ($P_{inj} = 0.04$ MPa): (a) vertical distribution of recharge-induced head rise and Darcy flow around the recharge well; (b) horizontal distribution of recharge-induced head rise in the principal aquifer at $z = -25$ m within Layer III.

4.3 Effects of screen configuration and injection pressure on recharge performance

To isolate the influence of screen length from that of screen elevation, the screen centre was fixed at $z_c = -21.5$ m and the total screen length L_{scr} was varied symmetrically from 10 to 25 m under the representative pressurized-recharge condition of $P_{inj} = 0.04$ MPa. All formation properties, well parameters, and external hydraulic boundaries were kept unchanged. As shown in Fig. 7(a), increasing L_{scr} produces a clear enhancement in total recharge capacity, with Q increasing from 20.21 to 35.22 $\text{m}^3 \cdot \text{h}^{-1}$, corresponding to an overall increase of approximately 74 %. However, the increase is distinctly nonlinear. The incremental recharge gain is 4.45 $\text{m}^3 \cdot \text{h}^{-1}$ from 10 to 15 m, increases to 6.70 $\text{m}^3 \cdot \text{h}^{-1}$ from 15 to 20 m, and then decreases to 3.86 $\text{m}^3 \cdot \text{h}^{-1}$ from 20 to 25 m. Expressed per metre of additional screen, the corresponding gains are approximately 0.89, 1.34, and 0.77 $\text{m}^3 \cdot \text{h}^{-1} \cdot \text{m}^{-1}$, respectively. The hydraulic benefit of screen extension therefore depends strongly on the hydrostratigraphic units intersected by the newly activated portions of the screen rather than on added screen length alone. This is particularly evident for the increase in L_{scr} from 15 to 20 m, which activates an additional 2.5 m of screen above and below the fixed centre.

The upward extension increases the hydraulic connection with Layer II, whereas the downward extension increases the overlap with Layer III and begins to intersect Layer IV. The relatively large recharge gain over this interval therefore reflects the combined contribution of newly connected hydraulic pathways rather than a simple proportional response to increased screen area. The layer-resolved flow partition provides the mechanism underlying this nonlinear behaviour, as shown in Fig. 7(b). At $L_{scr} = 10$ and 15 m, recharge is distributed only between Layers II and III, with Layer III carrying approximately three quarters of the total flow. This dominance reflects both the relatively large overlap of the active screen with Layer III and the high hydraulic acceptance capacity of this permeable unit. When the screen is extended to 20 m, Layer IV becomes hydraulically connected to the well and contributes 14.02 % of the total recharge, while the contributions of Layers II and III are 26.48 % and 59.5 %, respectively. At $L_{scr} = 25$ m, Layer IV fraction increases further to 22.98 %, whereas the Layer III fraction decreases to 49.20 % even though the total well recharge rate continues to increase. The absolute flows show the same redistribution more clearly.

Recharge through Layer III increases from $15.58 \text{ m}^3 \cdot \text{h}^{-1}$ at 10 m to $18.66 \text{ m}^3 \cdot \text{h}^{-1}$ at 20 m, but decreases to $17.33 \text{ m}^3 \cdot \text{h}^{-1}$ at 25 m. Between $L_{\text{scr}} = 20$ and 25 m, the contribution of Layer IV increases from 4.40 to $8.09 \text{ m}^3 \cdot \text{h}^{-1}$, while that of Layer II increases from 8.30 to $9.80 \text{ m}^3 \cdot \text{h}^{-1}$. Screen extension therefore does not simply add independent infiltration area. Instead, it changes the hydraulic connection between the well and the surrounding stratified aquifer and redistributes the imposed recharge among competing flow pathways. Consequently, the contribution of an individual aquifer can decrease even while the total recharge capacity increases. This behaviour is consistent with previous studies showing that partial penetration and screen configuration can alter the groundwater-flow field and redistribute recharge among hydraulically connected aquifer intervals rather than producing a recharge increase proportional to screen length alone (Li et al. 2020; Martinez and Widdowson 2024). The reduced marginal gain beyond $L_{\text{scr}} = 20$ m further indicates that screen length alone is not an adequate measure of recharge efficiency; the vertical placement of the active screen relative to transmissive strata is equally important.

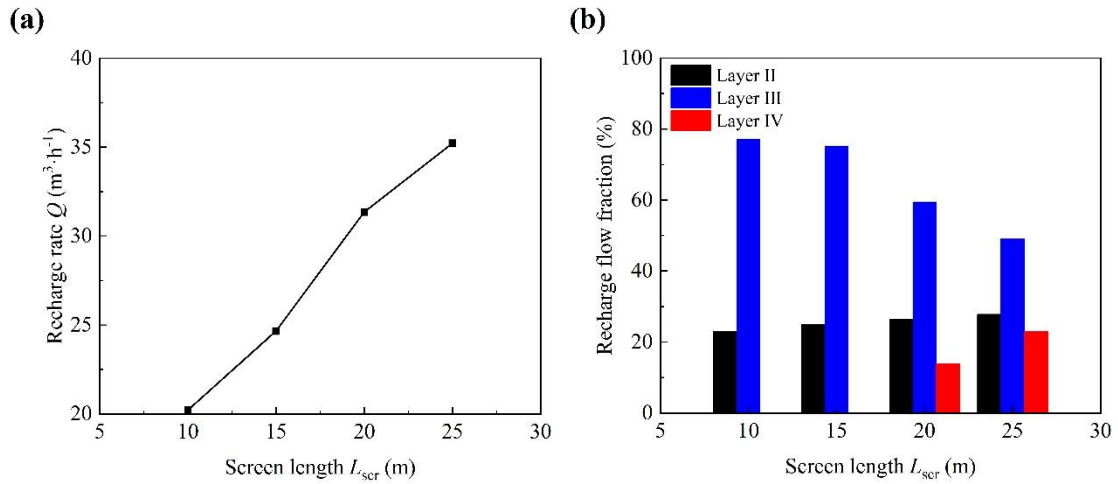


Fig. 7. Effect of screen configuration on recharge performance under the representative pressurized-recharge condition ($P_{\text{inj}} = 0.04 \text{ MPa}$): (a) variation in total recharge rate with screen length; (b) distribution of recharge flow among the intersected hydrogeological layers.

The pressure-dependent simulations further show how this screen-controlled hydraulic capacity responds to changes in operating conditions. As expected from the linear Darcy-flow formulation and the prescribed-head recharge boundary, the recharge rate increases approximately linearly with injection pressure for all four screen lengths,

while increasing L_{scr} shifts the pressure–recharge relationship toward higher flow rates. The response curves retain a similar shape and ordering throughout the investigated pressure range, with no evident change in curvature. This behaviour indicates that screen extension primarily increases the hydraulic transmission capacity of the well–aquifer system rather than fundamentally changing its response to pressurization. The result is consistent with the layer-resolved mechanism identified in Fig. 7: a longer screen establishes effective hydraulic connection with a larger portion of the layered formation, thereby increasing the available flow-transmission capacity. Once these pathways are established, increasing P_{inj} mainly strengthens the hydraulic driving force acting through them. Longer screens therefore produce larger absolute recharge increments for the same pressure increase, while the overall form of the pressure response remains similar.

This distinction between screen-controlled hydraulic capacity and pressure-controlled driving force is quantified in Fig. 8(b). The pressure-induced recharge increment, $\Delta Q_p = Q_{0.04} - Q_0$, increases by approximately 74 % as L_{scr} increases from 10 to 25 m, closely matching the enhancement in the underlying recharge capacity caused by screen extension. In contrast, increasing P_{inj} from 0 to 0.04 MPa produces an approximately 69.4 % increase relative to the corresponding zero-pressure recharge rate for all four screen lengths. The nearly invariant relative amplification is consistent with the adopted linear Darcy-flow formulation and the use of a pressure-independent transfer coefficient. Within this modeling framework and the investigated pressure range, screen extension therefore modifies the available hydraulic transmission capacity, whereas increasing P_{inj} primarily scales the hydraulic driving force acting through that capacity. The increase in recharge with applied pressure is consistent with previous field studies of confined and semiconfined aquifers, in which pressurized recharge produced greater well intake than gravity recharge (Zheng et al. 2018; Cao et al. 2022). Within the present simulations, screen length and injection pressure therefore perform distinct but complementary hydraulic functions: screen configuration determines the effective hydraulic connection and transmission capacity between the well and the stratified aquifer, whereas injection pressure scales the recharge flow through that available

capacity. Increasing pressure therefore cannot fully compensate for insufficient hydraulic connection associated with an inadequately configured screen. From a recharge-design perspective, establishing effective connection with the principal transmissive layers should precede the use of additional pressurization to increase the absolute recharge rate.

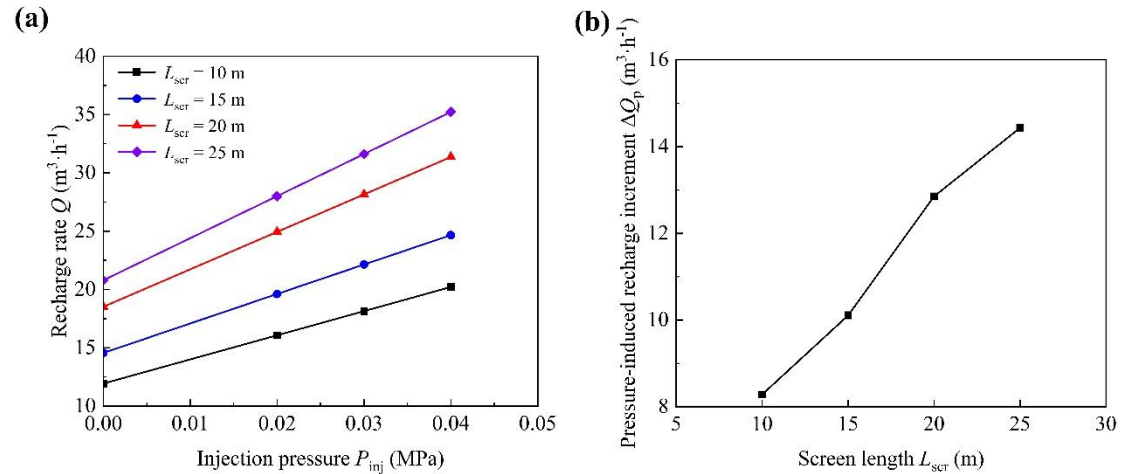


Fig. 8. Combined effects of injection pressure and screen length on recharge performance: (a) variation in recharge rate with injection pressure for different screen lengths ($L_{scr} = 10, 15, 20$, and 25 m); (b) pressure-induced recharge increment, $\Delta Q_p = Q_{0.04} - Q_0$, as a function of screen length, where $Q_{0.04}$ and Q_0 denote the recharge rates at $P_{inj} = 0.04$ MPa and 0 MPa, respectively.

4.4 Effects of well spacing on hydraulic interference

The evaluated single-well model was extended to a two-well configuration to examine how hydraulic interference modifies recharge performance as the spacing between adjacent wells changes. As shown in Fig. 9(a), under the representative operating condition of $P_{inj} = 0.04$ MPa and $L_{scr} = 25$ m, the head-rise fields generated by two wells at $S = 10$ m overlap strongly, producing an elongated high-head zone along the line connecting the wells rather than two hydraulically independent quasi-radial perturbation fields. The merging of the head contours is particularly pronounced in the inter-well region, demonstrating that the hydraulic influence of each well extends into the near-field environment of the other. Because the prescribed head at each recharge well remains unchanged, the head rise generated by the neighbouring well elevates the ambient groundwater head surrounding the screen. This reduces the hydraulic-head difference available to drive water from the well into the formation. Hydraulic interference therefore does not result from a reduction in the imposed injection pressure

itself, but from a reduction in the effective hydraulic gradient between each well and its surrounding aquifer. As the wells are brought closer together, each well consequently operates within a progressively elevated hydraulic environment, and the recharge capacity available to the individual well decreases. The merged head field in Fig. 9(a) thus provides the spatial mechanism underlying the loss of recharge capacity under closely spaced operation.

The spacing dependence of this interference is quantified by the retained recharge capacity shown in Fig. 9(b). Within the spacing range representative of the field layout ($S = 7\text{--}16.5$ m), the retained capacity increases from approximately 76.2 % to 85.3 %. Thus, simultaneous operation within the field spacing range can reduce the available recharge capacity by approximately 14.7–23.8 % relative to hydraulically isolated operation. The recovery is not uniform with increasing spacing. At $S = 20$ m, the retained capacity reaches approximately 87.1 %, and it increases further to approximately 90.8 % at $S = 25$ m. Increasing the spacing from 25 to 30 m produces essentially no additional recovery, with the retained capacity remaining close to 90.7 %. The results therefore indicate a progressive transition from strong to weak hydraulic interference. The progressive weakening of hydraulic interference with increasing well spacing is consistent with previous field-constrained and numerical studies showing that recharge-well spacing is an important control on individual-well and multi-well recharge performance (Zhang et al. 2017b; Mukhopadhyay et al. 2022). At relatively small spacings, increasing S effectively separates the overlapping high-head zones and produces a clear recovery in recharge capacity. At larger spacings, however, the incremental hydraulic benefit of further separation becomes progressively smaller.

These results have direct implications for the layout of multi-well recharge systems. Well spacing should not be selected solely to maximize the number of installed recharge wells. Excessively close spacing permits a greater well density but also intensifies the overlap of recharge-induced head fields, thereby reducing the effective contribution of each well. Conversely, increasing the spacing generally reduces hydraulic interference but eventually provides only a small additional gain in individual-well capacity while decreasing the number of wells that can be accommodated within a given area. The

recharge-system layout therefore involves a trade-off between well density and retained per-well capacity. For the hydraulic conditions investigated here, the marginal benefit of increasing spacing becomes small at approximately $S = 25$ m. This value should be interpreted as a site-specific transition rather than a universal design spacing because the magnitude and spatial extent of hydraulic interference also depend on aquifer transmissivity, hydrostratigraphic structure, screen configuration, and recharge operating conditions. Accordingly, well spacing should be evaluated together with these hydraulic and operational factors and the required total recharge capacity rather than treated as an independent geometric parameter.

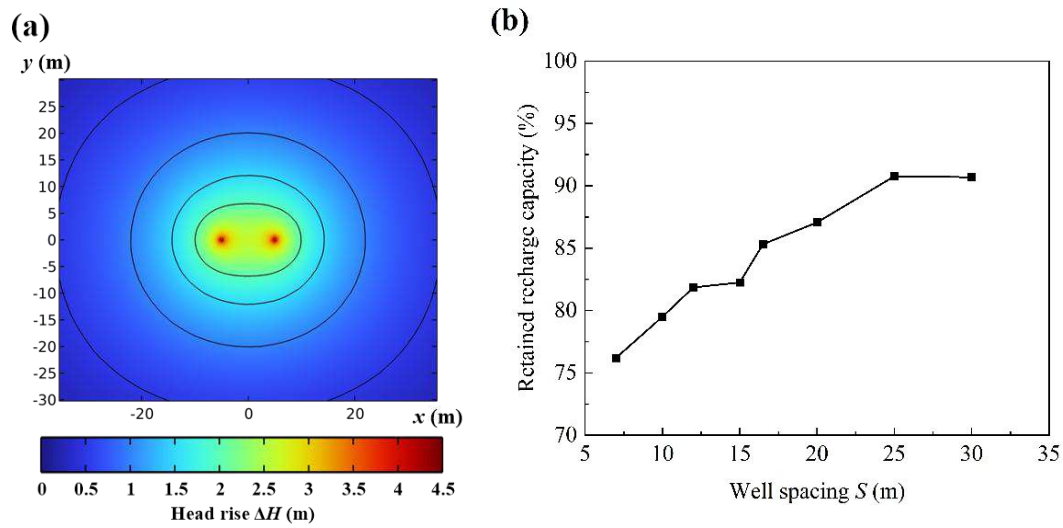


Fig. 9. Hydraulic interaction between adjacent recharge wells under the representative pressurized-recharge condition ($P_{inj} = 0.04$ MPa and $L_{scr} = 25$ m): (a) horizontal distribution of recharge-induced head rise at $z = -25$ m for a representative well spacing of $S = 10$ m; (b) variation in retained recharge capacity with well spacing.

The numerical results should be interpreted within the scope of the adopted modeling assumptions. The present model describes the stabilized hydraulic response and represents the complex Quaternary sequence through simplified hydrostratigraphic units characterized by layer-wise hydraulic properties. Hydraulic losses between the wellhead and aquifer are represented by a lumped, pressure-independent transfer coefficient. This representation does not explicitly resolve flow-rate-dependent well losses, progressive clogging, or other nonlinear near-well effects and therefore does not represent nonlinear pressure-recharge behaviour outside the investigated operating range. The same η_p was also retained across the screen-length scenarios to isolate

aquifer-side effects of screen–stratigraphy connectivity; therefore, potential changes in internal well and screen head losses caused by screen-length variation were not represented separately. The multi-well analysis is reduced to an idealized two-well configuration to isolate spacing-dependent interference. Consequently, the quantitative pressure–recharge relationships and spacing transition identified here are site-specific rather than universal design criteria. Nevertheless, the model provides a consistent basis for distinguishing the hydraulic roles of screen–aquifer connectivity, pressurization, and overlapping recharge-induced head fields under the investigated field conditions.

5. Conclusions

This study investigated well-based artificial recharge in a stratified aquifer using staged field tests and three-dimensional groundwater-flow modeling. The main conclusions are as follows.

(1) The field-constrained model reproduced the main pressure-dependent recharge trend across different well locations, supporting the use of a unified pressure-transfer representation for first-order site-scale analysis. Residual differences among wells indicate that local screen–aquifer connectivity and hydrogeological heterogeneity remain important sources of uncertainty.

(2) Artificial recharge generated a distinctly three-dimensional and vertically non-uniform hydraulic response. Recharge was characterized by local radial spreading near the well, preferential lateral migration through more permeable strata, and restricted vertical exchange across lower-permeability interbeds.

(3) Screen configuration and injection pressure played different but complementary roles in recharge performance. Increasing screen length enhanced recharge capacity nonlinearly by modifying screen–aquifer connectivity and redistributing flow among aquifer units, whereas pressurization primarily increased the hydraulic driving force through the available recharge pathways.

(4) Hydraulic interference between adjacent recharge wells reduced individual-well capacity because overlapping head fields raised the surrounding groundwater head and weakened the effective recharge gradient. Within the field-representative spacing range of 7–16.5 m, recharge capacity was reduced by approximately 15–24 % relative

740 to isolated operation, while increasing well spacing progressively weakened this
741 interference. Recharge-system design should therefore balance well density, screen–
742 stratigraphy connectivity, and retained per-well capacity.

References

- Bakker M (2001) An analytic, approximate method for modeling steady, three-dimensional flow to partially penetrating wells. *Water Resour Res* 37:1301–1308. doi:10.1029/2000WR900400
- Bayer-Raich M, Jordana S, Jaime OM, Lynch TD, McGillicuddy KB, Guimerà J, Jaime MJ (2022) Numerical modeling of head losses in different types of well screens. *Groundwater* 60:747–756. doi:10.1111/gwat.13196
- Bouwer H (2002) Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeol J* 10:121–142. doi:10.1007/s10040-001-0182-4
- Cao J, Li Q, Cheng X, Zheng G, Ha D, Zeng C (2022) Study on artificial recharge and well loss in confined aquifers using theoretical and back-analysis calculations of hydrogeological parameters from recharge and pumping tests. *Bull Eng Geol Environ* 81:483. doi:10.1007/s10064-022-02988-2
- Choi MR, Kim GB (2023) Optimum interval of artificial groundwater recharge wells, considering injection rate and economic feasibility. *Geosci J* 27:77–87. doi:10.1007/s12303-022-0019-9
- Cihan A, Zhou Q, Birkholzer JT (2011) Analytical solutions for pressure perturbation and fluid leakage through aquitards and wells in multilayered-aquifer systems. *Water Resour Res* 47:W10504. doi:10.1029/2011WR010721
- Dillon P, Stuyfzand P, Grischek T, Lluria M, Pyne RDG, Jain RC, Bear J, Schwarz J, Wang W, Fernandez E, Stefan C, Pettenati M, van der Gun J, Sprenger C, Massmann G, Scanlon BR, Xanke J, Jokela P, Zheng Y, Rossetto R, Shamrukh M, Pavelic P, Murray E, Ross A, Bonilla Valverde JP, Palma Nava A, Ansems N, Posavec K, Ha K, Martin R, Sapiano M (2019) Sixty years of global progress in managed aquifer recharge. *Hydrogeol J* 27:1–30. doi:10.1007/s10040-018-1841-z
- Guo F, Wang GH, Li ZC (2022) Influence of artificial recharge in a phreatic aquifer on deep excavation dewatering: a case study of Dongguantou Nan Station in Beijing, China. *Hydrogeol J* 30:673–689. doi:10.1007/s10040-021-02441-w
- Guttman J, Negev I, Rubin G (2017) Design and testing of recharge wells in a coastal aquifer: summary of field scale pilot tests. *Water* 9:53. doi:10.3390/w9010053

773 Javandel I, Witherspoon PA (1980) A semianalytical solution for partial penetration in
774 two-layer aquifers. *Water Resour Res* 16:1099–1106.
775 doi:10.1029/WR016i006p01099

776 Kumar R, Ohri A, Gaur S (2025) Sensitivity of permissible aquifer recharge rate to
777 hydrogeological and well design parameters. *J Hydrol* 660:133438.
778 doi:10.1016/j.jhydrol.2025.133438

779 Li J, Chen JJ, Zhan H, Li MG, Xia XH (2020) Aquifer recharge using a partially
780 penetrating well with clogging-induced permeability reduction. *J Hydrol*
781 590:125391. doi:10.1016/j.jhydrol.2020.125391

782 Liu NW, Peng CX, Li MG, Chen JJ (2022) Hydro-mechanical behavior of a deep
783 excavation with dewatering and recharge in soft deposits. *Eng Geol* 307:106780.
784 doi:10.1016/j.enggeo.2022.106780

785 Martinez MB, Widdowson MA (2024) Evaluating flow distribution in a multiaquifer
786 recharge well using an in situ flowmeter. *Groundwater* 62:605–616.
787 doi:10.1111/gwat.13379

788 Meles MB, Bradford S, Casillas-Trasvina A, Chen L, Osterman G, Hatch T, Ajami H,
789 Crompton O, Levers L, Kisekka I (2024) Uncovering the gaps in managed aquifer
790 recharge for sustainable groundwater management: a focus on hillslopes and
791 mountains. *J Hydrol* 639:131615. doi:10.1016/j.jhydrol.2024.131615

792 Mok CM, Carrera B, Hort H, Santi L, Daus A, Ferguson E (2024) Simulation-
793 optimization approach for siting injection wells in urban area with complex
794 hydrogeology. *Groundwater* 62:236–249. doi:10.1111/gwat.13317

795 Mukhopadhyay A, Akber A, Al-Saaidi M, Aladwani A (2022) Planning for a multi-well
796 artificial recharge field in Kuwait with the help of numerical modeling.
797 *Groundwater* 60:685–698. doi:10.1111/gwat.13166

798 Patton EM, Adam C, Steward DR, Datta S (2023) Effect of low-permeability layers on
799 vadose well recharge rates. *Groundw Sustain Dev* 21:100938.
800 doi:10.1016/j.gsd.2023.100938

801 Poursalehi F, Akbarpour A, Hashemi SR (2022) Locating optimal position of artificial
802 recharge wells in aquifer using grey wolf optimization algorithm and isogeometric

numerical method. Appl Water Sci 12:164. doi:10.1007/s13201-022-01686-4

Seidl C, Wheeler SA, Page D (2024) Understanding the global success criteria for managed aquifer recharge schemes. J Hydrol 628:130469. doi:10.1016/j.jhydrol.2023.130469

Shandilya RN, Bresciani E, Runkel AC, Higgins R, Lee S, Kang PK (2022) Influence of inter-aquifer leakage on well-injection capacity: theory and aquifer-scale mapping for artificial recharge. J Environ Manage 322:116035. doi:10.1016/j.jenvman.2022.116035

van Lopik JH, Hartog N, Schotting RJ (2020) Taking advantage of aquifer heterogeneity in designing construction dewatering systems with partially penetrating recharge wells. Hydrogeol J 28:2833–2851. doi:10.1007/s10040-020-02226-7

van Lopik JH, Sweijen T, Hartog N, Schotting RJ (2021) Contribution to head loss by partial penetration and well completion: implications for dewatering and artificial recharge wells. Hydrogeol J 29:875–893. doi:10.1007/s10040-020-02228-5

Wu P, Comte JC, Ma Z, Li F, Chen H (2023) Scaling of groundwater flow subject to managed aquifer recharge using injection boreholes: physical experiments and upscaled numerical models. Urban Clim 51:101651. doi:10.1016/j.uclim.2023.101651

Wu P, Shu L, Comte JC, Zuo Q, Wang M, Li F, Chen H (2021) The effect of typical geological heterogeneities on the performance of managed aquifer recharge: physical experiments and numerical simulations. Hydrogeol J 29:2107–2125. doi:10.1007/s10040-021-02375-3

Zeng CF, Zheng G, Xue XL (2019a) Responses of deep soil layers to combined recharge in a leaky aquifer. Eng Geol 260:105263. doi:10.1016/j.enggeo.2019.105263

Zeng CF, Zheng G, Xue XL, Mei GX (2019b) Combined recharge: a method to prevent ground settlement induced by redevelopment of recharge wells. J Hydrol 568:1–11. doi:10.1016/j.jhydrol.2018.10.051

Zhang YQ, Li MG, Wang JH, Chen JJ, Zhu YF (2017a) Field tests of pumping-recharge technology for deep confined aquifers and its application to a deep excavation.

833 Eng Geol 228:249–259. doi:10.1016/j.enggeo.2017.08.019

834 Zhang YQ, Wang JH, Chen JJ, Li MG (2017b) Numerical study on the responses of

835 groundwater and strata to pumping and recharge in a deep confined aquifer. J

836 Hydrol 548:342–352. doi:10.1016/j.jhydrol.2017.03.018

837 Zheng G, Cao JR, Cheng XS, Ha D, Wang FJ (2018) Experimental study on the artificial

838 recharge of semiconfined aquifers involved in deep excavation engineering. J

839 Hydrol 557:868–877. doi:10.1016/j.jhydrol.2018.01.020

840 Zhu Y, Guo Z, Wan S, Chen K, Wang Y, Zeng Z, Shen H, Ye J, Zheng C (2026)

841 Evaluating long-term effectiveness of managed aquifer recharge for groundwater

842 recovery and nitrate mitigation in an overexploited aquifer system. Hydrol Earth

843 Syst Sci 30:693–708. doi:10.5194/hess-30-693-2026

844