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Articles

Managed artificial recharge through drywells

Recarga artificial mediante pozos secos

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Abstract

Managed aquifer recharge (MAR) is a water management strategy that uses aquifers for the seasonal or inter-annual storage of exceeding surface water. Systems that implement artificial recharge use infiltration ponds or shallow or deep infiltration wells. While artificial recharge through infiltration ponds requires large areas and infiltration through deep wells demands high investment, infiltration through drywells, which inject water to the vadose zone, is often a preferred option because of its low cost and relatively easy implementation. We present results of detailed numerical simulations to assess the operation of a single drywell to implement an artificial recharge system. We demonstrate that depending upon the distribution and property of the geological materials that compose the subsurface, the operation of the well can produce quite different results in terms of effective recharge. We expect that these findings will help design real MAR systems and provide supporting information for decision-makers in charge of approving and financing such water management systems.

Keywords: Unsaturated flow, numerical simulations, artificial recharge, aquifer recharge, water management, aquifer storage and recovery (ASR).

Resumen

La recarga artificial (*managed aquifer recharge*, MAR) es una estrategia de gestión de los recursos hídricos que utiliza a los acuíferos para el almacenamiento temporal de excedentes de agua superficial. Los sistemas que implementan la recarga artificial de acuíferos usan piscinas, o pozos profundos o someros para infiltrar agua. Mientras la recarga artificial a través de piscinas requiere grandes extensiones de terreno y la recarga mediante pozos profundos demanda altos costos de inversión, la infiltración mediante pozos secos —que inyectan agua a la zona no saturada— es usualmente preferida como alternativa de recarga debido a su bajo costo y simple implementación. En este artículo presentamos resultados de simulaciones numéricas detalladas para evaluar la operación de un sistema de recarga artificial compuesto de un solo pozo seco. Demostramos que dependiendo de la distribución y de las propiedades de los sedimentos que componen el subsuelo, la operación del pozo puede producir diferentes resultados en términos de recarga efectiva. Esperamos que estos resultados sean útiles para el diseño de sistemas de recarga artificial y sirvan de soporte para tomadores de decisión a cargo de aprobar y financiar sistemas similares de gestión de agua.

Palabras clave: flujo no saturado, simulaciones numéricas, recarga artificial, recarga de acuíferos, gestión del agua, almacenamiento de agua en acuíferos y recuperación.

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Introduction

Economic development and population growth combined with the effects of climate change have resulted in increasing stress on groundwater systems, particularly in arid and semi-arid regions of the world (Lall, Josset, & Russo, 2020). The implementation of artificial or managed aquifer recharge (MAR) systems has gained interest in recent decades as a water management strategy (Kimrey, 1989; Sharma, Sharma, Mehta,

& Marwaha, 2000; Gale, Neumann, Calow, & Moench, 2002; DGA, 2013; Dillon *et al*., 2019; CNR, 2020; Ebrahim, Lautze, & Villholth, 2020; Alqahtani, Sale, Ronayne, & Hemenway, 2021). The basic principle of such systems is using the storage space available in the subsurface to store water between periods of exceedance and shortage (Bouwer, 1996; Bouwer, 2002). The successful implementation of artificial recharge projects requires (Bouwer, 1996; Bouwer, 2002): water that can be stored during at least a specific period, storage volume in the subsurface, and infiltration capacity to permit injecting a significant amount of water with small effort. Often, the implementation of MAR systems aim at using the recharged water for an environmental purpose, e.g. the recovery of depleted aquifers or springs. Alternatively, recharged water is recovered for a different use, in which case they are known as aquifer storage and recovery (ASR) systems (Pyne, 2017; Alqahtani *et al*., 2021). Additionally, artificial recharge serves to recover overexploited aquifers, prevent subsidence underneath urban areas, prevent or control saline intrusion in coastal aquifers, dispose of excess water due to dewatering during construction projects and store treated wastewater (NRC, 1994; Wilson *et al*., 1995; Dillon *et al*., 2019; van Lopik, Hartog, & Schotting, 2020).

There are several technical options to enhance recharge that can be broadly classified into three categories: surface systems such as ponds or trenches, shallow wells that penetrate only into the vadose zone (also known as drywells), and deep wells that extend below the water table and reach the aquifer as shown in Figure 1 (Bouwer, 2002). Infiltration ponds or trenches have been implemented in many locations worldwide due to their simplicity and low cost. However, these systems require extensive land area to attain significant infiltration rates, thus, they are difficult to implement in urban areas where land is relatively scarce and expensive. Moreover, the adequacy of infiltration ponds to produce effective recharge may be relatively low in locations where the water table is deep because of the occurrence of perched aquifers and the long time that may take water to reach the water table (Flint, Ellett, Christensen, & Martin, 2012). Drywell systems are also relatively inexpensive to build, since in most cases, they are dug by hand or using inexpensive drilling equipment or, are installed using direct push (Händel, Liu, Dietrich, Liedl, & Butler, 2014). Since the infiltration rate depends on the height of the water column inside the well, they can provide good infiltration capacity compared to shallow systems implemented with ponds (Bandeen, 1988; Edwards, Harter, Fogg, Washburn, & Hamad, 2016; Justino, Failache, & Barbassa, 2021). However, the infiltration capacity of shallow wells may degrade due to the accumulation of fine sediments carried by the infiltrated water and/or the development of a biological layer around the well casing (bioclogging). This clogging creates an operational problem due to the impossibility of applying some re-development techniques such as periodic pumping (Bouwer, 2002; Glass, Šimůnek, & Stefan, 2020). Finally, the implementation of deep well systems may require considerably more technical skill and the use of more expensive drilling equipment, which usually results in much higher implementation and operational costs (Bouwer 1996; Bouwer, 2002; Gale *et al*., 2002; Dillon *et al*., 2019).

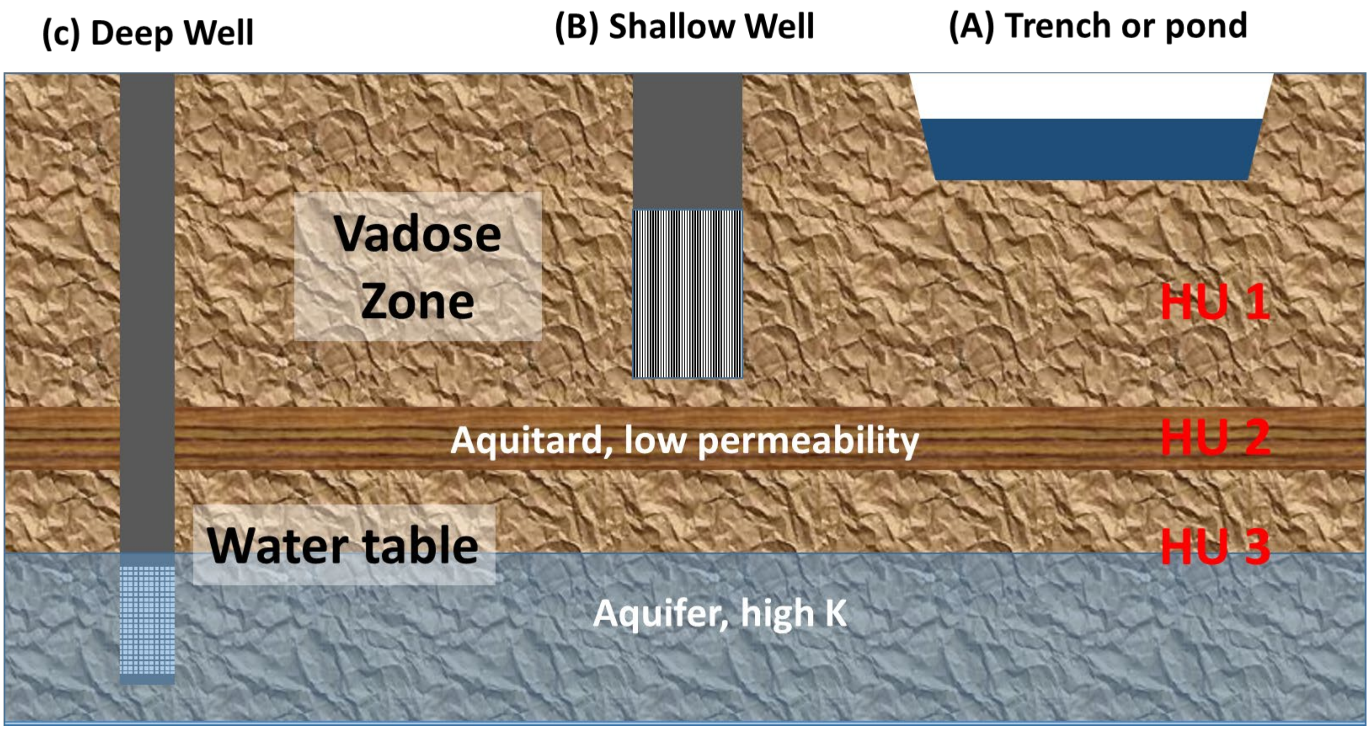

Figure 1. Schematic of artificial recharge systems: trenches or ponds (A), infiltration wells that infiltrate into the vadose zone known as drywells (B), and deep wells that infiltrate directly into aquifers (C). Materials that composed the subsurface are classified into hydrostratigraphic units (HU) that exhibit certain uniformity.

Infiltration ponds and shallow infiltration wells inject water into the unsaturated zone, hence they allow for natural treatment of the infiltrated water due to the filtration capacity of soils and the occurrence of chemical and biological processes, such as denitrification (Sasidharan, Bradford, Šimůnek, & Kraemer, 2020; Gorski, Dailey, Fisher, Schrad, & Saltikov, 2020; Hägg *et al*., 2021). Therefore, this type of system is preferred in some cases due to the potential enhancement of the recharged water

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quality (Bouwer, 1996; Edwards *et al*., 2016; Dillon *et al*., 2019). For example, they are used to implement soil aquifer treatment systems, SAT (e.g. Wilson *et al*., 1995). This enhancement can be a major consideration for implementing MAR systems in countries or areas where regulation is strict concerning the recharged water quality.

The infiltration rate into shallow unsaturated soils (vadose zone) depends on the saturated hydraulic conductivity of the sediments (K), the hydraulic head at the infiltration point (water depth and elevation), and the negative pressure head (h) at the tip of the saturation front, i.e. the volume of soil within which moisture content increases due to infiltration (Bouwer, 1996; Bouwer, 2002). For wells, it also depends on the effective radius; wells with a larger diameter can infiltrate more water. Water moves preferentially downward from the infiltration point through a homogeneous material until it reaches a material of lower permeability that may act as a flow barrier inducing a lateral or horizontal movement of water (Händel *et al*., 2014; Maples, Fogg, & Maxwell, 2019; Wu *et al*., 2021). The net result is a much slower overall vertical water movement across the soil column and, hence, less effective recharge. If the source of the infiltration stops, water accumulated within the initially unsaturated sediments drains under the action of gravity. This drainage process may take a long time to complete after the infiltration source stops providing water (Bouwer, 1996; Alqahtani *et al*., 2021). The reduction in the vertical infiltration capacity produced by lower permeability units results in a leaking system composed of saturated materials overlying higher permeability units that are partially saturated (Flint *et al*., 2012). Similar partially saturated leaking flow configurations occur in natural systems, e.g. beneath river systems with low permeability sediments covering the streambed (Brunner, Cook, & Simmons, 2009).

Infiltrated water may take a long time, of the order of years to decades, to reach the water table and contribute to recharge in presence of aquitards or hydrostratigraphic units with reduced K. This may render the recovery of the infiltrated water difficult (Bouwer, 1996; Flint *et al*., 2012; Sasidharan, Bradford, Šimůnek, & Kraemer, 2019; Sasidharan *et al*., 2020; Alqahtani *et al*., 2021). In addition, the recovery can be problematic due to difficulties in pumping groundwater from perched aquifers that might develop around the infiltration point (Bouwer, 2002). Such a long transit time can reduce the interest in this type of project by investors that seek returns in a limited time frame (Gale *et al*., 2002). Therefore, selecting one or another system must weight several technical and economic factors (Table 1). When new systems are implemented using ponds or short infiltrations wells that inject into the vadose zone due to lower costs, lower technical barriers and potential advantages for improving the quality of the infiltrated water; the potential delay of the benefits due to the delayed recharge should also be accounted for (Gorski *et al*., 2020; Hägg *et al*., 2021).

Table 1. Factors considered for the design and operation of artificial recharge systems. Alternative methods correspond to infiltration pond (A), dry (B) and deep (C) infiltration wells.

	Description	Low cost	Easy construction	Easy operation	Natural filtration	Water recovery
A	Infiltration pond	X	X	X	X	
B	Drywell	X	X		X	
C	Deep well					X

Source: Bouwer (2002), Dillon *et al*. (2019), Edwards *et al*. (2016), Gale *et al*. (2002), Hägg *et al*. (2021), NRC (1994), Sharma *et al*. (2000), Wilson *et al*. (1995).

Drywells have been analyzed in detail in several studies due to their advantages in terms of: construction cost, use of space in urban or well-developed agricultural areas, enhanced infiltration capacity in comparison to ponds or trenches, and their ability to infiltrate water into the vadose zone (Bandeen, 1988; Händel *et al*., 2014; Edwards *et al*. 2016; Liang, Zhan, & Zhang, 2018; Sasidharan *et al*., 2019; Sasidharan *et al*., 2020; Fuentes, Chávez, Quevedo, Trejo-Alonso, & Fuentes, 2020; Glass *et al*., 2020; van Lopik *et al*., 2020; Justino *et al*., 2021). Bandeen (1988) used numerical simulations to study the operation of a single drywell for the infiltration of excess rainfall considering a layered aquifer and a relatively shallow water table (30 meters deep). He simulated infiltration for a few hours after the beginning of a single rainfall event of 1 hr duration, considering only a small area around the well (< 30 meters). Händel *et* *al*. (2014) used numerical simulations to evaluate the potential performance of small diameter shallow infiltration wells installed with direct push. They demonstrated that drywells are cost-effective *versus* infiltration ponds because of the higher infiltration capacity that they may attain. They concluded that the presence of low permeability units significantly reduces the infiltration capacity. They considered only systems with a shallow water table so that infiltrated water always reached the aquifer. Edwards *et al*. (2016) review the literature related to drywells and comment on their advantages and limitations. They conclude that drywells are effective to enhance natural recharge to aquifers, but that their performance depends on well maintenance, quantity and quality of available water for recharge and local subsurface conditions. Liang *et al*. (2018) derive analytical solutions to model water infiltration produced by drywells and compare them with numerical simulations considering uniform materials. Sasidharan *et al*. (2020) performed numerical simulations of the operation of a drywell considering homogeneous and heterogeneous materials in a 2D axisymmetric domain delimited by a distance of 48 meters from the injection well. They evaluated ten realizations of heterogeneous materials generated with a geostatistical model that considered variance and spatial correlation in the horizontal and vertical directions and a water table located 20 meters below the injection point. They concluded that the arrival time and location of the recharge water can be substantially different depending on the heterogeneity of the materials. Glass *et al*. (2020) proposes a model to incorporate variations in hydraulic conductivity due to clogging during the operation of MAR systems. They used the model to simulate two laboratory experiments and evaluate several hypothetical recharge systems. They concluded that clogging can produce significant reductions in infiltration rates and large increases in pressure head that may create problems for the operation of real systems.

Previous studies demonstrated that the performance of drywells in sites where the shallow water table can be controlled, at least locally around the injection well, by the distribution and characteristics of the sediments. We aim at extending the previous analyzes to a larger scale and to sites where the water table is deeper. We perform detailed numerical simulations to analyze the performance of a single infiltration well for different scenarios defined by the stratigraphy of the sediments located between the infiltration point and the water table. The level of detail of the simulations and the unsaturated flow modeling allow us to make a realistic evaluation of this kind of recharge system. Unlike previous studies, we simulate a large volume around the infiltration well that extends a few hundred meters from the well and considers a deep water table. We simulate the operation of a relatively deep drywell (> 50 m) to represent real conditions of wells specifically constructed for infiltration in aquifers with a deep water table (> 50 m). These wells can take advantage of a longer water column to attain high well head pressure and, hence, high infiltration rates. We use the results of the numerical simulations to estimate infiltration rates and transit times to reach the water table. The main objective of this article is assessing potential advantages and limitations of recharge systems based on drywells considering conditions similar to a real-world setting. We expect that the findings can be useful for the design and implementation of similar systems and, hence, will contribute to the further development of artificial recharge projects.

Numerical simulations

Setup

The conceptual model for the simulation setup considered field conditions found in Santiago, Chile, which corresponds to a semi-arid climate (average rainfall < 300 mm/year). There, the water table is relatively deep and sediments are a mixture of alluvial sediments that originate from the Andes and fluvial deposits near rivers. Figure 2 shows the stratigraphic sequence observed in a more than 80 meters deep gravel pit, which is a good example of the sediments found in the area.

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Figure 2. Stratigraphic sequence observed in a gravel pit near the Maipo River, Santiago, Chile, which served as basis for the conceptualization of the numerical simulations. The pit is approximately 80-90 m meters deep.

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We consider a site where the water table is more than 100 m deep and sediments are composed of a mixture of clays, sandy and gravely materials that form a relatively uniform stratigraphic column with not easily recognizable hydrogeological units (HU). For a similar geological setting, Sudicky (1986) reports changes in K measured through permeameter tests of 5 cm undisturbed soil samples of more than one order of magnitude within 2 meters of a shallow sandy aquifer located in Borden, Canada (Figure 5 in Sudicky, 1986). The sediments of the Borden aquifer were described as: ”primarily horizontal, discontinuous lenses of medium-grained, fine-grained, and silty fine-grained sand”, based on a very detailed laboratory characterization of thousands of soil samples (Sudicky, 1986). This characterization of the sediments was performed as part of a large-scale field experiment that had as main purpose to understand the role of natural geological heterogeneity for solute transport in groundwater (Sudicky & Illman, 2011). The level of detail and sophistication used for the characterization of the Borden site sediments are well beyond the one routinely applied in hydrogeological projects. Identifying different hydrogeological units in similar geological settings is usually difficult to achieve based on borehole logging alone, which is the standard method used in most practical applications.

We want to evaluate the potential impact that mild heterogeneity, such as the one reported for the Borden site, could produce for the practical implementation of an artificial recharge system based on shallow infiltration wells that do not reach the water table. Hence, we divide the model domain into three main horizontal hydrogeological units defined by

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different hydraulic conductivity values (Table 2), which allows us to assess the potential impact of the presence of HUs with different hydraulic properties. This conceptualization is akin to the multilayered aquifer system used in many hydrogeological studies (e.g. Matheron & De Marsily, 1980; Fuentes *et al*., 2020). The hydraulic conductivity values assigned to the different HUs of the model have relatively minor changes between different HUs, with a maximum ratio between the most and least permeable units of less than 100. For all HUs, we assume an anisotropy ratio $K_h/K_v = 10$, hence resistance to horizontal flow is less than to vertical flow. We evaluate six different scenarios based on the combination of K values for each one of the three HUs: One that considers the presence of only one homogenous material (S1) with a single value of K and five heterogeneous (S2 to S6) that consider different values of K for each HU (Table 2). For S1, we assume a value of K equal to the effective value for flow perpendicular (vertical) to the layered units of scenario S2. The unsaturated flow properties (see Appendix for details), i.e. water retention curve and relative permeability, were set equal to the corresponding to a loamy sand soil using the van Genuchten model (van Genuchten & Nielsen, 1985), and were considered equal for all three hydrogeological units. Hence, we only tested the influence of considering different values of saturated hydraulic conductivity. Considering different retention and relative permeability curves would result in relative minor differences in the results discussed below.

Table 2. Scenarios simulated assuming three hydrogeological units (HU): upper and lower sand-gravel units and middle sand with fine sediments unit. Scenarios S5 and S6 are similar to S4 except by the extension of the middle low permeability unit, which extends to only 300 (S5) and 550 (S6) meters from the injection well. Porosity for all layers was set equal to 0.41, while initial moisture was set equal to the residual moisture content of a loamy sand, 0.057.

Scenario	Unit	Top Depth (m)	Bottom Depth (m)	Kh (m/d)	Kv (m/d)
S1	Single	0	230	43.30	4.33
S2	Upper	0	90	18.20	1.82
	Lower	90	230	60.70	6.07
S3	Upper	0	80	18.20	1.82
	Fine	80	90	1.10	0.11
	Lower	90	230	60.70	6.07
S4	Upper	0	80	18.20	1.82
	Fine	80	90	0.11	0.01
	Lower	90	230	60.70	6.07

We simulate the operation of a single injection well using VS2DT (Lappala, Healy, & Weeks, 1987), which simulates unsaturated flow. VS2DT solves Richards' equation formulation based on pressure head using a finite difference approximation with a fully implicit backward time approximation. The non-linear partial differential equation is linearized using a Newton-Raphson scheme, and relative permeability and hydraulic

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conductivity are evaluated using upstream weighting and harmonic average, respectively (Lappala *et al*., 1987).

We used a two-dimensional grid assuming axial symmetry so that the coordinates of the grid correspond to the distance from the injection well, r, and the elevation, z. Figure 3 shows a schematic of the model setup, including boundary conditions. The numerical grid is equivalent to a cylindrical domain that extends 600 m from the injection well located at r = 0 m. To simplify the analysis, we consider that the origin of the vertical coordinate system (z = 0 m) coincides with the position of the ground surface and that it points downward. Vertically, the domain includes two zones: a fully saturated of height Hsat = 90 m and an unsaturated height Hunsat = 140 m above the water table. Including a saturated zone below the water table explicitly simulates a more realistic interaction between vertical infiltration and groundwater than assuming a free drainage boundary condition as used in other studies (e.g. Glass *et al*., 2020; Sasidharam, 2019, 2020). In particular, it allows evaluating changes in piezometric levels that could be monitored in real recharge systems to evaluate the magnitude and time evolution of the effective recharge.

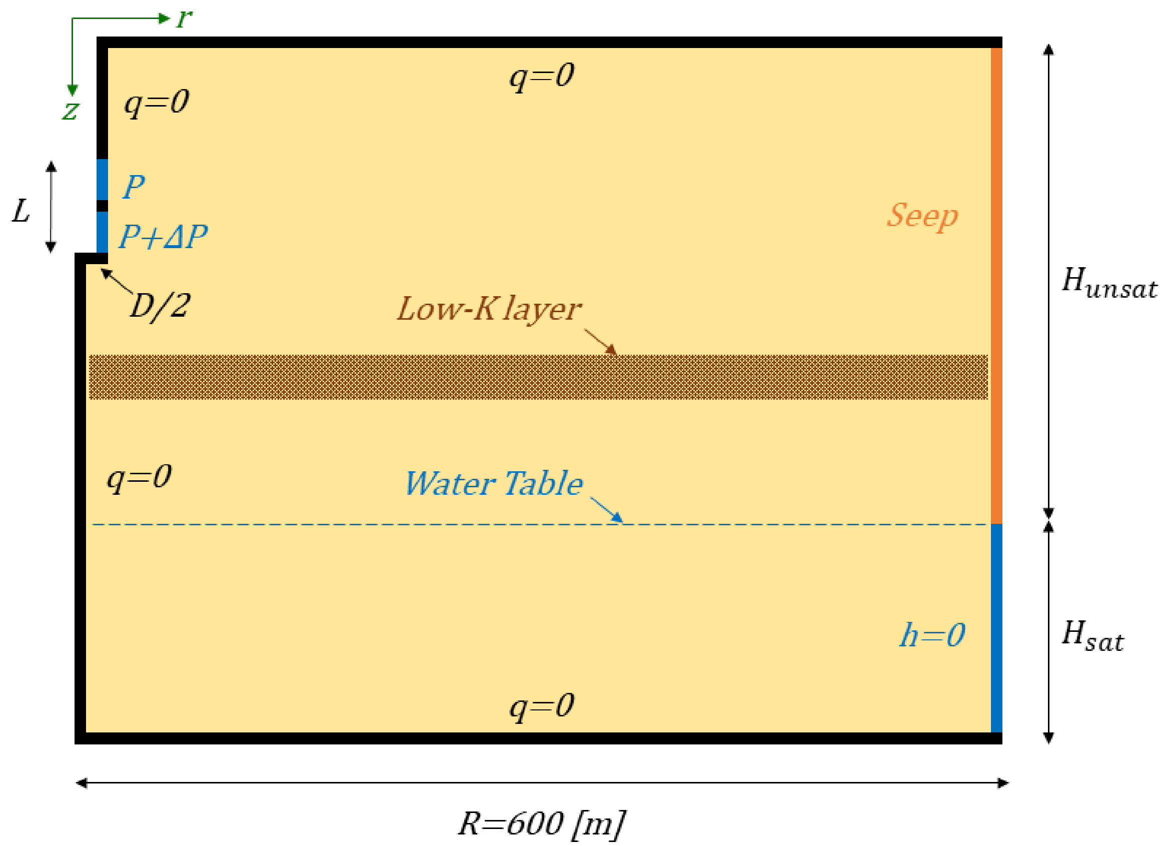

Figure 3. Schematic (not drawn to scale) of simulated artificial recharge system. Injection well (left) simulated as a prescribed pressure boundary condition, while the right boundary was set as a gravity drainage condition to allow infiltrated water to exit the domain.

The extension of the domain is long enough to allow the development of a perched aquifer in some of the simulated scenarios and small enough to allow for the use of fine grid discretization for the sought spatial scale and level of detail. The model domain is discretized into rectangular cells with variable horizontal spacing from 0.05 m near the well, to 10 m at the outer boundary (r = 600 m). Vertically, the domain is discretized into layers of Δz = 1 m, except for the layers that cross the well that had a finer discretization of Δz = 0.5 m. Preliminary simulations showed that this level of refinement was sufficient to simulate changes in pressure and water table elevation near the well for the simulated scenarios, while maintaining the computational effort within reasonable levels.

No flow boundary conditions are specified for the top and bottom boundaries of the domain and for the left boundary, which coincides with the center of the well or symmetry axis. The right boundary condition (r = 600 m) above the initial water table was specified as a seepage boundary (Lappala *et al*., 1987), however the domain size is such that the perched aquifer that develops in some of the simulations never reaches this boundary. Below the initial water table, the boundary condition preserves the initial hydrostatic pressure distribution, so that water that reaches the boundary exits the domain. We consider a single injection well 57 m long and diameter D = 0.3 m with a screen (open section for flow) at the bottom of the well of length L = 13 m. Within the well section where water enters the domain, prescribed pressure increases with depth to simulate a quasi-hydrostatic pressure distribution along a 44 m water column stored inside the well casing. We simulated the operation of the system for two years: A one-year injection period, followed by a similar drainage period. Although the simulated scenarios are rather simple, they are a good approximation to real sites where the subsurface tends to exhibit quasi-horizontal stratifications.

However, the setup of the simulations does not consider potentially relevant processes such as: cyclic operation of the recharge system, air trapping and hysteresis due to application of wetting/drying cycles, heterogeneity within each hydrogeological unit (e.g. Sasidharan *et al*., 2019; Sasidharan *et al*., 2020), capillary forces and potential temporal changes in properties due to clogging or chemical process (e.g. Glass *et al*., 2020). Adding some of those processes could potentially modify, at least in part, the results discussed below and, hence, should be considered for future work to improve on the simulation of the operation of real artificial recharge systems. Nevertheless, the results presented below represent a wide range of real drywell systems.

Results

Figure 4 shows 2D sections of simulated saturation, i.e. the fraction of the available pore space occupied by water, after 50 days and 1 year since injection started and after 1 year since injection stopped. The distribution of the simulated saturation for the homogenous case (S1) shows the development of a mounding zone directly below the injection well that extends almost 100 m from the well and remains almost constant during the injection period (first year). After injection stops, the water that was within this area drains under the action of gravity, so that by the end of the simulated period, saturation within this volume is smaller than 0.4. The results for scenario S2 are similar, but show a lower saturation value below the contact between HU1 and HU3 that is due to the lower K in HU3

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and thus a lower vertical water flow. For the third scenario, that includes the presence of the low *K* unit (HU2) with *K* = 1.1 m/d, the lower infiltration rate in this unit produces as result the development of a perched aquifer that rapidly extends towards the outer boundary of the domain. The final extension of the perched aquifer is such that the total vertical infiltration is equal to the infiltration rate at the well. For example, considering a vertical velocity, V_v, between the upper and lower aquifers of the order of the vertical hydraulic conductivity of the low *K* layer (0.01 m/d) assuming that vertical flow away from the well is mainly gravitational, results in the following mass balance equation:

$$I = V_v \cdot \pi \cdot R^2$$

where I is the infiltration rate and R is the maximum extension of the perched aquifer under steady-state conditions. For example, for S4, S5 and S6 the infiltration rate is about 190 l/s (16550 m^3/d); then *R* can be estimated as 725 meters, which is longer than the domain size.

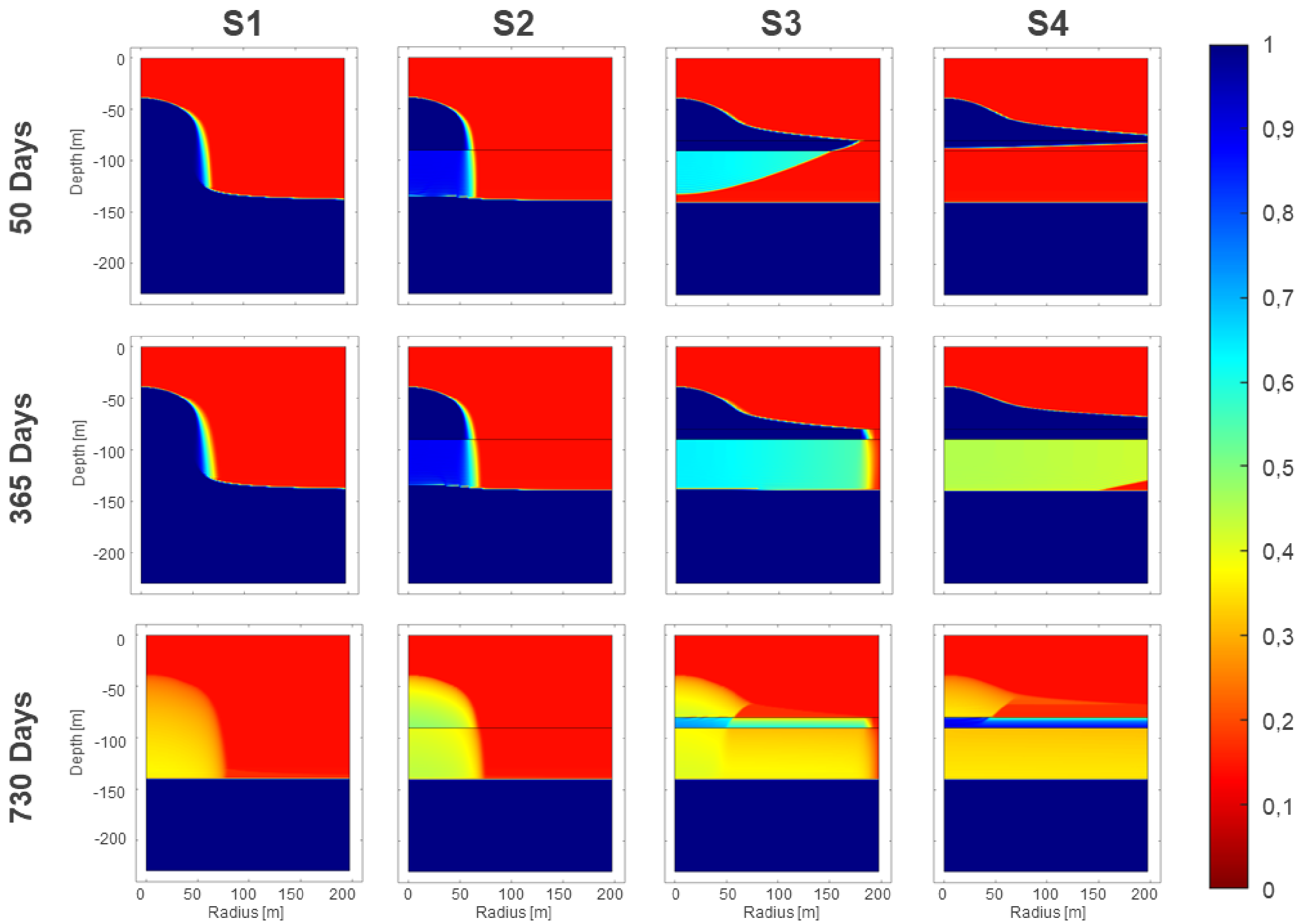

Figure 4. Vertical 2D saturation profiles after 50, 365 and 730 days since injection started. Columns show results for the four simulated scenarios.

The area below HU2 shows intermediate saturation values during and after the injection period, i.e. the soil in that area never gets fully saturated. At the end of the simulated period, saturation is still above 0.5

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for all HU2. Figure 5 shows a 3D reconstruction of the results for this scenario, where the development of the perched aquifer can be easily identified after 5 and 365 days since injection started. Finally, the distribution of saturation for scenario S4, which considers a lower value of K for HU2 (K = 0.11 m/d), also shows the development of a perched aquifer during the injection period, which continues extending horizontally by the end of the simulated period due to the lower vertical infiltration rate that is allowed through HU2.

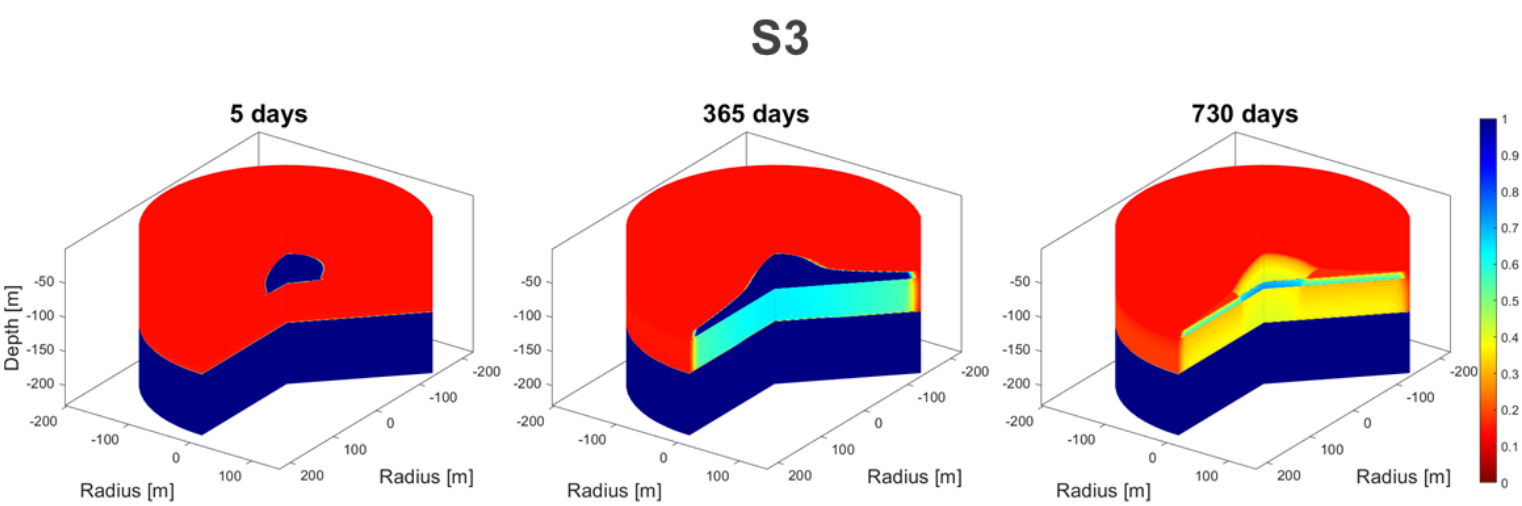

Figure 5. Simulated saturation for scenario S3 after 5, 365 and 730 days since injection started. 3D reconstruction from results of 2D axisymmetric simulations.

Analyzing the hydraulic connection between the injection zone and the water table also provides a quantitative measure of the differences between the scenarios. Figure 6 shows the simulated water pressure *versus* time for points located along the domain right below the water table (z = 140 m). The change in pressure is maximum for the homogeneous case where there is a full hydraulic connection between the injection zone and the water table below. In this case, pressure increases by almost 10 meters below the injection well. The pressure increase is lower for the other scenarios because of the development of a perched aquifer or the presence of a partially saturated zone between the injection zone and the water table. The increase in pressure is the lowest for scenario S4, which considers the lowest K value for HU2. The increase in pressure for scenarios S2, S3 and S4 is due to the mounding of the water table produced by the increased vertical infiltration in the surroundings of the injection well, where the spatial variation of the piezometric head is maximum. These differences can have practical implications for the design of monitoring systems that rely on the observation of variations of piezometric levels in monitoring boreholes and their interpretation (Gale *et al*., 2002). Relatively small changes in hydraulic conductivity values for some of the HUs can result in differences in pressure rise of up to a few meters during an initial period that might extend for a few months or years. In practice, small increases in pressure may be difficult to associate to the direct effects of artificial recharge; hence, they may not provide enough evidence of the effectiveness of the system and its benefits (Gale *et al*., 2002).

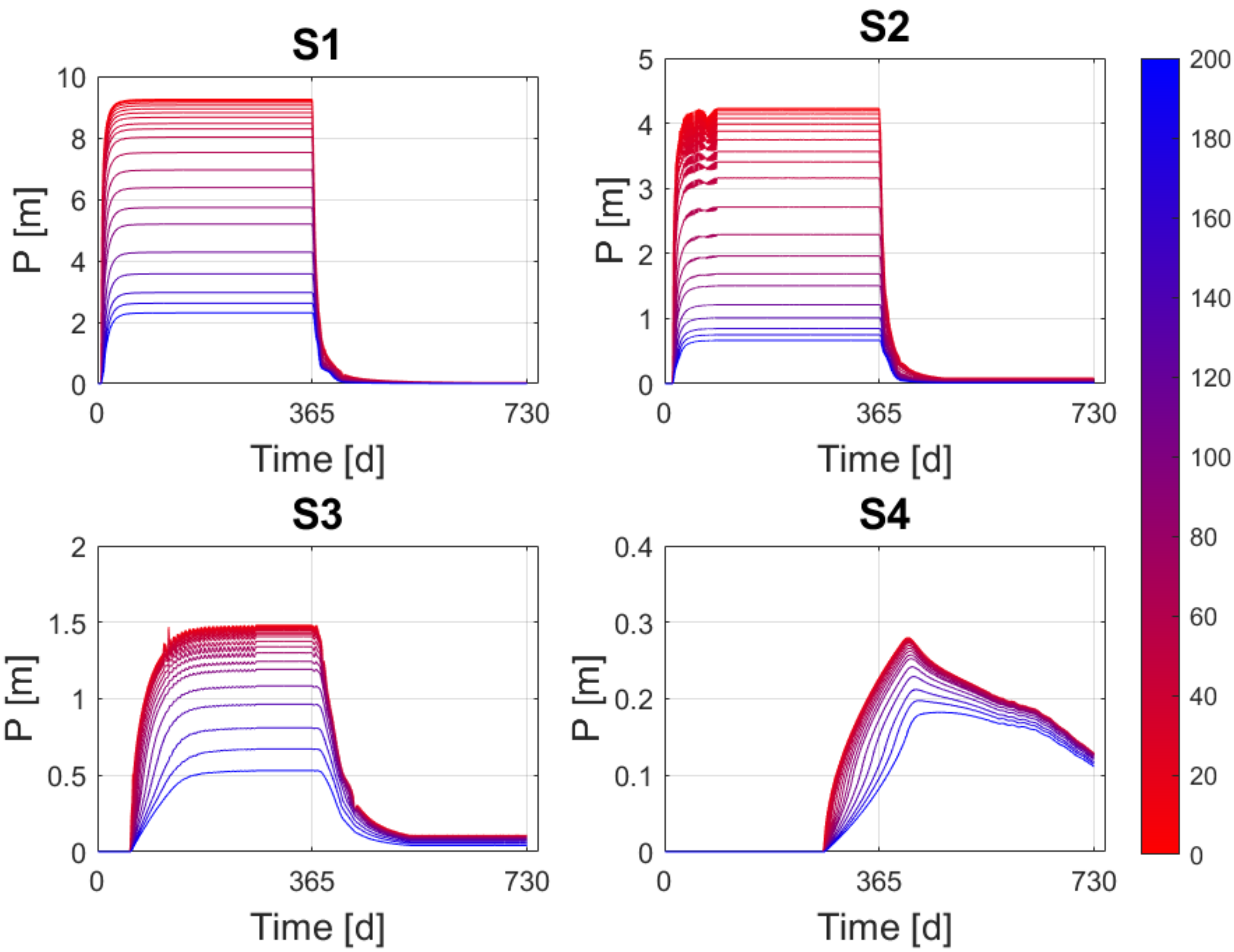

Figure 6. Pressure profiles along initial position of the water table (*z* = 140 m). Colors indicate distance from injection well in meters.

Figure 7 shows simulated saturation for scenarios S2, which considers only two HUs, and scenarios S5 and S6, which are similar to scenario S4, but with a low hydraulic conductivity layer that extends only up to 300 and 550 meters, respectively. The saturation front around the well is similar for all three scenarios at early time (5 days), but it is significantly different at later times. Like in S4, the presence of the middle low K layer results in a perched aquifer that extends for a few hundred meters. In the case of S5, the perched aquifer extends up to the limit of the low K layer (300 meters), where water spills through a narrow vertical zone until reaching the water table. For scenario S6, the perched aquifer develops without reaching the limit of the low K layer (550 m) by the end of the injection period (365 days). Hence, the saturation distribution for S5 is similar to the one for S4, except for the section close to the border.

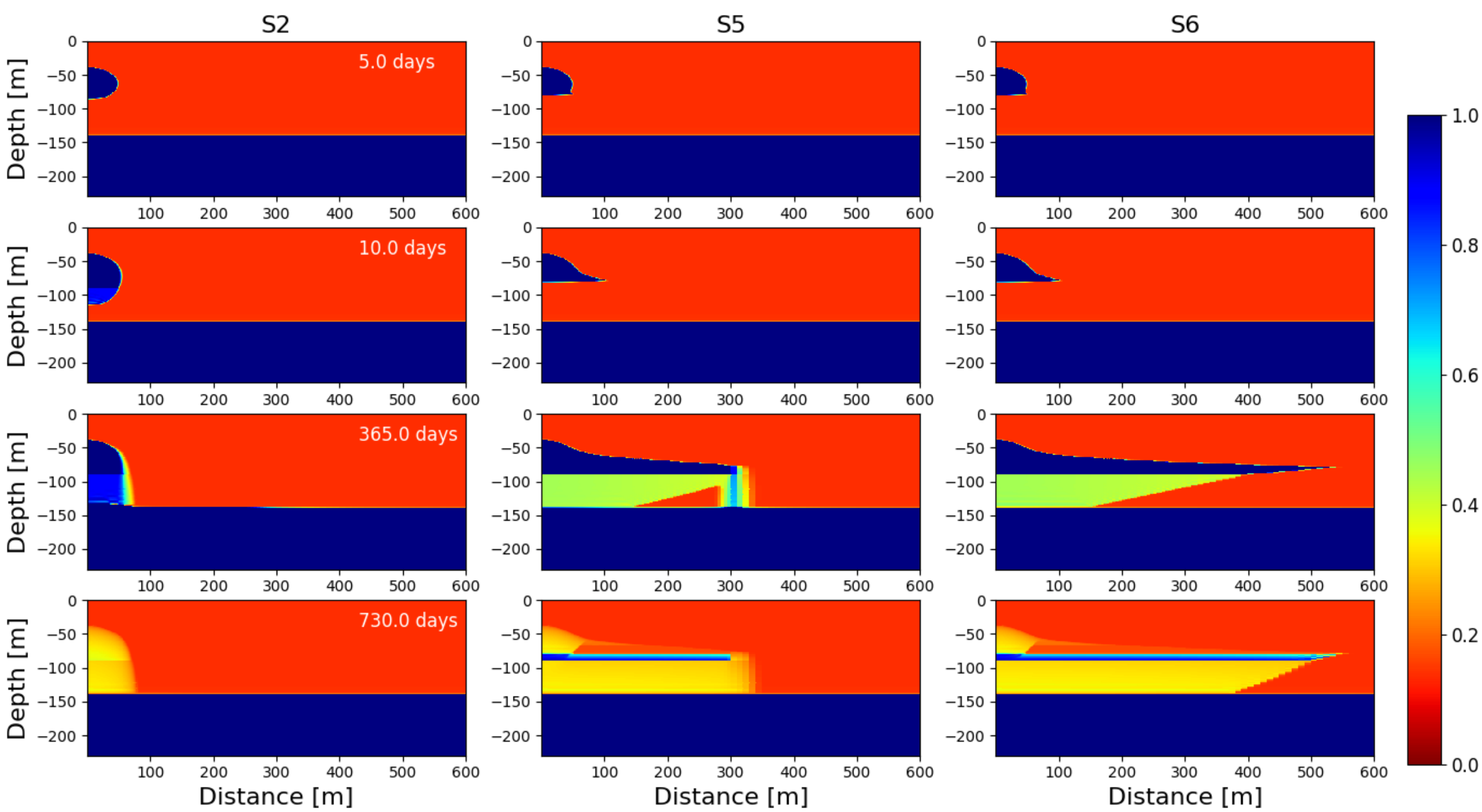

Figure 7. Simulated saturation for Scenarios S2, S5 and S6 after 5, 10, 365 and 730 days since injection started.

Figure 8 shows the simulated piezometric head, h, distribution for Scenarios S2, S5 and S6. The contour for $h = 0$ meters indicates the position of the boundary of the saturated zone that develops around the injection well and the original position of the water table. In all three scenarios, the upper saturated zone by the end of the injection period (365 days) extends only up to the position of the horizon between the upper aquifer and the underneath HU, lower K aquifer for S2, or low K middle unit for S5 and S6.

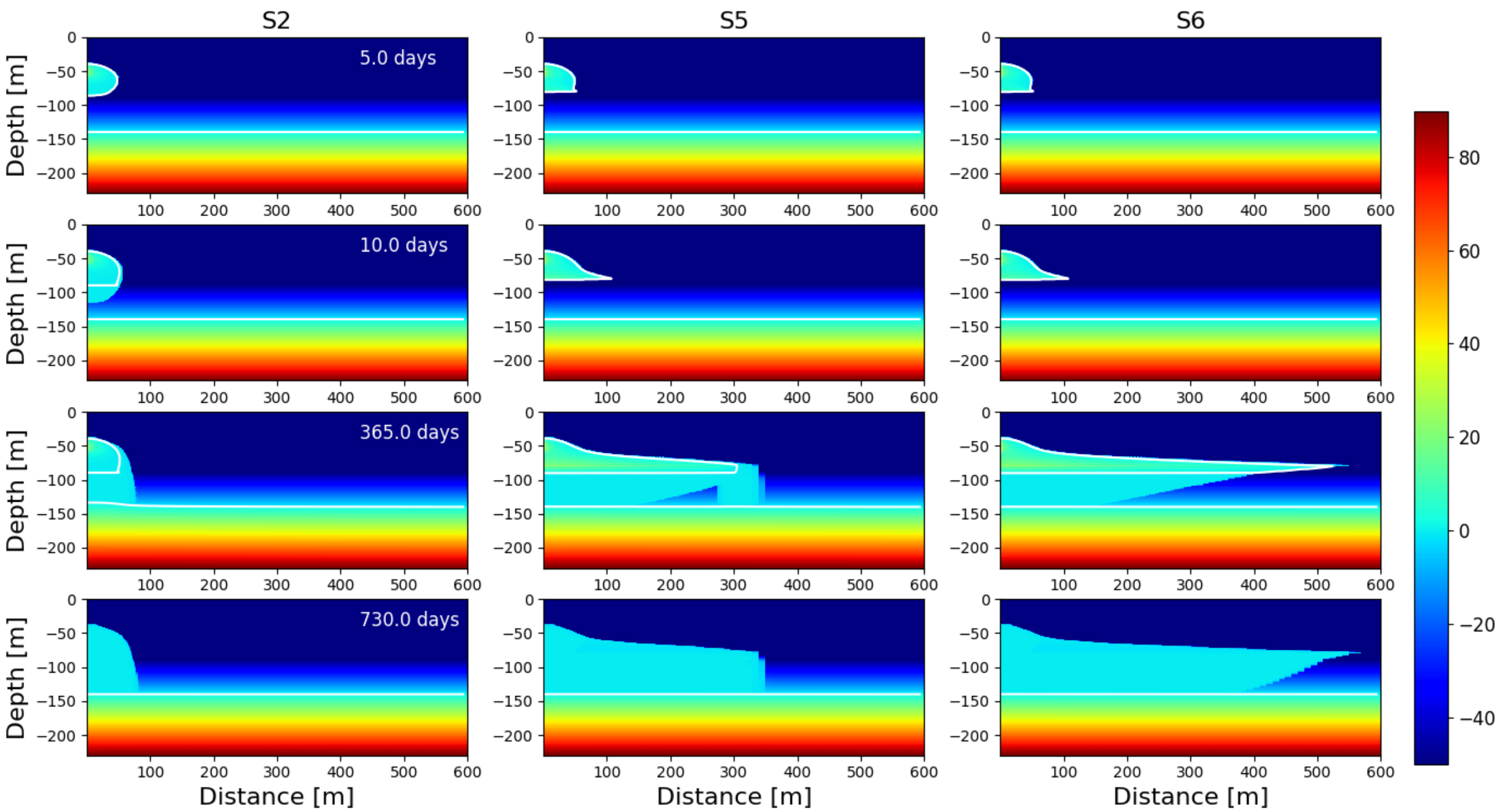

Figure 8. Simulate pressure head (m) for Scenarios S2, S5 and S6 after 5, 10, 365 and 730 days since injection started. White line indicates where pressure head equal to 0, i.e. boundary of saturated sediments.

Figure 9 shows the normalized cumulative volume of infiltrated water that remains in the domain *versus* time (Table 3). For the first two scenarios, most of the injected water reaches the water table and leaves the domain quickly. The increase in storage produced by the injection is relatively minor in comparison to the total infiltrated volume after a short initial period. In a real case, this means that most of the infiltrated water can be recovered from the aquifer through the operation of deep wells that reach below the water table. For scenarios S3 and S4, the proportion of the injected water that remains in the domain is higher, particularly for S4, because of the presence of the low K unit (HU2) that enhances the development of a perched aquifer and slows down the drainage of the infiltrated water after injection stops. This result can also have important practical implications since recovering water from a shallow perched aquifer can be more difficult than recovering it from the main existing aquifer (Bouwer, 1996; Bouwer, 2002). Alternatively, the implementation of a deep recovery system that extracts water directly form the aquifer should consider a potential long delay between recharge and the time the recharged water reaches the aquifer.

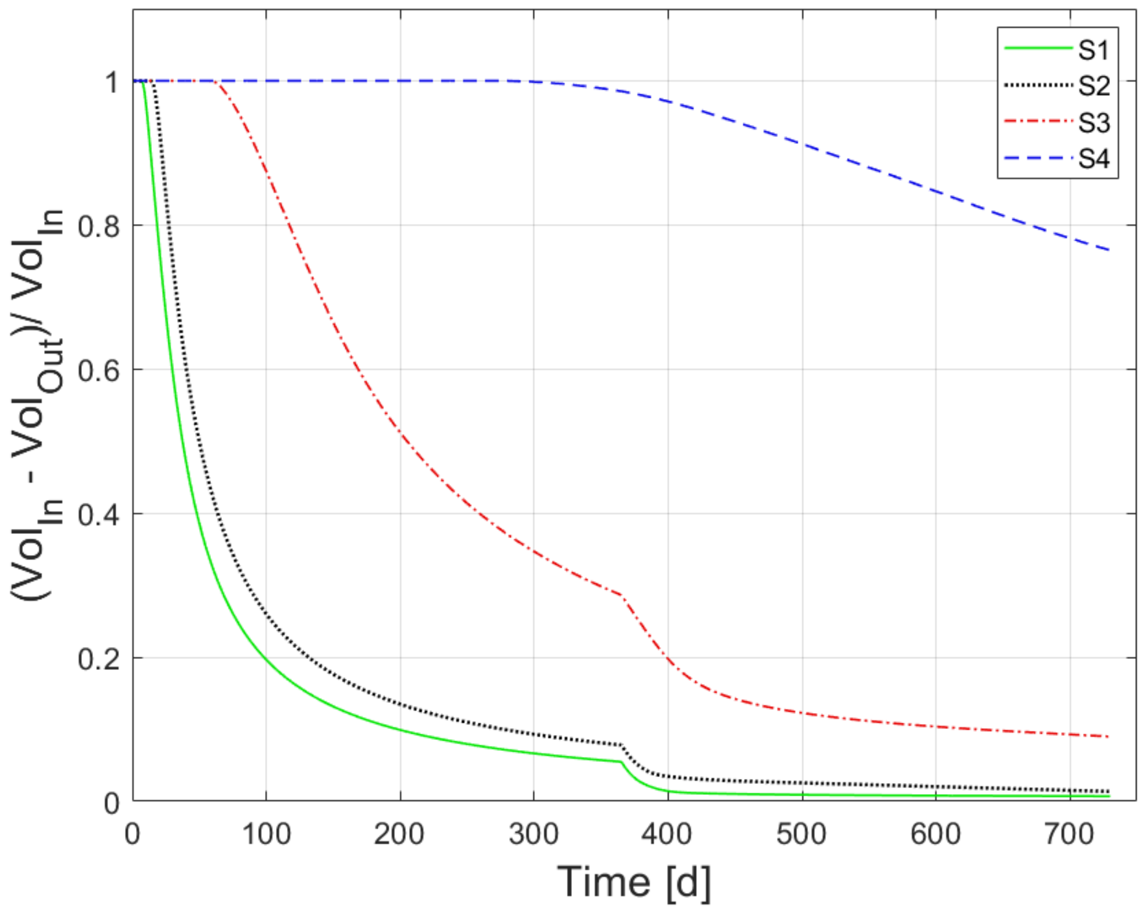

Figure 9. Normalized net recharged volume within model domain *versus* time.

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Table 3. Mean infiltration rate and volume retained in domain at the end of the simulated period (2 years since injection started). Normalized values correspond to the ratio between the values and the maximum value in each column.

Scenario	Infiltration rate (m^3/d)	Infiltration rate (l/s)	Normalized infiltration rate	Retained Volume 2 years ($x10^3$ m^3)	Normalized retained volume 2 years
S1	41 200	477	1.00	106	0.02
S2	17 320	200	0.42	87	0.02
S3	17 020	197	0.41	558	0.12
S4	16 450	190	0.40	4 630	1.00
S5	16 629	192	0.40	2 086	0.45
S6	16 597	192	0.40	4 635	1.00

Conclusions

We performed detailed numerical simulations of an artificial recharge system composed of a single drywell that injects water into the vadose zone. The results of the simulation demonstrate that significant differences in the performance of the system in terms of injection rate, recharged volume and hydraulic connection between the injection well and the existing aquifer; can occur depending on the distribution of materials that compose the subsurface and some of their characteristic hydraulic parameters.

For practical purposes, it may be advantageous to implement injection systems that directly inject water into existing aquifers to avoid the potential development of perched aquifers, which can difficult the recovery of the injected water and delay the effective recharge to the main aquifer system. This may be particularly important in locations where the vadose zone includes a few low permeability units or the water table is deep as often happens in arid or semi-arid climates. Moreover, the design and implementation of monitoring systems to measure the performance of recharge systems can also be challenging in presence of heterogeneous hydrogeological units. In those cases, changes in piezometric head measured in monitoring boreholes might not provide relevant information to quantify recharge. Hence, potential cost savings due to using less expensive shallow infiltration systems, can be rendered of little worth due to the impossibility to recover the injected water within a reasonable time frame. These findings can be contradictory to recommended practices in some countries, where regulatory guidelines advice the injection of water into the vadose zone to profit from the potential filtration and natural chemical and biological mechanisms that can enhance the quality of the infiltrated water.

Future work to extend the results of this study should consider other factors that can potentially impact the performance of a recharge system, such as clogging due to the transport of fine sediments, chemical reactions induced by the difference between the water quality of the injected and resident water, or the growth of microorganisms around the injection point. Studies that analyze the potential performance of specific sites should consider a detailed characterization of the sediment properties, particularly unsaturated flow properties and anisotropy. Nevertheless, these additional improvements would affect only quantitatively the conclusions of this study but would not change their spirit.

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Appendix: Unsaturated flow properties

The unsaturated properties were set according to the van Genuchten model (van Genuchten & Nielsen, 1985), which includes the following equations:

$$s_e = \frac{1}{\left(1+|\alpha \cdot h|^{\beta}\right)^{\gamma}} \quad \text{(A1)}$$

$$k_r = \frac{(1-C \cdot D^{-\gamma})^2}{D^{\frac{\gamma}{2}}} \quad \text{(A2)}$$

With:

$$C = |\alpha \cdot h|^{(\beta-1)}$$

$$D = 1 + |\alpha \cdot h|^{\beta}$$

Where:

s_e: effective saturation or reduced water content (-), equal to $s_e = (\theta - \theta_r)/(n - \theta_r)$

k_r: relative permeability (-).

θ: volumetric water content (-).

θ_r: residual volumetric water content (-).

n: porosity (-).

h: pressure head (m).

α: parameter of the model (1/m).

β: parameter of the model (-).

$\gamma = 1 - 1/\beta$

In all simulations, we considered a loamy-sand soil with parameters summarized in Table A1. Figure A1 shows the corresponding water retention and relative permeability curves.

Table A1. Parameters that define unsaturated flow properties for the loamy sand soil considered in all simulations (Lappala *et al*., 1987).

Parameter	Value
Saturated Hydraulic Conductivity K (m/d)	3.50
Porosity, n (-)	0.41
α (1/m)	12.4
β	2.28
γ	0.56
Residual Water Content, θ_r	0.057

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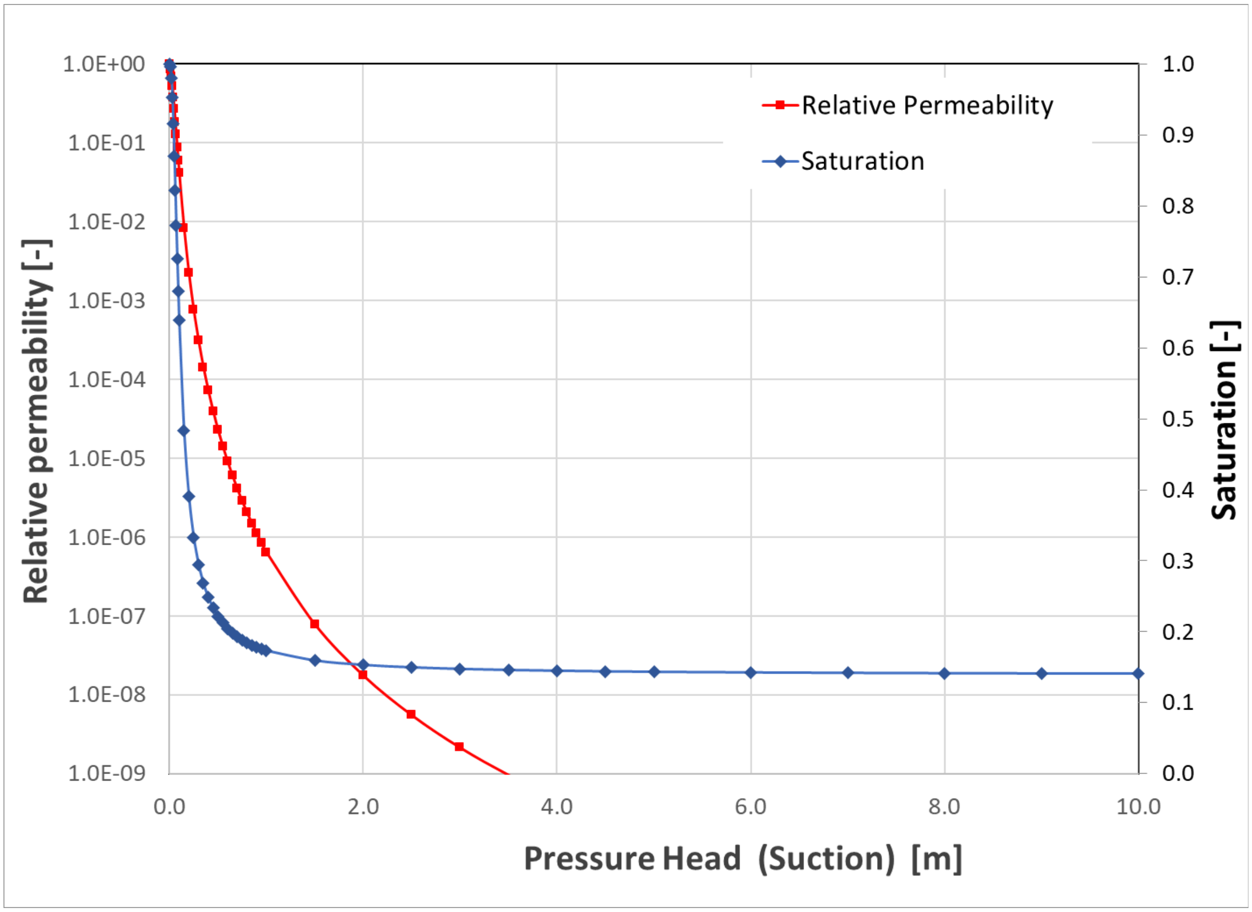

Figure A1. Water retention and relative permeability curves for the loamy sand soil considered in all simulations.

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