Groundwater flow numerical model to evaluate the water mass balance and flow patterns in Groundwater Circulation Wells (GCW) with varying aquifer parameters

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Abstract

Groundwater Circulation Wells (GCW) can be an effective in-situ remediation option allowing high mass recovery of contaminants in cases where contamination hotspots are located in saturated soil having low hydraulic conductivity. Traditional treatment options such as Pump&Treat, Air Sparging (AS)/Soil Vapor Extraction (SVE) and Multi Phase Extraction (MPE) typically require long operation times and significant costs for long-term plume management. GCWs induce meaningful changes in the groundwater flow introducing vertical flows both downward and upward, generating a “circulation cell”, which facilitates contaminant desorption from the soil. This study aims to understand the effects of a GCW on an aquifer in terms of both groundwater flow directions and water balance. A groundwater numerical model was built using MODFLOW-2005 to simulate the effect of the hydraulic parameters of the aquifer on the hydraulic circulation pattern of the GCW. The use of particle tracking simulated by MODPATH 7 showed the circulation cells and the impact on groundwater directions induced by different configurations of hydraulic parameters. The water flowing into the cell comes from both the injection well and the surrounding aquifer and the model shows how the hydraulic parameters of the aquifer, in particular the horizontal and vertical hydraulic conductivity, have a paramount influence in determining the shape and dimension of the circulation cell. A water mass balance analysis was carried out. It allowed to predict the groundwater flows exchanges between the GCW system and the surrounding aquifer, and to verify the sensitivity of the water budget to specific aquifer parameters. The results of this study are useful for further understanding the hydraulics of a GCW remediation system in order to support the design and to predict its performance.
Introduction

Groundwater pollution is a crucial issue both for the water cycle and for a safe drinking supply (Li et al. 2021). Consequently, groundwater pollution must be managed in order to guarantee the good quality status of water resources (Di Curzio et al. 2022). One of the most important tasks to properly manage contamination is the definition of a good conceptual model on which to design properly remediation systems. Groundwater numerical models help hydrogeologists to understand and evaluate the efficiency of designed remediation systems by evaluating the effect of both modelling and design parameters (Stefania et al. 2018, Formentin et al. 2019).

Groundwater Circulation Wells (GCWs) represent an in-situ groundwater remediation technology, alternative to the traditional Pump&Treat (Herrling et al. 1991; Miller and Roote 1997; McCarty et al. 1998), where the groundwater extracted from the aquifer is treated in a processing unit and re-injected in the same aquifer long the same vertical but at a different depth.

The combination of negative pressure induced at the GCW extraction point and the overpressure performed at the injection point generates a vertical hydraulic gradient in the aquifer that, interfering with the sub-horizontal natural gradient of the aquifer, establishes a high-velocity groundwater circulation pattern, which promotes both the removal of the dissolved contamination and the desorption of the adsorbed contamination in the soil.

This GCW system characteristic allows to avoid discharging the extracted groundwater, or running into additional costs for the transport to an external treatment plant (Elmore and DeAngelis 2004). Another advantage of this system is to prevent huge net groundwater withdrawal that may lead to potential issues involving, for example, saltwater intrusion or subsidence, which hit the most sensitive geological areas, i.e. coastal plains, karst areas and alpine lake margins (Berti et al. 2018).

GCW systems generally have a higher capital cost than Pump&Treat. However, they are advantageous in case of contamination hotspots, site-specific conditions that make the formation of a groundwater cone problematic, the need to treat off-site contamination and difficulty in delivering the treated groundwater to a receiving water body (Elmore and Hellman 2001). Moreover, remediation systems applying GCW technology are easily adjustable as they can be scaled to either a single well or hydraulic barrier to the source of contamination.

The forced groundwater circulation induced by the GCW increases the vertical hydraulic gradient near the well and provides a fundamental help for a faster depletion of the contaminant, especially in presence of Dense-non-aqueous Phase Liquids (DNAPLs; Tatti et al. 2019).

The flow field established by the activation of a GCW can create a local rise of the piezometric level that allows to reach and therefore treat some unsaturated levels placed above the aquifer’s smear zone (Mohrlok et al. 2010).

The first GCW system for the treatment of contaminated groundwater was presented by Herrling and Baumann (1990) and Herrling et al. (1990). These authors investigated the flow regime through numerical modeling and simplified assumptions. More detailed studies were conducted on the numerical modeling of 3-D circulation patterns established by GCWs (Herrling and Stamm 1991; Herrling and Stamm 1992; Herrling and Stamm 1993; Stamm et al. 1996; Stamm 1997; Elmore and DeAngelis 2004; Johnson and Simon 2007).

Previous studies based on numerical models (Elmore and Hellman 2001; Mohrlok et al. 2010; Tatti et al. 2019) allowed to improve the knowledge on the circulation pattern generated by GCWs investigating the effect of the hydraulic performance of the system due to site-specific parameters i.e. transmissivity, aquifer thickness and anisotropy (Elmore and DeAngelis 2004; Zlotnik et al. 2010) and GCW project parameters (e.g. filtering sections thickness, circulation flow rates). However, previous studies never address the study of GCW from the groundwater mass balance point of view.

The experimental investigations and field experiments conducted so far with the GCW systems indicate that a detailed knowledge of the aquifer heterogeneity near the treated area is essential to the proper design of GCW systems. In this light, numerical modeling represents a useful tool to support the definition of the well configuration and evaluate the effect of the hydraulic parameters on the system's performance. Since GCWs establish an increased vertical flow, the ratio between horizontal and vertical hydraulic conductivity assumes an important role that has to be considered during the design phase of this technology (Alesi et al. 1991; Herrling and Stamm 1991). For this reason, the use of site-specific values for hydraulic parameters, such as the hydraulic conductivity and anisotropy is a key aspect.

In this study, numerical modeling is used as a preliminary step to support the design of a GCW system. In particular, the aim of the model is to investigate how the circulation cell induced by GCW is influenced by hydraulic parameters of the aquifer in terms of groundwater flow direction, dimension of the circulation cell and water mass balance.

The proposed numerical simulation approach provides a basis for proper real-case system design, as it allows not only to calculate the size of the GCW-induced recirculation cell depending on different aquifer parameters, but also to quantify the water flowrates involved, distinguishing between the contribution of the circulation cell and the contribution exchanged to and from the aquifer from the capture zone, and release zone.
Materials and Methods

Hydrogeological conceptual model

The present case study synthesizes a real case-study aquifer from which the hydraulic parameters, the structure of the aquifer and the distribution of the contamination source were derived.

The groundwater flow model was developed considering hydraulic parameters derived from field data, which were averaged in order to construct a generalized numerical flow model that allows the study of the behavior and effects of the GCW system on the aquifer.

Field data were collected using a Hydraulic Profiling Tool (HPT) system manufactured by Geoprobe Systems®, which allows to estimate hydraulic conductivity values ($k$) in the saturated formation with a high resolution.

According to Brandenburg, (2020) the horizontal hydraulic conductivity ($k_h$) can be calculated as the arithmetic mean of the $k$ values measured by the HPT within a homogeneous lithotype. The vertical hydraulic conductivity ($k_v$) can be estimated either (i) assuming a ratio of 10 (standard anisotropy) between horizontal and vertical hydraulic conductivity (Freeze and Cherry 1979) or (ii) by calculating $k_v$ as the harmonic mean of the $k_h$ data derived from the HPT survey (field anisotropy) (Brandenburg 2020).

In the present case study, the investigated aquifer has a thickness of about 10 meters and two different lithotypes: a sandy silt layer with a thickness of 5 m lies on a silty sand layer of 5 m. The silty sand layer is completely saturated, whereas the sandy silt layer is saturated only for 3 meters.

The gradient was calculated in the order of about 5‰. The contamination in the real-case aquifer is distributed throughout the saturated thickness, therefore a GCW system was applied with standard circulation: both screens have a thickness of 1 m, and are located one (injection) immediately below the water table, the other (extraction) immediately above the bottom of the aquifer. The GCW system is operated with a flow rate of 72 m$^3$/d at both the injection and extraction screen, identified via preliminary studies.

In order to properly develop the GCW system, a numerical groundwater flow model was built to test hydraulic parameters variations in six different scenarios (Tab. 1).

Groundwater numerical model design

The numerical groundwater flow model was developed using MODFLOW-2005 (Harbaugh 2005) assuming steady-state conditions. Groundwater flow direction was simulated by particle tracking by means of MODPATH 7 (Pollock 2016) and Groundwater Vistas version 8 (Rumbaugh and Rumbaugh 2020) was used as a Graphical User Interface.

A model domain with 1 x 1 km dimensions was built with the GCW system located exactly in the middle, and it was discretized both horizontally and vertically. The grid cells were refined horizontally from a maximum cell size 20 x 20m (at the model boundary) to a minimum cell size 1 x 1 m (at the CGW location; Fig. 1). This refinement allows to achieve higher resolution in the simulation of the piezometric level close to the well. The model domain was subdivided vertically into 10 layers of 1 m thickness each, 8 of which represent the saturated zone.

Taking into account the real-case aquifer, the top and the bottom of the model were built considering a constant slope of 5‰, equally imposed to all layers. The use of a constant slope to build the model grid allows to keep a constant saturated thickness of the aquifer across the entire modeled area.

As for the boundary conditions, two constant heads were imposed at the western and eastern boundaries of the model domain, obtaining a natural hydraulic gradient of 5‰ oriented from west to east.

![Fig. 1 - Model domain and boundary conditions. On the left, the model grid and a cross-section. On the right, the refinement of the grid and zoomed cross-section on the well. The blue line represents the Constant head, the full circle represents the Injection well, and the empty circle represents the Extraction well](image_url)

Fig. 1 - Dominio di calcolo e condizioni al contorno. A sinistra la griglia di calcolo e una sua sezione. A destra l’infittimento applicato alla griglia nell’area del pozzo e una sezione. Le linee blu rappresentano la condizione al contorno “Constant head”. Il cerchio colorato in blu rappresenta il filtro di iniezione, il cerchio vuoto rappresenta il filtro di emungimento.
The GCW was simulated by means of the well package of MODFLOW with a standard flow configuration: the injection is from the upper filter (1 m thick) and the extraction is from the lower filter (1 m thick). The model grid, the cross-section of the model and the location of the boundary conditions are shown in Figure 1.

Regarding the hydraulic parameters of the aquifer: a detailed description of the hydraulic conductivity was reported in paragraph 2.3, while the storage coefficient and porosity are neglected in the model as it was developed under stationary conditions. A porosity value from the literature was used in the calculation of water retention times within the recirculation cell (result section): 0.15 for sandy silt and 0.2 for silty sand (Jhonson 1967).

**Hydraulic conductivity values of the simulated hydrogeological systems**

The numerical groundwater model was used to evaluate the effect of the hydraulic conductivity on the circulation cell induced by the GCW. For this purpose, six scenarios with different configurations of the hydraulic conductivity and the ratio between horizontal \( k_h \) and vertical \( k_v \) hydraulic conductivity, were compared. The hydraulic conductivity and anisotropy values (the ratio \( k_h/k_v \)) used in each scenario have been summarized the Table 1. Scenarios from 1 to 4 are representative of a homogeneous aquifer, while scenarios from 5 and 6 consider an aquifer composed of two overlapping zones with different hydraulic conductivities, and they are derived from the real-case aquifer conditions.

Scenarios 1 and 2 consider a low value of \( k_h \), (typical of the sandy-silt deposits) and allow to compare the effect in the use of two different anisotropy values, equal to 10 and 37, respectively. The former anisotropy value was defined considering the standard anisotropy (i.e. 10) typically used in literature (Freeze and Cherry 1979), whereas the latter is calculated as the harmonic mean of the \( k_h \) data derived from the field HPT survey, following the approach proposed in Brandenburg 2020.

Scenarios 3 and 4 consider a higher \( k_h \) value (typical of silty-sand deposits) than the scenarios 1 and 2 and compare two different anisotropy values, equal to 10 and about 16. As in the previous scenarios, the used anisotropy values were derived from the application of the standard anisotropy (i.e. 10), and the harmonic mean of the \( k_h \) data derived from the HPT survey, respectively.

As mentioned above, scenarios 5 and 6 consider an aquifer composed of two overlapping levels with different hydraulic conductivities using two different anisotropy values. In particular, scenario 5 use the standard anisotropy value, whereas scenario 6 uses the field anisotropy value. In accordance with the conceptual model of the aquifer, the lower value of the hydraulic conductivity was applied from layer 1 to 5, whereas the highest value was applied from layer 6 to 10.

| Scenario | Model layers | \( k_h \) (m/d) | Anisotropy \( (k_h/k_v) \) |
|----------|--------------|----------------|------------------------|
| Scenario 1 | 1-10 | 5.1 | 10 |
| Scenario 2 | 1-10 | 5.1 | 37 |
| Scenario 3 | 1-10 | 15.6 | 10 |
| Scenario 4 | 1-10 | 15.6 | 16 |
| Scenario 5 | 1-5 | 5.1 | 10 |
| Scenario 6 | 1-5 | 5.1 | 37 |

**Particle tracking**

In order to display the flow directions induced by the action of the GCW system, the particle tracking method was applied using MODPATH 7 code. The analysis of the flow direction and the movement of water particles around the well was carried out through simulations with forward and backward tracking in order to identify the particles captured and released by the abstraction and injection section of the GCW.

Particles were arranged along the vertical of the GCW, from layer 3 (injection screen) to layer 10 (extraction screen) as a circle around the vertical of the well.

The backward simulation has been useful to understand flow direction from upgradient the GCW, instead, the forward simulation has been performed to figure out the flow direction from the GCW to downgradient.

The results of backward and forward simulations allow to determine the shape of the circulation cell induced by the GVW. Furthermore, the simulation makes it possible to distinguish the section of the cell fed by the injection from the section fed by the abstraction of the GCW.

**Mass balance setting**

In order to understand the behaviour and the efficiency of the circulation cell induced by simultaneous injection and abstraction of water from the GCW into the aquifer, the groundwater mass balance performed by MODFLOW was analysed. For this purpose, the model domain was discretized into 4 different zones: the aquifer of interest (CC), the injection well (IW) and the extraction well (EW). Figure 2 represents the GCW system as discretized in the mass balance analysis: the injection well (IW) distributes water both to the circulation cell (with a flowrate \( Q_{in} \)) and the downgradient aquifer (with a flowrate \( J_{2out} \)). Likewise, the extraction well (EW) captures water from both the circulation cell (with a flowrate \( Q_{out} \)) and the upgradient aquifer (with a flowrate \( J_{1out} \)). Meanwhile, the circulation cell (CC) exchanges water with IW and EW (with flowrates equal to \( Q_{in} \) and \( Q_{out} \), respectively), and in addition, receives water from the upgradient aquifer (\( J_{1in} \)) and returns water to the downgradient aquifer (\( J_{1out} \)). Then the extracted groundwater,
with a recirculation flowrate $Q_r$, is sent to an external treatment unit (TU) before being re-injected in the aquifer.

The above zones were defined using the Hydrostratigraphic Units (HSU) package of Groundwater Vistas which using the ZONE BUDGET code (Harbaugh 1990) calculate the water flux in terms of water exchanged between neighbouring zones based on the MODFLOW solution.

**Results**

**Local water table rise**

One of the most direct effects of the injection of water into the aquifer due to the use of GCW wells is the local rise in the piezometric level close to the GCW location. The water table rise contributes one hand to increase the area treated by the well, and on the other hand, it could generate interactions with underground structures such as tanks, cables, etc.

The rising of the water table takes on a shape like an asymmetric bell with the maximum piezometric level aligned with the injection filter of the GCW ad located above the undisturbed groundwater level. The model was used to quantify the effect of the change in hydraulic conductivity on the rising of the piezometric level. Figure 3 shows the piezometric levels reached by the water table on the GCW in the six simulated scenarios and concerning the undisturbed aquifer.

The maximum increase in piezometric level occurs in scenario 1 (1.42 m) and the minimum in scenarios 3 and 4 (0.46 m). The increase, therefore, appears to be strongly dependent on the aquifer’s permeability (as expected, higher water table rise is observed with lower permeability), and to a negligible extent on anisotropy.
**Particle tracking**

The particle tracking performed by the code MODPATH7 in backward and forward mode, allowed to identify the shape and volume of the capture zone and the release zone, respectively. The circulation cell was identified as the envelope volume of backward and forward simulations.

Figure 4 shows the result of the particle tracking simulations, with the subdivision between the three zones.

Figure 4 shows the cross-section of each of the simulated circulation cells along the main groundwater flow direction, while Table 2 summarizes the volume and the maximum length of each cell. The results show that circulation cells have an irregular shape due to the presence of a hydraulic gradient, confirming what has already been described in the literature (Johnson and Simon 2007). The inclination of the circulation cell is related to the groundwater gradient. In fact, reference model simulations groundwater gradient equal to zero were performed for every scenario, and they resulted in symmetrical circulation cells with no inclination, confirming what is reported in the literature (Herrling et al. 1991).
As expected, the model results confirm that (i) an increase in the horizontal hydraulic conductivity value generates a smaller circulation cell (as it can be seen from the comparison between Scenario 1 and 3), and (ii) an increase in the anisotropy value generates a decrease in the vertical hydraulic conductivity, and therefore a larger circulation cell, as it can be clearly seen from the comparison between Scenario 1 and 2.

Figure 5 shows the extension of the capture and release zone of the GCW. Based on the simulations results in the different scenarios, it is clear that these features of the GCW are also sensitive to the variation in the hydraulic parameters: an increase in horizontal hydraulic conductivity value generates a narrower capture (or release) zone, an increase in anisotropy value generates a wider capture (or release) zone.

![Scenario 1](image1.png)
![Scenario 2](image2.png)
![Scenario 3](image3.png)
![Scenario 4](image4.png)
![Scenario 5](image5.png)
![Scenario 6](image6.png)

**Fig. 5** - Shape of the circulation cell in the different scenarios simulated (view from below). Red lines represent capture zone; blue lines represent release zone. See Table 2 for a comparison of scenarios.

**Tab. 2** - Volume and maximum length along the groundwater flow direction of the circulation cell in the six simulated scenarios. Capture and release zones are shown in Figure 4.

| Scenario | Volume \((m^3)\) | Maximum length along gw flow direction \((m)\) | Capture zone width \((m)\) | Release zone width \((m)\) |
|----------|-----------------|-----------------------------------------------|-----------------------------|-----------------------------|
| 1        | 8400            | 44                                            | 62                          | 55                          |
| 2        | 18300           | 73                                            | 108                         | 106                         |
| 3        | 3500            | 33                                            | 50                          | 49                          |
| 4        | 4400            | 40                                            | 62                          | 60                          |
| 5        | 4700            | 38                                            | 50                          | 52                          |
| 6        | 8000            | 54                                            | 68                          | 92                          |

**Tab. 2** - Volume ed estensione massima nella direzione di flusso della cella di ricircolo nei sei scenari simulati. Le zone di cattura e resa sono visibili in Figura 4.
Groundwater mass balance

Based on the results obtained from the particle tracking simulation it was possible to set the Hydrostratigraphic Units (HSU) used to calculate the water mass balance of the circulation cell. Once represented in the model, the ZONE BUDGET code (Harbaugh 1990) returns information about the mass balance between the different HSU. For each scenario, the results of the calculated water mass balance have been analysed.

Table 3 and Figure 6 summarize the results obtained in the six scenarios. Comparing scenarios 1 and 2, a higher volume of water flows directly from the injection well to the aquifer when anisotropy increases, from 8.05 m$^3$/d to 18.95 m$^3$/d (2.35 times higher). The same happens in scenarios 3 and 4 and scenario 5 and 6, but in a less evident way due to the less marked increase of the anisotropy value, from 27.77 m$^3$/d to 34.78 m$^3$/d (scenarios 3 and 4, 1.25 times higher) and from 16.92 m$^3$/d to 28.55 m$^3$/d (scenarios 5 and 6, 1.69 times higher). The same considerations can be made for the extraction well. In all scenarios a portion of water is exchanged with the surrounding aquifer: in scenarios 2 and 4, this water flows through the circulation cell to the extraction well (respectively 0.57 m$^3$/d and 0.28 m$^3$/d), whereas in the other scenarios (1-3-5-6) water flows from the injection well through the circulation cell to the aquifer (respectively 2.63 m$^3$/d, 0.15 m$^3$/d, 2.41 m$^3$/d, 1.50 m$^3$/d).

It can be immediately verified that the flowrate values estimated by the ZONE BUDGET code respect the mass conservation/continuity equations in steady state conditions.
Tab. 3 - Bilancio di massa di acqua negli scenari simulati. Portate espresse in m³/d.

| IW mass balance | CC mass balance | EW mass balance |
|----------------|----------------|----------------|
| J_{1in} | Q_{in} | Q_{r} | Q_{in} | J_{1in} | J_{2in} | J_{2out} | Q_{out} | J_{2in} | Q_{out} | Q_{r} |
| Scenario 1  | 8.05  | 63.95  | 72  | 63.95  | 37.88  | 40.51  | 61.32  | 10.68  | 61.32  | 72  |
| Scenario 2  | 18.95 | 53.05  | 72  | 53.05  | 55.32  | 54.75  | 53.62  | 18.38  | 53.62  | 72  |
| Scenario 3  | 27.77 | 44.23  | 72  | 44.23  | 64.67  | 64.82  | 44.08  | 27.92  | 44.08  | 72  |
| Scenario 4  | 34.78 | 37.22  | 72  | 37.22  | 66.65  | 66.37  | 37.50  | 34.50  | 37.50  | 72  |
| Scenario 5  | 16.92 | 55.08  | 72  | 55.08  | 55.32  | 57.73  | 52.67  | 19.33  | 52.67  | 72  |
| Scenario 6  | 28.55 | 43.45  | 72  | 43.45  | 68.30  | 69.80  | 41.95  | 30.05  | 41.95  | 72  |

(Σ\(Q_{in}\) = Σ\(Q_{out}\)) in the overall system, as well as in each one of the nodes where water flows are exchanged (IW, EW and CC in the simplified block diagram).

Once all the mass balance fluxes are known, it is possible to calculate the Hydraulic Retention Time (HRT) of groundwater within the system composed by the circulation cell, the injection cell and the extraction well. For each simulation, the HRT of the system can be estimated as the total pore volume of the aquifer system involved in the circulation pattern (assumed equal to the volume of the circulation cell \(V_{cc}\) derived from the particle tracking simulations, multiplied for the aquifer’s effective porosity), divided for the total flowrate \(J_{1out} + J_{2out}\). The following formula can be used:

\[
HRT [d] = \frac{V_{cc} [m^3]}{J_{1out} + J_{2out} [m^3/d]} \cdot \varphi [-]
\]

The HRT values calculated for the simulated scenarios are summarized in Table 4.

As it can be seen from the comparison between Scenarios 1-2 and Scenarios 3-4, the highest HRT values in the circulation systems are obtained with lower aquifer permeability, since low horizontal permeability values produce greater circulation cell volumes, and lower flowrates \(J_{1out}\) and \(J_{2out}\) to the downgradient aquifer. In particular, the groundwater flowrate discharged from the injection well to the aquifer \(J_{2out}\) appears to be more sensitive to the variations of permeability compared to the CC flowrate to the aquifer \(J_{1out}\).

The increase in the aquifer anisotropy has the effect of further increasing the water retention time in the system, as expected, due to an increase in the vertical hydraulic conductivity, as it can be noticed by comparing HRT values between Scenarios 1 and 2, Scenarios 3 and 4, Scenarios 5 and 6.

**Discussion**

The analysis of the different simulations allows to compare the dimensions of the circulation cell and the water mass balance as the \(k_h\) value varies while maintaining the same anisotropy value. For example, a comparison between Scenario 1 and Scenario 3 shows that an increase in the \(k_h\) value generates a reduction in size of the recirculation cell, an increase in the flowrates exchanged with the aquifer resulting, overall, in an decreased hydraulic retention in the circulation system. Moreover, the increased hydraulic conductivity dramatically impacts the hydrogeological balance of the aquifer system involved in the circulation pattern by (i) increasing the percentage of water discharged from the IW directly to the downgradient aquifer compared to the flow injected into the circulation cell, and at the same time (ii) increasing the percentage of water abstracted from the upgradient aquifer compared to the groundwater flow drawn from the circulation cell at the EW. Finally, at higher aquifer permeability conditions, the injection well is able to discharge to the downgradient aquifer a higher amount of (completed treated) groundwater compared to the groundwater discharge (partially treated) from the circulation cell volume, thus potentially resulting in a better groundwater quality dowgradient the GCW.

As explained above, two different approaches have been used to estimate the vertical hydraulic conductivity, which allow to study the effect of varying anisotropy on the features of the circulation system induced by the GCW. For example, comparing Scenarios 1 and 2 with the same horizontal hydraulic conductivity, an increase in the value of the anisotropy (decrease in the vertical hydraulic conductivity) from 10 to 37 results in a larger circulation cell, and is associated with a doubled hydraulic retention time in the circulation system. At the same time, the decrease in
vertical hydraulic conductivity enhances the capacity of the GCW to interact with the surrounding aquifer compared to the interaction with the circulation cell by (i) increasing the percentage of water discharged from the IW directly to the downgradient aquifer compared to the flow injected into the circulation cell, (ii) increasing the percentage of water abstracted from the upgradient aquifer compared to the groundwater flow drawn from the circulation cell at the EW.

As shown in Scenario 1 in the presence of lower hydraulic conductivity and standard aquifer anisotropy (10), a higher flowrate of groundwater coming from the circulation cell is expected to be discharged to the downgradient aquifer compared to the treated groundwater flow from the IW. Additional studies are needed to better investigate how the composition of the groundwater fluxes exchanged with the downgradient aquifer (coming from the IW and from the CC) may influence groundwater quality downgradient the GCW system.

The analysis of the results for the heterogeneous aquifer (i.e. Scenarios 5 and 6) leads to similar considerations made above for the homogeneous aquifer. In particular, the larger anisotropy values used in Scenario 6 generates an increase in the circulation cell size, and increases the flowrate of groundwater from the injection well compared to that from coming from the circulation cell, reaching the downgradient aquifer.

All simulation show that the use of higher anisotropy is generally less conservative, as it may lead to underestimate the flowrate of partially treated groundwater being discharged from the circulation cell to the downgradient aquifer, escaping the zone of influence of a GCW system. Therefore, a calculation method for anisotropy that avoids overestimation should be preferred in the design phase of a GCW system.

Conclusions

Previous papers have investigated in terms of flow dynamics Groundwater Circulation Wells as an in situ groundwater remediation technology. These works provided useful information about the implementation of this technology in real case studies. However, the dynamic of the induced circulation cell has never been assessed in terms of water mass balance.

This study examined the circulation cells induced by GCW wells by analyzing the effect of varying aquifer parameters in the groundwater flow pattern, as well as in the hydrogeological balance of the system. The visualization of the flow paths showed that the circulation cell has a complex shape, inclined with respect to the axis of the well. The mass balance analysis has highlighted how hydraulic conductivity and anisotropy (both in the case of homogeneous and heterogeneous aquifers) influence the volume of the circulation cell, as well as the water fluxes between the latter and the aquifer. These results imply that hydraulic conductivity and anisotropy significantly impact the solute transport, adsorption, and desorption mechanisms of the potential contaminants downgradient the GCW.

The different results obtained in the simulated scenarios confirm that it is important to rely on robust input data concerning the hydraulic properties of the aquifer, e.g. because the overestimation of the anisotropy value could lead to an overestimation of the capture area and the water retention time inside the circulation system.

The use of the numerical model has allowed quantifying the local rise of the water table induced by the GCW injection. The quantification of this rise can be a crucial aspect that must be carefully evaluated especially in contexts where the rising of the water table could interfere with underground technological systems and/or bring in solution contaminants in the unsaturated soil.

The results of this study are useful to better understand the hydraulics of the GCW remediation system, support its design, and predict its performance determining the extension of the circulation cells and, therefore, the area subjected to treatment. Additional studies are needed in order to:

(i) fully understand the impacts of aquifer parameters, aquifer gradient, and flow and mass balance contributions in the performance of a GCW system in terms of downgradient mass transport;
(ii) confirm the simulated scenarios with site-specific data after the designed system is implemented in the field.

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The authors declare no competing interest.

Author contributions

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