

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

Modello numerico del flusso delle acque sotterranee finalizzato alla comprensione del bilancio idrogeologico e all'analisi delle direzioni di flusso di pozzi di ricircolo (GCW) al variare dei parametri idrogeologici

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Riassunto

I pozzi di ricircolo (*Groundwater circulation Well* - GCW) rappresentano un'efficace alternativa di bonifica in-situ che consente un elevato recupero di massa di contaminante nel caso in cui siano presenti hotspot localizzati nel suolo saturo anche in livelli litologici a bassa permeabilità. Le tradizionali tecnologie Pump & Treat, *Air Sparging* (AS)/*Soil Vapor Extraction* (SVE) e *Multi Phase Extraction* (MPE) possono dimostrarsi poco efficaci per la rimozione di contaminazione adsorbita, implicando lunghe tempistiche di trattamento, con un conseguente costo significativo per la gestione dell'intervento nel lungo termine. I GCW generano significative modifiche della direzione di flusso delle acque sotterranee introducendo flussi verticali orientati verso il basso e verso l'alto che nel complesso formano la "cella di ricircolo". La formazione di tale cella ha l'effetto di facilitare il desorbimento fisico (*flushing*) del contaminante. Lo scopo del presente studio è quello di comprendere l'effetto dell'attivazione di un sistema GCW sull'acquifero sia sotto l'aspetto delle direzioni di flusso, sia dal punto di vista del bilancio idrico. A tale scopo è stato costruito un modello numerico di flusso delle acque sotterranee basato sul codice MODFLOW-2005 al fine di comprendere meglio l'effetto dei parametri idraulici sulla cella di ricircolo indotta dai GCW. L'utilizzo del particle tracking simulato con codice MODPATH ha permesso di visualizzare la cella di ricircolo e il cambiamento del campo di moto delle acque sotterranee indotto dal GCW. I risultati del modello mostrano che i parametri idrogeologici, in particolare la conducibilità idraulica orizzontale e verticale, hanno una importante influenza sulla forma della cella di ricircolo. L'analisi del bilancio di massa delle acque sotterranee ha consentito di quantificare i flussi di falda scambiati tra il sistema GCW e la falda acquifera circostante e di verificare la sensibilità del bilancio idrico a specifici parametri della falda acquifera. I risultati di questo studio sono utili per comprendere meglio l'idraulica di un sistema di bonifica GCW al fine di supportarne la progettazione e prevederne l'efficacia di trattamento.

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 or site characteristics.

The circulation induced by GCW may generate water oxygenation due to the induced turbulence, stimulating the in-situ aerobic biodegradation (Lakhwala et al. 1998) with the simultaneous advantage of accelerating the remediation times in aquifers that have unfavorable geochemical properties to microbial activity (Semprini et al. 1990).

GCW are particularly interesting as they allow to integrate the hydraulic barrier effect to in-situ remediation techniques through the injection of reagents and/or amendments

(Petrangeli Papini et al. 2016; Pierro et al. 2017; Alesi et al. 2018).

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 Buermann (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 m³/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 GCW 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.

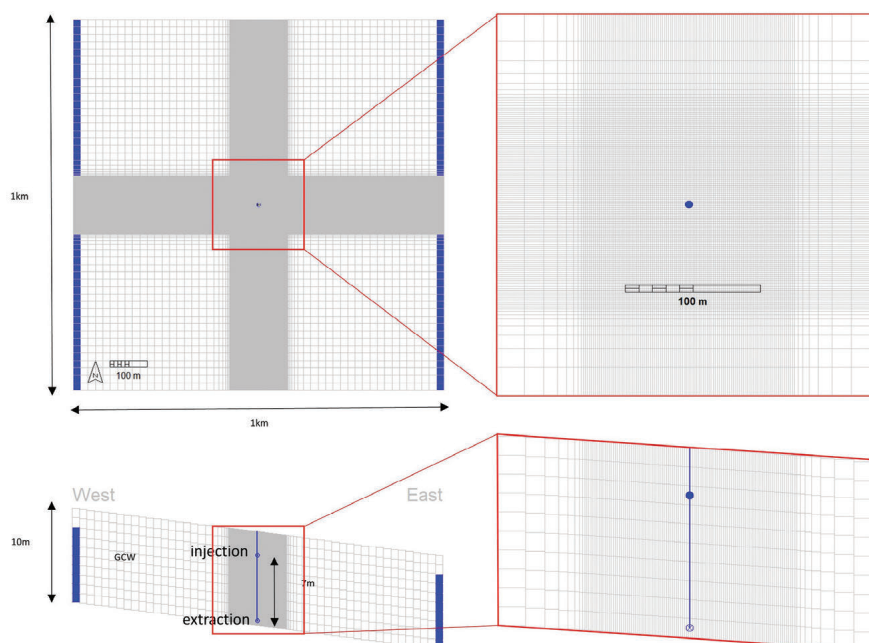


Fig. 1 - Model domain and boundary conditions. On the left, the model grid and a cross-section. On the right, the refinement of the grid and zoomed cross-section on the well. The blue line represents the Constant head, the full circle represents the injection well, and the empty circle represents the extraction well

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 (1m 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_b) and vertical (k_v) hydraulic conductivity, were compared. The hydraulic conductivity and anisotropy values (the ratio k_b/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_b , (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_b data derived from the field HPT survey, following the approach proposed in Brandenburg 2020.

Scenarios 3 and 4 consider a higher k_b 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_b 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.

Tab. 1 - Hydraulic conductivity and anisotropy values used in the simulated scenarios.

Tab. 1 - Valori di conducibilità idraulica e anisotropia utilizzati negli scenari simulati.

Scenario	Model layers	k_b (m/d)	Anisotropy (k_b/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
	6-10	15.6	10
Scenario 6	1-5	5.1	37
	6-10	15.6	16

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, the circulation cell (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_{2in}). 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,

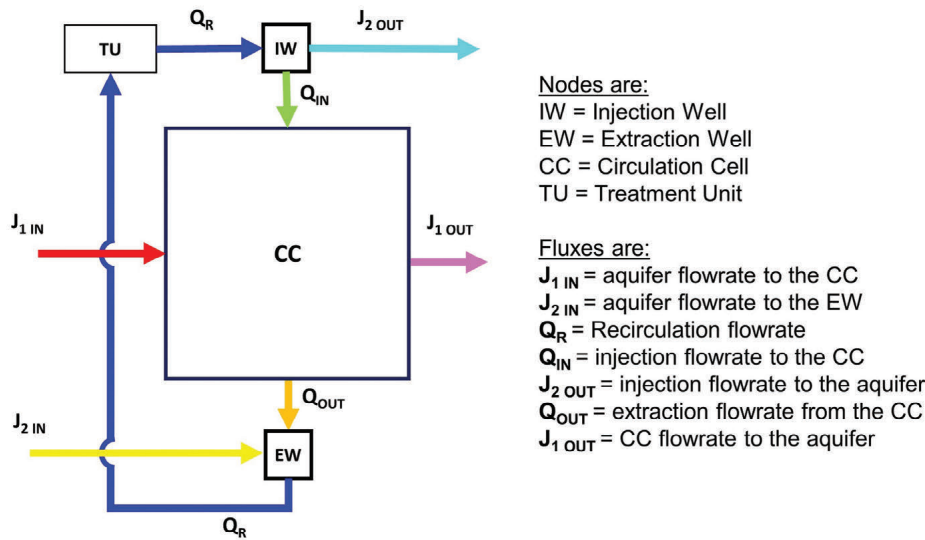


Fig. 2 - Block diagram representing the mass balance of the groundwater circulation well.

Fig. 2 - Diagramma a blocchi che rappresenta il bilancio di massa del pozzo di ricircolo.

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 and 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.

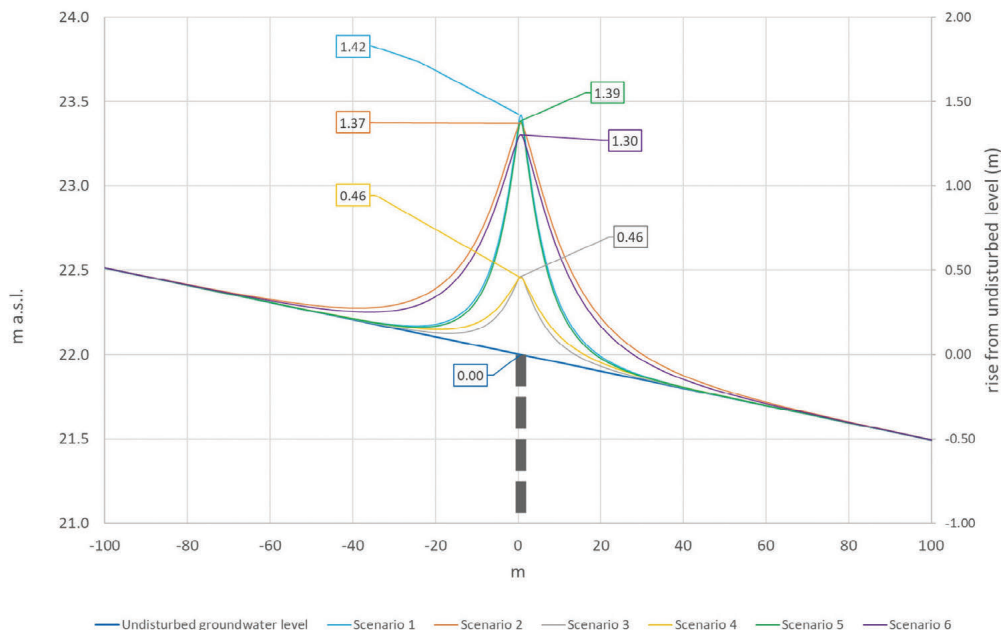


Fig. 3 - Piezometric level along the GCW vertical in the different scenarios simulated.

Fig. 3 - Livello piezometrico lungo la verticale del pozzo GCW nei diversi scenari simulati.

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).

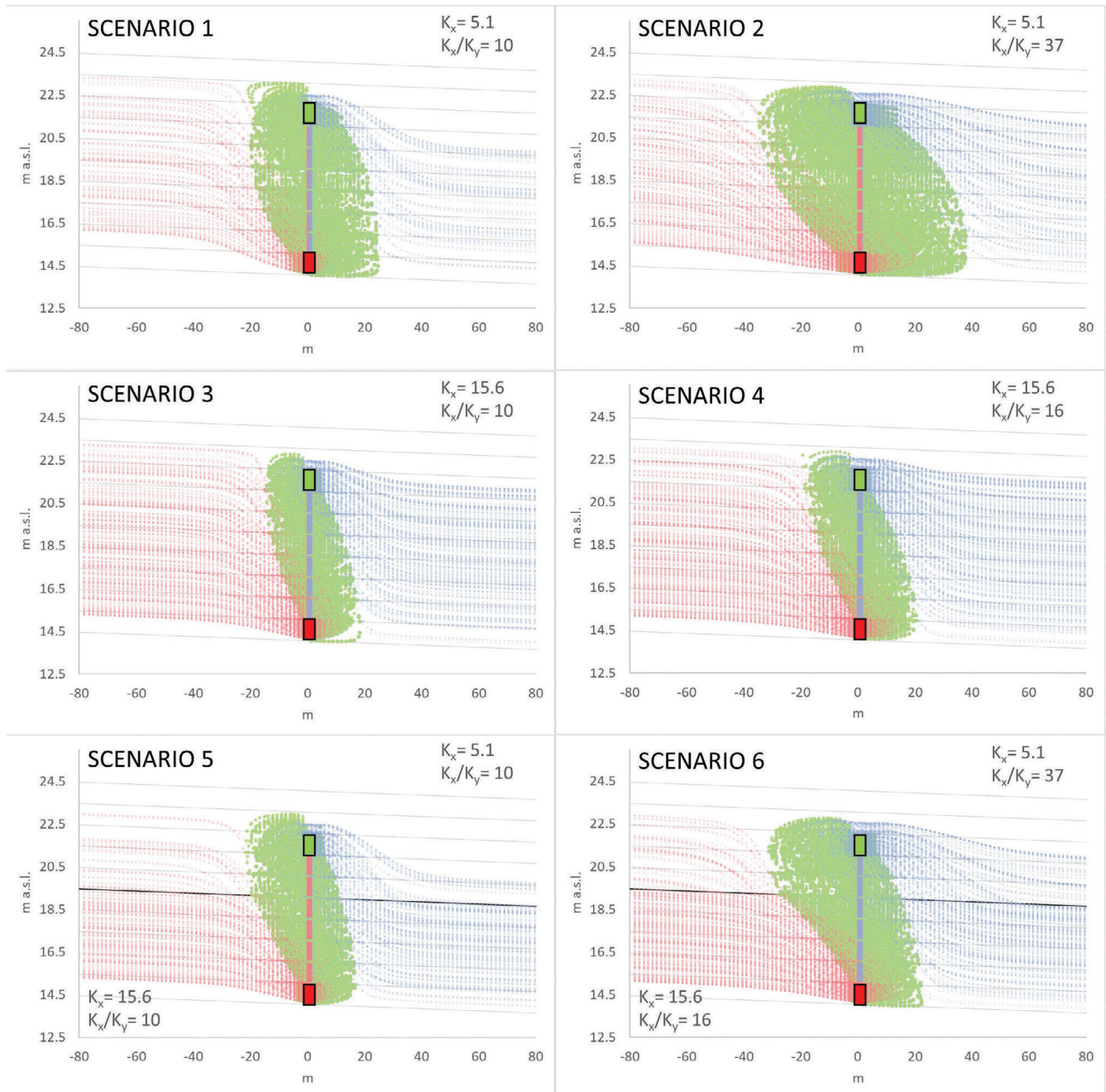


Fig. 4 - Cross-section of the circulation cell obtained in the six simulated scenarios. Green dots represent the circulation cell, the blue dots represent the release zone and the red dots represent the capture zone. Green rectangle represents injection screen; red rectangle represents extraction screen.

Fig. 4 - Sezioni della cella di ricircolo ottenuta nei sei scenari simulati. I punti verdi rappresentano la cella di ricircolo, i punti blu rappresentano la zona di resa, i punti rossi la zona di cattura. Il rettangolo verde rappresenta il filtro di iniezione; quello rosso il filtro di emungimento.

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.

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.

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.

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

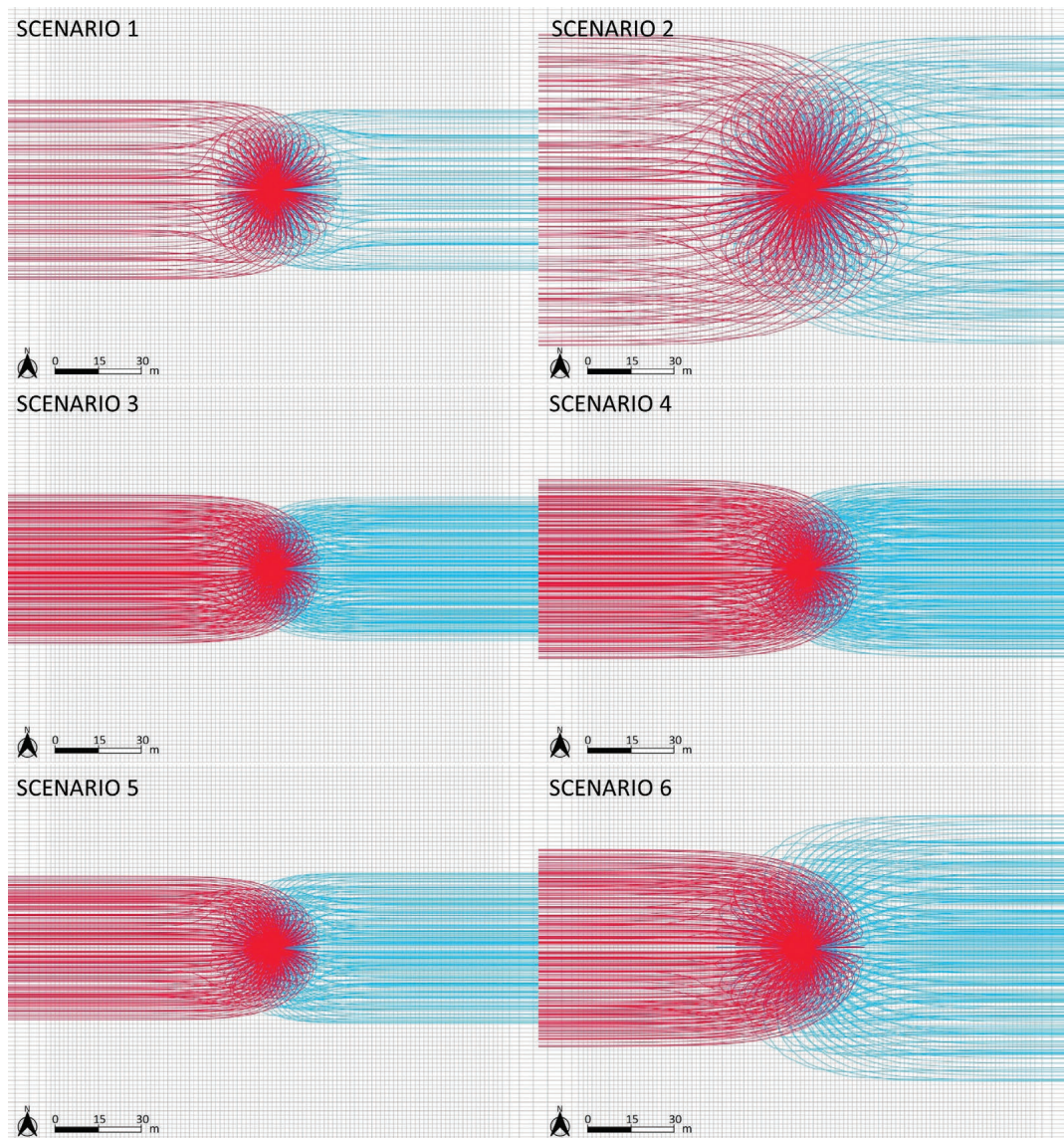


Fig. 5 - Shape of the circulation cell in the different scenarios simulated (view from below). Red lines represent capture zone; blue lines represent release zone. See Table 2 for a comparison of scenarios.

Fig. 5 - Forma della cella di ricircolo nei diversi scenari simulati (visione dal basso). Le linee rosse rappresentano la zona di cattura; le linee blu rappresentano la zona di rilascio. Vedi Tabella 2 per un confronto tra gli scenari.

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 m³/d to 18.95 m³/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 m³/d to 34.78 m³/d (scenarios 3 and 4, 1.25 times higher) and from 16.92 m³/d to 28.55 m³/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 m³/d and 0.28 m³/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 m³/d, 0.15 m³/d, 2,41 m³/d, 1.50 m³/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

	IW mass balance		CC mass balance		EW mass balance	
	IN	OUT	IN	OUT	IN	OUT
Scenario 1	100.00%	11.18% 88.82%	18.60% 31.40%	19.89% 30.11%	14.83% 85.17%	100.00%
Scenario 2	100.00%	26.32% 73.68%	48.95% 51.05%	50.52% 49.48%	25.53% 74.47%	100.00%
Scenario 3	100.00%	38.57% 61.43%	40.62% 59.38%	40.48% 59.52%	38.78% 61.22%	100.00%
Scenario 4	100.00%	48.31% 51.69%	35.83% 64.17%	36.10% 63.90%	47.92% 52.08%	100.00%
Scenario 5	100.00%	23.50% 76.50%	49.89% 50.11%	52.29% 47.71%	26.85% 73.15%	100.00%
Scenario 6	100.00%	39.65% 60.35%	38.88% 61.12%	37.54% 62.46%	41.74% 58.26%	100.00%



Fig. 6 - Groundwater mass balance pie charts expressed in percentages in simulated scenarios. The distribution of inflow and outflow is shown for each mass balance zone.

Fig. 6 - Grafici a torta del bilancio di massa dell'acqua espressi in percentuale per ciascuno scenario simulato. Per ciascuna zona del bilancio di massa viene riportata la ripartizione dell'acqua in ingresso e in uscita dalla singola zona.

Tab. 3 - Groundwater mass balance in the simulated scenarios. Flowrates are expressed in m³/d.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 _{2 out}	Q _{in}	Q _r	Q _{in}	J _{1in}	J _{1out}	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

($\Sigma Q_{in} = \Sigma Q_{out}$) 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 leaving the aquifer system in steady state conditions (i.e., the sum of J_{1out} and J_{2out}). The following formula can be used:

$$HRT [d] = \frac{V_{cc} [m^3] \cdot \phi [-]}{J_{1out} + J_{2out} \left[\frac{m^3}{d} \right]}$$

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}

Tab. 4 - Hydraulic Retention Time in the circulation aquifer system in the simulated scenarios.

Tab. 4 - Tempo di ritenzione dell'acqua all'interno del sistema di ricircolo negli scenari simulati.

Scenario	V _{CC} (m ³)	Total pore volume in the CC (m ³)	J _{1out} + J _{2out} (m ³ /d)	HRT (d)
1	8400	1260	48.56	25.95
2	18300	2745	73.7	37.25
3	3500	700	92.59	7.56
4	4400	880	101.15	8.70
5	4700	870	74.65	11.65
6	8000	1480	98.35	15.05

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_b 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_b 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 downgradient 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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REFERENCES

- Alesi EJ, Brinnel P, Herding B, Hirschberger F, Sick MR, Stamm J (1991) In situ groundwater remediation of strippable contaminants by vacuum vaporizer wells (UVB): operation of the well and report about cleaned industrial sites. Third Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International, Dallas, TX.
- Alesi EJ, Veluvali Laxmipathy P, Abad Gonzales A, Altschuh P, Kneer A, Nestler B (2018) Groundwater remediation – numerical models and experiments, *Forschung Aktuell*, Page 59–63.
- Brandenburg JP (2020), *Geologic Frameworks for Groundwater Flow Models*. The Groundwater Project, Guelph, Ontario, Canada,
- Berti D, Blumetti AM, Brustia E, Calca Terra S, Chiarolla D, Comerci V, Di Manna P, Gambino P, Guerrieri L, Iadanza C, Leoni G, Lucarini M, Niceforo D, Nisio S, Pompili R, Spizzichino D, Triglia A (2018) Pericolosità Geologiche “*Geological Hazards*” ISPRA-MIT.
- Di Curzio D, Rotiroti M, Preziosi E (2022) Procedures for the environmental remediation of contaminated sites in Italy: food for thought from the Roundtable at Flowpath 2021 in Naples. *Acque Sotterranee - Italian Journal of Groundwater*, 11(1), 79–84. <https://doi.org/10.7343/as-2022-562>
- Elmore AC, DeAngelis L (2004) Modeling a ground water circulation well alternative. *Groundwater Monitoring & Remediation*, 24.1: 66-73.
- Elmore AC, Hellman (2001) Model-predicted groundwater circulation well performance. *Pract. Period. Hazard. Toxic Radioact. Waste Manage*, 54, 203–210.
- Formentin G, Terrenghi J, Vitiello M, Francioli A (2019). Evaluation of the performance of a hydraulic barrier by the Null space Monte Carlo method. *Acque Sotterranee - Italian Journal of Groundwater*, 8(4). <https://doi.org/10.7343/as-2019-420>
- Freeze RA, Cherry JA (1979) *Groundwater*. Englewood Cliffs, NJ: Prentice-Hall.
- Harbaugh AW (1990) A computer program for calculating subregional water budgets using results from the U.S. Geological Survey modular three-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 90-392, 46 p.
- Harbaugh AW (2005) MODFLOW-2005, the U.S. Geological Survey modular ground-water model - the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.
- Herrling B, Beurmann W (1990) A new method for in-situ remediation of volatile contaminants in groundwater - numerical simulation of the flow regime. *Proc. of the “VIII International Conference on Computational Methods in Water Resources”, Venice/Italy, June 11-15, 1990.*
- Herrling B, Beurmann W, Stamm J (1990) In-situ-beseitigung leichtflüchtiger Schadstoffe aus dem Grundwasserbereich mit dem UVB-Verfahren. *Neuer Stand der Sanierungstechniken von Altlasten. “In-situ removal of volatile pollutants from groundwater using the UVB method. New state of the art in remediation techniques for atlases”*. IWS-Schriftenreihe, H.P. Luehr et al., eds., Erich Schmidt, Berlin, 71–99.
- Herrling B, Stamm J (1991) Results of Modeling 3-D Circulation systems around special screened wells for physical or biological in situ ground-water remediation (UVB Technology) EOS, *Transactions, Amer. Geophys. Union*, Vol. 72, No. 44, p. 152.
- Herrling B, Beurmann W, Stamm J (1991) In situ groundwater remediation of strippable or volatile contamination using the UVB method. *Proc., European Conf. Advances in Water Resources Technology*, G. Tsakiris, ed., Balkema, Rotterdam, The Netherlands, 315–321.
- Herrling B, Stamm J (1992) Hydraulic Circulation System for In Situ Remediation of Strippable Contaminants and In Situ Bioreclamation (GZB/UVB Method). *Proceedings “Hydrochemistry 1993” May 24 - 29, 1993 Rostov-on-Don, Russia.*
- Herrling B, Stamm J (1993) Numerische Untersuchungen zum unterdruck-verdampfer-brunnen UVB und zum Grundwasserzirkulations-brunnen GZB. “*Numerical studies of the vacuum evaporator well UVB and the groundwater circulation well GZB*”. Rep. No. 702, Institute for Hydromechanics, Univ. of Karlsruhe, Germany.
- Johnson AI (1967) U.S. Geological Survey Water Supply, Government Printing Office, Washington, paper 1662-D
- Johnson RL, Simon MA (2007) Evaluation of groundwater flow patterns around a dual-screened groundwater circulation well, *Journal of Contaminant Hydrology* 93, 188–202.
- Lakhwala FS, Mueller JG, Desrosiers RJ (1998) Demonstration of a Microbiologically Enhanced Vertical Ground Water Circulation Well Technology at a Superfund Site. *Ground water monitoring and remediation* 18, no. 2, 97-106.
- Li P, Karunanidhi D, Subramani T, Srinivasamoorthy K (2021) Sources and consequences of groundwater contamination. *Archives of environmental contamination and toxicology*, 80(1), 1-10. <https://doi.org/10.1007/s00244-020-00805-z>
- McCarty PL, Goltz MN, Hopkins GD, Dolan ME, Allan JP, Kawakami BT, Carrothers TJ (1998). Full scale evaluation of in situ cometabolic degradation of trichloroethylene in groundwater through toluene injection. *Environmental Science & Technology* 32 (1), 88–100.
- Miller PG, Roote, DS, 1997. In-well Vapor Stripping. *GWRTAC Technology Overview Report TO-97-01.*
- Mohrlock U, Kirubakaran SC, Eldho TI (2010) Transport Characteristics in a 3D Groundwater Circulation Flow Field by Experimental and Numerical Investigations. *Practice periodical of hazardous, toxic, and radioactive waste management*. ASCE. Pages 185-194.
- Petrangeli Papini M, Majone M, Arjmand F, Silvestri D, Sagliaschi M, Sucato S, Alesi E (2016) First pilot test on integration of GCW (groundwater circulation well) with ENA (enhanced natural attenuation) for chlorinated solvents source remediation, *Chemical Engineering Transactions*, 49, 91-96.
- Pierro L, Maturro B, Rossetti S, Sagliaschi M, Sucato S, Alesi EJ, Bartsch E, Arjmand F, Petrangeli Papini M (2016) Polyhydroxyalkanoate as a slow-release carbon source for in-situ bioremediation of contaminated aquifers: From laboratory investigation to pilot-scale testing in the field. *New Biotechnology*, Vol. 37, July 2017, pp 60-68.
- Pollock DW (2016). Extending the MODPATH algorithm to rectangular unstructured grids. *Groundwater*, 54(1), 121-125. <https://doi.org/10.1111/gwat.12328>
- Rumbaugh JO, Rumbaugh DB (2020) *Groundwater Vistas version 8 manual*. Environmental Simulations, Leesport, PA (2020).
- Semprini L, Roberts PV, Hopkins GD, McCarty PL (1990) A Field Evaluation of In-Situ Biodegradation of Chlorinated Ethenes: Part 2, Results of Biostimulation and Biotransformation Experiments, *Ground Water* 28 no.5 715-727.
- Stamm J, Scholz M, Loseke M (1996) 3D vertical circulation flows around groundwater circulation wells (GZB) for aquifer remediation: Numerical calculations and field experiments. *Contaminated soil*, W. J. van den Brink, R. Bosman, and F. Arendt, eds., Kluwer Academic, Dordrecht, The Netherlands, 171–181.
- Stamm J (1997) Numerische berechnung dreidimensionaler strömungsvorgänge um grundwasser-zirkulations-brunnen zur in-situgrundwassersanierung. “*Numerical calculation of three-dimensional flow processes around groundwater circulation wells for in-situ groundwater remediation*”. Ph.D. thesis, Univ. of Karlsruhe, Germany, Reihe 15, VDI-Verlag, Düsseldorf.
- Stefania GA, Rotiroti M, Fumagalli L, Zanotti C, Bonomi T (2018). Numerical modeling of remediation scenarios of a groundwater Cr (VI) plume in an alpine valley aquifer. *Geosciences*, 8(6), 209.
- Tatti F, Petrangeli Papini M, Torretta V, Mancini G, Boni MR, Viotti P (2019) Experimental and numerical evaluation of Groundwater Circulation Wells as a remediation technology for persistent, low permeability contaminant source zones. *J Contam Hydrol.*; 222:89-100.
- Zlotnik VA, Cardenas MB, Toundykov D (2011) Effects of multiscale anisotropy on basin and hyporheic groundwater flow. *Ground Water*, 49(4):576-83. doi: 10.1111/j.1745-6584.2010.00775.x.