Groundwater for Sustainable Development 24 (2024) 101068

Contents lists available at ScienceDirect

Groundwater for Sustainable Development

journal homepage: www.elsevier.com/locate/gsd

Review article

Review on groundwater circulation wells (GCWs) for aquifer remediation: State of the art, challenges, and future prospects

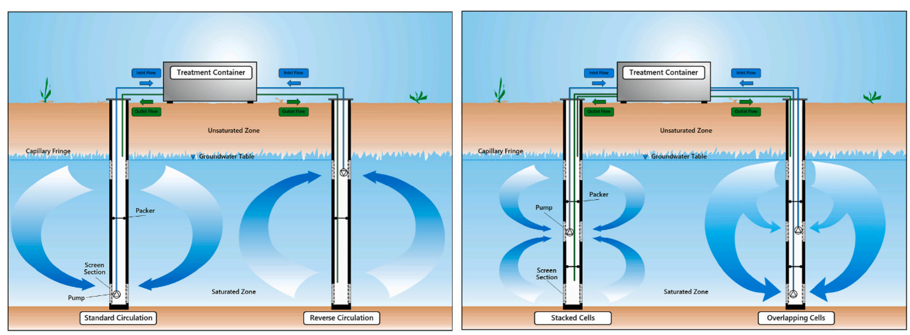
Paolo Ciampi [a,*], Carlo Esposito [a], Marco Petrangeli Papini [b]

[a] Department of Earth Sciences, Sapienza University of Rome, Piazzale Aldo Moro 5, 00185, Rome, Italy
[b] Department of Chemistry, Sapienza University of Rome, Piazzale Aldo Moro 5, 00185, Rome, Italy

HIGHLIGHTS

- Applications of groundwater circulation wells (GCW) are reviewed.
- GCWs are addressed in matematical, laboratory, and field studies.
- GCWs enhance physicochemical removal and biological degradation of contaminants.
- Coupling GCWs with a myriad of technologies gives many remediation solutions.
- Review emphasizes research needs to exploit the flexibility of GCWs in future work.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Groundwater circulation well
Dipole flow
Vertical circulation well
Review
Remediation
Groundwater

ABSTRACT

Groundwater circulation wells (GCWs) are emerging as an alternative technology for groundwater remediation. GCWs have also been used for the hydraulic characterization of aquifers, which is a necessary step toward remediation. However, the wide range of academic research on recirculating wells is quite fragmented and does not facilitate the consolidation of the findings gained in the past 30 years. Given the absence of a review on GCWs in the literature, this article aims to provide a critical overview of this topic. The analysis of pertinent literature identifies three main fields where recirculating wells are addressed: (1) mathematical models, (2) laboratory studies, and (3) field applications. The categorization of studies on GCWs within the aforementioned thematic areas highlights the main findings, contradictory results, technological limitations, implications, and opportunities for future research. The literature review introduces studies that debate the mathematical models governing the flow driven by GCWs and details the advantages and disadvantages of numerical simulations and laboratory testing. The discussion of field applications emphasizes the flexibility of recirculation systems, the possibility of coupling with other remediation technologies and numerous reagents, the targeted flushing of contaminated areas, the mobilization of pollutants from low-permeability areas triggered by hydraulic manipulation, and the reduction in remediation time and water consumption over traditional systems such as pump-and-treat (P&T). This review represents a summary in the current state of knowledge, challenges, and potential of GCWs for groundwater remediation. It guides future efforts and endeavors to fully harness the potential of GCWs, offering additional ideas and research insights.

* Corresponding author.
E-mail addresses: paolo.ciampi@uniroma1.it (P. Ciampi), carlo.esposito@uniroma1.it (C. Esposito), marco.petrangelipapini@uniroma1.it (M. Petrangeli Papini).

https://doi.org/10.1016/j.gsd.2023.101068
Received 2 August 2023; Received in revised form 11 December 2023; Accepted 12 December 2023
Available online 15 December 2023

1. Introduction

The concept of groundwater recirculation via a vertical well was first introduced by Herrling et al. (1991a, 1991b). They presented the technology of groundwater circulation wells (GCWs), which has become an increasingly attractive in-situ groundwater remediation solution. Numerous remediation techniques evolved in tandem with vertical circulation flow, treatable pollutants, and numerical results concerning the impact of hydrologic conditions and well parameters on the radius of influence (ROI) (Alesi and Leins, 1995; Herrling and Stamm, 1992; Stamm, 1997). The system is broadly defined in the literature as a vertical circulation well (VCW) (Chen and Knox, 1997; Kahler and Kabala, 2018), and groundwater flow driven by a GCW is also known as dipole flow (DF) (Xiang and Kabala, 1997; Sutton et al., 2000). Also groundwater injection-extraction well tandems are commonly referred to in the context of circulating well terminology, although they primarily enhance horizontal flow (Bennett et al., 2007; Chu et al., 2018; Ponsin et al., 2014). While this review primarily explores GCWs, examining a broad spectrum of literature that characterizes injection-extraction well pairs as recirculating groundwater systems or uses varied terminology to describe vertical wells inducing dipolar flow offers a comprehensive overview of the current state of the art. The review synthesizes and critically assesses research within the context of groundwater circulating well terminology, identifying trends and inconsistencies in previous study results, presenting a summary of the methodological approaches used, offering a critical perspective on existing evidence, and guiding the direction of future research.

A groundwater circulation well (GCW), much like a vertical circulation well (VCW), is a vertical well consisting of at least two hydraulically separated screened sections (Herrling et al., 1991a, 1991b). Groundwater is generally extracted by a pump from one screened section and then re-injected into another distinct screened section of the vertical well. The extracted water is treated by an appropriate above-ground plant before being re-injected. The resulting vertical flow creates one or more ellipsoidal and axially symmetric cells for groundwater recirculation and vertical hydraulic gradients (Tatti et al., 2019). In standard circulation mode, water is pumped from the lower screen and re-injected into the upper section of the vertical well, causing a downward movement of groundwater. In the reverse pattern mode, water is withdrawn from the upper screened segment and then recirculated back into the lower segment, leading to an upward movement of groundwater (Fig. 1) (Ciampi et al., 2022b; Vats et al., 2020).

The choice of circulation pattern depends on the nature of the pollutant and the hydrogeologic conditions of the site. GCWs can impact dissolved and adsorbed pollutants in the saturated and unsaturated domains. Standard circulation is typically used for denser-than-water-nonaqueous phases (DNAPLs), such as chlorinated solvents, to mobilize adsorbed fractions present in the lower parts of the aquifer (Ciampi et al., 2019a; Petrangeli Papini et al. 2016; Pierro et al., 2017). In contrast, reverse circulation is preferred for contamination caused by lighter-than-water nonaqueous phases (LNAPLs) (Boyd et al., 2001; Montgomery et al., 2002; Ponsin et al., 2014). The latter generates a cone of depression at the upper pumping screen, which helps mobilize residual phases found in the smear zone. Both modes of operation manipulate groundwater recirculation without a net water removal from the aquifer. GCWs can also have more than two screened sections to create multiple overlapping or stacked recirculation cells (Fig. 2). The operating and recirculation mode can be adjusted in near-real time based on field observations (Ciampi et al., 2023a).

Groundwater circulation wells (GCWs) have two primary practical applications. The first is for in situ aquifer remediation, where they can be coupled with chemical and biological approaches to enhance remediation efforts (Herrling et al., 1991a; EPA, 1998; McCarty et al., 1998; Lakhwala et al., 1998). The method for using GCWs in in-situ

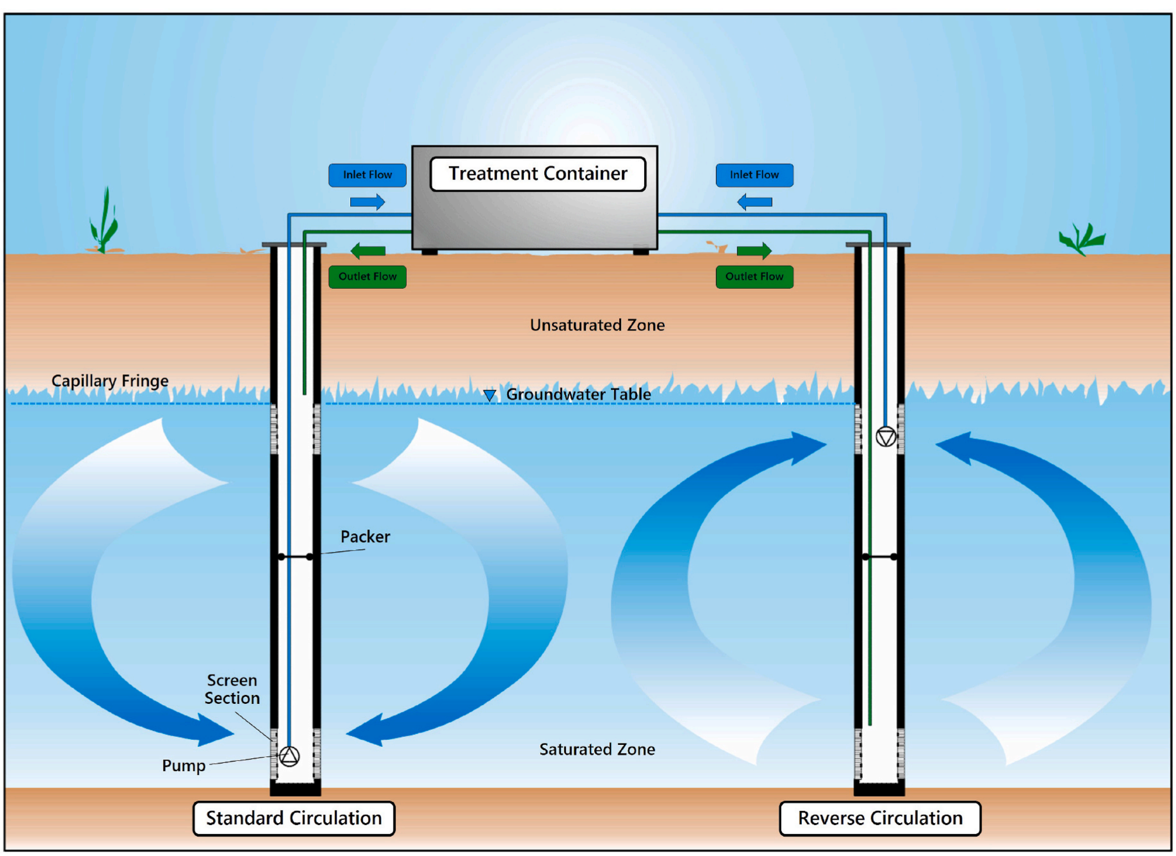


Fig. 1. Schematic of a groundwater circulation well (GCW) with two screened sections operating in standard and reverse configuration mode.

remediation was introduced by Herrling et al. (1991a, 1991b), who employed an in-well stripping system for dissolved volatile organic compounds (VOCs). Recirculating wells have successfully enhanced the physical mobilization of DNAPLs and arsenic (As) both in unconsolidated deposits and in rock formations (Ciampi et al., 2019a, 2023a; Petrangeli Papini et al., 2016; Pierro et al., 2017). Coupling with various chemicals as dissolved oxygen, carbohydrate, propane, whey, nitrate, phosphate, and soluble nutrients has also promoted the development of biodegradative processes of LNAPLs and chlorinated ethenes (Boyd et al., 2001; Bennett et al., 2007; Ciampi et al., 2022b; Ponsin et al., 2014).

The second practical application of GCWs is to determine hydrogeological parameters. Furthermore, hydraulic characterization of aquifers is a crucial preliminary step toward the remediation of plumes and contamination sources (Kalhor et al., 2019; Singh et al., 2020). Kabala (1993) introduced the vertical dipole flow test (DFT) to evaluate the hydrodynamic parameters, mimicking the flow pattern of the VCW. A DFT can be used to determine the hydraulic conductivity of unconsolidated and fractured aquifers and can be coupled with classical hydrogeologic tests such as the tracer test (Goltz et al., 2008; Halihan and Zlotnik, 2002; Zlotnik et al., 2001; Zlotnik and Zurbuchen, 1998). Also, Kabala's work (1993) led to the development of mathematical solutions describing the streamlines, flow field, hydraulic dynamics, and transport of chemicals driven by a GCW (Peursem et al., 1999; Christ et al., 1999; Chen et al., 2010).

Several authors have used finite difference and finite element models to delve into the hydraulics of the recirculating system. They simulate the flow field, path lines, reactive transport, and hydraulic zones that feature the system, such as the capture, recirculation, and release zone (Elmore and Hellman, 2001; Miller and Elmore, 2005; Cirpka and Kitanidis, 2001; Xia et al., 2019). By combining modeling evidence and laboratory data, researchers have revealed that the reproducibility of experimental observations through numerical simulation can be impacted by heterogeneity, sudden variations in hydraulic conductivity, presence of bypass flows near the GCW, local cross-flows resulting from incomplete hydraulic separation of screens, geometry of the laboratory experiment that compresses radial circulation in the third dimension, differences between the actual and modeled flow fields (Mohrlok et al., 2010; Pinto et al., 1997; Tatti et al., 2019).

After reviewing the literature, upscaling the characterization and remediation processes with GCWs from the laboratory to the field emerges as a typical step-by-step progression of activities (Sabatini et al., 1997; Zhu et al., 2020). This process is sometimes accompanied by modeling at both scales, which simulate advection/dispersion processes, adsorption, and biotic reactions. Such models can also predict GCW-driven dynamics based on robust theoretical-mathematical principles and rigorous experimental evidence. Once satisfactory modeling experimental evidence is obtained, the equipment can be installed in situ, taking into account optimal design parameters such as recirculation rate, screen size, and location.

Over the past three decades, GCWs have been addressed in three main fields of study: (1) mathematical models, (2) laboratory studies, and (3) field applications. However, the large amount of research on recirculating wells runs the risk of fragmenting the significant breakthroughs acquired in different fields. Therefore, this paper aims to provide a comprehensive and critical overview of the topic by systematizing GCW studies in the aforementioned fields. This approach highlights the major findings, contradictory results, technological limitations, and implications outlined in the literature, providing readers with an understanding of GCWs and serving as a basis for new ideas and research endeavors. Ultimately, this collection of information can help to advance the current state of knowledge, identify challenges, and explore the potential of GCWs for groundwater remediation.

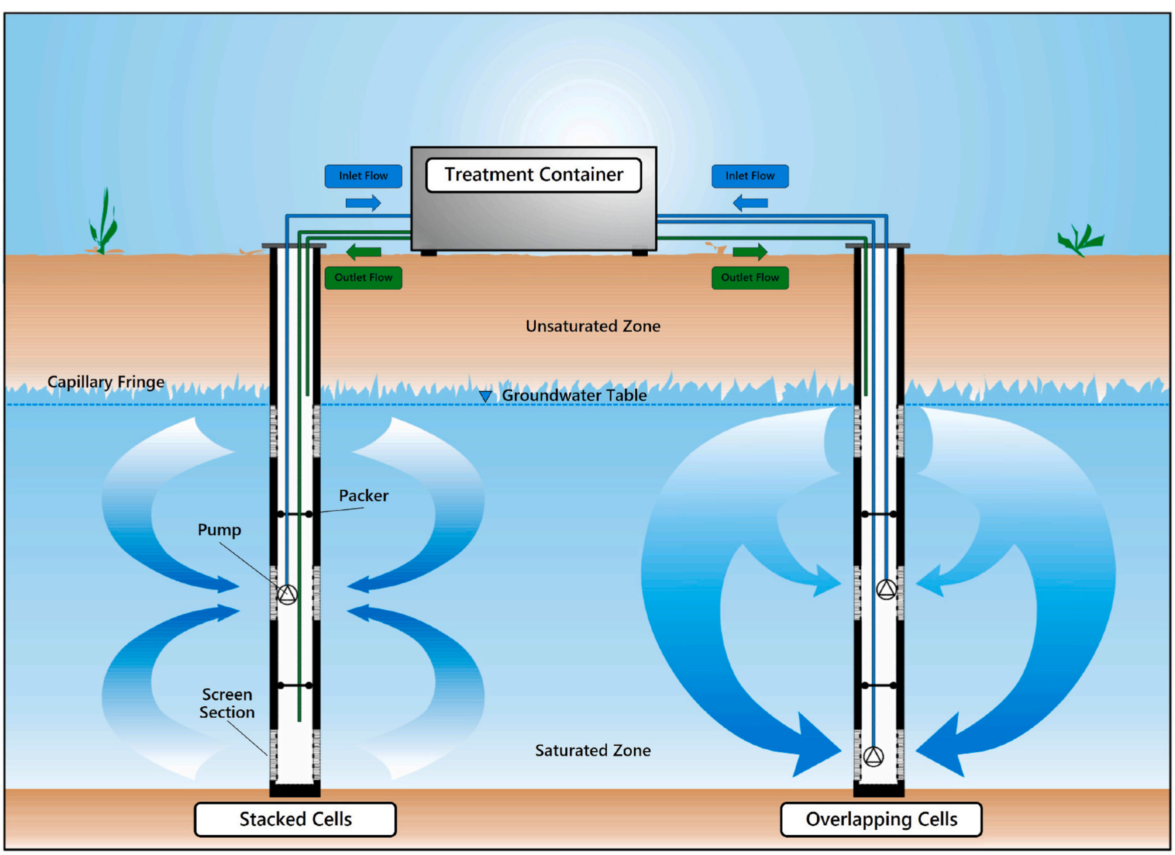


Fig. 2. Schematic of some groundwater recirculation configurations with stacked and overlapping cells generated by a GCW with three screens.

2. Fields of study

2.1. Mathematical models

Analytical models and numerical simulations have been widely adopted in the fields of characterization and remediation with GCWs to understand the movement of groundwater, contaminants, solutes, and the associated chemical, physical, and biological reactions (Table 1).

Kabala (1993), Xiang and Kabala (1997), and Zlotnik and Ledder (1996) have developed governing equations and boundary conditions to model the flow field of a VCW. Kabala (1993) also introduced the vertical dipole flow test (DFT) to evaluate the hydraulic conductivities and specific storativity of the aquifer by analyzing the transient hydraulic head drawdown in the screened segments. Xiang and Kabala (1997) extended this framework for heterogeneous aquifers. MacDonald and Kitanidis (1993) used the boundary element method to evaluate the free surface of a GCW system in an unconfined aquifer and presented an analytical approximation to estimate the critical flow rate for instability. Peursem et al. (1999) presented mathematical solutions for the flow lines and drawdown of a GCW, while Christ et al. (1999) developed an analytical model for the groundwater flow recirculated from tandem circulation wells, defining the capture zone width and interflow between a pair of wells for the treatment of polluted groundwater. Huang and Goltz (2005) varied the system design parameters to investigate the capture zone width and interflow.

Sutton et al. (2000) added a tracer to the DFT to obtain the anisotropy ratio of hydraulic conductivities by analyzing the solute concentrations measured in the extracting section, and the hydraulic head drawdown recorded in the extracted and injected screened intervals. However, the model does not account for transverse dispersion, compromising an accurate prediction of solute redistribution in an aquifer.

Tu et al.'s (2020) model displays a symmetric distribution of drawdown that varies with distance from the well. Gradients are found to be higher near the well. Also, it becomes clear that radial hydraulic conductivities and screened segment width have a considerable influence on drawdown. Ma et al. (2022) investigated the flow into a neighboring aquifer, suggesting hydraulic communication among aquifer bodies due to groundwater recirculation. Morozov (2021) presented a semi-analytical model for the challenge of steady-state and transient groundwater flow in a vertically circulating well in an anisotropic aquifer. They attempted to consider the skin effect on the screened sections of the well in altering the permeability of the medium. The outcomes are affected by the parameters of anisotropy.

Early studies by Herrling et al. (1991a, b) present the first groundwater recirculation systems for aquifer remediation. They model the vertical flow and symmetric and ellipsoidal recirculation patterns induced by a GCW, highlighting how the anisotropy ratio plays a key role in well design. From simulations, a greater ratio between horizontal and vertical conductivity results in a wider ROI. Later, Philip and Walter (1992) proposed a semi-analytical method to estimate the width of the capture zone of a GCW, highlighting the sensitivity of the zone to factors such as hydraulic conductivity anisotropy, extraction and recharge screen lengths, and screen separation distance. Xia et al. (2019), provide simple visualizations of flow patterns guided by GCWs, with the hydraulic zones discretized in 3D rendering to elucidate the impact of hydraulic parameters.

Elmore and Hellman (2001) used groundwater models like Modflow and MT3D to study the hydraulics of a GCW system, including the capture zone associated with groundwater extraction and circulation cell dimensions. However, they concluded that the state of the practice for evaluating and designing GCW systems was not as advanced as for pump-and-treat systems. Miller and Elmore (2005) used Modflow and Modpath to simulate the flow field and path lines of a GCW that pretreats water before entering a domestic well. They improperly concluded that detailed hydraulic conductivity data does not appear necessary for

Table 1
Sources and characteristics of mathematical models addressing circulation systems.

Field	Modeling theoretical framework	Focus	Reference
Remediation	Flow and transport	Capture, recharge, and recirculating hydraulic zones	Herrling et al., (1991a), b
Remediation	Flow and transport	Predicting the steady-state hydraulic head and flow fields induced by VCWs	Philip and Walter (1992)
Characterization	Flow	Analytical estimation of hydraulic conductivity ratio and specific storativity from DFT	Kabala (1993)
Remediation	Flow	Critical pumping rate causing a drawdown of groundwater table	MacDonald and Kitanidis (1993)
Characterization	Flow	Estimation of capture zone and hydraulic conductivity ratio in uniform anisotropic aquifers	Zlotnik and Ledder (1996)
Characterization	Flow	Estimation of anisotropy ratio distribution in a layered aquifer	Xiang and Kabala (1997)
Remediation	Flow and transport	Flow structure of a VCW in a uniform anisotropic aquifer considering skin effect	Peursem et al. (1999)
Remediation	Flow, transport, and reaction	Fraction of recirculation between wells and capture zone width	Christ et al. (1999)
Characterization	Flow and transport	Estimation of aquifer parameters	Sutton et al. (2000)
Remediation	Flow, transport	GCW treatment area dimensions	Elmore and Hellman (2001)
Remediation	Flow and transport	Prediction of capture, recharge, and circulation zones	Elmore and De Angelis (2004)
Remediation	Flow	Interflow of water circulating between two treatment wells	Huang and Goltz (2005)
Remediation	Flow	Stochastic modeling in flow simulation	Miller and Elmore (2005)
Remediation	Flow, transport, and reaction	Bioreactive transport in a flow field driven by circulation wells	Cirpka and Kitanidis, 2001
Remediation	Flow and transport	Transport of a remedial reagent in a dipole flow field	Chen et al. (2010)
Characterization	Flow and transport	Determination of longitudinal dispersivity and hydraulic conductivity	Chen et al. (2011)
Remediation	Flow and transport	Dipole flow field and hydraulic zones	Xia et al. (2019)
Remediation	Flow, transport, and reaction	Contaminant removal process in low-permeability lens	Feng et al. (2022)
Characterization	Flow	Effects of hydraulic conductivity and the length of the sealed section on drawdown	Tu et al. (2020)
Characterization	Flow	Groundwater flow considering skin and wellbore storage effects	Morozov (2021)
Characterization	Flow	Cross-formation flow	Ma et al. (2022)
Remediation	Flow and transport	Particle tracking and groundwater mass balance	Toscani et al. (2022)

simulating the capture and recharge zones of a GCW, as hydraulic conductivity can be assigned using a probabilistic analysis. However, Elmore and De Angelis (2004) applied a GCW at the same site. The model predicted drawdown and induced head did not match the observed field data. Cirpka and Kitanidis (2001) modeled the flow of two vertical circulation wells: one with an upward flow and the other with a downward flow, to mix substrates for in situ cometabolic degradation of chlorinated ethenes. They proposed a substrate injection scheme to avoid well clogging and aquifer biofouling (Gvirtzman and Gorelick, 1992; Liu et al., 2019).

Chen et al. (2010) developed a mathematical model to describe the transport of remedial reagents in an anisotropic aquifer's vertical circulation flow field. While varying both the hydrodynamic parameters and the position of the screened sections, the reagent transport induced by recirculation was unable to effectively cover the bottom region of the aquifer, thus presenting difficulties in the remediation of sorbed DNAPL. Hydraulic anisotropy affected the radial and vertical dispersion of dissolved reagent and the innermost region adjacent to the VCW was flushed more times by the reagent. The findings suggested the necessity of using a larger quantity of reagent to impact and flush the bottom of the contaminated aquifer effectively. Chen et al. (2011) applied the model to assess how transverse dispersion affects the solute concentrations in the extracting section. Transverse dispersion was found to alter the path and velocity of particles, inducing a solute mass exchange between the internal and external flowlines of the dipole. The migration of the tracer has indeed impacted the screened extraction interval at the base of the aquifer, where residual DNAPL may be present.

Zhu et al. (2020) proposed a particle-tracking solution to predict the rate of recycled particles versus the corresponding travel time. Additionally, the authors employed a finite difference approach to portraying multispecies reactive transport and discussed the need to test the theory and associated hypotheses to address real-world issues such as geological heterogeneity and bioclogging. Feng et al. (2022) established a finite element numerical model for the remediation of contaminant sources in low-permeability regions by GCWs considering biodegradation and adsorption. This resulted in a theoretical framework describing the evolutionary path of the remediation process. Finally, Toscani et al. (2022) used Modflow-2005 and particle tracking via Modpath 7 to simulate the impact of the aquifer's hydrological factors such as hydraulic conductivity and anisotropy on the GCW's hydraulic circulation pattern and concluded that field implementations are necessary to confirm simulated scenarios.

2.2. Laboratory studies

Various laboratory studies have been conducted to experimentally investigate groundwater circulation systems (Table 2).

Goltz et al. (2008) employed tandem circulation wells to perform a dipole flow test and a tracer test and measure the horizontal and vertical hydraulic conductivity of an isotropic aquifer without pumping groundwater. For a remediation test, Pinto et al. (1997) compared modeling findings to laboratory data from a small tank aquifer with homogeneous and isotropic media. The reduction in simulated and experimentally observed concentrations was generally consistent. Emerging differences have been related to the inconsistencies between the simulated and actual flow fields. Sabatini et al. (1997) discussed the significance of coupling in laboratory testing and numerical studies for surfactant-enhanced remediation using a VCW. The optimization of the injection and extraction flow rate ratio of the recirculation well can generate a large treatment zone and recover the injected surfactant. Numerical modeling suggested that to recover all of the injected fluid, it is necessary to pump at a substantially greater flow rate than injection. This would result in wastewater that needs to be treated. However, laboratory results contradicted the numerical simulation, showing the recovery of approximately 80% of the supernatant through recirculation.

Chen and Knox (1997) experimented with two different VCW systems, defined as Type A and Type B, in combination with surfactants to enhance the removal of tetrachloroethylene (PCE) in a 3D sand tank. They found that Type B (two injecting sections separated by an intermediate extracting section) was more hydraulically efficient than Type A (one injecting section and one extracting section) in removing both PCE and mobilized microemulsions. During surfactant-enhanced mobilization, the Type A VCW system failed to recover the microemulsion formed during mobilization due to the increased viscosity of the microemulsion and the resulting decrease in hydraulic conductivity. Similarly, Mohrlok et al. (2010) characterized the 3D flow of a GCW with a tracer test coupled with numerical simulation. The tracer appeared to be much more dispersed than expected, and the numerical models did not faithfully reproduce both the test responses and variations of the experimental hydraulic conductivity. This highlighted the sensitivity of transport processes in complex systems to heterogeneity.

Zhao et al. (2016) investigated the use of an in-well bioreactor with biofilm in a GCW for the biodegradation of low-volatile contaminants such as aniline. The experimental setup effectively treated the plume

Table 2
Sources and details of laboratory tests with recirculation systems.

Well type	Construction scheme	Circulation mode	Tank material	Focus	Reference
VCW	Not available	Not available	Sand	Surfactant-enhanced remediation	Sabatini et al. (1997)
VCW	Type A[a] and type B[b]	Standard (type A[a]) and stacked cells (type B[b])	Sand	Surfactant-enhanced remediation	Chen and Knox, 1997
Tandem circulation wells	Two screened sections	Standard	Coarse Sand	Hydraulic characterization	Goltz et al. (2008)
GCW	Two screened section	Standard	Heterogeneous porous media	Flow field and tracer transport	Mohrlok et al. (2010)
GCW	Two screened sections	Standard	Medium sand	In situ bioremediation	Zhao et al. (2016)
VCW	Two screened sections	Not available	Well-sorted crushed glass	Accelerated removal of contaminants	Kahler and Kabala (2018)
GCW	Three screened sections	Standard	Quartz sand and two lenses of quartz flour	Remediation of low permeability source zones	Tatti et al. (2019)
GCW	Two screened sections	Reverse	Glass beads	Saltwater intrusion control	Vats et al. (2020)
Tandem circulation wells	Full screened	Horizontal	Sandy sediments	Bioelectrochemical remediation of CAHs	Yuan et al. (2021)
GCW	Two screened sections	Standard and Reverse	Fine sand and illite	Delivery of reagents under a GCW-driven flow field	Wang et al. (2023)

Footnote: [a]Two screened sections, [b]Three screened sections.

through biodegradation and aeration. Kahler and Kabala (2018) configured a VCW with two screens inside a cylindrical chamber filled with crushed glass and found that rapid, pulsed pumping accelerated dye recovery compared to a steady-state flow. Tatti et al. (2019) combined laboratory tests with modeling to compare the impact of different pumping systems on secondary sources of contamination. They found that GCWs increase the diffusive flux of contaminant released from low-permeability lenses compared to physical extraction systems, generating vertical gradients that cannot be reproduced by conventional wells or natural groundwater flow.

Vats et al. (2020) analyzed the impact of a GCW on the dynamics of saltwater intrusion in a laboratory tank. They found that GCWs limit salt wedge intrusion from the boundaries of the flow tank, acting as a barrier to saltwater intrusion and suggesting a solution to manage and control the problem in coastal areas. Yuan et al. (2021) exploited groundwater electrolysis coupled with a recirculation system to control electron donor and electron acceptor dosage and stimulate TCE degradation biotically in a laboratory tank. Li et al., (2022) coupled a laboratory test with a numerical simulation to solve the flow field of a GCW. They concluded that verifying the findings of the numerical modeling represents an important research task to resolve the flow field of recirculation. Finally, Wang et al. (2023) used models and 2D sandbox tests to examine the GCW-induced reagent movement mechanisms. They found that the chemicals migrate primarily through high permeability pathways, but the GCW-driven flow field vertically crosses the low-permeability zones. Furthermore, low permeability zones store and release the remedial reagents. Lastly, the standard recirculation mode appeared more efficient than the reverse method for reagent transfer.

2.3. Field applications

In the realm of aquifer characterization, various applications of circulation systems have emerged to examine recirculation dynamics and acquire crucial hydrodynamic and hydrogeological parameters (Table 3).

For instance, a dipole test has proven useful in demonstrating that variations in piezometric head observed in the screened segments are controlled by aquifer properties, reach the steady state quickly, fluctuate linearly with recirculation pumping rate, and depend on the size of the screened sections (Zlotnik and Zurbuchen, 1998). Furthermore, the vertical patterns of permeability have been found to match particle size measurements. To limit the water consumption of traditional pumping tests, dipole flow testing can delineate spatial trends of hydraulic conductivity. Zlotnik et al. (2001) have extended the application of this tool to statistically evaluate the variability of aquifer hydraulic properties. In another study, Halihan and Zlotnik (2002) modified the recirculation technique to gather information about fractured aquifer parameters. By introducing an asymmetric DFT and changing the elevation of screens and packer of the vertical well while recirculating groundwater, they were able to expand the applicability of Kabala's (1993) DFT model to fractured aquifers. Johnson and Simon (2007) took a more comprehensive approach to studying flow dynamics induced by recirculation by coupling multiple data sources, including piezometric level, tracer test, concentration data, core samples, hydraulic test, and groundwater velocity sensors. They then used numerical modeling to gain insights and elucidate the flow dynamics. The harmonization of a large amount of site-specific data coupled with modeling resulted in a reasonably coherent portrait of the GCW-driven flow and transport. Jin et al. (2015) compared field data and numerical simulations to determine that groundwater drawdown is directly proportional to recirculation rate, inversely proportional to aquifer conductivity, and only mildly impacted by anisotropy around the well. Moreover, they found that the location of the extraction screen plays a more impactful role in the dynamics of groundwater drawdown and flow lines than the injection screen.

Table 3
Sources and characteristics of GCW applications for aquifer characterization.

Construction scheme	Circulation mode	Aquifer lithology	Investigated parameters	Reference
Two screened sections	Reverse	Sand and gravel	Vertical variations of hydraulic conductivity	Zlotnik and Zurbuchen (1998)
Two screened sections	Reverse	Sand and gravel	Statistics of horizontal hydraulic conductivity	Zlotnik et al. (2001)
Two screened sections	Reverse	Fractured dolomite	Connectivity of fractures and hydraulic conductivity	Halihan and Zlotnik, 2002
Two screened sections	Standard	Coarse to fine sand	Vertical and horizontal hydraulic conductivity, contaminant concentration, hydraulic head, and tracer data	Johnson and Simon (2007)
Two screened sections	Reverse	Fine to medium sand and gravel	Drawdown, flow rate, aquifer conductivity, screen position	Jin et al. (2015)

Beyond hydrogeological applications, several papers demonstrated the flexibility of GCWs in dealing with different pollutants in various geologic settings and employing a diverse range of operational configurations (Table 4).

Knox et al. (1997) used a recirculating well to redistribute surfactants and promote enhanced solubilization of residual TCE and jet fuel. The results showed enhanced removal rates and 95% recovery of extractives with GCW. McCarty et al. (1998) employed two VCWs with a reverse recirculation configuration for the redistribution of reactive substrates in two aquifers separated by an aquitard. Toluene injection generated an in-situ treatment reactive zone for cometabolic TCE abatement of 97–98% in about 400 days. Recirculation of hydrogen peroxide inhibited microbial growth around the VCW and the occurrence of clogging, producing oxygen necessary for bioremediation. Montgomery et al. (2002) evaluated the potential of a recirculating system in increasing aromatic hydrocarbon bioavailability and bacterial productivity. The biodegraded mass of benzene, toluene, ethylbenzene, and xylene (BTEX) amounted to 4.3 percent of that abiotically removed by GCW.

Gandhi et al. (2002a, 2002b) monitored an in-situ bioremediation experiment using a large-scale monitoring network and a field-scale tracer test. The recirculation was created by pumping water upward in one well and downward in another well. Surprisingly, the results of coupled simulation analyses indicated a limited impact of aquifer heterogeneity on forced recirculation. Although the water short-circuiting at a poorly sealed open monitoring well generated anomalous flows, the model constrained by the data allowed quantification of the contaminant mass removed by the bioremediation process.

The use of a dual-screened vertical circulation well to inject and extract cyclodextrin-containing solutions and improve the removal of TCE from a heterogeneous sedimentary aquifer was discussed by Blanford et al. (2007). They recorded an increase in TCE concentrations in the extracted water and a 94% reduction in concentrations compared with initial conditions. Bennett et al. (2007) assessed the hydraulic performance of a groundwater circulation well pair as a delivery device for introducing carbohydrate to groundwater with high nitrate contents. The establishment of a well-mixed stable treatment zone stimulated in situ reduction of TCE and *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) via a microbiologically driven mechanism. TCE, DCE, and vinyl chloride concentrations fell from around 500 to about 10 $\mu g\ L^{-1}$ after 21 months of operation. The authors suggested that kinetic limits may prevent the full transformation of vinyl chloride to ethene, resulting in DCE and vinyl chloride buildup and persistence. The accumulation of low

Table 4
Sources and characteristics of recirculation system applications for aquifer remediation.

Well-type and construction scheme	Circulation mode	Aquifer material	Target contaminant	Treatment process	Reference
VCV with two screened sections	Standard	Not available	PCE and jet fuel	Surfactant enhancement of contaminant elution	Knox et al. (1997)
Two treatment wells with two screens	Standard and Reverse	Fine to medium sand with silt	TCE	Injection of toluene, oxygen, and hydrogen peroxide enhancing ISB	McCarty et al. (1998)
GCW with two screens	Standard	Sands, silts, and clay	Benzene, toluene, ethylbenzene, and xylene (BTEX)	In-well air stripping and in situ bioremediation (ISB)	Boyd et al., (2001); Montgomery et al., (2002)
Two treatment wells with two screens	Standard and Reverse	Sand and gravel with fingers of clay	TCE	Cometabolic bioremediation	Gandhi et al., (2002a), 2002b
Dual-screened VCW	Standard	Gravelly-silty sand and sandy-clayey silt	TCE	Cyclodextrin-enhanced solubilization flushing	Blanford et al. (2007)
Tandem wells	Horizontal	Clayey sand and gravel	TCE and 1,2-dichloroethylene (1,2-DCE)	Carbohydrate delivery to enhance ISB	Bennett et al. (2007)
Tandem wells	Horizontal	Gravel and sand	BTEX and petroleum hydrocarbons	Stimulation of ISB by injection of nitrate and phosphate	Ponsin et al. (2014)
Tandem wells	Horizontal	Alluvial and fluvial deposits	1,4-dioxane, TCE and 1,2-dichloroethane (1,2-DCA)	Amendment with propane and oxygen to stimulate ISB	Chu et al. (2018)
Tandem wells	Horizontal	Silt, clay, sand, and granite	Chlorinated ethenes	Thermally enhanced ISB	Němeček et al. (2018)
GCW with two screens	Standard	Limestone and dolomite	Methyl tertiary butyl ether (MTBE)	Oxidation with ultraviolet/ hydrogen peroxide (UV/H_2O_2)	Tawabini and Makkawi (2018)
GCW with three screened sections	Overlapping cells	Sandy silt, clayey silt, gravel, and sand	1,2-DCE and vinyl chloride (VC)	In situ biological reductive dechlorination (BRD)	Ciampi et al., (2019a), 2021; Petrangeli Papini et al. (2016); Pierro et al., (2017)
GCW with two screen	Standard and reverse	Sand and sandy silt	Chlorinated aliphatic hydrocarbons (CAHs)	Nutrient injection enhancing in situ BRD	Ciampi et al. (2022b)
GCW with four screened sections	Overlapping cells	Fractured calcareous aquifer	Arsenic (As)	Oxidation and filtration	Ciampi et al., (2023a), 2023b

chlorinating compounds may arise from the lack of electron donors and dechlorinating organisms (Ebrahimbabaie and Pichtel, 2021; Matturro et al., 2018; Yu et al., 2018).

A network of injection and extraction wells has been explored to improve in-situ biological degradation of low concentrations of 1,4-dioxane, TCE, and 1,2-dichloroethane (1,2-DCA) in recirculated groundwater by supplementing it with propane and oxygen (Chu et al., 2018). As predicted by simulations, the process revealed the biodegradation zone's extension farther away from the injection well (Cirpka and Kitanidis, 2001). Ponsin et al. (2014) boosted biodegradation by recirculating nitrate (electron acceptor) and nutrients through a network of recirculation wells. During the test, hydrocarbon concentrations depleted and showed an irregular rebound, correlating to a decline in the pumping rate. Tracer monitoring proved that the system did not function in a closed-loop fashion. Reducing porosity and hydraulic conductivity was necessary to force numerical modeling of the recirculation test to match field behavior.

Petrangeli Papini et al. (2016) and Ciampi et al. (2019a) emphasized the possibility of enhancing the mobilization of chlorinated aliphatic hydrocarbons (CAHs) adsorbed to low-permeability layers by GCW-induced recirculation. The concentrations of 1,2-DCE mobilized by a GCW in two distinct operational phases average 9028.6 μg L^{-1} and 2602.2 μg L^{-1}, respectively. These values significantly exceed the average concentrations measured at two wells used for prolongated P&T, which are 645.7 μg L^{-1} and 494.0 μg L^{-1} (Ciampi et al., 2023b). Furthermore, poly-3-hydroxy-butyrate (PHB) has been utilized as a suitable slow-release source of redistributed electron donors in the aquifer by exploiting recirculation wells for the stimulation of biological reductive dichlorination (BRD) processes (Matturro et al., 2018; Pierro et al., 2017). The 3D representation of field data through a multisource conceptual model unmasked decontamination mechanisms and hydraulic dynamics induced by remediation wells (Ciampi et al., 2021). Such a data-driven approach has also been adopted for the application of a GCW in a fractured aquifer and accelerating the mobilization of secondary sources of As (Ciampi et al., 2023a). According to the evidence of Ciampi et al. (2023b) the pumping-induced groundwater table depression desaturated portions of the aquifer that cannot be flushed by conventional extraction wells. The findings also highlighted the higher contaminant mobilization potential of GCWs versus traditional wells while limiting water resource depletion of pump-and-treat (P&T) systems. The initiation of the GCW triggers a notable acceleration in source depletion processes, resulting in the mobilization of average concentrations of As reaching 14312.5 μg L^{-1}. These values exceed the concentrations observed in three long-term operational P&T wells within the source area, which stabilize at mean values of 2818.8 μg L^{-1}, 6813.6 μg L^{-1}, and 3429.4 μg L^{-1}, respectively. An innovative biocirculation system coupling GCWs and peripheral multilevel injection wells (MIWs) has been also tested to improve the distribution of a biostimulant in a heterogeneous aquifer for reductive dehalogenation and create an in-situ bioreactor for the enhanced treatment of CAHs (Ciampi et al., 2022b). Evidence from the first application at the field scale revealed the significant increase in the chloroethane biodegradation rate, the short-term effectiveness of the remediation strategy, and the persistence of dechlorinating microbiological activity. GCW-MIWs synergy increased the extension of bioactive surface in the circulation area through enhanced three-dimensional mixing of groundwater, contaminants, microorganisms, and biostimulants. The combined injection and distribution mechanism can potentially be extended to numerous other reagents by varying the target contaminants.

Further research looked at less common applications of GCWs for groundwater cleanup. Němeček et al. (2018) conducted an in-situ experiment of thermally enhanced bioremediation on groundwater contaminated with chlorinated solvents. Coupling tandem recirculating wells with heating and organic substrate injections induced a significant decline in CVOCs and an increase in total bacterial biomass. At the end of the heating period, CVOC concentrations were below their respective limits of quantification. A momentary but noticeable increase in TCE concentrations was recorded in groundwater affected by the heating but not impacted by the organic substrate injections. The authors attributed this behavior to enhanced desorption and increased solubility of TCE at higher temperatures. Tawabini and Makkawi (2018) coupled a circulation well and an ultraviolet/hydrogen peroxide (UV/H2O2) above-ground treatment unit to abate MTBE concentrations in groundwater. The study revealed a 98% reduction in contamination load in 30 min. Dinkel et al. (2020) investigated how the use of GCWs for geothermal energy production affects the groundwater quality in areas with different groundwater hydrochemistry. The operation of GCWs did not affect groundwater levels since water was reinjected at the same time as it was extracted. Changes to microbial communities and groundwater chemistry appeared to be negligible. Recirculating systems that incorporate particular engineering solutions can operate simultaneously in the unsaturated and saturated domains (Lakhwala et al., 1998). In the unsaturated zone, the application of vacuum extraction has the potential to remove gas-phase contaminants. In the saturated realm, pollutants can be mobilized by a flushing action and removed by combining stripping and biodegradation. A GCW with an internal air injection system effectively stripped BTEX compounds while benzene and toluene biodegradation rate was lower than the estimate for physical air-stripping (Boyd et al., 2001). Customized groundwater recirculation systems can operate effectively even in the case of aquifers with a reduced saturated thickness (Ciampi et al., 2022a). Such systems operate without pumping groundwater, injecting pressurized air into the well to promote pollutant stripping and stimulate passive groundwater recirculation.

3. Discussion

In this comprehensive review, we refrain from delving into the intricate details of the equations that describe the flow field and transport guided by the GCWs. Such an exploration necessitates exclusive treatment and falls beyond the scope of this panoramic work. However, it is imperative to acknowledge the significance of studies on the fundamental mathematical laws underlying the subject and governing the three-dimensional circulating dipole flow patterns. Upon a comprehensive review of the existing literature, GCWs emerge as a valuable tool in the hydraulic characterization of aquifers and the remediation of contaminated sites. There are both advantages and drawbacks associated with the use of GCWs for the hydrogeological characterization of aquifers. The dipole flow test eliminates the need to remove and dispose of groundwater (Zlotnik and Zurbuchen, 1998) and can be set up at different depths along the vertical (Halihan and Zlotnik, 2002). Also, DFT allows the test configuration to be adapted to site-specific characteristics and provides hydraulic conductivity values comparable to traditional tests. However, some authors elucidate the inability in determining the local anisotropy (Zlotnik et al., 2001) and the low sensitivity in assessing specific storage (Hvilshøj et al., 2000). The constraints highlighted here are undoubtedly going to frame the trajectory of future endeavors.

Drilling practices, biological activity, and the presence of low-permeability material can modify the hydraulic conductivity around the GCW. Skin effects can increase or decrease hydraulic conductivity around the well and accelerate or slow solute migration (Li et al., 2019; Morozov, 2021). This alters the three-dimensional hydrodynamic field of the GCW, which does not reproduce an ideal symmetrical flow (Wang et al., 2023). Also, field experience suggests that fine-grained sediments in the vicinity of the borehole and biomass buildup can increase pumping heads and may require redevelopment of wells, compromising the constant flows modeled in numerical simulations (McCarty et al., 1998). The impacts of bioclogging during modeling experiments are often not evaluated. Biomass growth can significantly decrease the flow rate and porosity of the medium. Additionally, the scale of the simulation generally covers a spatial extent ranging from a few meters to tens of meters (Lakhwala et al., 1998; US EPA, 1998; Miller and Elmore, 2005; Johnson and Simon, 2007). Lastly, numerical simulation often lacks to consider the hydraulic communication between some overlapping aquifer bodies, which occurs following the application of GCWs in the field and the generation of significant vertical gradients (Ma et al., 2022; Ciampi et al., 2022a) or water short-circuiting phenomena due to poorly sealed open monitoring wells (Gandhi et al., 2002a). Everything mentioned above frequently implies a simplistic approach and simulation of recirculation dynamics in a homogeneous and regular thickness aquifer, which impacts the ability to capture and replicate the variations in hydraulic parameters and the physical, chemical, and biological heterogeneities at the field scale (Zhu et al., 2020). Several authors have observed inconsistencies in porosity, hydraulic conductivity, flow field, and hydraulic head between laboratory or field experimental data and numerical simulations (Elmore and De Angelis, 2004; Li et al., 2022; Mohrlok et al., 2010; Ponsin et al., 2014).

In this regard, Zhu et al. (2020) highlight how modeling with particle-tracking and node-dependent finite difference (NDFD) methods represents a theoretical investigation to be tested at the field scale to verify the theory and associated hypotheses. The verification of the match between the predicted drawdown and the measured head represents a concrete possibility to calibrate and constrain the hydraulic input parameters and characterize the recirculation cell geometry in the field (Elmore and De Angelis, 2004; Li et al., 2022). The building of a straightforward computational model employing measurements of hydraulic conductivity and head emerges as an invaluable tool for conceptualizing the GCW and aligning simulation to field observation (Johnson and Simon, 2007).

Models for the prediction of the magnitude and extent of the groundwater recirculation environment have been presented in the literature, but simulations have not been adequately compared with field or laboratory data (Toscani et al., 2022). Failure to combine laboratory or field-measured data on conductivity or hydraulic head reduces numerical simulation to a mere scholastic exercise, unable to capture the impact of geological variability, the ratio of horizontal and vertical hydraulic conductivity, hydraulic stresses, preferential transport, and flow paths on the development and understanding of the recirculatory system (Ciampi et al., 2023b; Elmore and De Angelis, 2004; Gandhi et al., 2002a). Several authors highlight the difficulty in predicting the radial extent (ROI) of capture and recharge zones, the direction, and the velocity of flow characterizing the circulation cell (Stamm et al., 1998; Xia et al., 2019). The sphere of influence of a GCW is influenced by various factors such as aquifer anisotropy, thickness, pumping rate, and screen lengths. In the absence of natural groundwater flow, these factors become more prominent in determining the ROI. It's crucial to note that the natural groundwater flow field might exert an additional driving force on the GCW flow field (Herrling et al., 1991a). Notably, the circulation zone of a GCW may not fully develop in the presence of regional groundwater flow, implying that the pumping rate might not be sufficiently high (Miller and Elmore, 2005). Several studies extensively discuss the effects of ambient groundwater flow on the geometry of GCW flow fields (Huang and Goltz, 2005; Xia et al., 2019; Zhu and Wen, 2023). The flow field of a GCW in the presence of ambient flow is no longer radially asymmetric. Elevated groundwater flow velocities and the decrease in recirculation rates can result in a portion of water outflowing from the injection screen that cannot flow back into the extraction, eventually flowing away from the GCW or causing the breakage of the recirculation cell (Huang and Goltz, 2005; Xia et al., 2019). Zhu and Wen (2023) recommend adopting a higher injection/extraction rate or extending the unscreened segment as both injection and extraction screens increase in length to mitigate ambient groundwater effects. These statements generally apply to tandem wells as well, which, unlike GCWs, generate an interflow between injection and extraction screens of a pair of wells with a predominantly horizontal component (Huang and Goltz, 2005). Although doublets have the potential to encompass a larger volume of contaminated aquifer (Ponsin et al., 2014), they may fail to contain a closed loop of recirculation (Huang and Goltz, 2005). A tracer test conducted through a pair of injection-extraction wells by Ponsin et al. (2014) reveals leakage of the dipole and dispersion of tracer mass. The main factor contributing to the poor hydraulic performance of the dipole generated by tandem injection-extraction wells is a high groundwater flow velocity (Burbery et al., 2013). Field monitoring at various upstream and downstream monitoring wells of the recirculating wells emerges as an effective strategy to understand the flow patterns around the GCW and delineate the treatment zone. The combination of on-site measurements of hydraulic head, concentrations, and flow velocities, coupled with hydraulic tests for hydraulic conductivity determination and tracer tests, appears to be the way forward to capture the flow regime of the recirculation cell and optimize system operation (Gandhi et al., 2002a; Jin et al., 2015; Johnson and Simon, 2007; Lakhwala et al., 1998).

The statements above generally apply to laboratory tests as well. Although laboratory experiments explain phenomena that cannot be elucidated in field application, Wang et al. (2023) advise against applying experimentally derived quantitative parameters directly to aquifers due to differences in scale. The experimental setup generally exemplifies hydraulic conductivity variations as long as the porous medium exhibits horizontal isotropy, seriously impairing the validity of the adopted two-dimensional scheme (Tatti et al., 2019). Indeed, laboratory observations and corresponding numerical simulations also exhibit differences and incongruences in hydraulic heads and solute concentrations. Therefore, it is crucial to validate and constrain numerical models using experimental data under controlled conditions. This alignment can enable a faithful replication of the laboratory experiment in the numerical simulation and can provide valuable insights into the distribution and recovery of surfactants (Sabatini et al., 1997), the most effective recirculation mode to target specific contaminants (Chen and Knox, 1997), and the flow, transport, and decontamination mechanisms induced by a GCW (Li et al., 2022; Mohrlok et al., 2010; Tatti et al., 2019).

A variety of solutions are available for using GCWs to remediate contaminated groundwater. The parameters of a GCW significantly impact its flow field, mobilization, and migration processes (Jin et al., 2015). Length, distance of screens, and diameter of the well impact flow patterns, influencing the capability to target sources of contamination (Chen et al., 2011; Xia et al., 2019). Some operational parameters can be adjusted in near-real time, for example, by changing the direction of the circulation to flush the polluted zones delineated through the reconstruction of a robust conceptual model (Ciampi et al., 2023a). The ROI can be expanded by increasing the recirculating flow rate (Johnson and Simon, 2007; Stamm et al., 1998).

Zhang et al. (2019) outline the versatility of GCWs as a technique for improving the delivery of engineered materials and immobilizing or degrading contaminants without impacting the local site-specific hydrogeology. The use of non-Newtonian fluids, such as foams and gels, could further facilitate the distribution of reactive particles like zero-valent iron (ZVI) in porous media, overcoming limitations associated with geological heterogeneity (Alamooti et al., 2022). Circulation wells can act as distributors of electron donors and biostimulants to enhance in situ bioremediation (ISB), overcoming limitations caused by the lack of mixing and distribution observed in other substrate delivery techniques (Ciampi et al., 2019b). Additionally, GCWs do not cause a net removal of water and are therefore considered an alternative to limit geotechnical issues that may arise from pumping large volumes of water (i.e., soil consolidation, subsidence) (Jin et al., 2015).

In addition to analyzing the many application domains of circulation wells for groundwater remediation, the sustainability of GCWs in comparison to typical pumping wells warrants careful attention. Groundwater polluted with dissolved metals, LNAPLs, and DNAPLs is classically remediated using the pump and treat technique (P&T) (Mackay and Cherry, 1989). Although P&T devices have been in use for a long time at various sites, significant amounts of residual pollutants persist and are unaffected by such treatment (Brusseau and Guo, 2014). Conventional pumping technology is inefficient for remediating aquifers impacted by persistent plumes due to the back-diffusion mechanism (Mackay and Cherry, 1989; Guo and Brusseau, 2017; Tatti et al., 2018). Elmore and Graff (2002) emphasize the advantages of GCWs over more typical remediation technologies, such as P&T, providing a quantitative estimate of the operational costs for both technologies. Recirculating wells are inherently resource conservative because treated groundwater is recharged back into the aquifer by avoiding the transport of pumped water to the treatment plant. Furthermore, recirculating systems feature smaller logistical impacts on the land and prove to be very competitive in terms of overall remediation costs, although the extracted waters are treated before their re-injection. A comparative analysis of performance reveals that GCWs impact aged sources not influenced by prolonged pumping activities and mobilize higher concentrations of contaminants compared to conventional hydraulic systems, while recirculating a lower volume of water than that pumped by P&T (Ciampi et al., 2023b). GCWs accelerate the remediation process and are both suitable and sustainable for restoring long-term polluted sites and secondary contamination sources as an alternative cleanup technology to the conventional P&T. Table 5 summarizes the advantages and disadvantages of GCWs vs P&T for groundwater remediation.

GCWs represent a significant opportunity to replace traditional groundwater extraction systems that deplete groundwater resources. Such a perspective can be achieved by configuring a virtual GCW barrier that intercepts groundwater flow and contamination plume and recirculates decontaminated water to hydrogeological downstream (Stamm, 1997). The literature review also suggests the opportunity to employ GCWs following a flexible and versatile workflow. In an initial characterization phase, recirculating wells can be effectively utilized for the hydrodynamic parameterization of aquifers. In the second phase, the operational parameters obtained from DFTs can optimize the implementation of the remediation strategy, tailored to the field evidence. When thinking of upcoming breakthroughs, Palma et al. (2017) suggest the possibility of incorporating the bioelectric well idea into contemporary GCW configurations and bioremediation plans. GCWs can be exploited to stimulate selected dichlorination reactions, both reductive and oxidative, utilizing the indigenous groundwater microbial consortium and electricity (Dell'Armi et al., 2022). Among the potential technological advancements, the possibility of using GCWs for the simultaneous recovery of free-phase products deserves special mention. The induced flow from a GCW could be advantageously employed to accelerate the removal of both LNAPL and DNAPL from an aquifer,

Table 5
Pros and cons of GCWs compared to P&T technology for groundwater remediation.

Remediation technology	Pros	Cons
Groundwater Circulation Wells (GCWs)	• Efficient in-situ source treatment and containment of contaminant mass flux • No need for disposal or treatment of extracted groundwater, reducing waste generation • Effective in aquifers with heterogeneous geology • Can be combined with other remediation technologies, such as in situ bioremediation (ISB) for enhanced efficiency	• The design and implementation can be complex and costly, requiring a detailed understanding of the aquifer's characteristics • Significant monitoring and maintenance required • Require more specialized personnel
Pump and Treat (P&T)	• Proven technology with a track record for plume containment and mass reduction • Effective for removing dissolved, mobile contaminants • Immediate reduction of concentration in emergency situations • Applicable to various contaminants	• Energy-intensive, especially for large-systems • Potential for long remediation periods to achieve remediation goals • Challenges for disposal of large volumes of contaminated groundwater • Aquifer hydraulic alteration due to extensive pumping • Ineffectiveness for heterogeneous aquifers

tailoring the recirculation mode to the chemical and physical characteristics of the contaminant. The use of a submersible pump controlled by a sensor at the water-product interface could potentially facilitate the extraction of the exclusive separated phase while retaining the traditional treatment for the dissolved phase in the groundwater. The pump can be installed in the GCW, while an infrared refractive and electrical conductivity sensor can be used to detect floating and sinking hydrocarbons and distinguish water. The submersible pump could automatically recover mobilized non-aqueous product layers (LNAPLs and DNAPLs) that migrate into the GCW. The findings prepare the stage for more educated and sustainable groundwater remediation using GCWs in a variety of geological, hydrogeochemical, and hydraulic scenarios.

4. Conclusions

The literature review presented in this article categorizes the fragmented research on groundwater circulation wells over the last 30 years, discretizing the various fields of study of GCWs, such as (1) mathematical models, (2) laboratory studies, and (3) field applications. The main points and insights, as well as lessons learned and future prospects, can be summarized as follows.

- The hydrogeological and hydraulic characterization of aquifers using dipole flow tests appears an embryonic-stage research niche that requires further development and exploration for its practical application. Additional efforts and investigations are needed to establish its reliability and effectiveness.
- Numerical simulations can replicate the GCW-driven processes of advection, dispersion, and reactive transport if they are constrained or verified by experimentation at the laboratory or field scale.
- Laboratory experiments may suffer for scale reasons and isotropic approximation in the third dimension. However, these are incredibly valuable for understanding phenomena, mechanisms, and dynamics that cannot be explained by field application and for upscaling the remediation process.
- Recirculating systems enhance hydraulic manipulation capabilities, promote targeted flushing of specific aquifer sections, enable directional flow changes to target contaminated zones, mobilize contaminants from less permeable layers, increase mass fluxes of dissolved groundwater pollutants and their removal, decrease contamination in porous media and fractured rock, and reduce both remediation time and water consumption compared to traditional pump-and-treat (P&T).
- GCWs promote the effective distribution of chemicals in the aquifer, enhancing the three-dimensional mixing of groundwater, contaminants, microorganisms, and reagents and promoting the degradation of LNAPLs, DNAPLs, and metals by biotic and abiotic pathways.
- The design flexibility and potential coupling of GCWs with a myriad of technologies such as thermal desorption, air stripping, bioremediation, chemical oxidation, and various other reagents broaden the application of recirculating systems to many solutions by changing target pollutants and operating in the saturated and unsaturated realms.
- The versatility of the GCW in the field reflects its ability to adapt operational parameters and injectable materials to in situ hydrogeological and biochemical conditions.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Paolo Ciampi: Writing - original draft, Data curation, Conceptualization. **Carlo Esposito:** Writing - review & editing, Validation, Supervision. **Marco Petrangeli Papini:** Writing - review & editing, Supervision, Project administration, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The data reported in this study are deduced from a detailed literature review on the topic discussed. The totality of sources is carefully provided in the list of references.

References

Alesi, E.J., Leins, C.H., 1995. Multifunctional well implemented for in situ remediation of hydrocarbon contaminations in soil and groundwater. In: Van Den Brink, W.J., Bosman, R., Arendt, F. (Eds.), Contaminated Soil `95. Soil & Environment. Springer, Dordrecht, pp. 1135–1136. https://doi.org/10.1007/978-94-011-0421-0_41.

Alamooti, A., Colombano, S., Omirbekov, S., Ahmadi, A., Lion, F., Davarzani, H., 2022. Influence of the injection of densified polymer suspension on the efficiency of DNAPL displacement in contaminated saturated soils. J. Hazard Mater. 440, 129702 https://doi.org/10.1016/j.jhazmat.2022.129702.

Bennett, P., Gandhi, D., Warner, S., Bussey, J., 2007. In situ reductive dechlorination of chlorinated ethenes in high nitrate groundwater. J. Hazard Mater. 149 (3), 568–573. https://doi.org/10.1016/j.jhazmat.2007.06.092.

Blanford, W.J., Barackrnan, M.L., Boing, T.B., Klingel, E.J., Johnson, G.R., Brusseau, M. L., 2007. Cyclodextrin-enhanced vertical flushing of a trichloroethene contaminated aquifer. Ground Water Monit. Remediation 21 (1), 58–66. https://doi.org/10.1111/j.1745-6592.2001.tb00631.x.

Boyd, T.J., Montgomery, M.T., Spargo, B.J., Smith, D.C., Coffin, R.B., Kelley, C.A., Mueller, J.G., 2001. Effects of oxygenation on hydrocarbon biodegradation in a hypoxic environment. Ann. Finance 5 (2), 145–157. https://doi.org/10.1080/20018891079258.

Brusseau, M.L., Guo, Z., 2014. Assessing contaminant-removal conditions and plume persistence through analysis of data from long-term pump-and-treat operations. J. Contam. Hydrol. 164, 16–24. https://doi.org/10.1016/j.jconhyd.2014.05.004.

Burbery, L.F., Flintoft, M.J., Close, M.E., 2013. Application of the re-circulating tracer well test method to determine nitrate reaction rates in shallow unconfined aquifers. J. Contam. Hydrol. 145, 1–9. https://doi.org/10.1016/j.jconhyd.2012.11.006.

Chen, J.S., Jang, C.S., Cheng, C.T., Liu, C.W., 2010. Conservative solute approximation to the transport of a remedial reagent in a vertical circulation flow field. J. Hydrol. 390 (3–4), 155–168. https://doi.org/10.1016/j.jhydrol.2010.06.035.

Chen, J.S., Liu, C.W., Chan, Y.C., Ni, C.F., Kao, K., 2011. Effect of transverse dispersion on solute transport in a vertical dipole flow test with a tracer. J. Hydrol. 402 (3–4), 206–216. https://doi.org/10.1016/j.jhydrol.2011.03.005.

Chen, L., Knox, R.C., 1997. Using vertical circulation wells for partitioning tracer tests and remediation of DNAPLs. Ground Water Monit. Remediation 17 (3), 161–168. https://doi.org/10.1111/j.1745-6592.1997.tb00591.x.

Chu, M.Y.J., Bennett, P.J., Dolan, M.E., Hyman, M.R., Peacock, A.D., Bodour, A., Anderson, R.H., Mackay, D.M., Goltz, M.N., 2018. Concurrent treatment of 1,4-dioxane and chlorinated aliphatics in a groundwater recirculation system via aerobic cometabolism. Ground Water Monit. Remediation 38, 53–64. https://doi.org/10.1111/gwmr.12293.

Christ, J.A., Goltz, M.N., Huang, J., 1999. Development and application of an analytical model to aid design and implementation of in situ remediation technologies. J. Contam. Hydrol. 37 (3–4), 295–317. https://doi.org/10.1016/S0169-7722(99)00002-9.

Ciampi, P., Esposito, C., Petrangeli Papini, M., 2019a. Hydrogeochemical model supporting the remediation strategy of a highly contaminated industrial site. Water 11 (7), 1371. https://doi.org/10.3390/w11071371.

Ciampi, P., Esposito, C., Viotti, P., Boaga, J., Cassiani, G., Petrangeli Papini, M., 2019b. An integrated approach supporting remediation of an aquifer contaminated with chlorinated solvents by a combination of adsorption and biodegradation. Appl. Sci. 9, 4318. https://doi.org/10.3390/app9204318.

Ciampi, P., Esposito, C., Bartsch, E., Alesi, E.J., Petrangeli Papini, M., 2021. 3D dynamic model empowering the knowledge of the decontamination mechanisms and controlling the complex remediation strategy of a contaminated industrial site. Sci. Total Environ. 793, 148649 https://doi.org/10.1016/j.scitotenv.2021.148649.

Ciampi, P., Esposito, C., Bartsch, E., Alesi, E.J., Nielsen, C., Ledda, L., Lorini, L., Petrangeli Papini, M., 2022a. Coupled hydrogeochemical approach and sustainable technologies for the remediation of a chlorinated solvent plume in an urban area. Sustainability 14, 10317. https://doi.org/10.3390/su141610317.

Ciampi, P., Esposito, C., Bartsch, E., Alesi, E.J., Rehner, G., Petrangeli Papini, M., 2022b. Remediation of chlorinated aliphatic hydrocarbons (CAHs) contaminated site coupling groundwater recirculation well (IEG-GCW) with a peripheral injection of soluble nutrient supplement (IEG-C-MIX) via multilevel-injection wells (IEG-MIW). Heliyon 8 (11), e11402. https://doi.org/10.1016/j.heliyon.2022.e11402.

Ciampi, P., Esposito, C., Bartsch, E., Alesi, E.J., Rehner, G., Morettin, P., Pellegrini, M., Olivieri, S., Ranaldo, M., Liali, G., Petrangeli Papini, M., 2023a. A data-driven modeling approach for the sustainable remediation of persistent arsenic (As) groundwater contamination in a fractured rock aquifer through a groundwater recirculation well (IEG-GCW®). Environ. Res. 217, 114827 https://doi.org/10.1016/j.envres.2022.114827.

Ciampi, P., Esposito, C., Bartsch, E., Alesi, E.J., Petrangeli Papini, M., 2023b. Pump-and-treat (P&T) vs groundwater circulation wells (GCW): which approach delivers more sustainable and effective groundwater remediation? Environ. Res. 234, 116538 https://doi.org/10.1016/j.envres.2023.116538.

Cirpka, O.A., Kitanidis, P.K., 2001. Travel-time based model of bioremediation using circulation wells. Ground Water 39 (3), 422–432. https://doi.org/10.1111/j.1745-6584.2001.tb02326.x.

Dell'Armi, E., Zeppilli, M., Di Franca, M.L., Matturro, B., Feigl, V., Molnár, M., Berkl, Z., Németh, I., Yaqoubi, H., Rossetti, S., Petrangeli Papini, M., Majone, M., 2022. Evaluation of a bioelectrochemical reductive/oxidative sequential process for chlorinated aliphatic hydrocarbons (CAHs) removal from a real contaminated groundwater. J. Water Process Eng. 49, 103101 https://doi.org/10.1016/j.jwpe.2022.103101.

Dinkel, E., Braun, B., Schröder, J., Muhrbeck, M., Reul, W., Meeder, A., Szewzyk, U., Scheytt, T., 2020. Groundwater circulation wells for geothermal use and their impact on groundwater quality. Geothermics 86, 101812. https://doi.org/10.1016/j.geothermics.2020.101812.

Ebrahimbabaie, P., Pichtel, J., 2021. Biotechnology and nanotechnology for remediation of chlorinated volatile organic compounds: current perspectives. Environ. Sci. Pollut. Res. 28, 7710–7741. https://doi.org/10.1007/s11356-020-11598-y.

Elmore, A.C., De Angelis, L., 2004. Modeling a ground water circulation well alternative. Ground water monit. Remediat 24, 66–73. https://doi.org/10.1111/j.1745-6592.2004.tb00706.x.

Elmore, A.C., Graff, T., 2002. Best available treatment technologies applied to groundwater circulation wells. Remediation 12 (3), 63–80. https://doi.org/10.1002/rem.10034.

Elmore, A.C., Hellman, J.B., 2001. Model-predicted groundwater circulation well performance. Pract. Period. Hazard. Toxic, Radioact. Waste Manag. 5 (4), 203–210. https://doi.org/10.1061/(ASCE)1090-025X (2001)5:4(203).

EPA, 1998. Field Applications of in Situ Remediation Technologies: Ground-Water Circulation Wells. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington, DC, USA.

Feng, S., Cheng, D.W., Zhan, H.B., Yang, S.K., Zhao, X.H., Jin, H.Y., Zhang, L., 2022. Evolution characteristics of remediation process of secondary contaminant sources of low-permeability lens driven by circulating well. J. Hydrol. 613, 128408 https://doi.org/10.1016/j.jhydrol.2022.128408.

Gandhi, R.K., Hopkins, G.D., Goltz, M.N., Gorelick, S.M., McCarty, P.L., 2002a. Full-scale demonstration of in situ cometabolic biodegradation of trichloroethylene in groundwater 1. Dynamics of a recirculating well system. Water Resour. Res. 38 (4), 10–11. https://doi.org/10.1029/2001WR000379, 10-15.

Gandhi, R.K., Hopkins, G.D., Goltz, M.N., Gorelick, S.M., McCarty, P.L., 2002b. Full-scale demonstration of in situ cometabolic biodegradation of trichloroethylene in groundwater 2. Comprehensive analysis of field data using reactive transport modeling. Water Resour. Res. 38 (4) https://doi.org/10.1029/2001WR000380, 11-1-11-18.

Goltz, M.N., Huang, J.Q., Close, M.E., Flintoft, M.J., Pang, L.P., 2008. Use of tandem circulation wells to measure hydraulic conductivity without groundwater extraction. J. Contam. Hydrol. 100 (3–4), 127–136. https://doi.org/10.1016/j.jconhyd.2008.06.003.

Guo, Z., Brusseau, M.L., 2017. The impact of well-field configuration and permeability heterogeneity on contaminant mass removal and plume persistence. J. Hazard Mater. 333, 109–115. https://doi.org/10.1016/j.jhazmat.2017.03.012.

Gvirtzman, H., Gorelick, S.M., 1992. The concept of in-situ vapor stripping for removing VOCs from groundwater. Transport Porous Media 8, 71–92. https://doi.org/10.1007/BF00616893.

Halihan, T., Zlotnik, V.A., 2002. Asymmetric Dipole-Flow test in a fractured carbonate aquifer. Ground Water 40 (5), 491–499. https://doi.org/10.1111/j.1745-6584.2002.tb02533.x.

Herrling, B., Stamm, J., Buermann, W., 1991a. Hydraulic circulation system for in situ bioreclamation and/or in situ remediation of strippable contamination. In: Hinchee, R.E., Olfenbuttel, R.F. (Eds.), In Situ Bioreclamation. Butterworth-Heinemann, Boston, MA, USA, pp. 173–195.

Herrling, B., Stamm, J., Alesi, E.J., Brinnel, P., Hirschberger, F., Sick, M.R., 1991b. In situ groundwater remediation of strippable contaminants by vacuum vaporizer wells (UVB): operation of the well and report about cleaned industrial sites. In: Proceedings of the Third Forum on Innovative Hazardous Waste Treatment Technologies: Domestic and International. Dallas, TX, USA, June 11–13.

Herrling, B., Stamm, J., 1992. Numerical results of calculated 3D vertical circulation flows around well with two screen sections for in situ or on-site aquifer remediation. In: Proceedings of IX Int. Conf. On Computational Methods in Water Resources, June 1992. Denver, CO (USA).

Huang, J., Goltz, M.N., 2005. A three-dimensional analytical model to simulate groundwater flow during operation of recirculating wells. J. Hydrol. 314 (1–4), 67–77. https://doi.org/10.1016/j.jhydrol.2005.03.039.

Hvilshøj, S., Jensen, K.H., Madsen, B., 2000. Single-well dipole flow tests: parameter estimation and field testing. Ground Water 38, 53–62. https://doi.org/10.1111/j.1745-6584.2000.tb00202.x.

Jin, Y., Holzbecher, E., Sauter, M., 2015. Dual-screened vertical circulation wells for groundwater lowering in unconfined aquifers. Ground Water 54 (1), 15–22. https://doi.org/10.1111/gwat.12331.

Johnson, R.L., Simon, M.A., 2007. Evaluation of groundwater flow patterns around a dual-screened groundwater circulation well. J. Contam. Hydrol. 93 (1–4), 188–202. https://doi.org/10.1016/j.jconhyd.2007.02.003.

Kabala, Z.J., 1993. The dipole flow test: a new single-borehole test for aquifer characterization. Water Resour. Res. 29 (1), 99–107. https://doi.org/10.1029/92WR01820.

Kahler, D.M., Kabala, Z.J., 2018. Rapidly pulsed pumping accelerates remediation in A vertical circulation well model. Water 10, 1423.

Kalhor, K., Ghasemizadeh, R., Rajic, L., Alshawabkeh, A., 2019. Assessment of groundwater quality and remediation in karst aquifers: a review. Groundw. Sustain. Dev. 8, 104–121. https://doi.org/10.1016/j.gsd.2018.10.004.

Knox, R.C., Sabatini, D.A., Harwell, J.H., Brown, R.E., West, C.C., Blaha, F., Griffin, C., 1997. Surfactant remediation field demonstration using a vertical circulation well. Ground Water 35 (6), 948–953. https://doi.org/10.1111/j.1745-6584.1997.tb00166.x.

Lakhwala, F.S., Mueller, J.G., Desrosiers, R.J., 1998. Demonstration of a microbiologically enhanced vertical ground water circulation well technology at a superfund site. Ground Water Monit. Remediat 18 (2), 97–106. https://doi.org/10.1111/j.1745-6592.1998.tb00620.x.

Li, X., Wen, Z., Zhan, H., Zhu, Q., 2019. Skin effect on single-well push-pull tests with the presence of regional groundwater flow. J. Hydrol. 577, 123931 https://doi.org/10.1016/j.jhydrol.2019.123931.

Li, X., Zhang, J., Yang, Z., 2022. Simulation of migration law of organic pollutants in circulating wells. Adv. Civ. Eng. 7342604 https://doi.org/10.1155/2022/7342604.

Liu, P., Liu, M., Shang, M., Yi, X., 2019. Horizontal well test for simulating the in situ remediation of nitrate contaminated groundwater by microbial denitrification. Water Air Soil Pollut. 230, 189. https://doi.org/10.1007/s11270-019-4241-7.

Ma, C., Shi, W., Zhan, H., 2022. On the vertical circulation wells in a leaky-confined aquifer. J. Hydrol. 608, 127676 https://doi.org/10.1016/j.jhydrol.2022.127676.

Mackay, M.D., Cherry, J.A., 1989. Groundwater contamination: pump-and-treat remediation. Environ. Sci. Technol. 23, 630–636. https://doi.org/10.1021/es00064a001.

Matturro, B., Pierro, L., Frascadore, E., Petrangeli Papini, M., Rossetti, S., 2018. Microbial community changes in a chlorinated solvents polluted aquifer over the field scale treatment with poly-3-hydroxybutyrate as amendment. Front. Microbiol. 9, 1664. https://doi.org/10.3389/fmicb.2018.01664.

McCarty, P.L., Goltz, M.N., Hopkins, G.D., Dolan, M.E., Allan, J.P., Kawakami, B.T., Carrothers, T.J., 1998. Full-scale evaluation of in situ cometabolic degradation of trichloroethylene in groundwater through toluene injection. Environ. Sci. Technol. 32 (1), 88–100. https://doi.org/10.1021/es970322b.

MacDonald, T.R., Kitanidis, P.K., 1993. Modeling the free surface of an unconfined aquifer near a recirculation well. Ground Water 31 (5). https://doi.org/10.1111/j.1745-6584.1993.tb00850.x.

Miller, G.R., Elmore, A., 2005. Modeling of a groundwater circulation well removal action alternative. Pract. Period. Hazard. Toxic, Radioact. Waste Manag. 9, 122–129.

Montgomery, M.T., Spargo, B.J., Mueller, J.G., Coffin, R.B., Smith, D.C., Boyd, T.J., 2002. Bacterial production stimulated across the zone of influence of a ground water circulation well in a BTEX-contaminated aquifer. Ground Water Monit. Remediation 22, 144–150. https://doi.org/10.1111/j.1745-6592.2002.tb00763.x.

Mohrlok, U., Samuel Kirubaharan, C., Eldho, T.I., 2010. Transport characteristics in a 3D groundwater circulation flow field by experimental and numerical investigations. Pract. Period. Hazard. Toxic, Radioact. Waste Manag. 14 (3), 185–194. https://doi.org/10.1061/(ASCE)HZ.1944-8376.0000032.

Morozov, P.E., 2021. Groundwater flow near a vertical circulation well with a skin-effect. Water Resour. 48 (5) https://doi.org/10.1134/S0097807821050146, 737-7.

Něměček, J., Steinová, J., Špánek, R., Pluhař, T., Pokorný, P., Najmanová, P., Knytl, V., Černík, M., 2018. Thermally enhanced in situ bioremediation of groundwater contaminated with chlorinated solvents - a field test. Sci. Total Environ. 622, 743–755. https://doi.org/10.1016/j.scitotenv.2017.12.047.

Palma, E., Daghio, M., Franzetti, A., Petrangeli Papini, M., Aulenta, F., 2017. The bioelectric well: a novel approach for in situ treatment of hydrocarbon-contaminated groundwater. Microb. Biotechnol. 11 (1), 112–118. https://doi.org/10.1111/1751-7915.12760.

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. Chem. Eng. Trans. 49, 91–96. https://doi.org/10.3303/CET1649016.

Peursem, D.V., Zlotnik, V., Ledder, G., 1999. Groundwater flow near vertical recirculatory wells: effect of skin on flowgeometry and travel times with implications for aquifer remediation. J. Hydrol. 222 (1–4), 109–122. https://doi.org/10.1016/S0022-1694(99)00100-6.

Philip, R.D., Walter, G.R., 1992. Prediction of flow and hydraulic head fields for vertical circulation wells. Ground Water 30, 765–773. https://doi.org/10.1111/j.1745-6584.1992.tb01562.x.

Pierro, L., Matturro, B., Rossetti, S., Sagliaschi, M., Sucato, S., Alesi, E., Bartsch, E., Arjmand, F., Petrangeli Papini, M., 2017. Polyhydroxyalkanoate as a slow-release carbon source for in situ bioremediation of contaminated aquifers: from laboratory investigation to pilot-scale testing in the field. N. Biotech. 37, 60–68. https://doi.org/10.1016/j.nbt.2016.11.004.

Pinto, M.J., Gvirtzman, H., Gorelick, S.M., 1997. Laboratory-scale analysis of aquifer remediation by in-well vapor stripping, 2, Modeling results. J. Contam. Hydrol. 29, 41–58. https://doi.org/10.1016/S0169-7722(96)00092-7.

Ponsin, V., Coulomb, B., Guelorget, Y., Maier, J., Hoehener, P., 2014. In situ biostimulation of petroleum hydrocarbon degradation by nitrate and phosphate injection using a dipole well configuration. J. Contam. Hydrol. 171, 22–31. https://doi.org/10.1016/j.jconhyd.2014.10.003.

Sabatini, D.A., Knox, R.C., Harwell, J.H., Soerens, T.S., Chen, L., Brown, R.E., West, C., 1997. Design of a surfactant remediation field demonstration based on laboratory and modeling studies. Ground Water 35 (6), 954–963. https://doi.org/10.1111/j.1745-6584.1997.tb00167.x.

Singh, R., Chakma, S., Birke, V., 2020. Numerical modelling and performance evaluation of multi-permeable reactive barrier system for aquifer remediation susceptible to chloride contamination. Groundw. Sustain. Dev. 10, 100317 https://doi.org/10.1016/j.gsd.2019.100317.

Stamm, J., 1997. Vertical circulation flows for in-situ bioremediation in aquifers. In: Sikdar, K.S., Irvine, L.R. (Eds.), Bioremediation: Principle and Practice, Volume 1, Fundamentals and Applications. Technomic Publishing Co., Lancaster.

Stamm, J., Eldho, T.I., Scholz, M., 1998. Flow simulation of a system of groundwater circulation well and pumping well for NAPL site remediation. WIT Trans. Ecol. Environ. 23 https://doi.org/10.2495/CMWR980131.

Sutton, D.J., Kabala, Z.J., Schaad, D.E., Ruud, N.C., 2000. The dipole-flow test with a tracer: a new single-borehole tracer test for aquifer characterization. J. Contam. Hydrol. 44 (1), 71–101. https://doi.org/10.1016/S0169-7722(00)00083-8.

Tatti, F., Petrangeli Papini, M., Sappa, G., Raboni, M., Arjmand, F., Viotti, P., 2018. Contaminant back-diffusion from low-permeability layers as affected by groundwater velocity: a laboratory investigation by box model and image analysis. Sci. Total Environ. 622, 164–171. https://doi.org/10.1016/j.scitotenv.2017.11.347. –623.

Tatti, F., Petrangeli Papini, M., Torretta, V., Mancini, G., Boni, M.R., 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. https://doi.org/10.1016/j.jconhyd.2019.03.001.

Tawabini, B., Makkawi, M., 2018. Remediation of MTBE-contaminated groundwater by integrated circulation wells and advanced oxidation technologies. Water Supply 18 (2), 399–407. https://doi.org/10.2166/ws.2017.128.

Toscani, L., Stefania, G.A., Masut, E., Prieto, M., Legnani, A., Gigliuto, A., Feroli, L., Battaglia, A., 2022. Groundwater flow numerical model to evaluate the water mass balance and flow patterns in Groundwater Circulation Wells (GCW) with varying aquifer parameters. Acque Sotter. - Ital. J. Groundw. 11 (4), 9–19. https://doi.org/10.7343/as-2022-515.

Tu, K., Wu, Q., Simunek, J., Chen, C., Zhu, K., Zeng, Y., Xu, S., Wang, Y., 2020. An analytical solution of groundwater flow in a confined aquifer with a single-well circulation system. Water Resour. Res. 56, e2020WR027529 https://doi.org/10.1029/2020WR027529.

Vats, O.P., Sharma, B., Stamm, J., Bhattacharjya, R.K., 2020. Groundwater circulation well for controlling saltwater intrusion in coastal aquifers: numerical study with experimental validation. Water Resour. Manag. 34, 3551–3563. https://doi.org/10.1007/s11269-020-02635-z.

Wang, P., Li, J., An, P., Yan, Z., Xu, Y., Pu, S., 2023. Enhanced delivery of remedial reagents in low-permeability aquifers through coupling with groundwater circulation well. J. Hydrol. 618, 129260 https://doi.org/10.1016/j.jhydrol.2023.129260.

Xia, Q., Zhang, Q., Xu, M., Tang, Y., Teng, H., 2019. Visualizing hydraulic zones of a vertical circulation well in presence of ambient flow. Desalination Water Treat. 159, 151–160. https://doi.org/10.5004/dwt.2019.24098.

Xiang, J., Kabala, Z.J., 1997. Performance of the steady-state dipole flow test in layered aquifer. Hydrol. Process. 11, 1595–1605. https://doi.org/10.1002/(SICI)1099-1085(19971015)11:12%3C1595::AID-HYP489%3E3.0.CO,2-0.

Yu, R., Andrachek, R.G., Lehmicke, L.G., Freedman, D.L., 2018. Remediation of chlorinated ethenes in fractured sandstone by natural and enhanced biotic and abiotic processes: a crushed rock microcosm study. Sci. Total Environ. 626, 497–506. https://doi.org/10.1016/j.scitotenv.2018.01.064.

Yuan, S., Liu, Y., Zhang, P., Tong, M., Liu, H., 2021. Electrolytic groundwater circulation well for trichloroethylene degradation in a simulated aquifer. Sci. China Technol. Sci. 64 (2), 251–260. https://doi.org/10.1007/s11431-019-1521-7.

Zhang, T., Lowry, G.V., Capiro, N.L., Chen, J., Chen, W., Chen, Y., Dionysiou, D.D., Elliott, D.W., Ghoshal, S., Hofmann, T., Hsu-Kim, H., Hughes, J., Jiang, C., Jiang, G., Jing, C., Kavanaugh, M., Li, Q., Liu, S., Ma, J., Pan, B., Phenrat, T., Qu, X., Quan, X., Saleh, N., Vikesland, P.J., Wang, Q., Westerhoff, P., Wong, M.S., Xia, T., Xing, B., Yan, B., Zhang, L., Zhou, D., Alvarez, P.J.J., 2019. In situ remediation of subsurface contamination: opportunities and challenges for nanotechnology and advanced materials. Environ. Sci.: Nano 6, 1283–1302. https://doi.org/10.1039/C9EN00143C.

Zhao, Y., Qu, D., Zhou, R., Yang, S., Ren, H., 2016. Efficacy of forming biofilms by Pseudomonas migulae AN-1 toward in situ bioremediation of aniline-contaminated aquifer by groundwater circulation wells. Environ. Sci. Pollut. Res. 23, 11568–11573. https://doi.org/10.1007/s11356-016-6737-7.

Zlotnik, V., Ledder, G., 1996. Theory of dipole flow in uniform anisotropic aquifers. Water Resour. Res. 32 (4), 1119–1128. https://doi.org/10.1029/95WR03813.

Zlotnik, V., Zurbuchen, B.R., 1998. Dipole probe: design and field applications of a single-borehole device for measurements of vertical variations of hydraulic conductivity. Ground Water 36, 884–893. https://doi.org/10.1111/j.1745-6584.1998.tb02095.x.

Zlotnik, V.A., Zurbuchen, B.R., Ptak, T., 2001. The steady-state dipole-flow test for characterization of hydraulic conductivity statistics in a highly permeable aquifer: horkheimer insel site, Germany. Ground Water 39, 504–516. https://doi.org/10.1111/j.1745-6584.2001.tb02339.x.

Zhu, Q., Wen, Z., Zhan, H., Yuan, S., 2020. Optimization strategies for in situ groundwater remediation by a vertical circulation well based on particle tracking and node-dependent finite difference methods. Water Resour. Res. 56 (11), e2020WR027396 https://doi.org/10.1029/2020WR027396.

Zhu, Q., Wen, Z., 2023. Dipole flow tracer test models for identifying skin properties and ambient groundwater flow effects. Ground Water 61, 532–543. https://doi.org/10.1111/gwat.13269.