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RESEARCH ARTICLE

Passive convergence-permeable reactive barrier (PC-PRB): An effective configuration to enhance hydraulic performance

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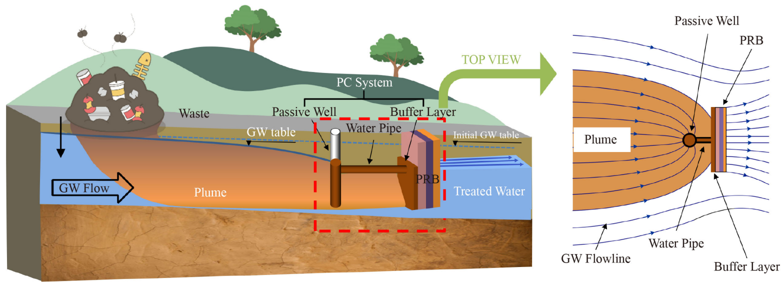
HIGHLIGHTS

- A novel PRB configuration based on passive convergent flow effect was proposed.
- A 2D finite-difference hydrodynamic model, PRB-Flow, was developed.
- PC-PRB can significantly enhance the hydraulic capture capacity of PRB.
- The PRB geometric dimensions and materials cost are effectively reduced.
- The dominant influential factor of the PC-PRB capture width is pipe length, L_p.

GRAPHIC ABSTRACT



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ABSTRACT

A novel permeable reactive barrier (PRB) configuration, the so-called passive convergence-permeable reactive barrier (PC-PRB), is proposed to overcome several shortcomings of traditional PRB configurations, such as high dependency to site hydrogeological characteristics and plume size. The PC-PRB is designed to make the plume converge towards the PRB due to the passive hydraulic decompression-convergent flow effect. The corresponding passive groundwater convergence (PC) system is deployed upstream of the PRB system, which consists of passive wells, water pipes, and a buffer layer. A two-dimensional (2D) finite-difference hydrodynamic code, entitled PRB-Flow, is developed to examine the hydraulic performance parameters (i.e., capture width (W) and residence time (t)) of PC-PRB. It is proved that the horizontal 2D capture width (W_h) and vertical 2D capture depth (W_v) of the PC-PRB remarkably increase compared to that of the continuous reactive barrier (C-PRB). The aforementioned relative growth values in order are greater than 50% and 25% in this case study. Therefore, the PRB geometric dimensions as well as the materials cost required for the same plume treatment lessens. The sensitivity analysis reveals that the dominant factors influencing the hydraulic performance of the PC-PRB are the water pipe length (L_p), PRB length (L_{PRB}), passive well height (H_w), and PRB height (H_{PRB}). The discrepancy between the W_h of PC-PRB and that of the C-PRB (i.e., ΔW_h) has a low correlation with PRB parameters and mainly depends on L_p, which could dramatically simplify the PC-PRB design procedure. Generally, the proposed PC-PRB exhibits an effective PRB configuration to enhance hydraulic performance.

1 Introduction

Permeable reactive barrier (PRB) has emerged as a promising and sustainable *in situ* groundwater remediation technology, which has the advantages of low maintenance costs, service longevity, and in situ treatment of a variety of groundwater pollutants (e.g., heavy metals, inorganic and organic pollutants) (Lu et al., 2016; Gibert et al., 2019; Jiang et al., 2019; Torregrosa et al., 2019; Ali and Abd Ali, 2020; Faisal et al., 2020;

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Falciglia et al., 2020). The total cost of a PRB system is at least 60% lower than that of an equivalent pump and treat system over extended periods (Painter, 2005; Maamoun et al., 2020). Between 1994 and 2005, approximately 200 PRB applications were installed in Europe, North America, and Australia, of which more than 60% were zero valence iron (ZVI)-based (Turner et al., 2005). Until 2010, more than 125 full-scale ZVI-based PRBs had been constructed worldwide (Gillham et al., 2010).

Two primary, interdependent hydraulic performance parameters of the PRB evaluated are the hydraulic capture zone width (W) and residence time (t) (Liu et al., 2011; Grajales-Mesa et al., 2020; Singh et al., 2020). The factor W represents the width of the groundwater area that passes through rather than bypasses the reactive barrier (Bekele et al., 2015). To effectively prevent contaminant plume migration, the length of the reactive barrier is generally designed to be about 1.2–1.5 times the maximum width of the contaminant plume (Craig et al., 2006). The parameter t denotes the contact time between pollutants and reactive materials in the PRB (Gupta and Fox, 1999), which is defined as the ratio between the flow-through thickness of the PRB and the groundwater flow velocity (Maamoun et al., 2020). A sufficient level of t must be guaranteed for pollutant removal; otherwise, a breakthrough of pollutants may occur (Puls, 2006; Gillham et al., 2010). The previous investigations showed that the numerical groundwater models are effective, flexible, and inexpensive tools to evaluate the W and t of the PRB (Lin et al., 2005; Jeen et al., 2011). Various explorations have demonstrated that W is inversely proportional to t (Gupta and Fox, 1999; Liu et al., 2011). Therefore, the PRB engineering design must find the right trade-off between maximizing W and t.

An appropriate PRB configuration is critical to the PRB engineering design, which should be selected considering site-specific hydrogeologic conditions and contaminant plume characteristics. The most common PRB configuration is the continuous permeable reactive barrier (C-PRB). This configuration has a simple structure, convenient installation, less disturbance to the natural groundwater flow field, and low sensitivity to the complexity of the groundwater flow field. However, for sites with deep groundwater depth and large plumes, the application of C-PRB is limited due to its high construction and materials cost (Bortone et al., 2013). Alternative PRB configurations have been suggested in the last decades, such as the funnel-gate system and discontinuous permeable barriers (Wilson et al., 1997; Hudak, 2008). A funnel-and-gate configuration uses impermeable barrier walls (i.e., a funnel) to direct groundwater towards a permeable treatment zone (the gate) (Courcelles, 2015). This configuration is more suitable for large plumes because it could reduce materials cost and improve remediation efficiency. In addition, its reactive materials can be centrally replaced. Nevertheless, it requires both large-scale destruction of hydrogeological conditions and construction of underground impervious walls, which have an irreversible effect on the groundwater flow field. Wilson et al. (1997) proposed a discontinuous permeable barrier consisting of one or more arrays of unpumped wells. The hydraulic conductivity difference between aquifer and well makes contaminated groundwater converge into the wells, which can serve as either an *in situ* reactor or a means of introducing amendments such as electron acceptors (e.g., oxygen, nitrate), electron donors, and microbial nutrients. Such a configuration is suitable for sites with deep groundwater depth and good aquifer permeability, which can be simply constructed and needs 20% fewer materials cost than a C-PRB system for treating the same plume (Santisukkasaem et al., 2015; Torregrosa et al., 2019). However, this configuration has also some drawbacks, such as high sensitivity to the groundwater flow field, limited remediation zones and reactive materials are not easily replaced.

To overcome the shortcomings of the PRB configurations mentioned above, we propose an innovative and sustainable PRB configuration, namely the passive convergence-permeable reactive barrier (PC-PRB). The PC-PRB is designed to make the contaminated groundwater converge towards the PRB system due to the passive hydraulic decompression-convergent flow effect. Herein, a two-dimensional (2D) finite-difference hydrodynamic code, entitled PRB-Flow, is carefully developed in the Pascal-Delphi environment to simulate and evaluate the hydrodynamic behavior of the PC-PRB in confined aquifers. The major objectives of the present study are summarized as: 1) demonstration of the hydraulic feasibility and superiority of the PC-PRB by comparing it with a C-PRB, 2) identification of the control factors affecting the hydraulic performance of the PC-PRB as well as examining their impacts.

2 Concept and principle of the PC-PRB

As demonstrated in Fig. 1, the PC-PRB is a novel PRB configuration consisting of a passive groundwater convergence (PC) system and a PRB system. The corresponding PC system is deployed upstream of the PRB system to regulate the groundwater flow field upstream of the PRB system. Furthermore, it makes the plume converge towards the PRB system both horizontally and vertically due to the passive hydraulic decompression-convergent flow effect. The PC system is composed of a passive well, a water pipe, and a buffer layer. The basic principles of the PC-PRB are provided in the following:

1) The passive well is a partially penetrated well installed upstream of the PRB. When the well discharges water at a specific flow rate through the water pipe, the head in the well is lower than that around the well, the so-called passive decompression effect. Therefore, the well

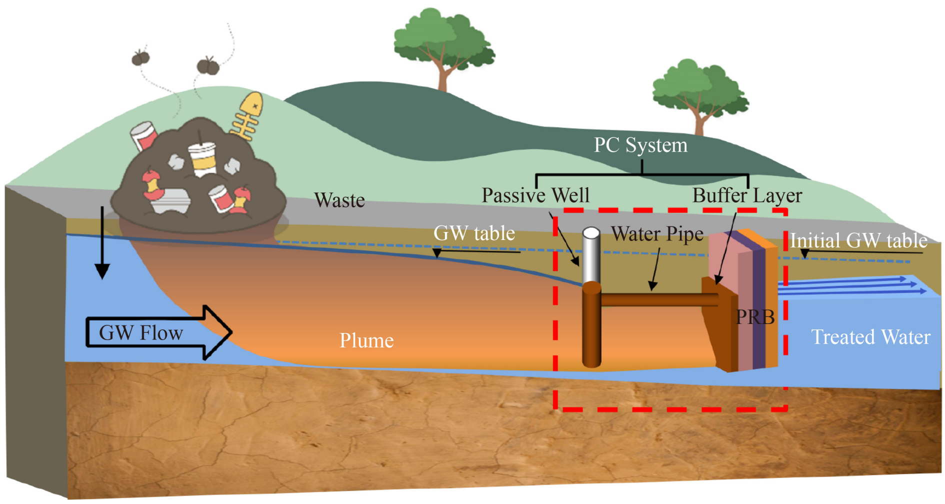

Fig. 1 A schematic view of the plume treatment by the PC-PRB system.

becomes a groundwater sink, and the contaminated groundwater close to the well intensively flows into the well through its wall and bottom, the so-called convergent flow effect.

2) A water pipe connects the passive well to the buffer layer. The converged groundwater in the passive well flows to the buffer layer through a water pipe driven by the head difference.

3) The buffer layer is located between the water pipe and the PRB system as a transition zone to allow the contaminated groundwater to flow evenly through the PRB system.

4) The reactive materials in the PRB system remove or capture pollutants from the contaminated groundwater representing the purification step.

3 PC-PRB simulation in PRB-Flow code

3.1 Model setup and validation

A 2D finite-difference hydrodynamic code, entitled PRB-Flow, has been developed in a Pascal Delphi environment to quickly simulate the hydrodynamic behavior of the PC-PRB in confined aquifers, which has been applied for software copyright (see Fig. S1). The major governing equation for 2D steady-state flow is described by:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)=0, \qquad (1)$$

where h is the hydraulic head, K_x and K_y in order represent the hydraulic conductivities along with the x and y directions, and ∂ denotes the partial symbol.

The partial differential equation of 2D steady-state flow can be also expressed in terms of the flow function, ψ, as follows:

$$\frac{\partial}{\partial x}\left(\frac{1}{K_x}\frac{\partial \psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{K_y}\frac{\partial \psi}{\partial y}\right)=0, \qquad (2)$$

and the boundary condition of ψ is displayed by:

$$\psi|_{\Gamma}=\int_{\Gamma}-v_y\,\mathrm{d}x+v_x\mathrm{d}y, \qquad (3)$$

in which v_x and v_y in order represent the components of the Darcy velocity along with the x and y axes, and Γ denotes the boundary of the understudy 2D domain.

The PRB-Flow code implements the finite-difference numerical method to simulate the 2D steady-state saturated groundwater flow in the porous media and PC-PRB. The main parameters evaluated are the hydraulic head, flow function and seepage velocity, while particle tracking and visualization display are also carried out by the developed code. It utilizes the rectangular difference grid with a central difference format, and iteratively solves the system of difference equations using the successive over relaxation (SOR) approach; therefore, the resulted numerical solution is relatively stable. In particular, the PRB-Flow code has the advantages of smaller memory requirements, easier operation, more flexible grid dissection and parameter assignment compared with traditional numerical simulation software such as Visual MODFLOW and Groundwater Modeling System. Although the PRB-Flow code suffers from some limitations, such as incapability in performing the 3D solute transport problems. Actually, this code is essentially exploited for the rapid analysis of the PC-PRB hydraulic performance in the early design stage.

The code validity of the PRB-Flow is checked by comparing some of the simulation results with those of the commercial groundwater simulation software Visual MODFLOW (see Figs. S2 and S3). The relative error (δ) of the PRB-Flow compared to Visual MODFLOW regarding the horizontal 2D capture width (W_{h}) and the corresponding residence time (t_{h}) of the PC-PRB at different pipe lengths (L_p) are all less than 5% (see Table S1). This reveals that the PRB-Flow could effectively simulate the hydrodynamic behavior of the PC-PRB in confined aquifers.

3.2 Simulation domain

In the present study, two confined aquifers are employed in the hydraulic performance analysis of the groundwater flow through the PC-PRB via the PRB-Flow code (see Fig. 2). The length and width of the horizontal 2D confined aquifer in order are 400 m and 200 m (see Fig. 2(a)), while the length and height of the vertical 2D confined aquifer in order are 400 m and 30 m (see Fig. 2(b)). The boundary conditions of these two confined aquifers are time-invariant. For the horizontal 2D confined aquifer, the northern and southern boundaries are assumed to be impermeable, and the eastern and western boundaries represent the constant hydraulic head whose corresponding head values in order are 5 m and 1 m (i.e., the hydraulic gradient value is 0.01). For the vertical 2D confined aquifer, the upper and lower boundaries are impermeable, while the left and right boundaries are specified by the constant hydraulic head with the hydraulic gradient is 0.01. The two considered confined aquifers are homogeneous and isotropic. Their hydraulic parameters and pertinent values have been presented in Table S2. The relative PRB/aquifer hydraulic conductivity (K_{PRB}/K_a) is set equal to 10.

3.3 PC-PRB simulation conditions

The PC system is the key module in the PRB-Flow. The preferential flow model is utilized to describe the preferential flow associated with macropores. This represents independent high-permeability media, embedded in the aquifer to explicitly simulate preferential flow conduits (Wilson et al., 1997; Xiao et al., 2019). Herein, the PC system could serve as preferential flow conduits that influence the groundwater flow field. The passive well, water pipe and buffer layer are considered high-permeability media whose hydraulic conductivity and porosity in order are 10000 m/d and 1. The pipe wall is assumed to be impermeable media, and its hydraulic conductivity and porosity are set equal to zero. The PC-PRB geometric parameters and their corresponding values are listed in Table 1. The model cell size in the vicinity of the PC-PRB is small enough to provide sufficient resolution.

4 Hydraulic performance comparison between the PC-PRB and C-PRB

4.1 Case of horizontal 2D confined aquifer

The horizontal 2D hydraulic performance comparison between the PC-PRB and C-PRB is carried out, as demonstrated in Figs. 3(a) and 3(b). The simulation results of the horizontal 2D capture width (W_h), the corresponding residence time (t_h), and the discrepancies between the PC-PRB-based values and those of the C-PRB-based ones (i.e., ΔW_h and Δt_h) are presented in Table 2. The results show that the W_h of the PC-PRB considerably increases by 52.8%, from 36 to 55 m, compared with the C-PRB. This issue is mainly attributed

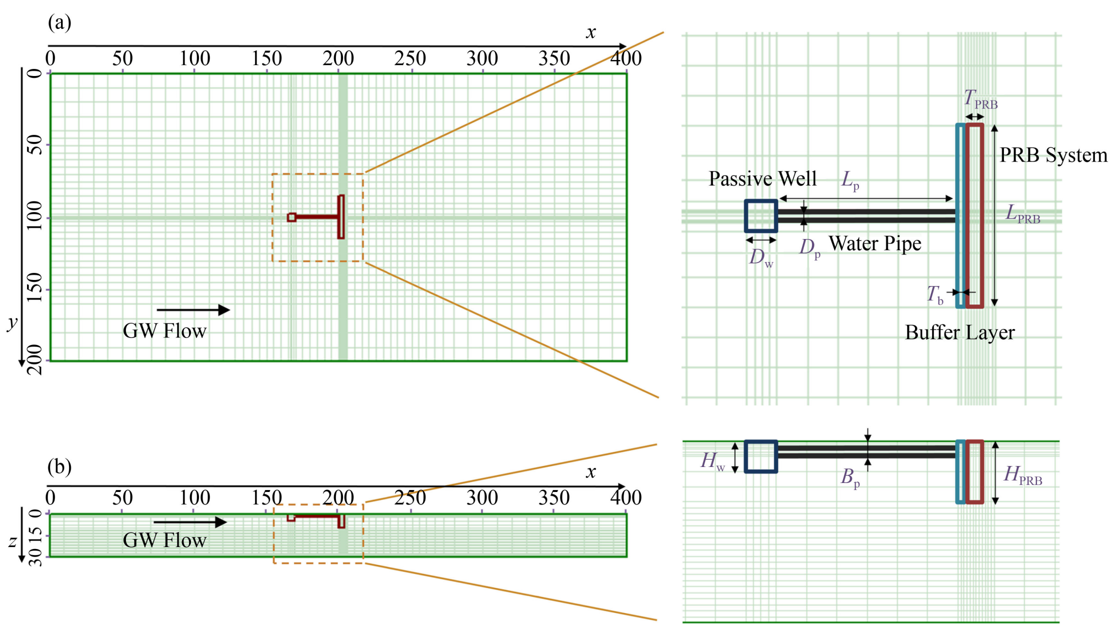

Fig. 2 The PC-PRB-based simulation and main design parameters representation: (a) The horizontal 2D confined aquifer, (b) the vertical 2D confined aquifer.

Table 1 Geometrical parameters and their corresponding values for the PC-PRB

System		Parameters	Values (m)
PC system	Passive well	Well diameter, D_w	5.0
		Well height, H_w	5.0
	Water pipe	Pipe length, L_p	30.0
		Pipe diameter, D_p	1.0
		Buried depth, B_p	2.5
	Buffer layer	Layer thickness, T_b	1.0
PRB system		PRB Length, L_{PRB}	30.0
		PRB Thickness, T_{PRB}	3.0
		PRB Height, H_{PRB}	10.0

to the head drop at the passive well for the PC-PRB by 0.33 m compared with the C-PRB, as shown in Figs. S4(a) and S4(b). Compared with Fig. 3(a), the contour line with the value of 3.25 m in Fig. 3(b) obviously bends to the left near the passive well, indicating that the water head at the passive well is lower than that at the contour line. It implies that the hydraulic head of the well is remarkably lower than that around the well. As a result, the passive well plays the role of a sink for contaminated groundwater (i.e., the groundwater in the vicinity of the well intensively flows into the well). The head loss of the groundwater flowing through the water pipe can be neglected since its corresponding velocity is fairly negligible (Park and Zhan, 2002). In this case study, the calculation results of the PRB-Flow code reveal that the head in the well is slightly higher than that in the buffer layer with a difference of about 0.0015 m. The groundwater nearby to the well intensively flows into the well, while the converged groundwater in the well can be transported naturally to the PRB system through the water pipe under the hydraulic head difference. Therefore, this enables the PC-PRB to capture a larger area of the contaminated groundwater.

As the value of W_h increases due to the passive hydraulic decompression-convergent flow effect, more contaminated groundwater passes through the PRB system per unit time, and therefore the t_h decreases accordingly. Compared to the C-PRB, the t_h associated with the PC-PRB is lessens by 36.68 d, a reduction of about 28.1%. This issue also puts forward higher requirements for the remediation efficiency of reactive materials due to the loss of hydraulic residence time of pollutants caused by the passive hydraulic decompression-convergent flow effect. At the same time, although t_h decreases with the growth of W_h, the mixed dilution effect of the passive well on the contaminant plume could reduce the maximum concentration of pollutants, thus effectively lessening the required residence time of pollutants in the PRB. This contradictory influence should be further paid attention to in subsequent studies and considered in the design of the PC-PRB.

4.2 Case of vertical 2D confined aquifer

A comparison of the vertical 2D hydraulic performance between the PC-PRB and C-PRB is also performed, as presented in Figs. 3(c) and 3(d). The simulation results of the vertical 2D capture zone depth (W_v), the corresponding residence time (t_v), the discrepancies between the predicted values by the PC-PRB and those of the C-PRB (i.e., ΔW_v and Δt_v) are provided in Table 2. The presented results show that compared with the C-PRB, the corresponding W_v value of the PC-PRB magnifies by 27.3%, from 11 to 14 m, although the present discrepancy is not considerable as W_h. This also can be attributed to the head drop at the passive well for the PC-PRB by about 0.33 m compared to the C-PRB (see Figs. S4(c) and S4(d)). Compared with Fig. 3(c), the contour line pertinent to the value of 3.2 m in Fig. 3(d) apparently curves to the left near the passive well, indicating that the hydraulic head at the passive well is lower than that below the well bottom. It implies that the contaminated groundwater below the well bottom flows into the well. The hydraulic head in the well is slightly higher than that in the buffer layer (the head difference is about 0.0004 m). This indicates that the converged groundwater in the passive well can be logically transported to the PRB system through the water pipe. As a result, this enables the PC-PRB to capture the deeper contaminated groundwater. Similarly, the value of t_v decreases with an increase in the W_v. Compared to the C-PRB, the t_v of the PC-PRB decreases by 10.4 d, presenting a reduction of about 8.0%. However, since the value of ΔW_v is smaller than the ΔW_h, the reduction in t_v is less apparent compared to that of t_h.

It is proved that the W_h and W_v of the PC-PRB remarkably increase compared to that of the C-PRB. In the examined case study, such growth rates in order are greater than 50% and 25%. Thereby, the PRB geometric dimensions as well as the materials cost required for the same plume treatment lessens. To sum up, the PC-PRB is a hydraulically feasible and superior PRB configuration to enhance hydraulic performance based on the analysis results of the above two cases.

5 Influential factors analysis of PC-PRB hydraulic performance

5.1 Dominant influential factors identification

The design of PC-PRB involves many factors (see Fig. 2), so we need to identify the dominant influential factors of the two hydraulic performance parameters (namely, W and t) of the PC-PRB through local sensitivity analysis, which is of great importance to simplify its design procedure. The sensitivity analysis is aimed to evaluate model outputs in response to the variations in the model input factors (Singh et al., 2020). The local sensitivity

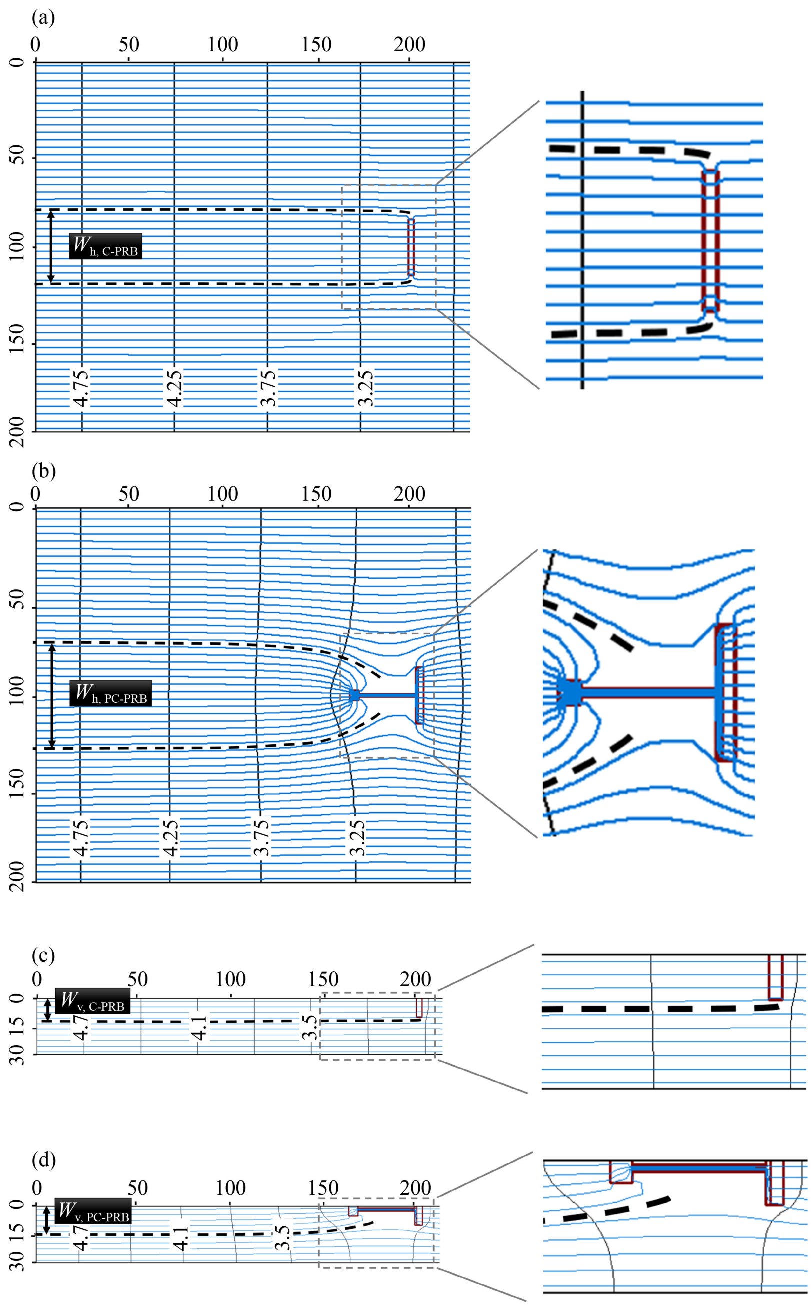

Fig. 3 Hydraulic capture width (W) comparison between PC-PRB and C-PRB: (a) The horizontal 2D capture width ($W_{h,\ C\text{-}PRB}$) of the C-PRB, (b) the horizontal 2D capture width ($W_{h,\ PC\text{-}PRB}$) of the PC-PRB, (c) the vertical 2D capture depth ($W_{v,\ C\text{-}PRB}$) of the C-PRB, (d) the vertical 2D capture depth ($W_{v,\ PC\text{-}PRB}$) of the PC-PRB.

Table 2 Comparison between the hydraulic performance factors of the PC-PRB and those of the PRB

Simulation domain	Configuration	W (m)	ΔW (m)	v (m/d)	t (d)	Δt (d)
Horizontal 2D confined aquifer	C-PRB	36	–	0.023	130.4	–
	PC-PRB	55	19	0.032	93.8	−36.6
Vertical 2D confined aquifer	C-PRB	11	–	0.023	130.4	–
	PC-PRB	14	3	0.025	120.0	−10.4

index (SI) is considered as an indicator of the input factor sensitivity. The corresponding changes in the model outputs are assessed at a 20% change in input parameter values.

The sensitivity analysis results of W_h, t_h, W_v, and t_v are presented in Fig. 4. In terms of the absolute value of SI (see Figs. 4(a) and 4(b)), the sensitivity rankings of W_h and t_h are given by $L_{PRB}>L_p>D_w>T_{PRB}>T_b=D_p$ and $T_{PRB}>L_p>L_{PRB}>D_w>T_b>D_p$, respectively. It is noticed that W_h represents the horizontal 2D width of the groundwater area that passes through rather than bypasses the PRB, and t_h denotes the contact time between the

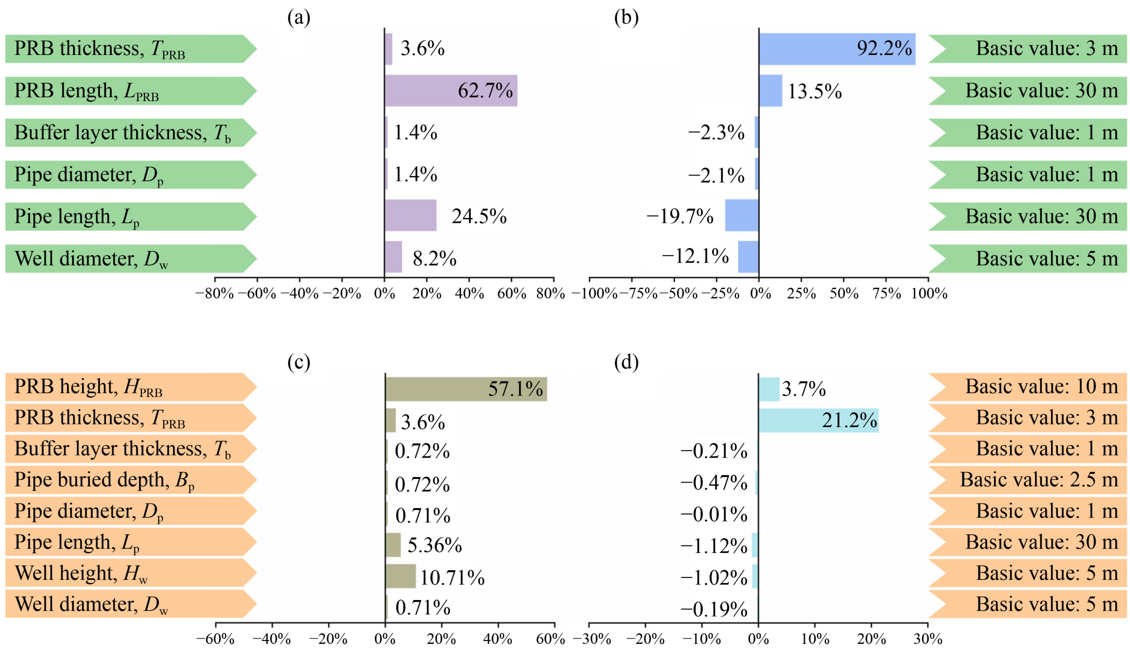

Fig. 4 The sensitivity index (SI) analysis of various factors: (a) W_h, (b) t_h, (c) W_v, (d) t_v.

pollutants and reactive materials in the horizontal 2D confined aquifer, which is determined by the T_{PRB} and the groundwater velocity through the PRB. Therefore, it is not difficult to understand that the L_{PRB} variation has a considerable influence on the W_h, and the same story holds true for the effect of T_{PRB} on t_h. These results are rationally consistent with those obtained by other researchers (Tan et al., 2016; Rad and Fazlali, 2020). Additionally, the value of W_h has a high sensitivity to the variation of L_p, which indicates that the L_p is the dominant influential factor on the hydraulic performance of the PC-PRB. As demonstrated in Figs. 4(c) and 4(d), the sensitivity ranks for W_v and t_v are represented by $H_{PRB}>H_w>L_p>T_{PRB}>T_b=B_p>D_w=D_p$ and $T_{PRB}>H_{PRB}>L_p>H_w>B_p>T_b>D_w>D_p$, respectively. The plotted results show that any changes in H_{PRB} and T_{PRB} greatly affect the variations of W_v and t_v, respectively, which is in accordance with the obtained results in previous studies (Singh et al., 2020). Furthermore, W_v is highly sensitive to the variation of H_w, while the t_v is less sensitive to other factors, except T_{PRB} and H_{PRB}.

In brief, in the design procedure of the PC-PRB, in addition to the two PRB system parameters (i.e., L_{PRB} and H_{PRB}) that influence the initial capture ability of the PRB, the two PC system parameters (i.e., L_p and H_w) that affect the increase in the hydraulic performance of the PC-PRB should also be preferentially considered. As a result, we will next focus on the effect of the two PC system parameters (i.e., L_p and H_w) on the ΔW and Δt.

5.2 Effect of water pipe length (L_p) variation

The effect of the variation of L_p in the range of 10–60 m on the two horizontal 2D discrepancies (namely, ΔW_h and Δt_h) is of interest. Herein, three levels of L_{PRB} (i.e., 10, 30, and 50 m) have been taken for such analysis. The values of other parameters are kept fixed as basic values, as presented in Table 1. The regression analysis between the two dependent variables (namely, ΔW_h and Δt_h) and the one independent variable (L_p) is conducted using OriginPro 2018 software. The linear and quadratic regression models are investigated to determine the best model for predicting the response of the dependent variables due to the variation of the independent variable (see Figs. 5(a) and 5(b)).

Regarding the effect of L_p on ΔW_h, the ΔW_h is considerably proportional to L_p, and the corresponding response relationship between them conforms to the linear regression model ($R^2 > 0.98$, $P < 0.001$) (see Fig. 5(a)). Further, there is a little difference between the response relationships of ΔW_h with L_p for the considered levels of L_{PRB}, which can be concluded that ΔW_h exhibits a significant response to L_p, but a low correlation with L_{PRB}. As demonstrated in Fig. S3(a), the head along the water pipe approximately does not change. In other words, the water pipe is similar to a connector, which can almost lessen the initial head of the well location to the initial head of the buffer layer place. This makes the groundwater nearby the well intensively flow into the well, thereby achieving the passive hydraulic decompression-convergent flow effect. Therefore, the length of the water pipe (L_p) directly determines the head drop in the well, and thus the ΔW_h exhibits a significant response to L_p. In contrast, L_{PRB} mainly determines the initial capture width of the PRB system and does not considerably affect the

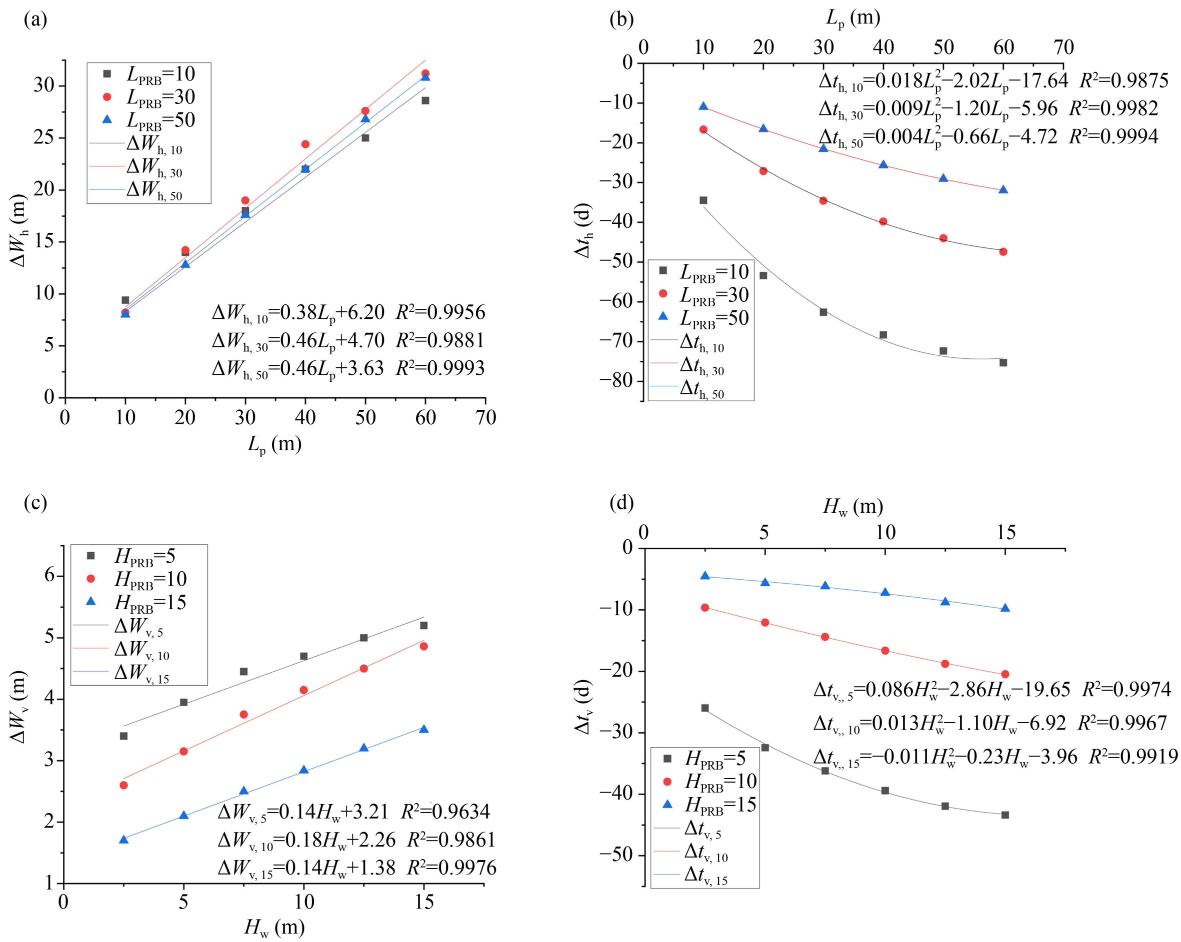

Fig. 5 Effects of L_p and H_w on crucial factors for various levels of L_{PRB} and H_{PRB}: (a) ΔW_h, (b) Δt_h, (c) ΔW_v, (d) Δt_v.

ΔW_h. The present finding that the ΔW_h has little relevance with the PRB parameters and its value mainly determined by L_p is particularly exciting since it will dramatically simplify the design process and enhance the application value of the PC-PRB. Regarding the effect of L_p on Δt_h, Δt_h is inversely proportional to L_p, and the response relationship between them follows a quadratic regression model (R^2 >0.98, P<0.01) (see Fig. 5(b)). Additionally, Δt_h is proportional to L_{PRB}, indicating that the longer the L_{PRB}, the smaller the loss of hydraulic residence time due to the hydraulic decompression-convergent flow effect. This is essentially attributed to the fact that for the same L_p (i.e., the same ΔW_h), the longer L_{PRB} yields less groundwater is equally distributed per unit PRB length.

5.3 Effect of passive well height (H_w) variation

The influence of the variation of H_w in the interval of 2.5–15 m for three values of H_{PRB} (i.e., 5, 10, and 15 m) on the vertical 2D discrepancies (namely, ΔW_v and Δt_v) is also of high concern. To this end, the values of other parameters are kept fixed as basic values (see Table 1). The linear and quadratic regression models are also examined to determine the best model to describe the response of the dependent variables (namely, ΔW_v and Δt_v) due to the variation of the independent variable (H_w) (see Figs. 5(c) and 5(d)). The obtained results reveal that there exists a proportional correlation between the ΔW_v and H_w, just like the corresponding correlation between the ΔW_h and L_p. This is accurately consistent with a linear regression model (R^2 >0.96, P<0.001) (see Fig. 5(c)). Although there is no considerable difference between the response relationships of ΔW_v with H_w for the considered levels of H_{PRB}, the influence of H_{PRB} on ΔW_v cannot be neglected. The ΔW_v is inversely proportional to H_{PRB}, which means that for the same H_w, the smaller the H_{PRB}, the greater the increment in the hydraulic capture depth. This may be caused by the fact that as the PRB height increases, the buffer layer height increases as well.

Regarding the effect of H_w on Δt_v, Δt_v has an inversely proportional relationship with H_w (R^2 >0.99, P<0.001) (see Fig. 5(d)). The response relationship between Δt_v and obeys a quadratic regression model. This is due to the fact that for a given H_{PRB}, the increase of H_w leads to an increase in the flow rate through the PRB, thereby increasing the reduction of t_v. Meanwhile, Δt_v is proportional to H_{PRB}, implying that the higher H_{PRB} results in the smaller loss of the hydraulic residence time due to the passive hydraulic decompression-convergent flow effect. This may be attributed to the fact that for the identical levels of H_w, the higher H_{PRB} results in a less average groundwater distribution per unit PRB height.

In general, the ΔW_h has a low correlation with the PRB factors and its value is significantly proportional to L_p. The parameter Δt_h is inversely proportional to L_p and positively proportional to L_{PRB}. However, ΔW_v relies on both H_w and H_{PRB}. In more detail, it is proportional to H_w and inversely proportional to H_{PRB}. Further, Δt_v is inversely proportional to H_w and directly proportional to H_{PRB}.

6 Conclusions

An innovative and sustainable PRB configuration, the so-called PC-PRB, was proposed to overcome several shortcomings of the traditional PRB configurations. The PC-PRB was designed to make the contaminated groundwater converge towards the PRB system due to the passive hydraulic decompression-convergent flow effect. Further, a 2D finite-difference hydrodynamic code, entitled PRB-Flow, was developed to evaluate the hydraulic performance of the PC-PRB. It was proved that the W_h and W_v of the PC-PRB remarkably increase compared to that of the C-PRB. The aforementioned increasing values were reported to be greater than 50% and 25%, respectively. Thus, the PRB geometric dimensions and materials cost required for the same plume treatment were reduced. The dominant influential factors on the hydraulic performance of the PC-PRB were water pipe length (L_p), PRB length (L_{PRB}), passive well height (H_w) and PRB height (H_{PRB}). The obtained results revealed that the ΔW_h has a low correlation with the PRB parameters and its value mainly determined by L_p, which can dramatically simplify the design and enhance the application value of the PC-PRB. Generally, the proposed PC-PRB exhibited an effective and superior PRB configuration to improve hydraulic performance.

However, although the PC-PRB can considerably broaden its application scenarios and conditions, such a configuration would be more suitable for larger slopes in terrain. This is because it is easier and cheaper to drill the passive wells, lay the horizontal water pipes, and construct the PRBs. Moreover, the cost counting and parameters optimization of the PC-PRB need to be further studied in the 3D solute transport cases.

Declaration of Competing Interest The authors do not have any conflicts of interest or financial disclosures to report.

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