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Review

An overview of permeable reactive barriers for *in situ* sustainable groundwater remediation

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HIGHLIGHTS

- Permeable reactive barriers (PRBs) are a technology for remediation of groundwater.
- There is a wide spectrum of contaminant that can be treated with PRBs.
- Zero valent iron still remains the most often applied material for PRBs.
- A key aspect for the design of the technology is an adequate site characterization.
- Long term performance of the barrier is still not well understood.

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ABSTRACT

Permeable reactive barriers (PRBs) are one of the innovative technologies widely accepted as an alternative to the 'pump and treat' (P&T) for sustainable *in situ* remediation of contaminated groundwater. The concept of the technology involves the emplacement of a permeable barrier containing reactive materials across the flow path of the contaminated groundwater to intercept and treat the contaminants as the plume flows through it under the influence of the natural hydraulic gradient. Since the invention of PRBs in the early 1990s, a variety of materials has been employed to remove contaminants including heavy metals, chlorinated solvents, aromatic hydrocarbons, and pesticides. Contaminant removal is usually accomplished via processes such as adsorption, precipitation, denitrification and biodegradation. Despite wide acknowledgment, there are still unresolved issues about long term-performance of PRBs, which have somewhat affected their acceptability and full-scale implementation. The current paper presents an overview of the PRB technology, which includes the state of art, the merits and limitations, the reactive media used so far, and the mechanisms employed to transform or immobilize contaminants. The paper also looks at the design, construction and the long-term performance of PRBs.

Contents

Abbreviations: PRBs, permeable reactive barriers; PRmBs, permeable reactive multi-barriers; P&T, pump and treat; ZVI, zero valent iron; PCE, tetrachlorocthylene (or perchloroethcne); TCE, trichloroethylcne (trichloroethene); DCE, dichloroethylcnc; VC, vinyl chloride; HAH, halogenated aliphatic hydrocarbons; BTEX, benzene, toluene, ethylbenzene, xylene; DDT, 1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane; DDD, 2,2-bis(*p*-chlorophenyl)-1,1-dichloroethylene; DDE, 1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethane; ORC, oxygen releasing compound; TCA, 1,1,1-trichloroethane; PCB, polychlorinated biphenyl; PAHs, polycyclic aromatic hydrocarbons; COD, chemical oxygen demand; AOX, adsorbable organic halogens; DOC, dissolved organic carbon; AC, activated carbon; GAC, granular activated carbon; SMZ, ssurfactant modified zeolites; OC, organic carbon; AMD, acid mine drainage; TRM, transformed red mud; AFO, amorphous ferric oxide; BOF, basic oxygen furnace; MTBE, methyl tertiary-butyl ether; SRB, sulfate reducing bacterial; O&M, operation and maintenance; PV, present value; CBA, cost-benefit analysis.

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1. Introduction

The quality of groundwater resources globally has been under serious threat due to their exposure to a broad spectrum of contaminants emanating from a variety of sources including agricultural systems, industries and mines (Tase, 1992; Schipper et al., 2010; Wiafe et al., 2013; Rodak et al., 2014). The conventional technology used to remediate contaminated groundwater has been the 'pump-and-treat' (P&T) systems. However, clean-up goals have hardly been met with this technique. Thus the past three decades have seen a lot of research directed toward the development of novel sustainable groundwater remediation techniques (Henderson and Demond, 2007).

Permeable reactive barriers (PRBs) are one of the innovative technologies being used for *in situ* remediation of contaminated groundwater (Tratnyek, 2002; USEPA, 2002). The PRB concept involves the emplacement of a reactive media perpendicular to the potential trajectory of the contaminated groundwater. As the contamination plume passively migrates through the media under the influence of the natural hydraulic gradient, the contaminants in the plume react with the media leading to either their transformation to less harmful compounds or fixation to the reactive materials (Powell et al., 1998; Carey et al., 2002; Skinner and Schutte, 2006). The decontamination of the groundwater, which usually occurs within and (or) downgradient of the barrier, depending on the type of reactive media used, is accomplished via destructive and/or non-destructive processes (Carey et al., 2002; Wilkin and Puls, 2003; Puls, 2006; Henderson and Demond, 2007; Chen et al., 2011a).

Since the serendipitous invention of the PRB technology in the early 1990s, its ability to remove groundwater contaminants has been extensively investigated. The results of some of these investigations are phenomenal, thereby presenting the PRB technology as a suitable alternative to the conventional P&T method (Korte, 2001; Carey et al., 2002; Wilkin and Puls, 2003; Puls, 2006; Skinner and Schutte, 2006; Henderson and Demond, 2007; Chen et al., 2011a). Despite this, there is still a dearth of empirical evidence regarding the long-term performance of PRBs as most of the investigations are laboratory based (Warner and Sorel, 2002). There have also been reports on pollution swapping in some types of PRBs (Schipper et al., 2010), which have necessitated their improvements to enable the treatment of a broad spectrum of contaminants, and thereby expand their remit. To date, however, PRBs are still considered a promising technology in the field of contaminant remediation, with a record of over 200 field installations since its inception (ITRC, 2011).

There are many published documents and reviews on PRBs; however, majority of them have focused on specific issues related to barriers with zero valent iron (ZVI) as a reactive material (Scherer et al., 2000; Korte, 2001; Henderson and Demond, 2007; Noubactep, 2010). Recently, Schipper et al. (2010) and Careghini et al. (2013) presented a review on bioreactors and biobarriers, respectively, which are a type of PRB. This paper is focusing on a contaminated groundwater/hydrogeology audience, although PRBs currently exist in many forms, e.g. denitrifying bioreactors which are used extensively in groundwater and tile drainage agricultural systems. It, therefore, presents an overview of PRBs including the current state of the technology; the merits and limitations; the reactive media used so far and the mechanisms employed to transform or immobilize contaminants. It also looks at the design, construction and the long-term performance of PRBs.

2. Advances in the PRB technology

The first field PRB studies were conducted at the Canadian Forces Base, Borden (O'Hannesin and Gillham, 1998). This has since been followed by a spate of investigations. According to Bone (2012), a total of 624 publications on PRBs were made between 1999 and 2009. Approximately 40% of these were laboratory-based investigations, with field studies accounting for ca. 32%. A comparison of the latter with the 16% estimated by Scherer et al. (2000) indicates that the number of field publications doubled in 10 years.

The PRB technology was first used to remediate groundwater contaminated with chlorinated solvents such as trichloroethylene (TCE), the three isomers of DCE (1,2-cis-, 1,2-trans- and 1,1-DCE) and vinyl chloride (VC) in the early stages. After proving to be effective in the treatment of these contaminants, its application was extended to include other contaminants. In Table 2, a list of the contaminants that have been treated with PRBs so far has been presented (Blowes et al., 1998; Conca et al., 2002; Köber et al., 2002; USEPA, 2002). The contaminants include halogenated aliphatic hydrocarbons, metals, metalloids, radionuclides, pesticides, petroleum hydrocarbons, and nutrients emanating from agricultural systems. Bone (2012), however, reported that 38% of the contaminants treated with PRBs at field scale from 1994 to 2009 were halogenated aliphatic hydrocarbons (HAH). Since the beginning of