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Capture and release zones of permeable reactive barriers under the influence of advective–dispersive transport in the aquifer

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ABSTRACT

The problem of permeable reactive barrier (PRB) capture and release behavior is investigated by means of an approximate analytical approach exploring the invariance of steady-state solutions of the advection–dispersion equation to conformal mapping. PRB configurations considered are doubly-symmetric funnel-and-gate as well as less frequent drain-and-gate systems. The effect of aquifer heterogeneity on contaminant plume spreading is hereby incorporated through an effective transverse macro-dispersion coefficient, which has to be known. Results are normalized and graphically represented in terms of a relative capture efficiency *M* of contaminant mass or groundwater passing a control plane (transect) at a sufficient distance up-stream of a PRB as to comply with underlying assumptions. Factors of safety *FS* are given as the ratios of required capture width under advective–dispersive and purely advective transport for achieving equal capture efficiency *M*. It is found that *M* also applies to the release behavior down-stream of a PRB, i.e., it describes the spreading and dilution of PRB treated groundwater possibly containing incompletely remediated contamination and/or remediation reaction products. Hypothetical examples are given to demonstrate results.

1. Introduction

Permeable reactive barriers (PRBs) are a popular technique for passive long-term interception and treatment of contaminant plumes in aquifers due to their cost effectiveness compared to pump and treat systems [3,28,40]. PRBs basically consist of a type of reactive material, which is installed in the pathway of a contaminant plume (e.g., in a trench across ambient groundwater flow driven by a natural gradient) and which degrades or retains contamination through chemical, biological or physical processes during the contaminant residence (or travel) time inside the reactive material [8,22,23,30]. For an effective application it is important that the PRB captures the target portion of the contaminated groundwater plume and that the contaminant residence time within the reactive material is adequate to achieve treatment objectives. In order to meet both requirements under a variety of conditions, different PRB configurations have been applied or proposed including (a) funnel-and-gate (FG) PRBs with impermeable funnel arms to increase the width of the capture zone; (b) velocity equalization walls (VEW) to achieve more uniform contaminant residence times in a reactor; and (c) drain-and-gate (DG) PRBs using trench-like drains to capture and release groundwater before and after passing a reactor. While FG PRBs, which may be reduced to continuous wall PRBs by using zero funnel length, are predominant, DG PRBs are limited to a smaller number of field applications (e.g., [7,37,42]). To the best of our knowledge, VEW PRBs have so far only been proposed conceptually [39]. Examples of these PRB types with groundwater stream lines, potential lines and capture zones are shown in Fig. 1.

Theoretical studies of aquifer hydraulics are complicated by the hydraulic conductivity contrast between aquifer and reactive materials as well as by the presence of impermeable (e.g., funnel) or highly permeable (e.g., drains) PRB structure elements. As a consequence, analytical solutions (e.g., [2,15,31–33]) are less frequent and numerical approaches have been applied predominantly (e.g., [29,36,39,43–45]). The hydrodynamic conditions are further complicated by the natural heterogeneity of the aquifer, most notably by the spatial variability of hydraulic conductivity. This spatial

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Nomenclature

Dimensionless

B	relative capture width for $R = 0$
$E()$	incomplete (with two arguments) or complete (with one argument) elliptic integral of the second kind
$F()$	incomplete elliptic integral of the first kind
$F_N()$	standard normal cumulative distribution function (cdf)
FS	factor of safety (relative increase in capture width required to achieve equal M under advective–dispersive as under purely advective transport)
$I()$	normalized indefinite integral defined by Eq. (10)
$K()$	complete elliptic integral of the first kind
$K_0()$	modified Bessel function of the second kind and order zero
M	capture efficiency (portion of contaminant mass discharge captured by PRB)
R	hydraulic reactor resistance defined by Eq. (21)
$R_{\max}$	maximum value of R to avoid flow divergence around reactor
$e_{(w)}$	auxiliary variables defined in Appendix C
$f_N()$	standard normal probability distribution function (pdf)
i	imaginary unit
$k^{(`)}$	(complementary) modulus of elliptic integral
n	aquifer porosity
$\Delta\alpha_t$	change (uncertainty) in α_t
ΔFS	change (uncertainty) in FS
τ_1	auxiliary conformal mapping plane

Lengths

H	average saturated thickness of flow in the reactor
L	travel distance from a contaminant source
a	reactor length (perpendicular to design flow direction)
b	reactor width (along design flow direction)
c	scaling factor for conformal mapping
f	length of funnel arms
s	curvilinear length coordinate along stream lines
t	curvilinear length coordinates transverse to stream lines
w	length of velocity equalization walls (VEW)
x	Cartesian coordinate
x_0	x-coordinate of transect
y	Cartesian coordinate
y_0	half of transect length in y-direction
Δs	longitudinal distance from a point source in uniform flow
Δt	transverse distance from a point source in uniform flow
Δx	distance between transect and PRB
$\Delta\varphi$	head drop required to drive flow Q through reactor
Φ	potential function normalized to unit q_0
Φ_0	potential function at line source (transect) location
Φ_{P}	potential function at capture point P
Φ_{point}	potential function at point source location
$\Phi^{*(*)}$	normalized potential function defined by Eqs. (11) and (14)
Ψ	stream function normalized to unit q_0
Ψ_{peak}	stream function at peak of Gaussian source distribution
Ψ_{point}	stream function at point source location
Ψ_P	half of capture width in stream line coordinates
$\Psi_{P1,P2}$	stream function at capture points
Ψ_0	half of transect length in steam line coordinates
$\Psi_{01,02}$	stream function at extremes of line source (transect)
$\Psi^{*(*)}$	normalized stream function defined by Eqs. (12) and (15)
Ω	complex potential normalized to unit q_0
α_l	longitudinal dispersivity
α_t	transverse dispersivity
φ	hydraulic head
σ_0	standard deviation of Gaussian source distribution

Others

C	contaminant concentration in the aqueous phase [M/L^3]
C_{point}	contaminant concentration corresponding to a point source in uniform flow under effects of transverse dispersion [M/L^3]
C_{tl}	contaminant concentration corresponding to a point source in uniform flow under effects of transverse and longitudinal dispersion [M/L^3]
D_l	effective longitudinal macro-dispersion coefficient [L^2/T]
D_t	effective transverse macro-dispersion coefficient [L^2/T]
K_f	hydraulic aquifer conductivity [L/T]
Q	flow through reactor [L^3/T]
m	constant describing mass release rate of contaminant point source [M/L^2]
q_0	specific discharge of undisturbed ambient groundwater flow [L/T]
v_s	magnitude of local pore water velocity [L/T]

variability is never fully characterized in the field giving rise to stochastic approaches, which honor some basic (geo) statistical parameters of hydraulic conductivity (e.g., mean, variance, correlation scale) and possibly some conductivity measurements at a limited number of locations. These stochastic approaches have so far been constrained to numerical solution methods of the aquifer hydraulics and include (to different levels of complexity) the work of Gupta and Fox [26], Bilbrey and Shafer [5], Elder et al. [19], Cirpka et al. [13], Hemsi and Shackelford [27] and Bürger et al. [9].

The present work focuses on an approximate analytical solution to the PRB capture and release behavior in the presence of aquifer heterogeneity and advective–dispersive transport due to a natural ambient gradient. Modeling of the remediation reactions in a PRB reactor is not considered here. As thoroughly discussed in the literature on stochastic groundwater hydrology (e.g., [16,24,41]), aquifer heterogeneity at a local (i.e., 1–10 m) scale leads to a well-known phenomenon called macro-dispersion (as opposed to micro-dispersion at pore scale). This results in a significant longitudinal and transverse spreading of contaminant plumes with travel distance or, equivalently, in a mixing of groundwater in the longitudinal and transverse directions to flow. Although more general in principle, our approach takes advantage of the conformal mapping solutions of Klammler and Hatfield [32] and Klammler et al. [33] to map a simple solution of the steady-state advection–dispersion equation onto flow domains containing the PRB configurations of Fig. 1. An effective macro-dispersion coefficient may be chosen to account for aquifer heterogeneity and a possibly variable ambient groundwater flow direction. By the assumption of Fickian transport, results become approximate for finite travel distances and provide some theoretical insight about (1) the portion of groundwater or contaminant mass (under simplified plume scenarios) passing an up-stream control plane (transect) and being captured by a PRB, as well as (2) the down-stream spreading and dilution of treated groundwater released by a PRB. The following sections