Available online at www.sciencedirect.com
ScienceDirect
Journal of Contaminant Hydrology 96 (2008) 128–149
JOURNAL OF Contaminant Hydrology
www.elsevier.com/locate/jconhyd

Parameters that control the cleanup of fractured permeable aquifers

Hillel Rubin [a,*], Sharon Yaniv [a], Martin Spiller [b], Jürgen Köngeter [b]

[a] Faculty of Civil and Environmental Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel
[b] Institute of Hydraulic Engineering and Water Resources Management, Aachen University (RWTH Aachen), D-52056 Aachen, Germany

Received 14 September 2004; received in revised form 15 October 2007; accepted 19 October 2007
Available online 13 November 2007

Abstract

This study develops a modeling approach for simulating and evaluating entrapped light nonaqueous-phase liquid (light NAPL–LNAPL) dissolution and transport of the solute in a fractured permeable aquifer (FPA). The term FPA refers to an aquifer made of porous blocks of high permeability that embed fractures. The fracture network is part of the domain characterized by high permeability and negligible storage. Previous studies show that sandstone aquifers often represent FPAs. The basic model developed in this study is a two-dimensional (2-D) model of permeable blocks that embed oblique equidistant fractures with constant aperture and orientation. According to this model, two major parameters govern NAPL dissolution and transport of the solute. These parameters are: 1) the dimensionless interphase mass transfer coefficient, K_{f0}, and 2) the mobility number, N_{M0}. These parameters represent measures of heterogeneity affecting flow, NAPL dissolution, and transport of the solute in the domain. The parameter K_{f0} refers to the rate at which organic mass is transferred from the NAPL into the water phase. The parameter N_{M0} represents the ratio of flow through the porous blocks to flow through the fracture network in regions free of entrapped NAPL. It also provides a measure of groundwater flow bypassing regions contaminated by entrapped NAPL. In regions contaminated by entrapped NAPL our simulations have often indicated very low permeability of the porous blocks, enabling a significant increase of the fracture flow at the expense of the permeable block flow. Two types of constitutive relationships also affect the rate of FPA cleanup: 1) the relationship between the saturation of the entrapped NAPL and the permeability of the porous blocks, and 2) the relationships representing effects of the entrapped NAPL saturation and the permeable block flow velocity on rates of interphase mass transfer. This study provides basic tools for evaluating the characteristics of pump-and-treat cleanup of FPAs by referring to sets of parameters and constitutive relationships typical of FPAs. The numerical simulations carried out in this study show that at high initial saturation of the entrapped NAPL, during initial stages of the FPA cleanup the contaminant concentration increases, but later it decreases. This phenomenon originates from significant groundwater bypassing the NAPL entrapped in the permeable blocks via the fracture network.

Keywords: Fractured porous formation; Fractured porous media; Fractured permeable formation (FPF); Fractured permeable aquifer (FPA); Aquifer cleanup; NAPL contamination; Pump-and-treat

1. Introduction

This study originates from field observations and laboratory measurements (Rubin and Braester, 2000) performed in a part of the Coastal Plain Aquifer (CPA) in Israel. Entrapped kerosene, which is a light nonaqueous-

* Corresponding author. Tel.: +972 4 829 2306; fax: +972 4 822 898.
E-mail address: hrubin@technion.ac.il (H. Rubin).

0169-7722/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jconhyd.2007.10.007

Nomenclature

B	distance between adjacent fracture intersections (L)
C	normalized solute concentration in the fracture flow
C_{av}	normalized flux average solute concentration in the cross-section
C_b	normalized solute concentration in the permeable block flow
C_{nv}	equilibrium volumetric concentration of solute
C^*	solute concentration in the fracture flow (ML^{-3})
C^*_{av}	flux average solute concentration in the cross-section (ML^{-3})
C^*_b	solute concentration in the permeable block flow (ML^{-3})
C^*_s	equilibrium concentration of solute (ML^{-3})
d	grain diameter (L)
D	free liquid diffusivity (L^2/T)
i	number of the vertical grid point
i_{max}	total number of vertical grid points
ibl	number of the permeable block
ifr	number of the fracture segment
J	hydraulic gradient
J_0	hydraulic gradient in regions free of entrapped NAPL
j	number of the longitudinal grid point
j_a	number of the grid point for the calculation of C_{av}
j_c	number of the downstream-end longitudinal grid point
K_b	hydraulic conductivity of permeable blocks (LT^{-1})
K_B	value of K_b at the fracture segment (LT^{-1})
K_{b0}	value of K_b in regions free of entrapped NAPL (LT^{-1})
K_f	dimensionless interphase mass transfer coefficient
K_{f0}	initial value of K_f
K_t	average cross-sectional hydraulic conductivity (LT^{-1})
K_{t0}	value of K_t in regions free of entrapped NAPL (LT^{-1})
k_f	lumped mass transfer coefficient (T^{-1})
k_{rn}	relative NAPL permeability
k_{rt}	cross-sectional relative water permeability
k_{rw}	relative water permeability
k_{rwB}	value of k_{rw} at the fracture segment
k_α	number of the fracture segment nodal point for calculating C_{av}
m	number of the time step
M_f	mobility of the fracture segment (L^2T^{-1})
N_M	mobility number
N_{M0}	value of N_M in regions free of entrapped NAPL
n	power coefficient used for permeability calculations
n_c	number of contaminated sections
n_p	coefficient for calculating permeability
Q_b	rate of permeable block flow (L^2T^{-1})
Q_{b0}	value of Q_b in regions free of entrapped NAPL (L^2T^{-1})
Q_f	rate of fracture segment flow (L^2T^{-1})
Q_{f0}	value of Q_f in regions free of entrapped NAPL (L^2T^{-1})
Q_R	ratio of Q_b to Q_f in a vertical cross-section
Q_t	total flow rate flowing through the subdomain cross-section (L^2T^{-1})
q_b	specific discharge of the permeable block flow (LT^{-1})
q_B	value of q_b entering the fracture segment (LT^{-1})