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Regulation of Contaminant Transport in Groundwater System using Barrier and Hydraulic Control– A Comparison

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E-mail: [1]er.jayashreepalce@gmail.com, [2]dibachakra@gmail.com Abstract

Abstract—*Control of contaminant transport in a groundwater system often becomes necessary for protecting water quality in the downstream pumping wells. Various methodologies, like hydraulic control, use of pump-and-treat, use of chemical barriers etc., have been reported in literature for achieving this objective. In this paper the effect of physical barrier has been studied with regard to the control of contaminant transport in the downstream water supply wells. The effect of physical barrier in conjunction with hydraulic control is also studied with a view to evaluating efficacy of the two methods. The study has been conducted for a hypothetical two dimensional groundwater system using single conservative contaminant. The USGS (United States Geological Survey) groundwater model SUTRA has been used in this study for simulating both flow and transport of contaminant in the groundwater system. The results obtained show that transport of contaminant can be regulated using low cost physical barrier in the groundwater system. Results also show that the use of physical barrier in conjunction with hydraulic control may be a better option in protecting water quality in the downstream water supply wells.*

1. INTRODUCTION

Groundwater quality maintenance is a costly affair in the present scenario. Various methodologies, like hydraulic control, use of pump and treat, use of permeable barriers, etc. have been reported in literature for regulating contaminant transport in groundwater system. This paper emphasizes the effect of physical barrier to protect the downstream wells used for domestic, agricultural and industrial purposes. Besides, hydraulic control of plume is also performed in order to assess the overall effect of barrier and the hydraulic control in mitigating the contaminant transport. This study reports the performance analysis of the proposed methodology in diminishing the contaminant concentration in the downstream water supply wells.

Ahlfeld and Heidari[1] hydraulic control involving simulation and linear programming for protecting water quality in water supply wells. Al-Yousfi[2], et al, has studied the characteristics of "water-loving" trees as a natural remediation which substitutes the pump and treat method and serves as a hydraulic barrier. Though this method is economical and environment friendly, huge amount of groundwater is extracted by these plants leading to the depletion of groundwater resource. Groundwater quality management is done considering uncertainties, design of multi-objective dynamic monitoring, system analysis and optimization techniques by Birke[3], Datta[4,5], Gorelick[6,7,8], Wagner[10], and Yeh[11].

The well-established groundwater flow and transport simulator, SUTRA (Saturated-Unsaturated Transport), developed by Voss and Provost[10] is a computer program which simulates the flow and transport of energy or dissolved substances in the subsurface environment. SUTRA is capable of monitoring the plume movement in the groundwater system both in steady and unsteady conditions. The code is written in FORTRAN which uses both finite element and finite difference methods in to approximate the governing equations.

2. GOVERNING EQUATIONS

The simulation model for groundwater flow to predict aquifer behavior is SUTRA. SUTRA is a platform which can handle both two- and three- dimensional finite element and finite difference method. It has widespread utilization in simulating saturated-unsaturated fluid flow of varying density along with energy transport or reactive and sorptive single species solute transport. In this paper, constant density, saturated and transient flow in two-dimensional groundwater system is assumed, while the solute transport is considered transient and non-sorptive for a conservative pollutant.

2.1 Characteristics of Fluid flow

Fluid movement in porous media occurs due to two reasons: (a) Pressure difference and (b) Density difference. Depending on these two factors, a generalized form of Darcy's Law is used for the flow simulation. The equation is as follows:

$$v = -\left(\frac{kk_r}{\epsilon S_{w\mu}}\right).(\nabla p - \rho g) \quad (1)$$

where, v(x,y,[z],t) =Average Velocity (L/T)

k(x,y,[z]) =Solid Matrix Permeability (L^2)

k_r(x,y,[z],t) =relative permeability to fluid flow[1]

g = Acceleration due to gravity [L/T]

2.2 Solute Transport in groundwater

The transportation of solute in porous medium takes place by advection and molecular or ionic diffusion along the hydraulic gradient. The solute transport simulation deals with a single species mass and solute-cum-species mass. The general expression of solute and adsorbate mass balances for a single species is shown separately for both situations:

$$\frac{\partial(\varepsilon\rho C)}{\partial t} = -f - \nabla.(\varepsilon\rho v C) + \nabla.[\varepsilon S_w \rho (D_m I + D).\nabla C] + \varepsilon S_w \rho \Gamma_w + C^* Q_P \quad (2)$$

$$\frac{\partial[(1-\varepsilon)\rho_s C_s]}{\partial t} = +f + (1-\varepsilon)\rho_s \Gamma_s \quad (3)$$

where,

f(x,y,[z],t) =Volumetric adsorbate source($M_s/L^3.T$)

D_m =Apparent molecular diffusivity of solute in solution (L^2/T).

I =Identity Tensor (1).

D(x,y,[z],t) =Dispersion tensor (L^2/T).

Γ_w (x,y,[z],t) =solute mass source in fluid for production reactions (M_s/M.T)

$C^*(x, y, [z], t)$ =Solute concentration of the fluid sources (M_s/M)

$C_s(x, y, [z], t)$ =Specific concentration of adsorbate on solid grains (M_s/M_G)

ρ_s =Density of soil solid (M_G/L_G^3)

$\Gamma_s(x, y, [z], t)$ =Adsorbate mass source for production reactions within adsorbed material (soil) (M_s/M_G.T).\

2.3 Fluid Mass Balance in Groundwater System

The water-table aquifer fluid mass balance equation which depicts a time derivative, a non-linear term including space-derivative and a source term is:

$$S_o \frac{\partial h}{\partial t} - \nabla.(K\nabla h) = Q^* \quad (4)$$

where $Q^* = Q_P/\rho$

and

$S_o(x, y)$ =Specific storativity (L^{-1})

h(x,y,t) =Hydraulic head (L)

K(x,y) =Hydraulic Conductivity (L/T)

Q^*(x,y) =Volumetric Fluid Source (T^{-1})

$Q_P(x, y)$ =Fluid mass source (M/L^3.T)

ρ =Fluid Density (M/L^3)

This equation is the simplified form for saturated conditions, constant concentration and temperature, constant density and isotropic media. The flow takes place only areally with fixed impermeable base and a moveable free surface. The z-direction is the vertical thickness of the aquifer. The fluid is assumed to be in vertical hydrostatic equilibrium at every point in the hypothetical system. Aquifer thickness is measured as the distance along z from the free surface to the aquifer base and may change with time. The equation for aquifer transmissivity is:

$$T \equiv KB \equiv K(h - Base) \quad (5)$$

where, T(x,y,t) =Aquifer transmissivity (L^2/T)

B(x,y,t) =Aquifer thickness (L)

Base(x,y) =Elevation of aquifer base (L)

3. METHODOLOGY

A hypothetical aquifer is assumed to demonstrate the regulation of contaminants using barriers. The aquifer assumed is having areal extent of 1500m by 1400m as shown in Fig. 1. The head of the aquifer in the left boundary is 95m and right boundary is 85m. The soil property and the fluid property are listed in the Table-1 below:

Table 1: Soil Property and fluid property data

Properties	Value
Longitudinal Hydraulic Conductivity of soil (K_{xx})	$2.0X10^{-4}$ m/s
Transverse Hydraulic Conductivity of soil (K_{yy})	$2.0X10^{-4}$ m/s
Porosity of soil (ε)	0.25
Longitudinal Dispersivity of soil media (α_L)	40 m
Transverse Dispersivity of soil media (α_T)	9.6 m
Soil Matrix Compressibilty (α)	$1.3X10^{-7}(kg/m.s^{2})^{-1}$
Thickness of aquifer	150 m
Fluid Compressibility (β)	$4.8X10^{-10}(kg/m.s^{2})^{-1}$
Fluid Viscosity (μ)	$1.0X10^{-3}$ kg/m.s
Density of fluid (ρ)	1000 kg/m^3
Acceleration due to gravity (g)	9.81 m/s^2

The two sources of pollutants (S-1 and S-2) are located at the upstream side of the aquifer. The observation wells (OBS-1 and OBS-2) are at the downstream side of the aquifer. The effect of contaminant plume from the source on the observation wells has been studied in seven different cases.

In the first case, which is indicated as 'Initial Condition' in observation graphs (Fig. 7 and 8), two sources are placed and no regulation is done. The concentration rate of contaminant injected through source, S-1is 58.8g/s and S-2 is 47.7g/s for first six months of the simulation period. The total duration of the simulation period is twenty years. The observations are taken at an interval of two months duration.

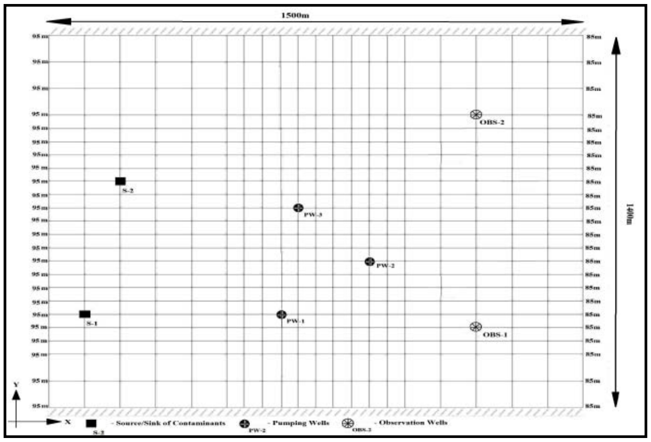

Fig. 1: Schematic Diagram of hypothetical aquifer

In the second case (indicated as ‘Condition After Pumping without Barriers’), two sources along with three pumping wells are placed on the path of plume is shown in Fig. 1. The sources are active for the same duration having the above mentioned injection rate. The rate of pumping through PW-1, PW-2 and PW-3 are $0.1m^3/s$ for ten years starting from two months of simulation time.

In the third case (indicated as Scenario-1 shown in Fig. 2), sources and pumping wells remain the same like the second case. A C-shaped physical barrier is placed in the aquifer system as shown in Fig. 2. This barrier has a hydraulic conductivity of $1.4X10^{-5}m/s$ and longitudinal and transverse dispersivities of 7.625m and 3.05 m respectively.

In the fourth case (indicated as Scenario-2 shown in Fig. 3), the physical barrier used is L-shaped. Other conditions are the same as used in the second case.

In the fifth case (indicated as Scenario-3 shown in Fig. 4), keeping the basic features of source and pumping wells same, two types of barriers are used. They are C- and oblique shaped.

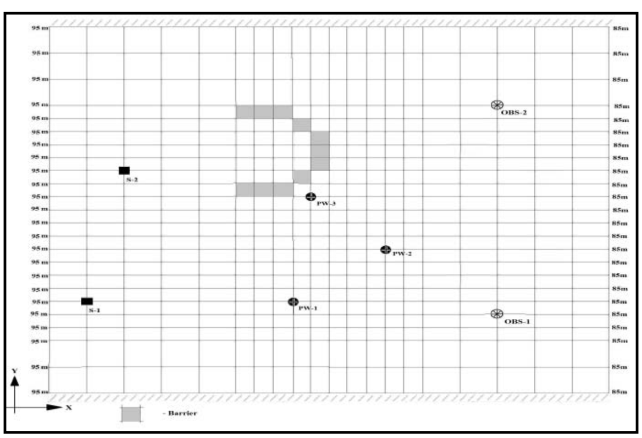

Fig. 2: Scenario-1

In the sixth case (indicated as Scenario-4 shown in Fig. 5), C-shaped and L-shaped barriers are used, while the rest conditions are same.

In the seventh case (indicated as Scenario-5 shown in Fig. 6), Oblique and L- shaped barriers are used in the aquifer system.

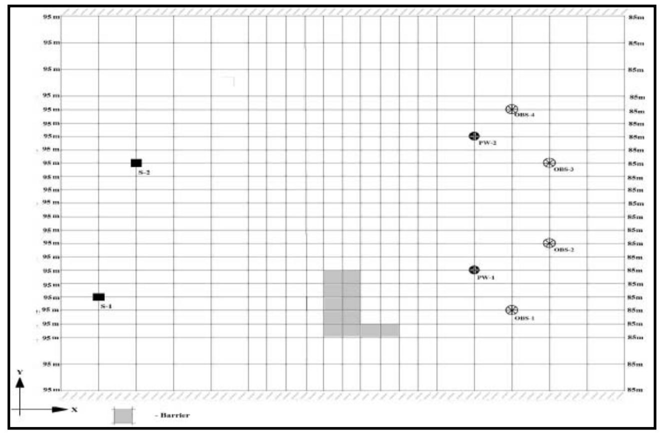

Fig. 3: Scenario-2

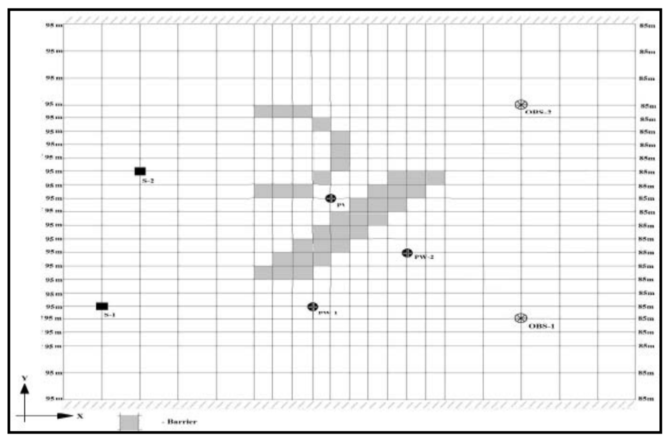

Fig. 4: Scenario-3

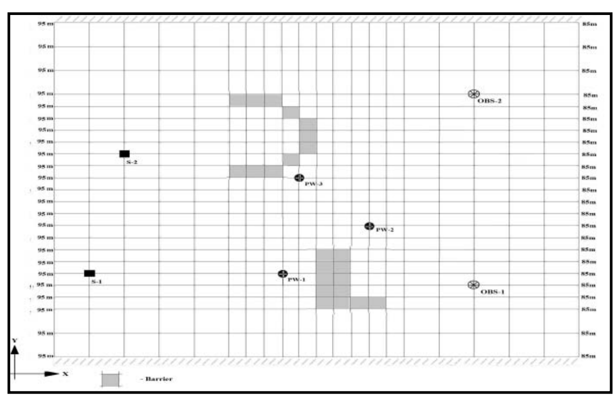

Fig. 5: Scenario-4

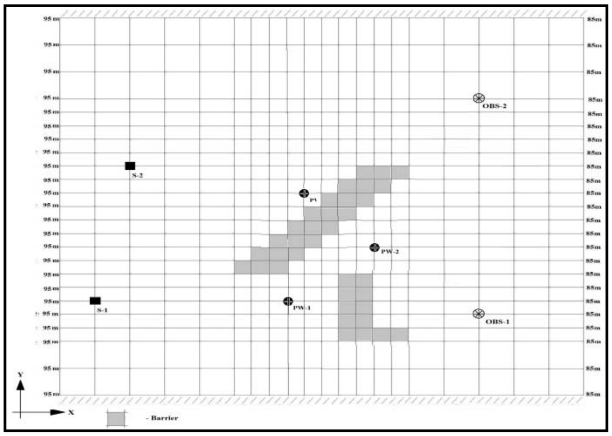

Fig. 6: Scenario-5

4. RESULT

The concentrations observed in observation well-1 and observation well-2 for the seven different cases are depicted in Fig. 7 and Fig. 8.

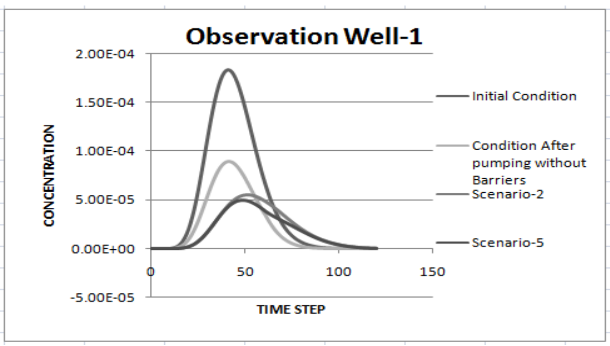

Fig. 7: Concentration at Observation Well-1

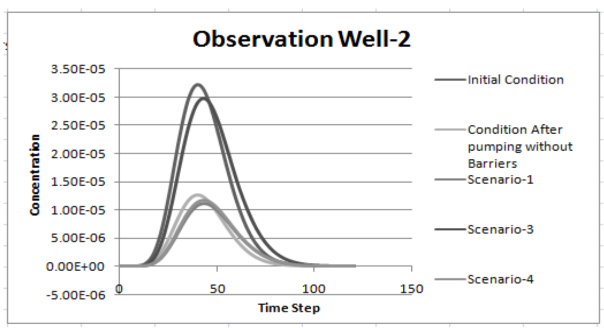

Fig. 8: Concentration at Observation Well-2

Results show that the breakthrough curves got shifted to the right when physical barriers and hydraulic control have been employed. There have been substantial reductions of various magnitudes in the peak concentration also.

5. DISCUSSION

The results shown in the Fig. 7 clearly shows that for Scenario-5 the oblique and L-shaped barriers work very efficiently in regulating the contaminants for observation well-1. From Fig. 8, it can be concluded that Scenario-1, that is, C-shaped barrier provides good regulation to the contaminants.

This paper depicts the regulation of contaminants by delaying the contaminant movement in the downstream and attenuating the concentration of the contaminants in the downstream water supply wells. However, an optimal strategy is undoubtedly required in order to design an efficient contaminant regulation strategy.

6. ACKNOWLEDGEMENT

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