

NON BIODEGRADABLE CONTAMINANTS TRANSPORT MODELING WITH VARYING TRANSMISSIVITY FOR AQUIFER AT WEST CAMPUS HBTI KANPUR

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Abstract: Groundwater is the major source of water for drinking, irrigation and industrial use because of its availability, quality and low cost. Groundwater modelling is an effective way to predict the flow of groundwater within an aquifer. Groundwater modelling aims at studying the temporal and spatial distribution of such contaminants in the aquifer and formulates sustainable groundwater management strategies. This paper aims at studying the problem of groundwater contamination of HBTI west campus area, Kanpur (U.P.) and also analyzes the effect of varying aquifer transmissivity on the transport of contaminants in groundwater and the comparison of contaminants concentration when hydrological parameter (ie, transmissivity) of aquifer material is variable and constant. In this respect, groundwater flow and contaminant transport process was simulated over the study area using a computer based model, MOC v3.1 [2]. This work also utilizes the breakthrough curves to explore various monitoring wells which cross threshold limit in simulation period.

Keywords: Groundwater, Transmissivity, Log Normal Distribution, Monitoring Network, Monitoring Well, MOC.

I. INTRODUCTION

Groundwater is the major source of water available at low cost and good quality. Groundwater can become contaminated in many ways. Ground water can become contaminated from natural sources or numerous types of human activities. Residential, municipal, commercial, industrial, and agricultural activities can all affect ground water quality. Contaminants may reach ground water from activities on the land surface, such as releases or spills from stored industrial wastes; from sources below the land surface but above the water table, such as septic systems or leaking underground petroleum storage systems; from structures beneath the water table, such as wells; or from contaminated recharge water [1]. Due to continuously increasing load of population on this invaluable natural resource it becomes imperative upon us to study the pattern in which groundwater is contaminated.

Groundwater modelling is an effective way to predict the flow of groundwater within an aquifer. Groundwater modelling aims at studying the temporal and spatial distribution of such contaminants in the aquifer and formulates sustainable groundwater management strategies. During the last three decades, research activities in this area have accelerated to a revolutionary level. Different investigators have studied the solute transport from different perspectives. Groundwater models can be divided into groundwater flow models and solute transport models. Groundwater flow models solve for the distribution of heads, whereas solute transport models solve for concentration of solute as affected by advection, dispersion and chemical reactions [3]. Groundwater models can be both analytical and numerical. While the analytical models are wholly based on subjective human judgments, numerical models simulate groundwater flow

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indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model [13].

This study work aims, ground water modelling with varying transmissivity. The concept of varying hydrological parameter (i.e transmissivity) was first introduced by R Allen Freeze [4]. All soils and geologic formations, even the ones that are homogeneous, show random variations in the values of the hydro geological parameters through space; that is, they are non uniform, and a measure of the non uniformity is provided by the standard deviation of the frequency distributions [4].

II. OBJECTIVES

This paper aims to address the spatial and temporal distribution of water table and contaminant concentrations in an assumed confined aquifer in the HBTI west campus, Kanpur with the following objectives:

- a) Identification of various groundwater extraction, recharge and contaminating elements in the area of HBTI west campus.
- b) Implementation of a computer model MOC v3.1 for groundwater flow and contaminant transport for the area.
- c) To study contaminant transport in variable transmissivity of soil.
- d) Comparative analysis of temporal distribution of contaminant concentrations when hydraulic conductivity (ie. transmissivity) of aquifer material is variable and non variable.

III. GROUNDWATER FLOW EQUATION

The equation describing the transient two-dimensional areal flow of a homogeneous compressible fluid through a non-homogeneous anisotropic aquifer in Cartesian tensor notation can be written as [5]:

$$\frac{\partial}{\partial x_i} \left(T_{ij} \frac{\partial h}{\partial x_j} \right) = S \frac{\partial h}{\partial t} + W \quad i, j = 1, 2 \quad \dots \dots \dots (1)$$

Where:

- T_{ij} = transmissivity tensor, [L^2/T];
- $= K_{ij}b$;
- K_{ij} = hydraulic conductivity tensor, [LT^{-1}];
- b = saturated thickness of aquifer, [L];
- h = hydraulic head, [L];
- S = storage coefficient, (dimensionless);
- t = time, [T];
- W = volume flux per unit area (positive sign for outflow and negative for inflow), [L/T];
- and
- x_i and x_j are the Cartesian coordinates, [L].

IV. CONTAMINANT TRANSPORT EQUATION

The equation used to describe the two dimensional areal transport and dispersion of a given non-reactive dissolved chemical species in flowing ground water is as follows [6] and [7]:

$$\frac{\partial(Cb)}{\partial t} = \frac{\partial}{\partial x_i} \left(bD_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (bCV_i) - \frac{C'W}{\epsilon} \quad \dots \dots \dots (2) \quad i, j = 1, 2$$

Where:

- C = concentration of the dissolved chemical species, [M/L^3];
- D_{ij} = coefficient of hydrodynamic dispersion (a second-order tensor), [L^2/T];
- b = saturated thickness of the aquifer, [L]; and
- C' = concentration of the dissolved chemical in a source or, sink fluid, [M/L^3].

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V. ASSUMPTIONS CONSIDERED IN MODEL

The various assumptions considered by the model are:

1. Darcy's law is valid and hydraulic-head gradients are the only significant driving mechanism for fluid flow.
2. The porosity of the aquifer is constant with time, and porosity is uniform in space.
3. Gradients of fluid density, viscosity, and temperature do not affect the velocity distribution.
4. No chemical reactions occur that affect the concentration of the solute, the fluid properties, or the aquifer properties.
5. Ionic and molecular diffusion are negligible contributors to the total dispersive flux.
Vertical variations in head and concentration are negligible

VI. RANDOM FIELD GENERATORS AND LOG NORMAL DISTRIBUTION

All soils and geologic formations, even the ones that are homogeneous, show random variations in the values of the hydro geological parameters through space; that is, they are non uniform, and a measure of the non uniformity is provided by the standard deviation of the frequency distributions [4].

Random field generators are used in spatial statistical methods to generate fields of stochastic properties, such as hydraulic conductivity, that have known statistical attributes. Randomly generated fields cannot replace actual measurements, as they are only as representative of reality as the statistical or geological model that they are based on [10].

Synthetic random fields have been used in investigating the effects of spatially varying aquifer properties on the mean transport of contaminants [10].

Random Field can be Generated by log-normal distribution which is a continuous probability distribution of a random variable whose logarithm is normally distributed. Thus, if the random variable Y is log-normally distributed, then $X=\log(Y)$ has a normal distribution. A random variable which is log-normally distributed takes only positive real values.

If the hydraulic conductivity K is log normally distributed, then $Y=\log K$ this normally distributed; $Y: N [\mu_y, \sigma_y]$, where μ_y is the mean and σ_y is standard deviation. In that K values vary over some 12-14 orders of magnitude and μ_y would have a possible range of 10-12. If the K values are reported in centimetres per second, this range will include values from about -9 to +3. The range of values of σ_y cannot be predicted a priori [4].

VII. METHODOLOGY

The study area is discretized into a block-centred finite difference grid having rows and columns. A pumping well is represented as withdrawal (discharge) well and is specified as one pumping well per node. The model assumes that stresses developed in the aquifer are constant with time during each pumping period. But the total number of wells, as well as their locations, flux rates, and source concentrations, may be changed for successive pumping periods. The model specifies observation wells on potential locations. Other parameters like contaminant source, constant head boundaries, no-flow boundaries, transmissivity can be given as input in model as node identification array [11]. Steps for modelling are further describe.

Step 1:

The study area was suitably discretized into a block-centered finite difference grid.

Step 2:

The number of nodes in x and y directions were kept equal to 20. The width of finite difference cell in x direction came out to be 54.53m and in y direction it was 24.11m.

Step 3:

The maximum number of particles in the finite difference grid was limited at 6400 and the initial number of particles per node was set to 9.

Step 4:

The positions of all the ten observation wells were selected on the basis of potential locations.

Step 5:

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The locations of the two pumping wells were also specified along with their discharge (0.5935m).

Step 6:

A no flow boundary was identified around the study area. In the input, the boundary was demarcated on the finite difference grid falling outside the boundary as zero. The transmissivity within the aquifer was variable.

Step 7:

A node identification array was defined to clearly demarcate the constant head boundaries and contaminant sources in the grid.

Step 8:

Location of water table was identified on the grid. The location of the lake as a source of contamination was also identified. The potentiometric heads in the water table were assumed as 43.28m and 42.65m along the north-east and south-west boundaries respectively. The potentiometric head for the lake was assumed as 45.72m.

Step 9:

The lake also being a contaminant source was assumed to discharge a hypothetical contaminant with concentration of 530.88 mg/l in the groundwater.

Step10:

A single output file was obtained detailing the input values, head values and concentration values.

Step11:

This output was then used to obtain the contour maps and breakthrough curves.

VIII. DISCRETIZATION OF STUDY AREA

The area under study is the HBTI west campus, located in western part of Kanpur city at latitude 26.50° N and longitude 80.29° E. It has an area of 48 acres with a north-south extent of 480 meters and east-west extent of 1000 meters.

The study area is considered as an aquifer of rectangular shape. The rectangle itself a 20×20 grid is 3600 ft in x direction and 3200 feet in y direction with each cell having the dimensions of 54.53m in the x direction and 24.11 in the y direction. The upper-left corner was taken as the point of origin as required by the model. The map of the study area has been shown in Fig. 1.

IX. BOUNDARIES AND LOCATION OF STUDY AREA

The origin has been shown by the letter 'O' along with the grid in Fig. 1. The boundary selected for determining the area of the hbt west campus was confirmed with the data given by the local authorities. The total number of cells thus falling inside the boundary was numbered at 270 and thus the total area to be studied came out to be $270 \times 54.53 \times 24.11$ m² which is equal to 1158207.56m². As the model requires, the boundary was so chosen that the outermost cells of the whole grid be designated as a no flow boundary, essential care was taken to fit the grid in such a manner that the outermost cells fall under a no flow region while the concerned area would fall in the aquifer region. This condition was sufficed by putting the value of transmissivity of all cells falling outside the boundary equal to 0.0 while all the rest 270 cells were with variable value of transmissivity. With the value of aquifer thickness assumed as 30 feet the value of transmissivity translates into a value of permeability as 15 m/day. The hydro-geologic characteristics of the aquifer were assumed to be constant throughout the study period. The study area is located at the latitude 26.50° N and longitude 80.29° E.

The study area contains a small natural lake. This lake receives waste water from nearby residential areas and also accumulates rain water. Hence, this lake can be considered as a contaminant source and at the same time also a constant head location. The concentration of a hypothetical non-reactive contaminant present in the drain water, entering the lake, was assumed to be 530.88 mg/l.

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Figure 1. Map showing the study area with all boundaries, lake and observation wells

B Monitoring well
 Contamination source
 P1 ● Pumping well
 No flow boundary

X. PUMPING AND OBSERVATION WELLS

Based on the data collected during the survey of the study area, two pumping wells were found to exist, each with a discharge of $0.5935\text{m}^2/\text{sec}$. Their coordinates on the grid were identified to be (8, 9) and (7, 3). 10 imaginary monitoring wells were arbitrarily located on the grid. Their locations on the grid have been tabulated below and shown in Fig 1.

Table 1. Location of Monitoring Wells

Monitoring Well No.	Coordinates
B1	(6,6)
B2	(11,12)
B3	(8,14)
B4	(12,16)
B5	(3,5)

XI. PUMPING PERIOD

The total pumping period taken for the model execution was 5 years. During the five years, evaluation was done for every three months interval. The program was suitably modified to print the data at the required time intervals. The chemical output at each time step includes a concentration matrix and a tabulation of concentrations at each observation well.

XII. PARAMETERS AND HYDRO-GEOLOGICAL INPUTS

The model needs a set of variables or parameters for a streamlined simulation process. These inputs include defining a finite difference grid, specifying the pumping period, initial number of particles per node, maximum cell distance per particle move and convergence criterion for the numerical methods. The following parameters were specified for the model as:

Table 2. Parameters used in the model

Parameters	Value
Time Steps in a Pumping Period	1
Number of Pumping Periods	1
Total Pumping period	5 years
Nodes in x direction	20
Width of finite-difference cell in x direction	54.53m
Nodes in y direction	20
Width of finite-difference cell in y direction	48.03m

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Maximum number of particles	6400
Initial number of particles per node	9
Number of node identification codes	2
Maximum cell distance per particle move	0.50
Convergence criterion	0.0001

Apart from the above stated inputs, several other inputs regarding the hydro-geological characteristics of the aquifer were also needed by the model.

For a confined aquifer transmissivity is defined as the hydraulic conductivity of the aquifer per unit thickness. Transmissivities greater than 0.015 m²/s represent good aquifers for water well exploitation [12].

Effective porosity refers to the fraction of the total volume in which fluid flow is effectively taking place and includes dead-end pores (as these pores cannot be flushed, but they can cause fluid movement by release of pressure like gas expansion) and excludes closed pores or non-connected cavities [12].

The ratio of transverse to longitudinal dispersivities was assumed to be 0.3. The following inputs were given to the model:

Table.3 Hydro-geological inputs for the model

Parameter	Value
Aquifer Thickness	30 feet (9.14 m)
Potentiometric heads in the water table	39.62m in the north and north-east boundary and 30.48m on the south
Transmissivity	variable
Longitudinal Dispersivity	100 feet (30.48 m)
Transverse Dispersivity	30 feet (9.14 m)
Effective Porosity	0.30
Storage Co-efficient	0, due to steady state conditions
Number of Observation Wells	10
Number of Pumping Wells	3
Discharge of pumping well	0.5935m ² /sec

XIII. RESULTS AND ANALYSIS

The concentration matrices obtained in the output were used to prepare contour maps to study the nature and extent of spread of the contaminant. The concentration matrices obtained for every time step were used for contouring. The concentration values at all the nodes were interpolated in the entire study area by method of Kriging utilized by Surfer[®] 10. “Kriging is a statistical interpolation method that chooses the best linear unbiased estimate and unlike other interpolation methods, it preserves the field value at measurement points” [13]. The contours join all points of same concentration. The successive contour maps help to get an idea about the areal extent of contamination in ground water. The various contour maps obtained were then carefully superimposed over the study area [11].

For observing the temporal distribution of concentration, breakthrough curves were plotted at all the five identified potential locations for observation well installations. A breakthrough curve can be defined as a graph between concentration and time at a particular point in a soil block. The values on contour lines represent concentration values in mg/l. The threshold limit of groundwater contamination is assumed to be 300 mg/l. It was observed that a total of 167 cells, around 45 percent of the total study area cross the threshold limit at the end of simulation period of 5 years.

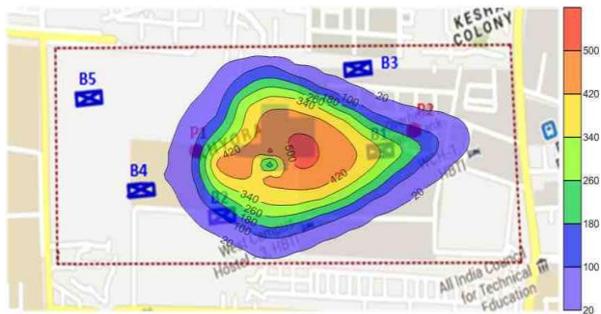
The spatial distribution of threshold limit of contaminant concentration at the end of simulation period of 5 years has been shown in Fig. V.

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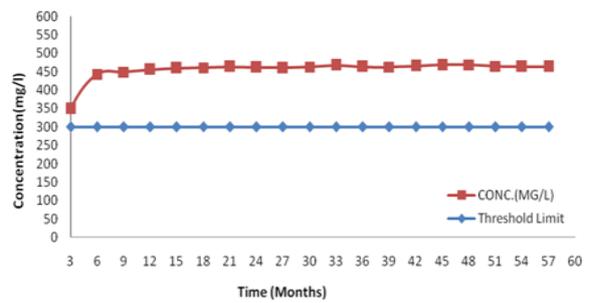
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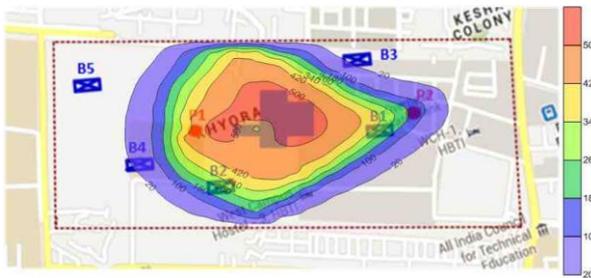
Following figures Shows the plume of contaminants at different time periods and the breakthrough curves and a threshold limit at various monitoring wells.



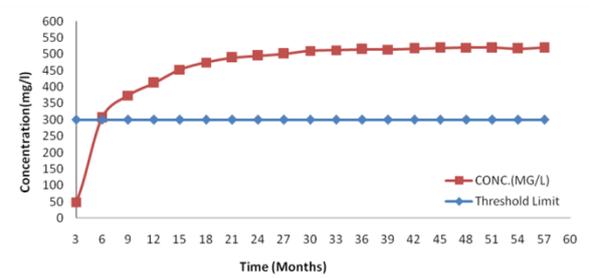
(i)



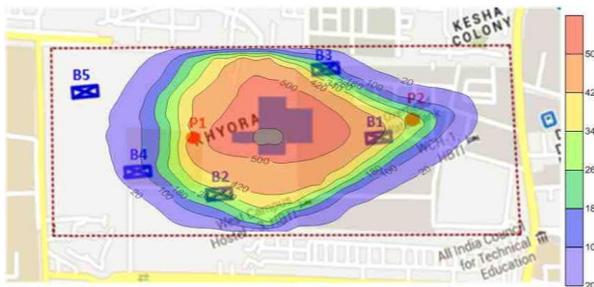
(a) Breakthrough curve for monitoring wells no B1.



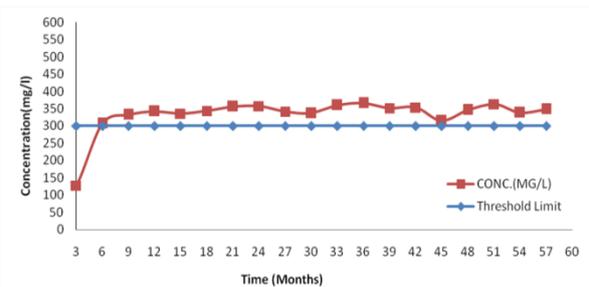
(ii)



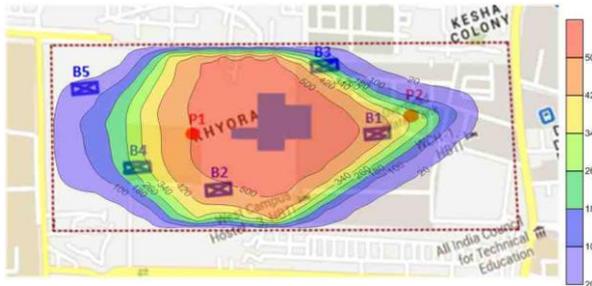
(b) Breakthrough curve for monitoring wells no B2.



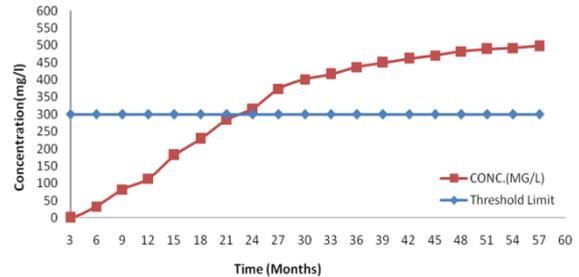
(iii)



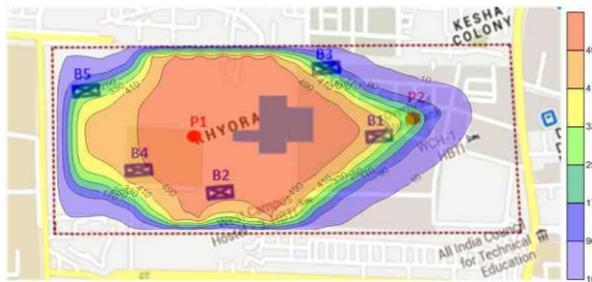
(c) Breakthrough curve for monitoring wells no B3.



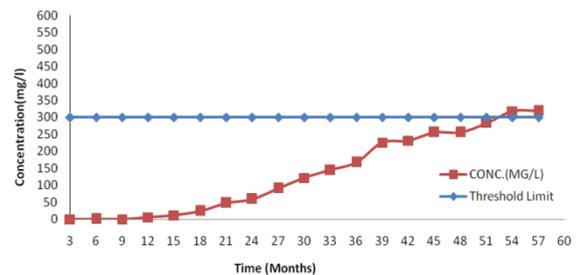
(iv)



(d) Breakthrough curve for monitoring wells no B4.



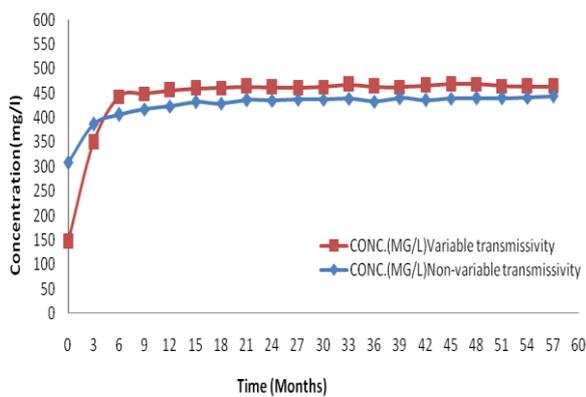
(v)



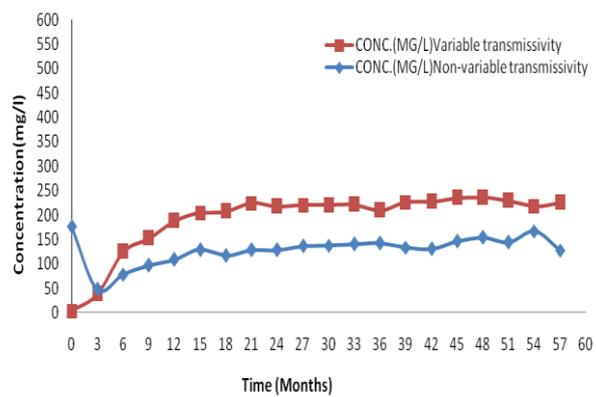
(e) Breakthrough curve for monitoring wells no B5.

XIV. COMPARATIVE ANALYSIS

For observing the temporal distribution of concentration, breakthrough curves were plotted for all monitoring wells. Following figures shows the variation in concentration of contaminants with varying and constant values of transmissivity over the simulation period.



(vi) Monitoring wells no B1.

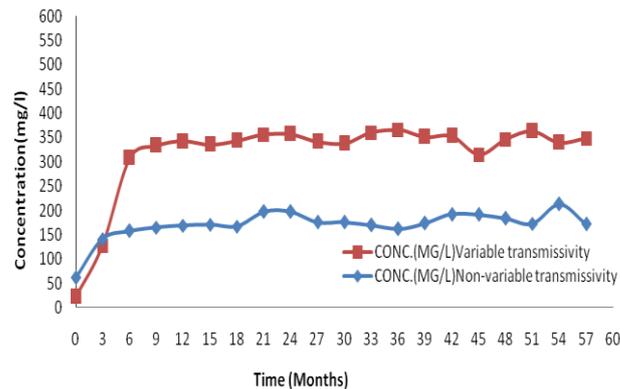


(vii) Monitoring wells no B2.

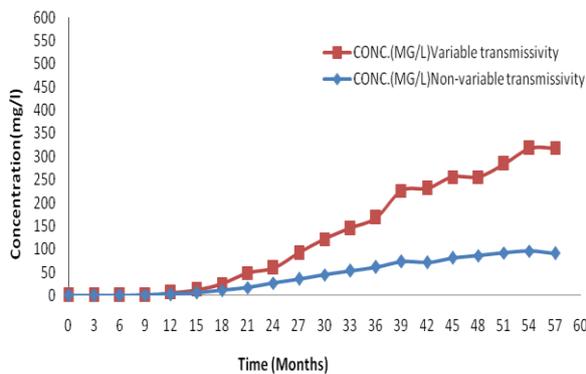
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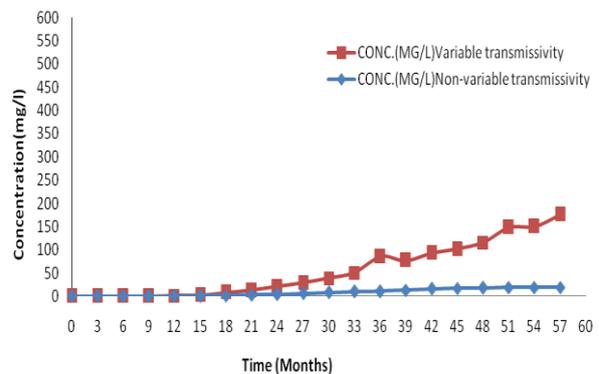
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(viii) Monitoring wells no B3.



(ix) Monitoring wells no B4.



(x) Monitoring wells no B5.

Fig. (vi)– (x) Breakthrough curves for various monitoring wells.

It has been observed from the comparative study that predicted contaminants concentration is varying much when analysed with constant transmissivity.

XV. CONCLUSION

For the practical purposes the soil parameter in aquifer varies largely so the transmissivity which is a derived parameter of soil permeability and the thickness of aquifer also varies.

It has been observed in analyses that the simulated concentration of contaminants are quantified that when transmissivity is considered constant. In case of hazardous contaminants this methodology performed well in decision making of monitoring well installation for those locations which have crossed the threshold limit. This study is based on two dimensional analysis and for further scope this can be extend to three dimensional analysis. Further some other hydrology parameter can also be considered as varying with space and time.

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