LEACHATE TRANSPORT PHENOMENON ON GROUNDWATER QUALITY: MODELING USING MODFLOW AND MT3DMS TOOLS

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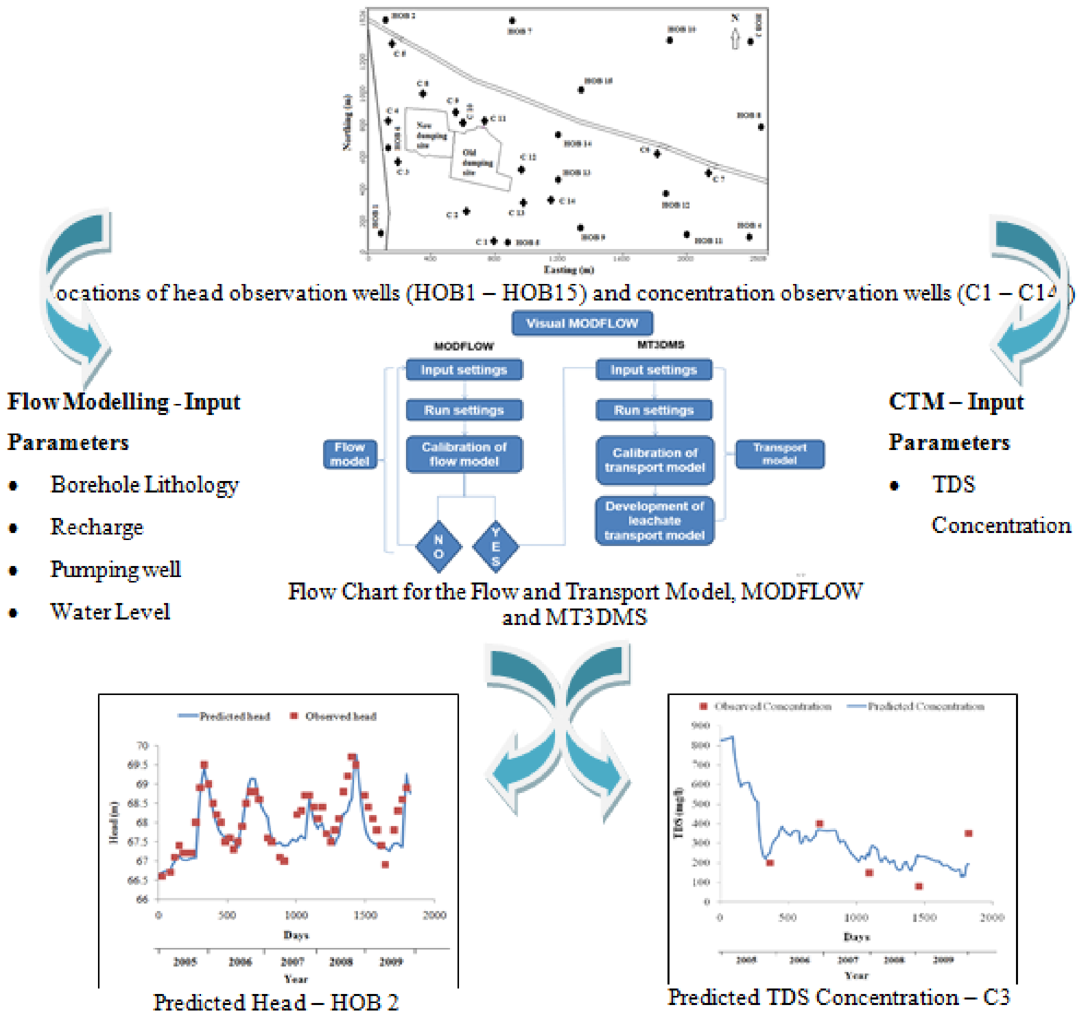
Graphical Abstract:



Abstract

The dumping of solid waste in uncontrolled landfills can cause significant impacts on the environment and human health. The open dumps cause the formation of leachate which contaminated the groundwater; use of these groundwater reported danger to the human health. The goal of groundwater protection is necessary to control the release and migration of pollutants from the leachate in the subsurface. In this paper, the above-mentioned problems were dealt with the case study of Ariyamangalam open dumping site, Tiruchirappalli, Tamilnadu. The dump site receives 71% of organic waste. The groundwater flow and leachate transport model was developed using Visual MODFLOW and MT3DMS (Version 4.3), to study the leachate transport in the subsurface and to predict the plume behavior under different scenarios. The conceptual model of the system was derived from the information on geology, geo physical and geo hydrology of the study area. The total dissolved solids (TDS) were taken as a parameter, to study the extent of contaminant plume for the next nine years (2014-2022). From the groundwater flow model, it was found that the increase in water level by 2.5 m above MSL from December 2010 (70.9 m above MSL) to December 2022 (73.4 m above MSL) around the study area. From the leachate transport model, the predicted TDS plume movement was identified towards the west and south east directions of the open dumping area. As a conclusion, the developed groundwater flow and leachate transport model can be effectively used for studying the leachate migration from the open dumping site into subsurface system.

Keywords: Solid Waste; Open Dumping; Leachate; Total Dissolved Solids; Visual MODFLOW.

1. Introduction

In recent years solid waste management creates a serious issue due to an increase of the urban population in developing countries (Ghose et al. 2006). Numerous reports stated that nearly 90% of generated Municipal Solid Waste (MSW) is disposed on the open lands in low lying area, which creates serious trouble to the public health and the environment (Dong et al. 2008; Shivayogimath et al. 2007; Sharholy et al. 2008). Management of leachate generation and its transport make a dangerous problem to the surrounding soil, ground and surface waters (Baccini et al. 1987; Jhamnani and Singh 2009; Kanmani and Gandhimathi 2013 a). Currently there has an increase in the contamination of groundwater occurred by the disposal of solid waste in landfills (Mor et al. 2006; Singh et al. 2008; Rahim et al. 2010). Paliya et al. (2022) conducted research on the disposal of polybrominated diphenyl ethers (PBDEs) at municipal solid waste (MSW) dumping site, Nagpur, India. The study found that the MSW disposal locations in India are PBDE sinks and may be harmful to human health. Leachate transport on groundwater continues to raise concern and have become the subject of recent and past investigations (Ahmed and Sulaiman 2001; Ikem et al. 2002; Pujari and Deshpande 2005; Singh et al. 2008; Mohan and Gandhimathi 2009; Ashraf et al. 2012; Han et al. 2013; Kanmani and Gandhimathi 2013 b). The contamination of underground water and gas emissions may have negative health effects on the exposed population living nearby, including both carcinogenic and non-carcinogenic effects (Siddiqua et. al. 2022). Knowing the transport of leachate in soil stratum is necessary to predict the potential for groundwater pollution from landfills (Islam and Singhal 2002). In 1856, the basis of groundwater flow modeling can be marked out to the experimental analysis through Darcy's law. Bredehoeft and Pinder (1973) analyzed the first application of numerical model in the transport problem on a regional scale. Gelhar and Wilson (1974) created a model to describe the groundwater quality in Massachusetts. The groundwater pollution in an aquifer in the Rocky Mountains of Colorado has made through advection-dispersion studies using Iterative Alternative Direction Implicit (IADI) finite difference method (Konikow, 1977). Consequently many of the model have been developed using finite difference or finite element methods to attain either analytical solutions or numerical solutions. The majority of the models are validated with the existing benchmarks and few of the researchers used these models for field applications. It includes USGS-MOC code (Konikow and Bredehoeft 1978), SUTRA (Voss and Souza 1987), USGS model MODFLOW (McDonald and Harbaugh 1988), MT3D (Zheng 1990), MMOC (Galeati et al. 1992) and Tough2 (Oldenburg and Pruess 1995), etc. Every model has its individual advantages and disadvantages, and these models may be either two-dimensional or three-dimensional. Wen and Fu (1985) solved the sanitary leachate transport equation through saturated zone using finite difference method. Yildiz et al. (2004) developed a mathematical model that simulates the distribution of leachate and pollutants through the landfill taking into consideration the effects of landfill development. Zuquette et al. (2005) studied the environmental assessment of an uncontrolled landfill. MODFLOW and MT3D software were used to simulate groundwater flow and contaminant transport modeling, as well as to predict changes due to the proposed remediation measures. Dang et al. (2009) simulated a mathematical model to trace the leachate plume from a municipal landfill in groundwater environment. The model demonstrated that the effect of the faults on the landfill site was the most important factor which controls the movement of the leachate to the outside. Morio et al. (2010) introduced a Flow Guided Interpolation (FGI) method to estimate the spatial distribution of contaminant concentrations in groundwater. Zhang and Hiscoch (2011) investigated an effect of forest cover in mitigating nitrate contamination of groundwater through the sherwood sandstone aquifer in the East Midlands, UK. Groundwater flow modelling (MODFLOW) and mass transport modelling (MT3DMS), were used to incorporate outputs from a groundwater recharge model. The purpose of this work is to study the leachate migration into subsurface system from dumping site through a contaminant transport model using Visual MODFLOW, Version 4.3. In order to demonstrate the usefulness of transport modeling as a tool, to predict the behavior of contaminants and thus help to determine the extent of the area affected by leachate infiltration. MODFLOW is a finite difference groundwater flow model that simulates three dimensional steady and transient state flows in heterogeneous layered aquifer systems, and predicts the plume movement using MT3DMS (Pollock 1994). The effect of three different scenarios was studied to understand the stress on the system in the next ten years.

2. Materials and Methods

In Ariyamangalam municipal solid waste dumping site, the waste is disposed directly without any pretreatment and segregation and also there is no surface lining to prevent the leachate entry into the ground. The dump site receives 71% organic wastes which includes vegetable matters, leaves, food wastes. In rainy seasons, the leachate generated directly seeps into the ground and pollutes the groundwater. Groundwater pollution in nearby wells was also observed. Water from wells up to 2 km radius is not used for drinking purpose due to bad odour and high concentration of TDS. The TDS concentrations in the leachate varied from 10000-60970 mg/l for fresh leachate samples and 6000-29000 mg/l for stabilized samples (Gandhimathi et al. 2013; Kanmani and Gandhimathi 2013b). Habitat around the dumping site quite often complained about the bad smell especially during the rainy seasons. Considering the groundwater resource problem in Ariyamangalam, Trichy city, the present study is undertaken to study the groundwater processes of the hydro geological system around the open dumping site, and to evaluate the impact of leachate migration on groundwater quality for three different scenarios of varying leachate concentrations from the open dumping site.

2.1 Study Area

The Ariyamangalam dumping site, Trichy, India has been in operation since 1967, covering a total surface area of 47.7 acres where the geological formation consists of mainly alluvium (Source: Public Works Department, Tamilnadu). The nature of the soil in the dumping site is of partially and highly weathered type of soil, and the color is yellow or reddish. The soil is moderately permeable and the infiltration rate can absorb most of the rain except for more intensive rains which can cause considerable surface flow and erosion. The dump site receives approximately 400–470 tonnes of MSW per day collected from four zones of Trichy City in the year 2010 (Kanmani and Gandhimathi 2013 a & b). The dumping site is located at 10°48’ N and 78°43’ E. The ground elevation of the dumping site is 78.875 m above Mean Sea Level. The layout of the study area is shown in Fig. 1. The fresh solid waste composition study shows that samples from the open dump site contained about 90–95 % combustible materials and non-combustible fraction is about 1–5 % (Kanmani and Gandhimathi 2013b). The fresh leachate sample possesses very high concentration of chemical parameters except pH, when compared to stabilized leachate samples (Gandhimathi et al. 2013). The physicochemical analysis indicated that chlorides (range between 215.15 and 4,098.73 mg/L) and TDS (ranges from 740 to14,200 mg/L) of the groundwater samples around the study area are higher than the permissible limits in all the sampling locations (Kanmani and Gandhimathi 2013 b).

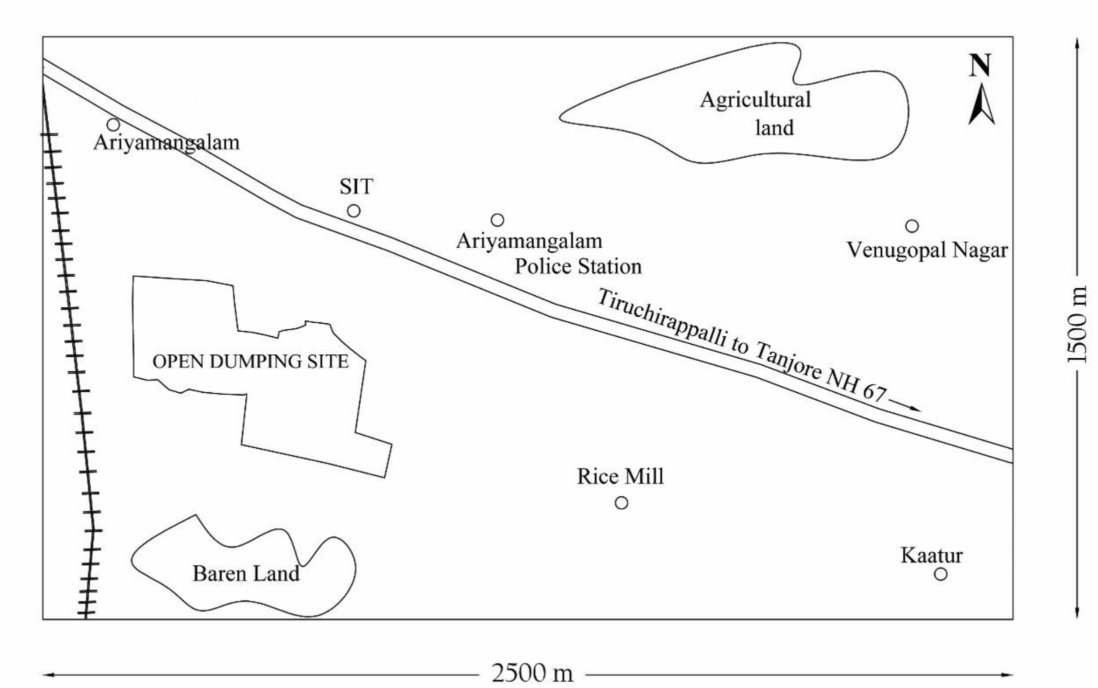


Fig. 1. Layout of Study Area

2.2 Model Development

The conceptual model of the system was derived from the information on geology, geo physical and geo hydrology of the study area. The TDS was taken as a parameter, to study the extent of contaminant plume for the next nine years. The groundwater flow and leachate transport model was developed using Visual MODFLOW and MT3DMS (Version 4.3), to study the leachate transport in the subsurface and to predict the plume behavior under different scenarios (Tanneeru. M et al., 2022).

The governing groundwater flow equation given below is restricted to fluids with a constant density or in cases where the differences in density or viscosity are extremely small or absent (Barends and Uffink 1997). This equation is derived mathematically by combining a water balance equation with Darcy's law.

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t}-w(x, y, z, t) \quad (1)$$

S_s = specific storage, m^{-1}

h = hydraulic head, m

t = time, min

K_x,K_y = hydraulic conductivity in the principal horizontal directions, m/sec

K_z = hydraulic conductivity in the vertical direction, m/sec

w (x,y,z,t) = the rate of groundwater discharge/recharge per unit area, m/sec

x, y, z = Carteisan coordinates directions

Eq. 1 describes groundwater flow under non equilibrium conditions in a heterogeneous and anisotropic medium provided the principal axes of hydraulic conductivity are aligned with the coordinate directions. The simulation of groundwater flow requires a thorough understanding of the hydro geologic characteristics of the site. It includes, subsurface extent and thickness of aquifers, Hydrologic boundaries (boundary conditions), which control the rate and direction of movement of groundwater, hydraulic properties of the aquifers and distribution and magnitude of groundwater recharge, pumping or injection of groundwater (S. Vivek et al., 2021).

The general form of the advective-dispersive equation in Cartesian coordinates for solute transport in three dimensional flows through the aquifer can be described by (Freeze and Cherry, 1979).

$$\frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right)-\left(\frac{\partial}{\partial x}(V_x C)\right)-\left(\frac{\partial}{\partial y}(V_y C)\right)-\left(\frac{\partial}{\partial z}(V_z C)\right)=\frac{\partial C}{\partial t} \quad (2)$$

where,

x,y,z	=	Cartesian coordinates directions
V_x V_y, V_z	=	the seepage velocities in the respective directions, m/sec
D_x D_y, D_z	=	the dispersion coefficients in the respective directions, m^2/sec
C	=	solute concentration mg/m^3
t	=	time, sec

2.2.1 Model Domain

The model domain covers a rectangular area of 2500 m in east west direction and 1500 m in north south direction with three layer aquifer system. The model domain was discretized into a grid of 200 rows and 200 columns, each cell representing, 12.5 m × 7.5 m in the field. The plan view of model domain is shown in Fig. 2.

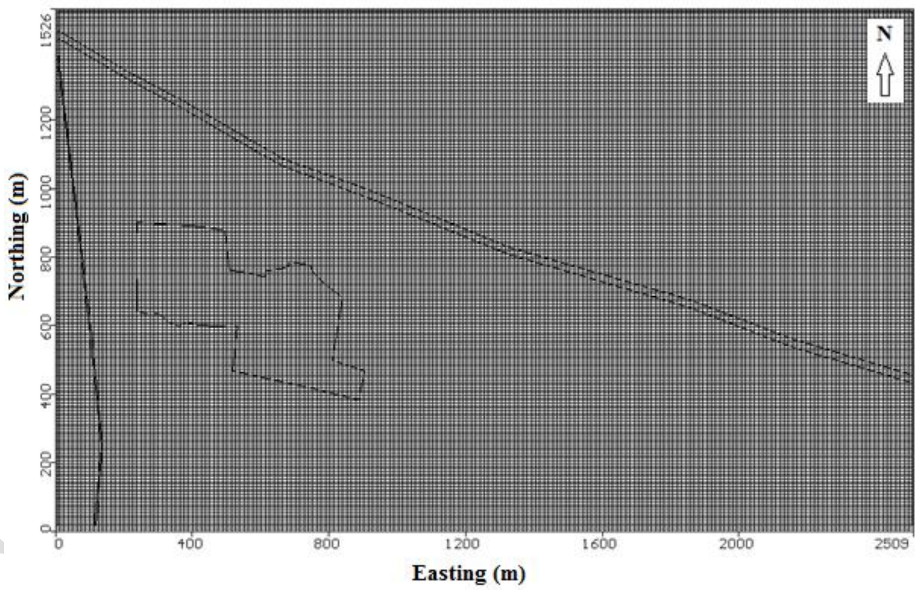
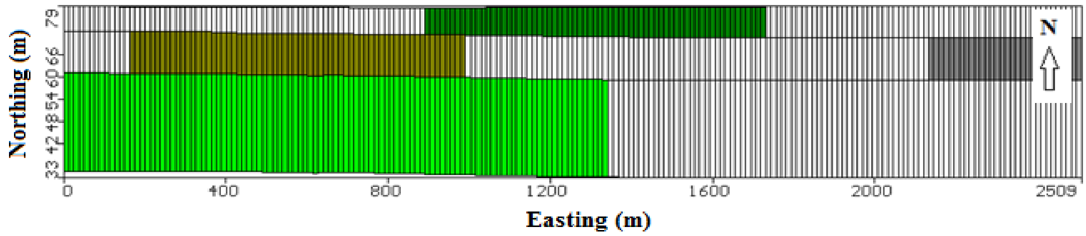


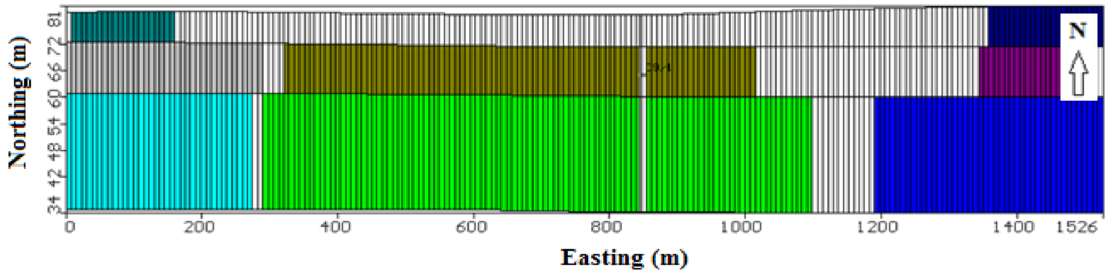
Fig. 2. Discretization of Model Domain

2.2.2 Borehole Lithology

Three distinct aquifer groups were identified based on the lithological logs collected from geology department, Trichy. The model domain was approximately 40 m thick and of variable elevation. The cross section of the aquifer system along east-west and north-south direction is shown in Fig. 3 (a) and (b) respectively.



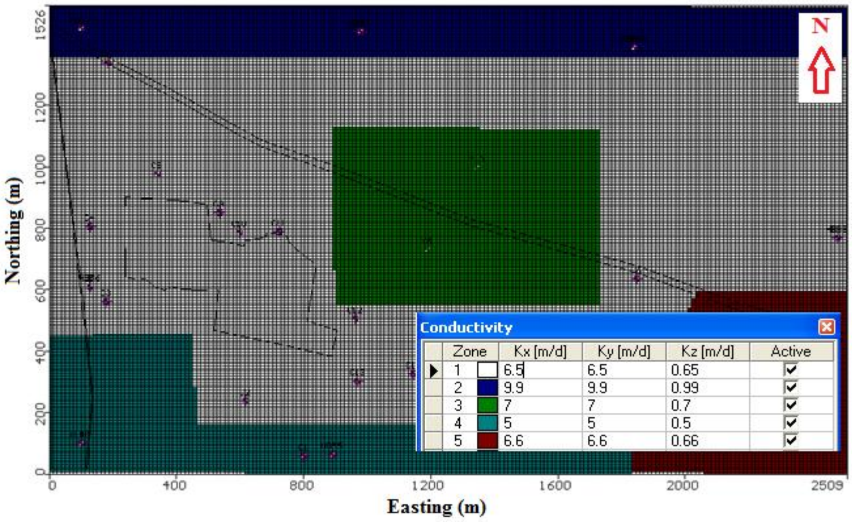
(a) East-West Direction



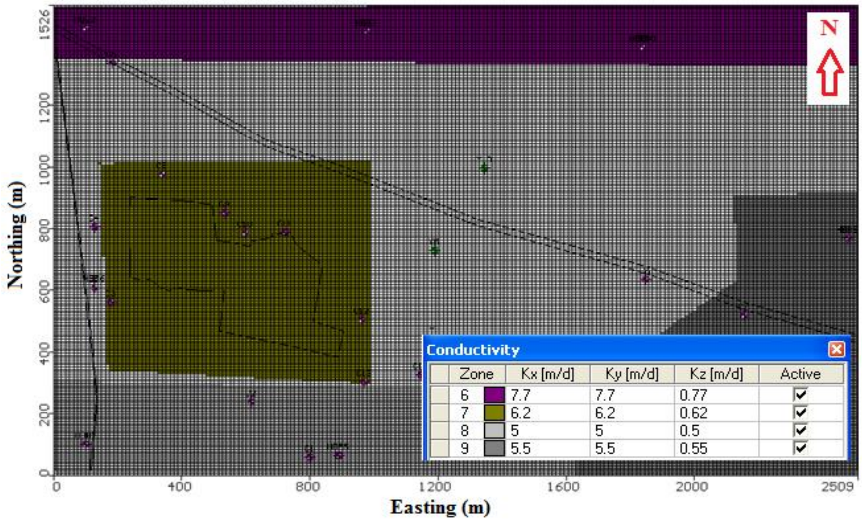
(b) North-South Direction

Fig. 3. Cross Section of the Aquifer System

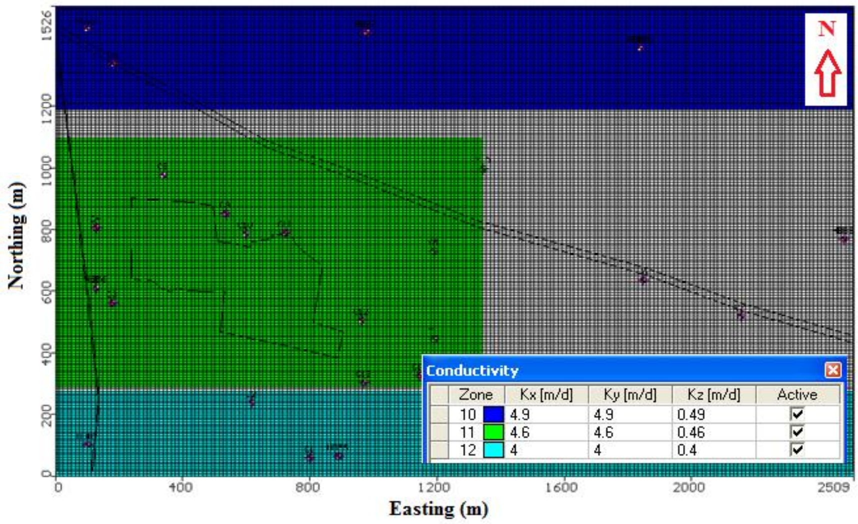
The elevation of the top layer was in the range between 77 m to 82 m above MSL. Based on the data collected from groundwater division, Chennai, the aquifer was represented by three layers of consistent thickness throughout the model domain: the first 6 m from the ground level consists of thick soft weathered soil type with hydraulic conductivity ranges from 5 to 9.9 m/day; 7 m – 22 m contained thick intermediate partially weathered soil layer (hydraulic conductivity range: 5 – 7.7 m/day), and the third layer made of a deep weathered soil layer with 22 m - 40 m thick (hydraulic conductivity range 4 – 4.9 m/day). The additional hydro geological input parameters pertaining to the study area such as specific yield (1 – 7.2%), transmissivity (49 – 216 m^2/day) and porosity (0.33 – 0.57) were collected from groundwater division, Chennai. Based on the type of soil, the hydraulic conductivity was assigned in the range from 5 to 9.9 m/day for three distinct aquifer groups along the study area and is shown from Fig. 4 (a) to (c).



(a) Layer – I



(b) Layer – II



(c) Layer – III

Fig. 4. Hydraulic Conductivity Zones in the Model Domain

2.2.3 Recharge

The top boundary of the groundwater flow model is represented as a specified flux (i.e., precipitation infiltration) surface. Groundwater recharge due to infiltration is dependent upon several factors including the soil permeability, surface cover, topography, amount of rainfall (duration and intensity), amount of snowfall, and timing of snowmelt (Seyf-Laye et al., 2012). The rainfall data (Table 1) collected from the Ponmalai station nearby Ariyamangalam open dumping site were used to assign the recharge values in the model domain. Based on the soil type, annual groundwater recharge of the study area was estimated to range from 5% to 25% of the average monthly precipitation (S. Vivek et al., 2022). The different recharge zones in the model domain are shown in Fig. 5.

Table 1. Rainfall data for the Ponmalai Station nearby Ariyamangalam Open Dumping Site (Groundwater Division, Chennai)

Year	Rainfall (mm)												Annual Rainfall (mm)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
2000	34.6	47.2	0.0	35.6	153.3	6.4	154.0	45.8	166.4	120.0	234.5	121.7	1119.5
2001	0.0	0.0	0.0	46.8	33.8	15.0	117.6	39.6	92.2	164.6	150.8	33.4	693.8
2002	0.0	110.8	0.0	0.0	47.0	152.6	0.0	13.6	39.8	166.2	29.2	18.0	577.2
2003	0.0	0.0	0.0	4.0	113.4	0.0	49.2	165.2	147.2	167.2	220.4	0.0	866.6
2004	1.6	0.0	0.0	6.2	224.4	41.8	83.0	3.8	310.4	177.2	159.2	0.0	1007.6
2005	0.0	1.5	1.8	68.6	67.8	0.0	20.4	46.6	37.4	428.5	349.4	130.2	1152.2
2006	11.2	0.0	34.0	47.4	75.4	23.2	0.0	212.4	107.0	194.8	116.8	14.6	836.8
2007	0.0	0.0	0.0	30.2	69.3	34.0	57.6	94.0	47.6	121.1	46.9	314.4	815.1
2008	4.2	21.0	133.0	5.0	59.2	3.4	116.0	161.5	29.6	125.6	356.4	36.8	1051.7
2009	0.0	0.0	8.2	21.2	11.4	50.6	0.0	98.2	66.6	20.2	474.0	76.2	826.6
2010	1.8	0.0	0.0	0.0	99.0	41.0	46.7	50.6	87.8	145.9	234.9	189.7	326.9

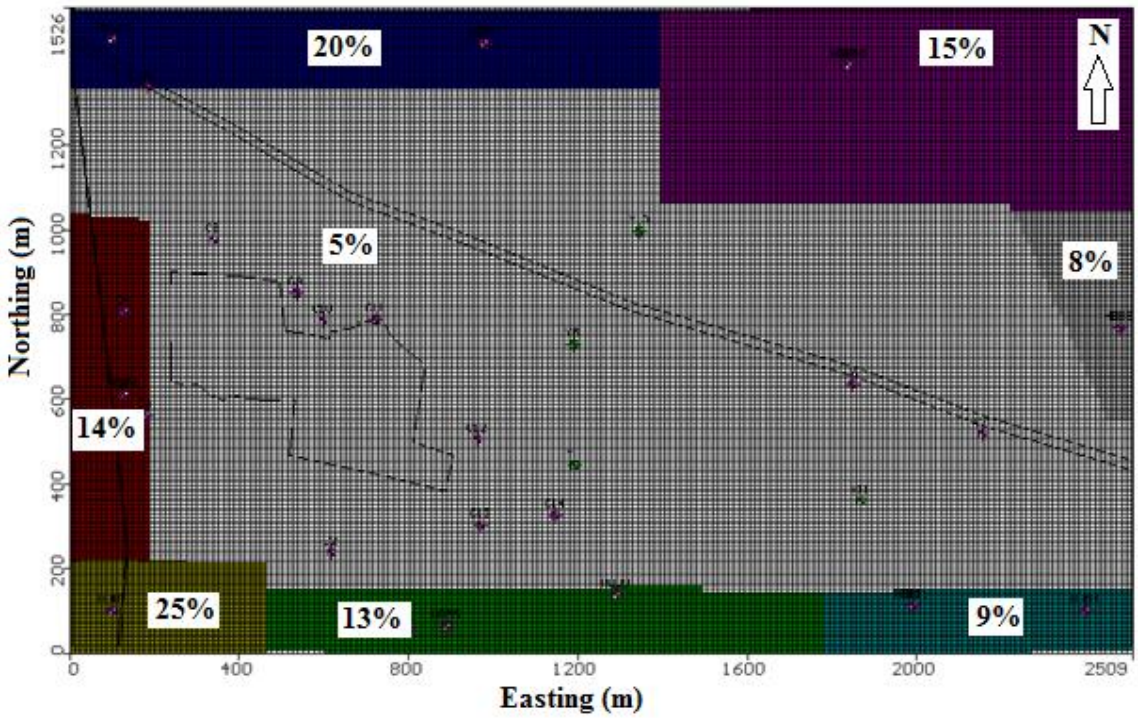


Fig. 5. Different Recharge Zones in the Model Domain

2.2.4 Pumping Well

Pumping wells represent groundwater sinks to the model. The pumping rate assigned to the wells in the model domain was determined based on the average use estimated by the Tiruchirappalli Corporation.

2.2.5 Water Level

For groundwater flow model development, the monthly water level data collected from the groundwater division, Chennai for the year 2005 - 2010 was used. The head values were assigned with respect to mean sea level (MSL) for all the head observation wells such as HOB 1 to HOB 15 (Fig. 6).

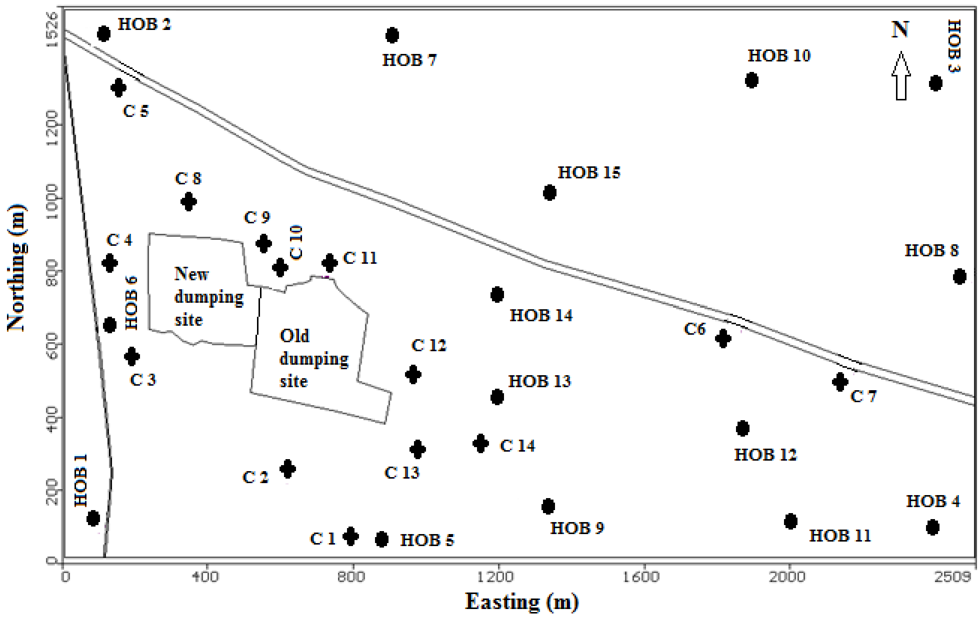


Fig. 6. Locations of head observation wells (● HOB 1 – ● HOB 15) and concentration observation wells (✚ C 1 – ✚ C 14))

2.2.6 Initial Head and Boundary Condition

The head values (water level with respect to MSL) observed during January 2005 in the observation wells around the study area were interpolated and assigned as initial head values. The time varying head boundary conditions were applied along all boundaries of the study area. A plan view of the assigned initial head contours and boundaries in the model domain is shown in Fig. 7.

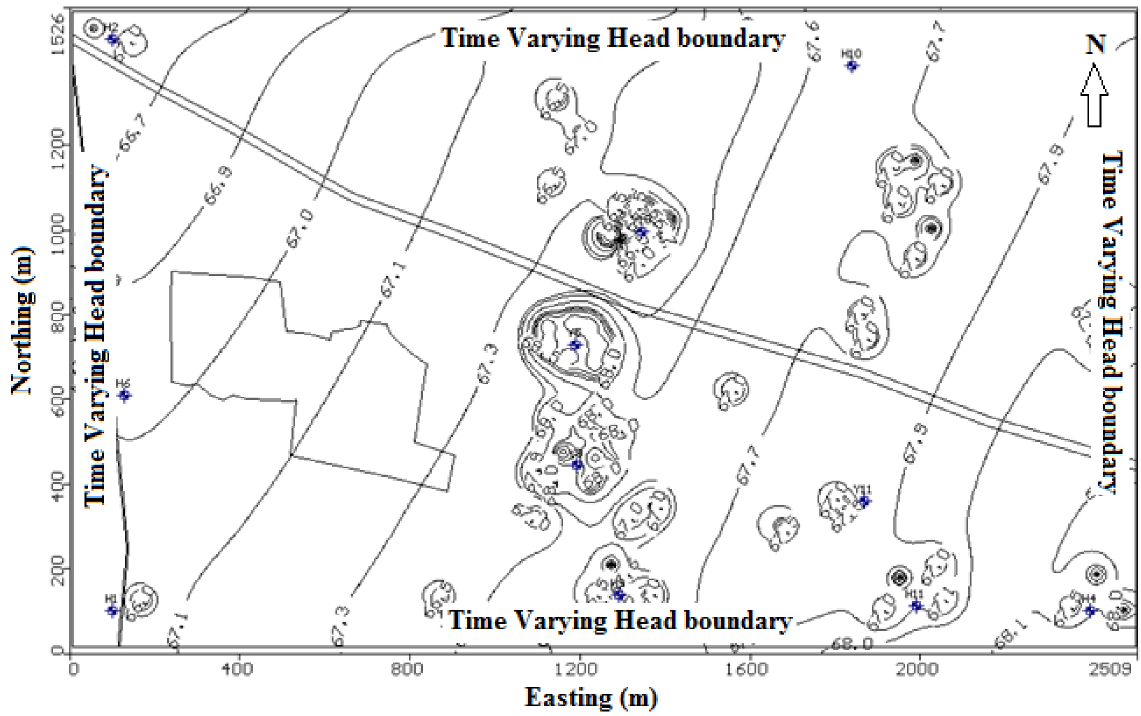


Fig. 7. Initial Head Contours and Boundary Conditions in the Model Domain

2.2.7 Input Parameters for Leachate Transport Model

Leachate transport model simulates the movement of contaminants as they move with groundwater through the subsurface. It requires the development of a calibrated groundwater flow model for an accurate determination of the velocity and direction of groundwater flow. To study the extent of contaminant plume, TDS was taken as a parameter. This will not affected by sorption or any other chemical reactions. For leachate transport model development, the monthly TDS concentrations in the groundwater were collected from the groundwater division, Chennai for the period 2005 - 2010. The TDS concentration values collected in January 2005 from all the concentration observation wells (C1 to C14) around the study area (Fig. 6) were interpolated and assigned as initial concentration values. The time varying concentration boundary conditions were applied along all boundaries of the study area. A plan view of the assigned initial TDS concentration values and boundaries in the model domain is shown in Fig. 8. Based on the leachate characteristics (Gandhimathi et al. 2013), different zones were identified in the new (Z1 and Z2) and the old (Z3 to Z7) dumping area. These zones were assigned as a constant TDS concentration source for the period 2005 – 2010. The details of TDS values assigned to different zones are shown in Fig. 9.

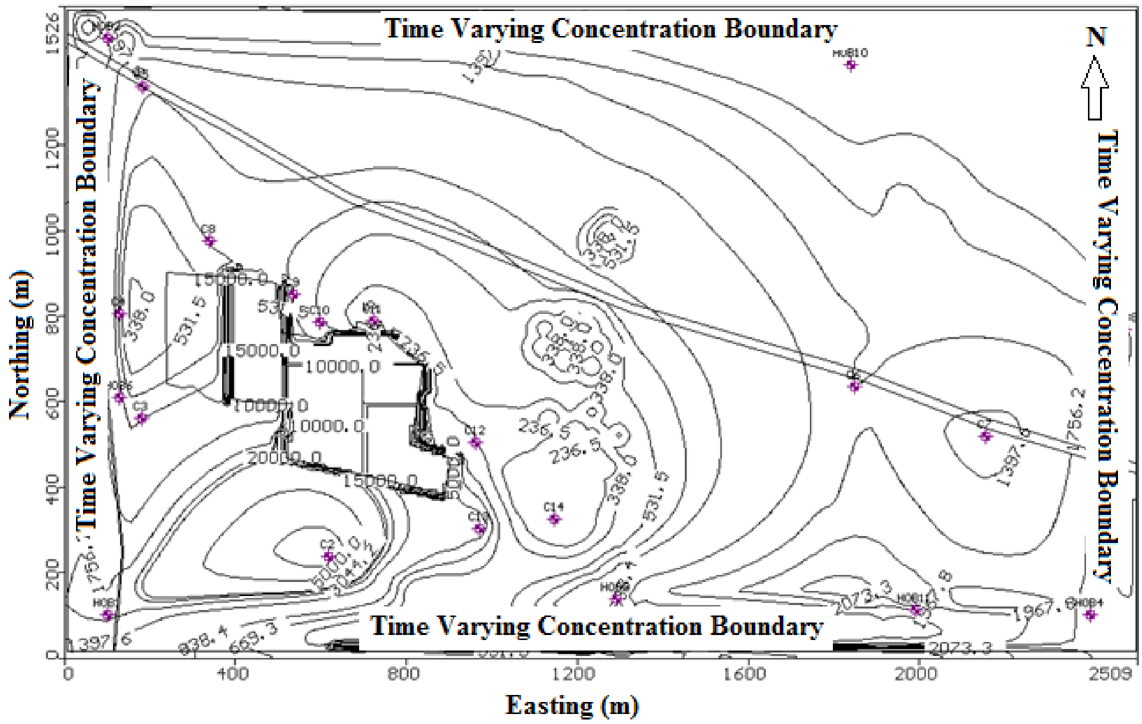


Fig. 8. Initial Concentrations and Boundary Conditions in the Model Domain

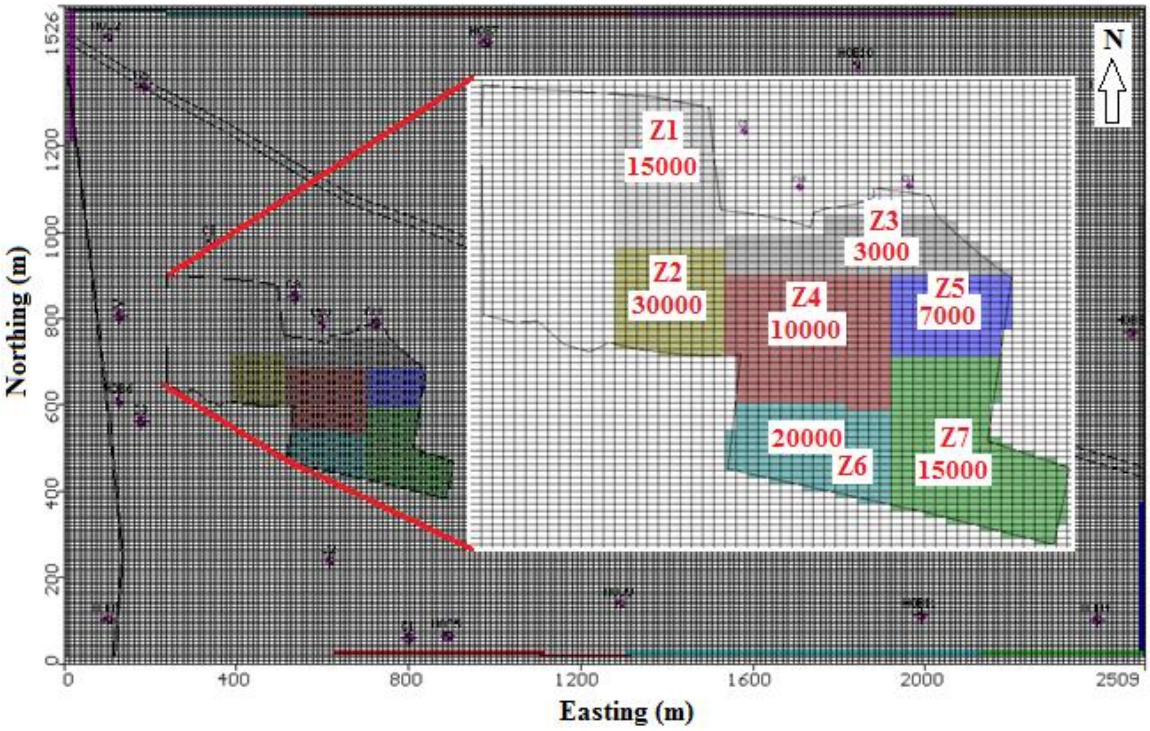


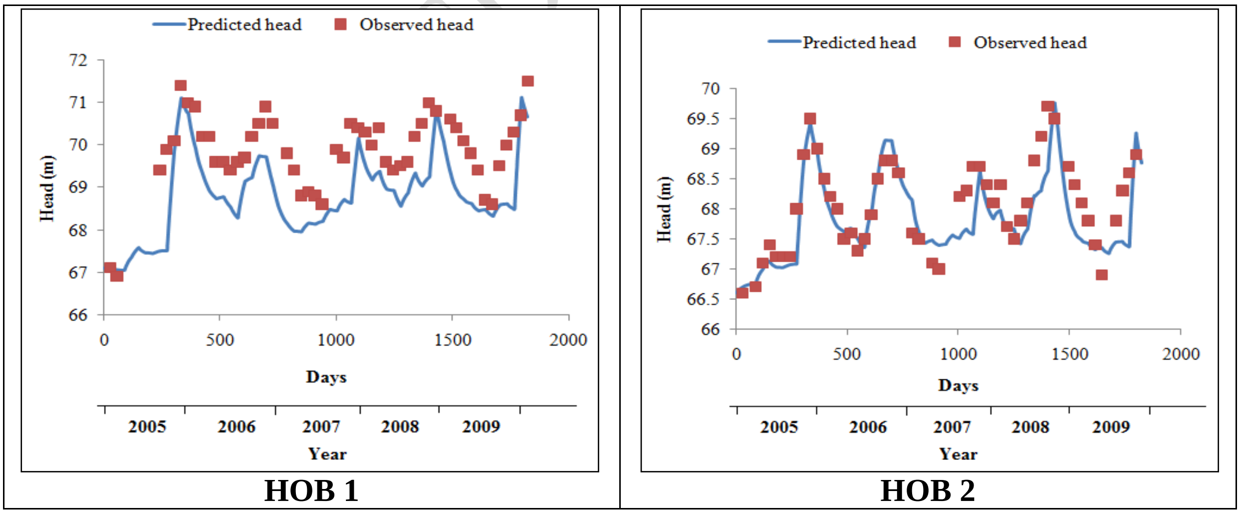
Fig. 9. Different Zones with Constant Concentration of TDS

3. Results

3.1 Model Calibration

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria. A calibrated model uses selected values of hydro geologic parameters, sources and sinks and boundary conditions to match historical field conditions (Yang et al. 2011). The flow model and leachate transport model accurately simulated the distribution of hydraulic head and concentration of TDS across the study area using MODFLOW and MT3DMS tool.

The head observation wells such as HOB 1 to HOB 15 and concentration observation wells such as C1 to C14 located in the model domain (Fig. 6) were used for flow and leachate transport model calibration. The observed water level and concentration of TDS pertaining to the years 2005 – 2009 were used for model calibration. First, the groundwater flow model was calibrated and then the leachate transport model was calibrated until the measured heads and TDS concentrations matched with simulated heads and concentrations, respectively. For flow model calibration, the hydraulic conductivity (5 to 10 m/day) and recharge (5% to 25%) were adjusted spatially to calibrate the simulated head of the spatial field data. The comparison between observed and predicted heads for the head observation wells are shown in Fig. 10 (a) and 10 (b).



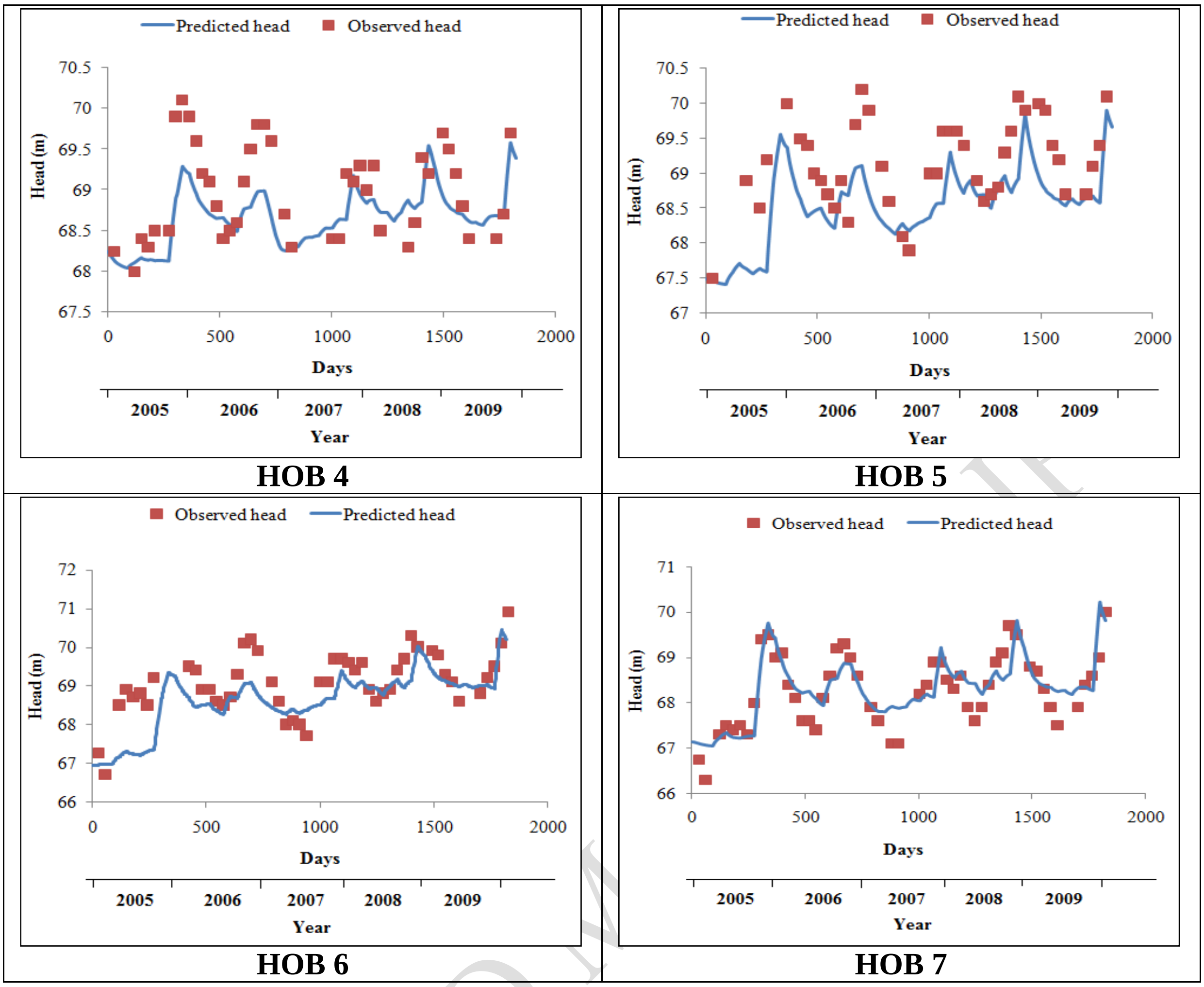
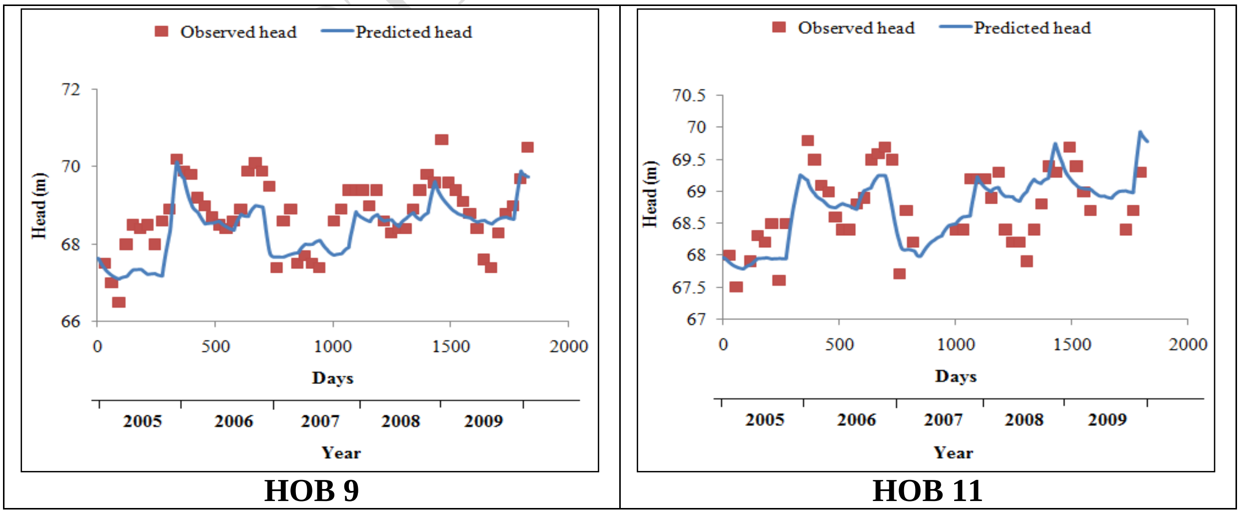


Fig. 10 (a). Comparison of Observed Heads with Predicted Heads



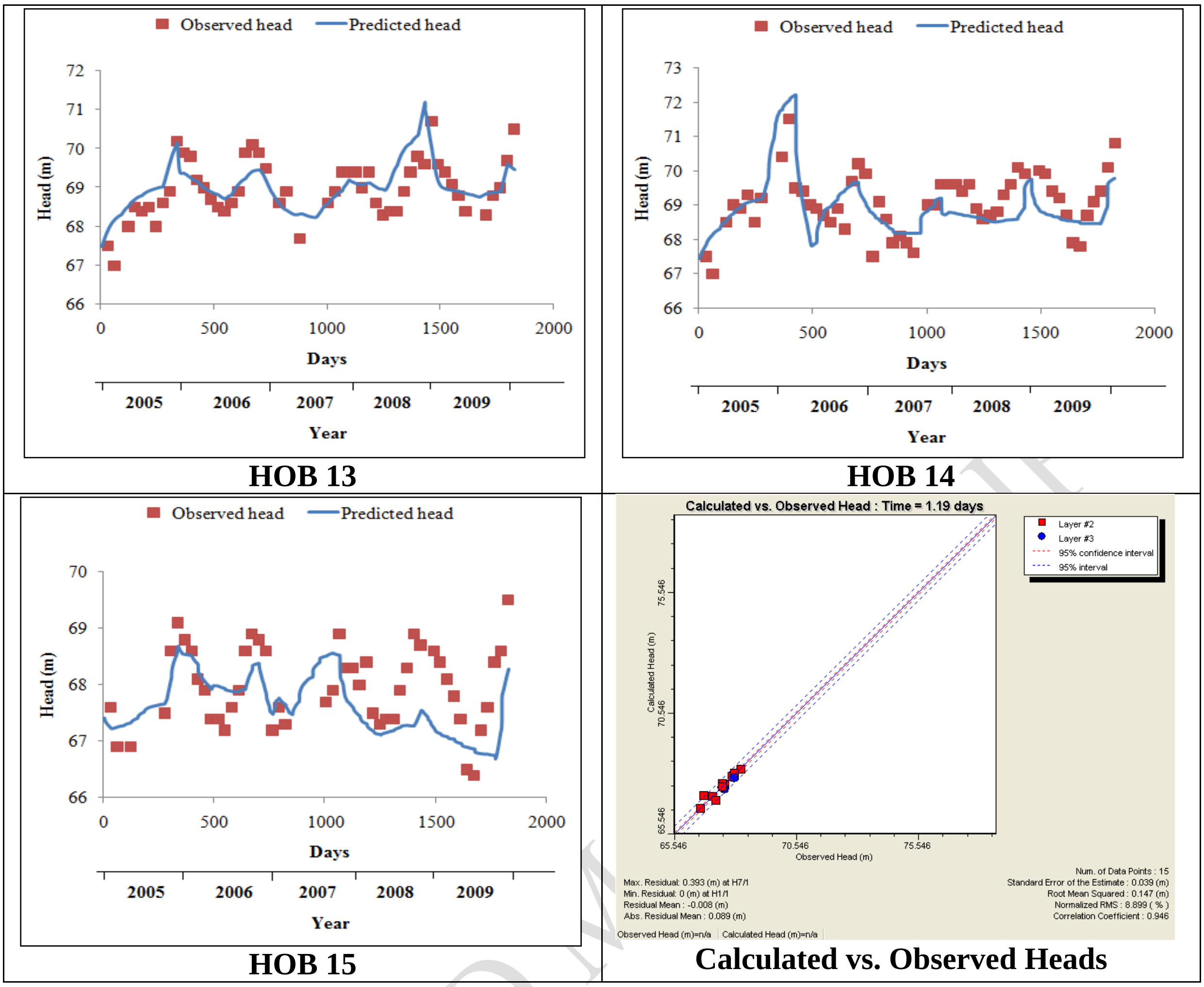


Fig. 10 (b). Comparison of Observed Heads with Predicted Heads

From the figures 10 (a) and (b), it was confirmed that there was a reasonable match between the observed and predicted heads through the entire simulation period. Fairly good visual comparison between the observed and simulated head was achieved at each observation well, with values differing by less than 1 to 1.5 m. In addition to that, the calibrated flow model of the study area was confirmed using the root mean squared error, correlation coefficient and standard error of the estimate. The correlation coefficient was used to quantify the goodness of fit between the simulated and observed head values for the verification model. The correlation coefficient and standard error of 0.946 and 0.039 m were obtained for the calibrated model, indicating an acceptable calibration.

For leachate transport model calibration, sensitivity analysis was carried out using dispersivity parameters such as longitudinal dispersivity (α_L), horizontal transverse dispersivity (α_{TH}) and vertical transverse dispersivity (α_{TV}). The dispersivity values were assigned based on the quantitative relationship between the α_L and flow length and is expressed as $\alpha_L = 0.1X$, where X is the flow distance. The α_{TH} was assumed to be 10% of the α_L. The value of α_{TV} was assumed to be two orders of magnitude smaller than α_{TH} (Zheng and Bennet 2002). Based on the relationship between α_L and flow distance, the value of α_L was varied in the range between 40 and 80 m for the leachate transport model calibration. Similarly, based on the assumptions the α_{TH} and α_{TV} were varied in the range of 0.06 – 12 m and 0.06 – 6 m respectively. The above dispersivity values were refined through model calibration with the observed data. Table 2 shows the variation in the dispersivity parameters for the sensitivity analysis.

Table 2. Parameters used for Sensitivity Analysis

Parameter	Range	Base value
Longitudinal dispersivity, *m* (α_L)	40 – 80	60
Horizontal transverse dispersivity, *m* (α_{TH})	0.06 - 12	6
Vertical transverse dispersivity, *m* (α_{TV})	0.06 - 6	0.6

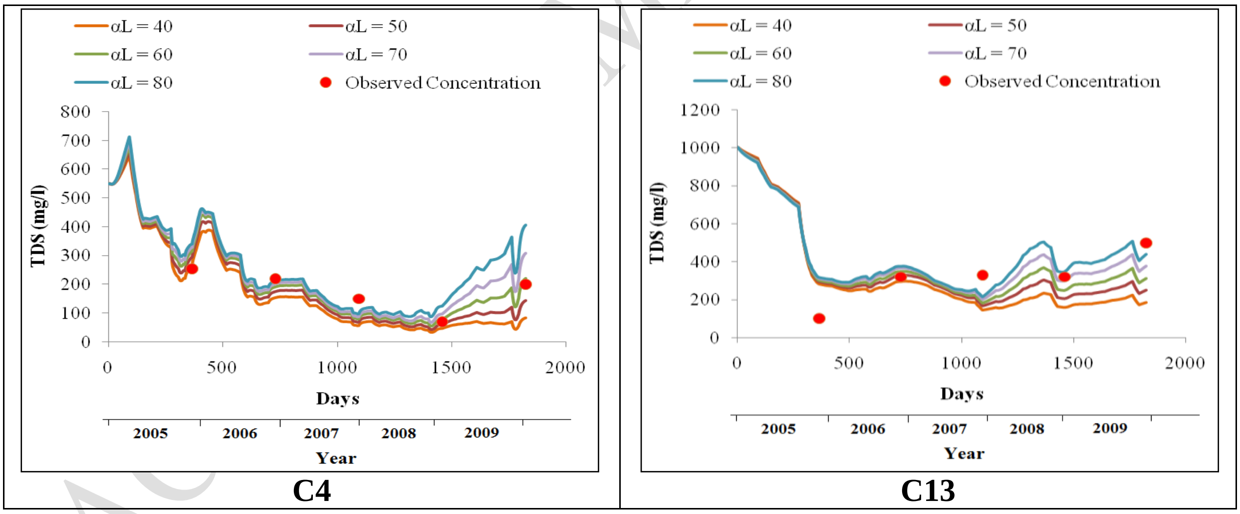


Fig. 11 (a). Effect of α_L on TDS Concentration

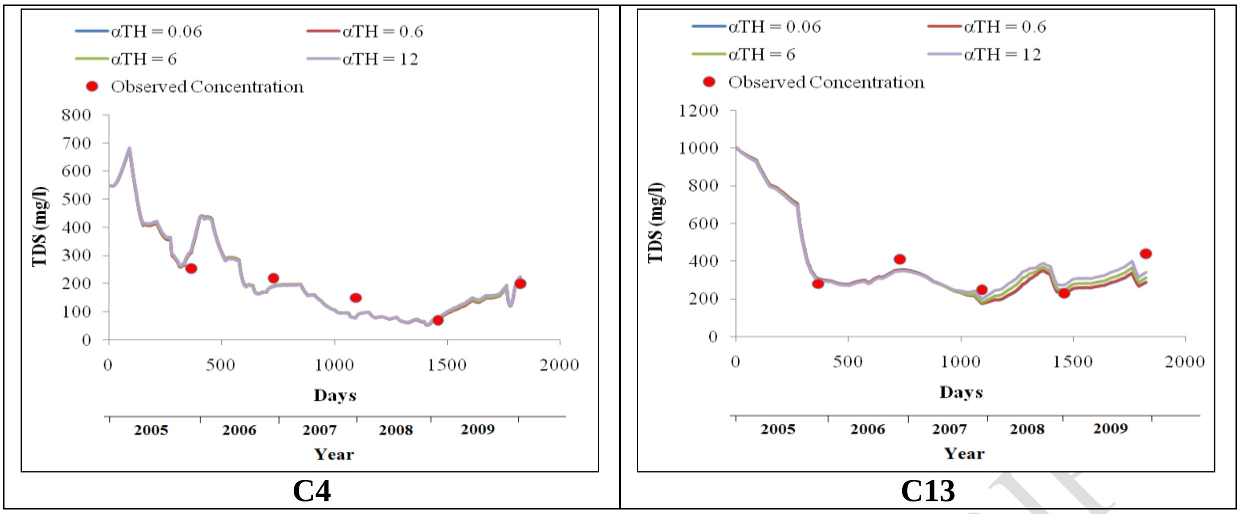


Fig. 11 (b). Effect of α_{TH} on TDS Concentration

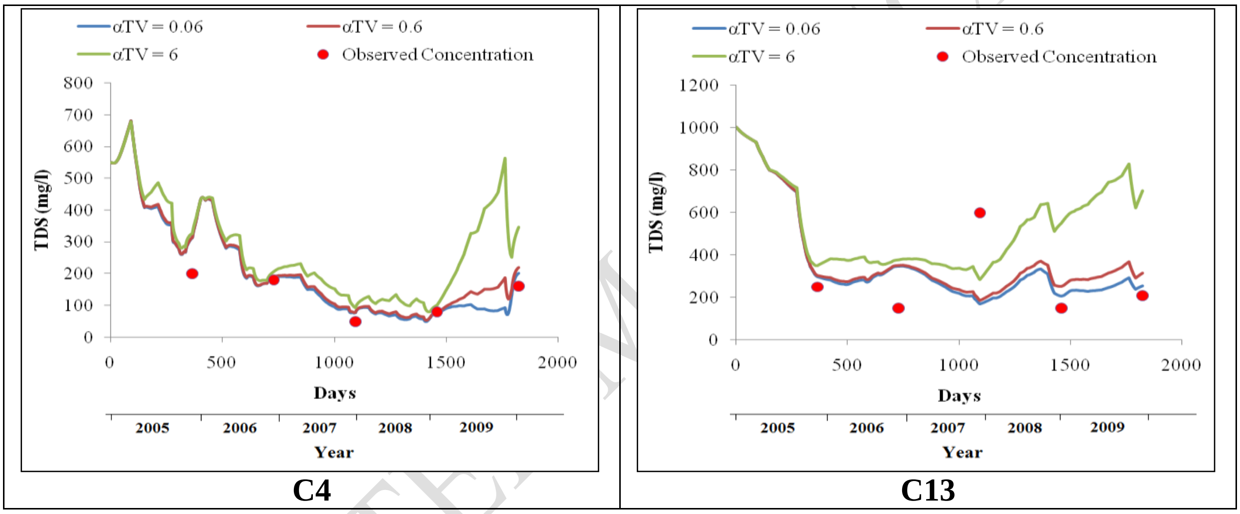
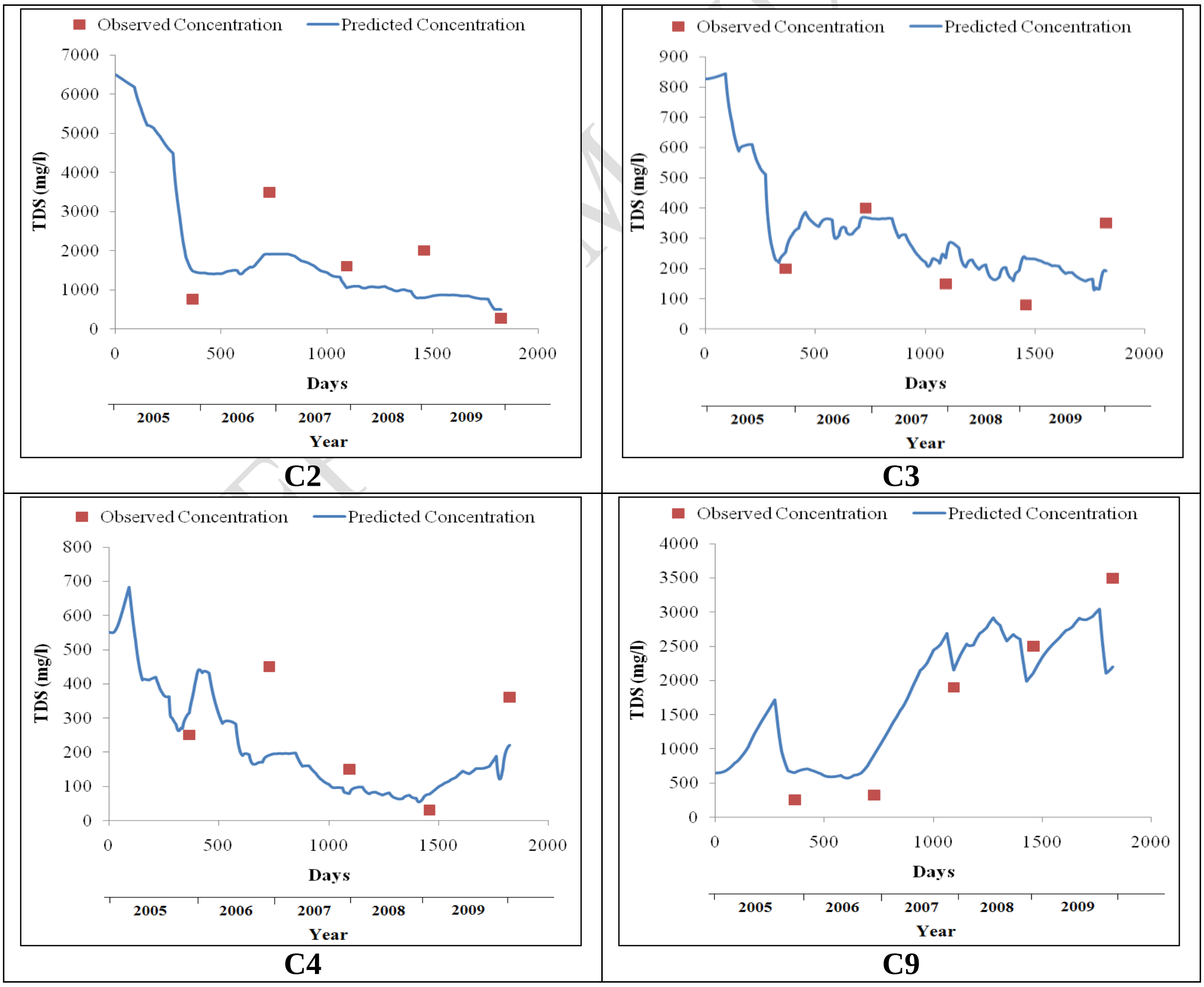


Fig. 11 (c). Effect of α_{TV} on TDS Concentration

The sensitivity analysis was carried out and the effects of α_{L}, α_{TH} and α_{TV} on the TDS concentration for the concentration observation wells are shown in Fig. 11(a) to (c) respectively. α_{L} denotes the leachate plume movement along the horizontal direction of the model domain. From the Fig. 11 (a), it was observed that the higher α_{L} results in higher TDS concentration in the observation wells. This may be due to more spreading of the plume along flow direction of the open dumping site. In one particular α_{L} value (60 m), the observed TDS concentration was matching with the predicted concentration. Thus, the longitudinal dispersivity value of 60 m was fixed as a base, and the other two parameters were incorporated into the sensitivity analysis.

The α_{TH} and α_{TV} indicates the leachate plume movement along y and z directions in three dimensional model domain. These parameters were also induced the changes in sensitivity of the simulated model. From the Fig. 11 (b), the effect of α_{TH} on TDS concentration in the well C4 was negligible when compared to well no. C13. This indicates that few changes were occurred on the leachate plume along horizontal transverse direction. The observed concentration matches with predicted concentrations when the value of α_{TH} was changed from 0.6 to 6.

Three different α_{TV} values was initiated to check the suitable match between the observed and predicted TDS concentrations. The analysis results showed (Fig. 11 (C)) that there was a huge variation in the predicted concentration when the value of α_{TV} as 6, in both the concentration observation wells (S. Vivek et al., 2019). The observed TDS concentrations of wells C4 and C13 match with predicted concentrations when the value of α_{TV} as 0.6. By using the base value of dispersivity parameters, the leachate transport model was well calibrated. The comparisons between the observed and predicted concentrations for the concentration observation wells are shown in Fig. 12. From the Fig. 12, it was found that the good calibration between the predicted concentrations and observed concentrations in the observation wells. There was very minimal error occurred due to the seasonal changes in the study area.



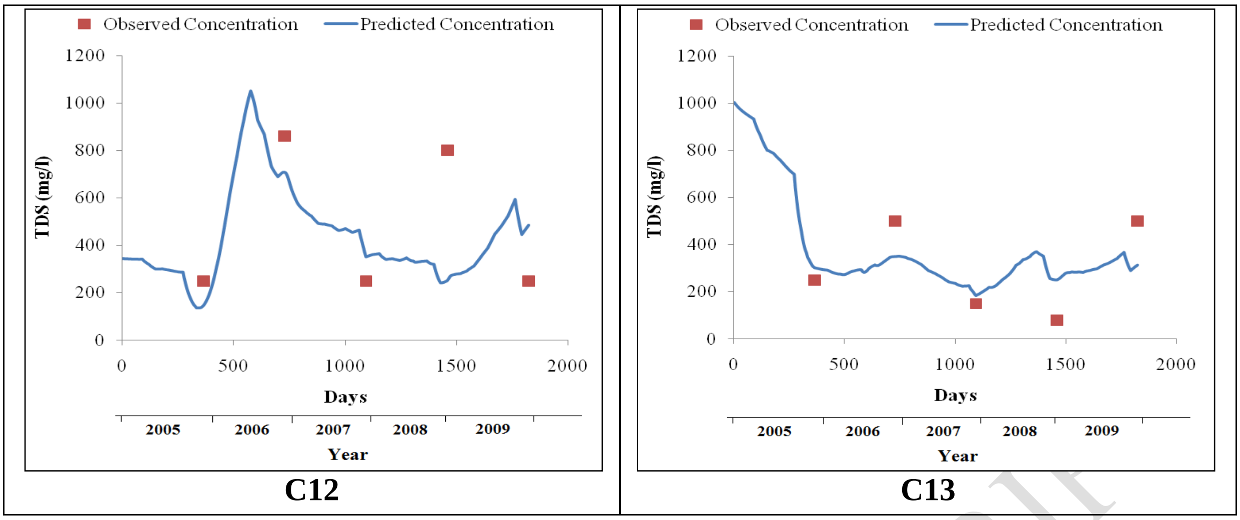


Fig. 12. Comparison of Observed Concentrations with Predicted Concentrations

3.2 Model Verification

Model verification has been defined as the process in which the calibrated model is shown to capable of reproducing a set of field observations independent of that used in model calibration (Konikow 1986; Zheng and Bennet 2002). Verification of the groundwater flow model was carried out by using the year 2010 data for all the head observation wells. The comparisons between the observed and predicted heads for the head observation wells up to the verification period (2010) are shown in Fig. 13. The flow model was validated successfully, on the basis of reasonable match between the observed and predicted heads in the verification period. The head contour with velocity vector for the year 2010 is shown in Fig.14. The groundwater flow pattern was predominantly moves towards the west and south east direction from the open dumping site.

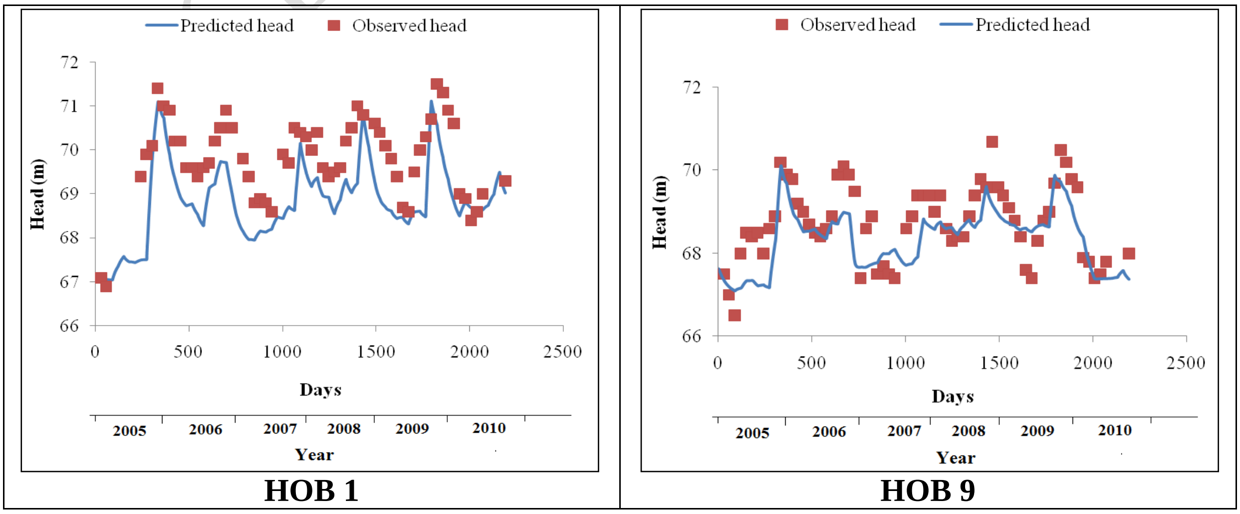


Fig. 13. Validation of Predicted Heads vs. Observed Heads (HOB 1)

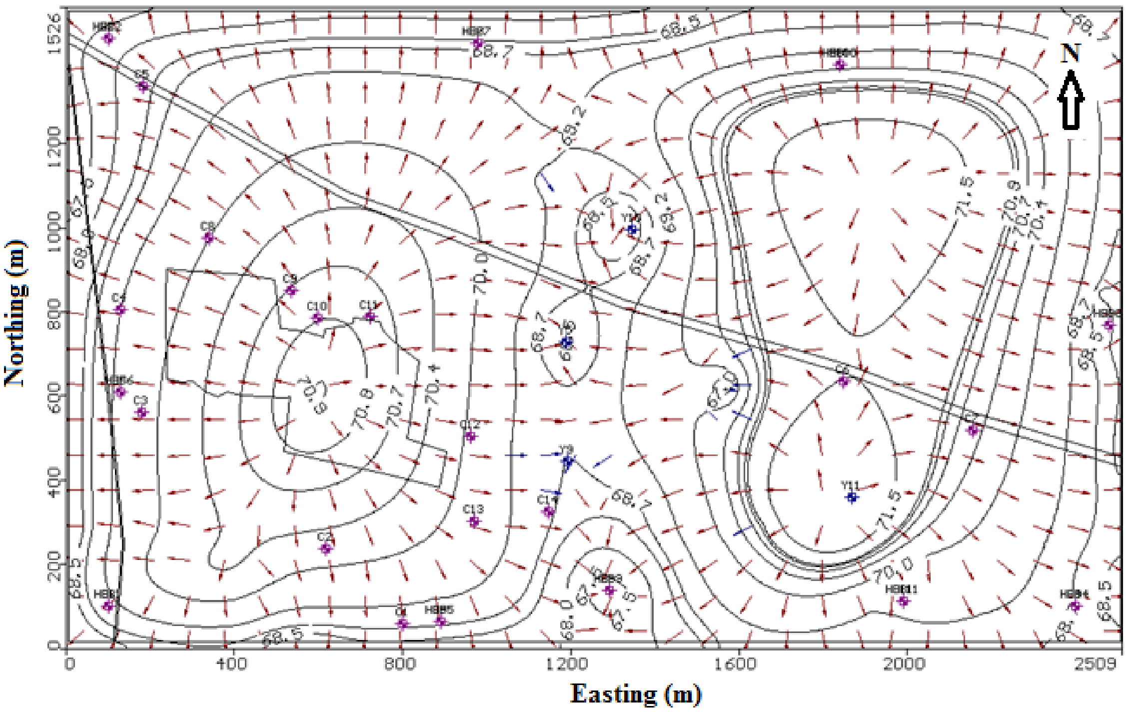


Fig. 14. Head Contour with Velocity Vector for December 2010

The TDS concentrations (collected from the groundwater division, Chennai) pertaining to the year 2011 and observed TDS concentrations around the study area for the year 2011 was used to validate the leachate transport model. The comparisons between the observed and predicted TDS concentrations for the concentration observation wells (C4 and C12) are shown in Fig. 15. The Fig. 15 indicated that a good validation between the predicted concentrations and observed concentrations for each observation wells during the validation period 2011. Good validation was accomplished in the head and concentration observation wells, indicating that the flow and leachate transport model was an accurate representation of the historical groundwater system and can be used for prediction purposes (M. Lenin Sundar et al., 2022).

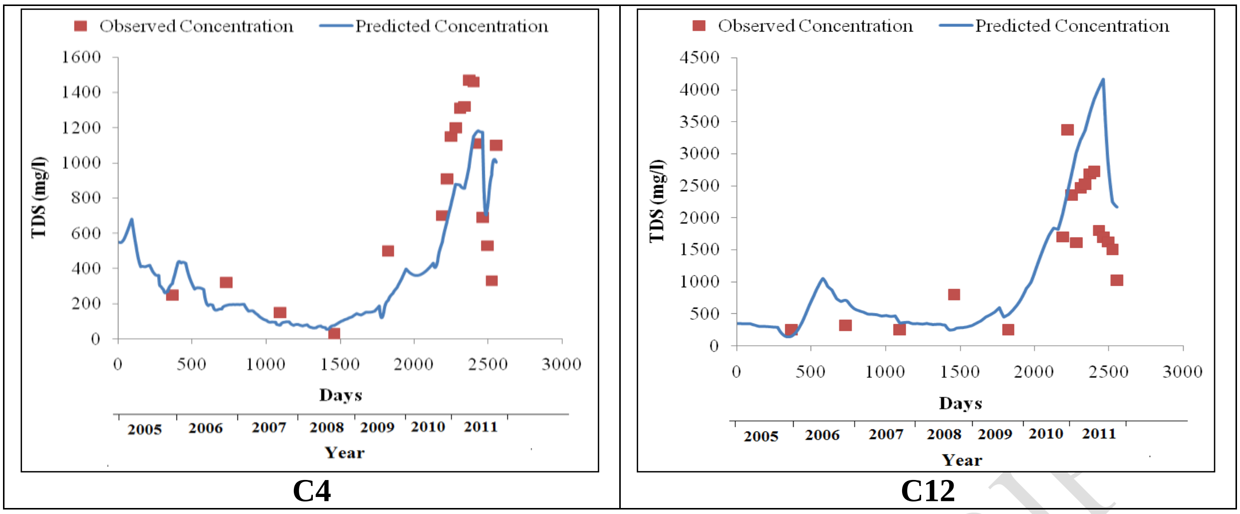


Fig. 15. Validation of Predicted Concentrations vs. Observed Concentrations

3.3 Model Prediction

Predictive simulations were used to estimate the hydraulic response of an aquifer, and the possible migration pathway of a contaminant from the source. The validated groundwater flow model was used to predict the head values along the model domain up to the year 2022. The predicted head contour along with velocity vector for the year December 2022 in the study area is shown in Fig. 16. A gradual increase in the water level was observed from the year 2010 to 2022.

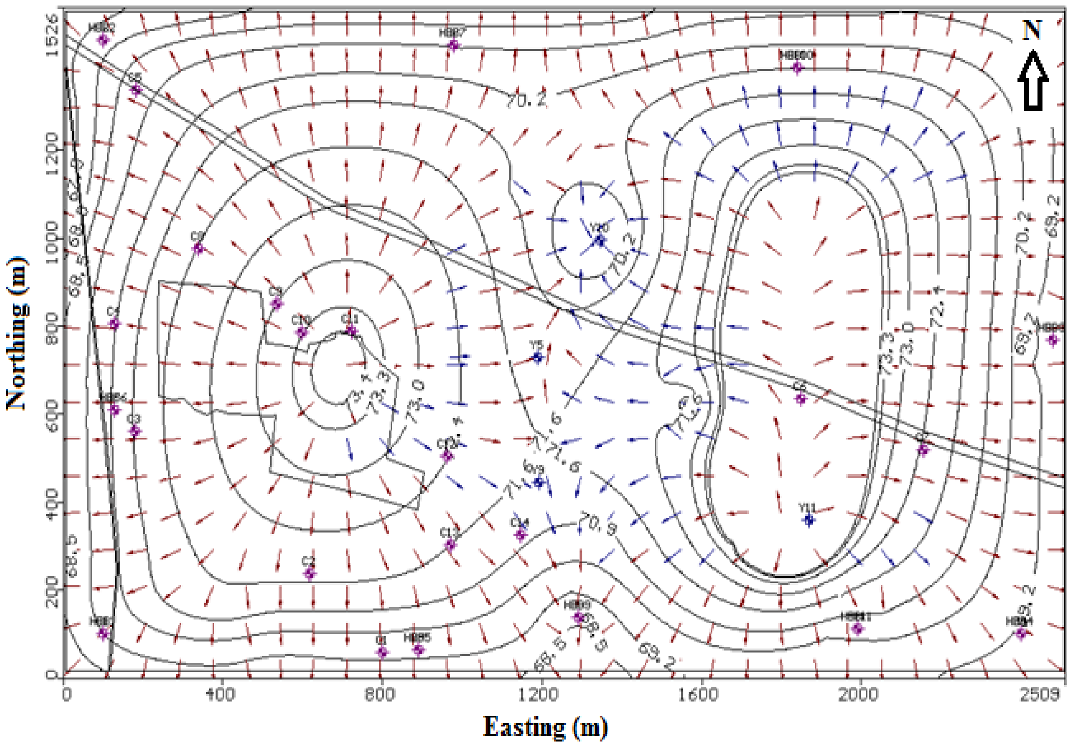


Fig. 16. Predicted Head Contour with Velocity Vector for December 2022

In the year 2010, the simulated water level near the dumping area was observed as 70.9 m above MSL. The water level of 72.3 m above MSL was observed in the open dumping area in the year 2016, and it was increased to 73.4 m above MSL in the year 2022. The elevation of the dumping site is 78.875 m above MSL; hence there will be no flooding in that area when the head level increases. Increase in recharge and decrease in drawdown have significant impacts on higher water level over the time scale of these simulations. However, south-western zone of the study area indicated the difference in contour pattern for every six years (Premkumar Sundararaj et al., 2022). This appropriate predicted groundwater flow model was used to forecast the leachate transport model for future years.

3.4 Scenario Analysis

In leachate transport model, three different scenario analyses were carried out namely, Scenario I: Continuing the same quantity of solid waste dumping with same concentration of leachate production for the future years; Scenario II: Yearly reduction of 500 mg/l of TDS in the old dumping area and a yearly increase of 500 mg/l of TDS in the new dumping area for the future years; Scenario III: TDS concentration reduced to zero level from 2014 onwards in new and old dumping area, as there is a plan to remediate the site. The leaching concentration of TDS from the open dumping site for the above three different scenarios are presented in Table 3 to 5. The predicted TDS plume movement from the open dumping site for three different scenarios is shown from Fig. 17 to Fig. 19.

Table 3. Leaching Concentration of TDS for Scenario I

Period		**TDS Concentration *(mg/l)***						
		New dumping area		**Old dumping area**				
Start year	**Stop year**	Z1	Z2	Z3	Z4	Z5	Z6	Z7
2009	2022	15000	30000	3000	10000	7000	20000	15000

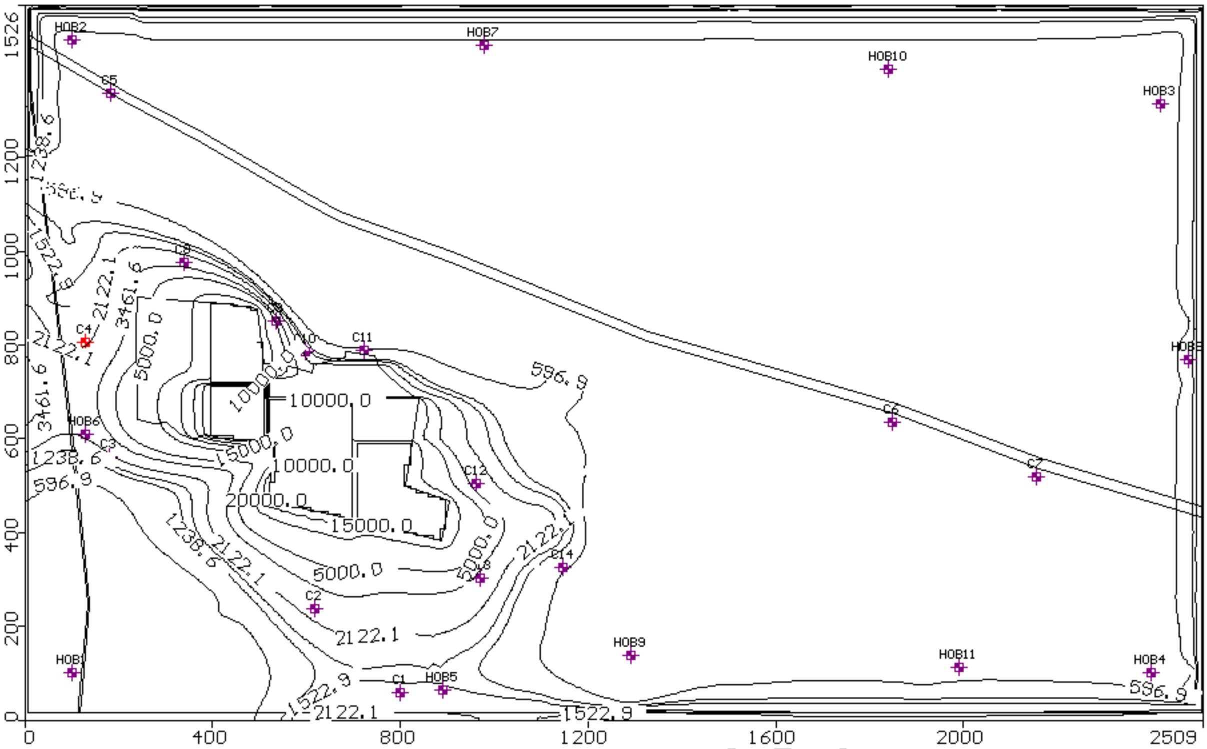
Table 4. Leaching Concentration of TDS for Scenario II

Period		**TDS Concentration *(mg/l)***						
		New dumping area		**Old dumping area**				
Start	**Stop**	Z1	Z2	Z3	Z4	Z5	Z6	Z7

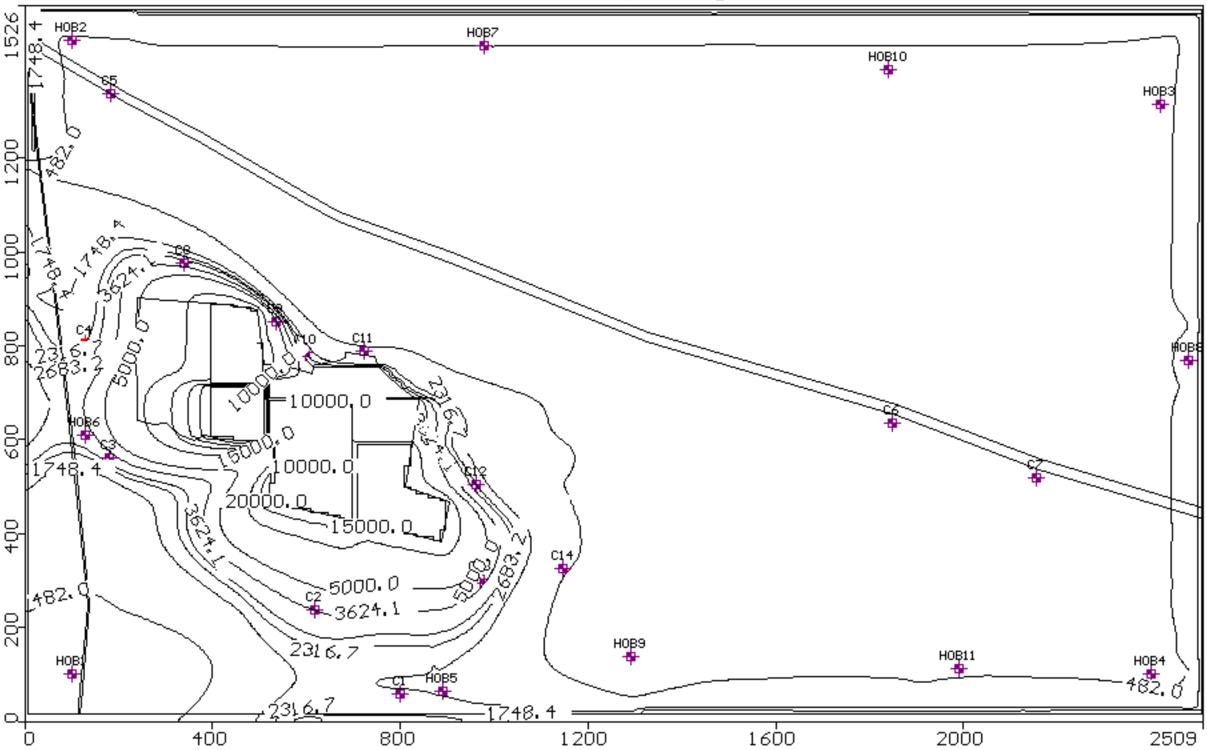
year	**year**							
2009	2010	15000	30000	3000	10000	7000	20000	15000
2010	2011	15500	30500	2800	9500	6500	19500	14500
2011	2012	16000	31000	2600	9000	6000	19000	14000
2012	2013	16500	31500	2400	8500	5500	18500	13500
2013	2014	17000	32000	2200	8000	5000	18000	13000
2014	2015	17500	32500	2000	7500	4500	17500	12500
2015	2016	18000	33000	1800	7000	4000	17000	12000
2016	2017	18500	33500	1600	6500	3500	16500	11500
2017	2018	19000	34000	1400	6000	3000	16000	11000
2018	2019	19500	34500	1200	5500	2500	15500	10500
2019	2020	20000	35000	1000	5000	2000	15000	10000
2020	2021	20500	35500	800	4500	1500	14500	9500
2021	2022	21000	36000	600	4000	1000	14000	9000

Table 5. Leaching Concentration of TDS for Scenario III

Period		**TDS Concentration *(mg/l)***						
		New dumping area		**Old dumping area**				
Start year	**Stop year**	Z1	Z2	Z3	Z4	Z5	Z6	Z7
2009	2010	15000	30000	3000	10000	7000	20000	15000
2010	2011	15500	30500	2800	9500	6500	19500	14500
2011	2012	16000	31000	2600	9000	6000	19000	14000
2012	2013	16500	31500	2400	8500	5500	18500	13500
2013	2014	0	0	0	0	0	0	0
2014	2015	0	0	0	0	0	0	0
2015	2016	0	0	0	0	0	0	0
2016	2017	0	0	0	0	0	0	0
2017	2018	0	0	0	0	0	0	0
2018	2019	0	0	0	0	0	0	0
2019	2020	0	0	0	0	0	0	0
2020	2021	0	0	0	0	0	0	0
2021	2022	0	0	0	0	0	0	0



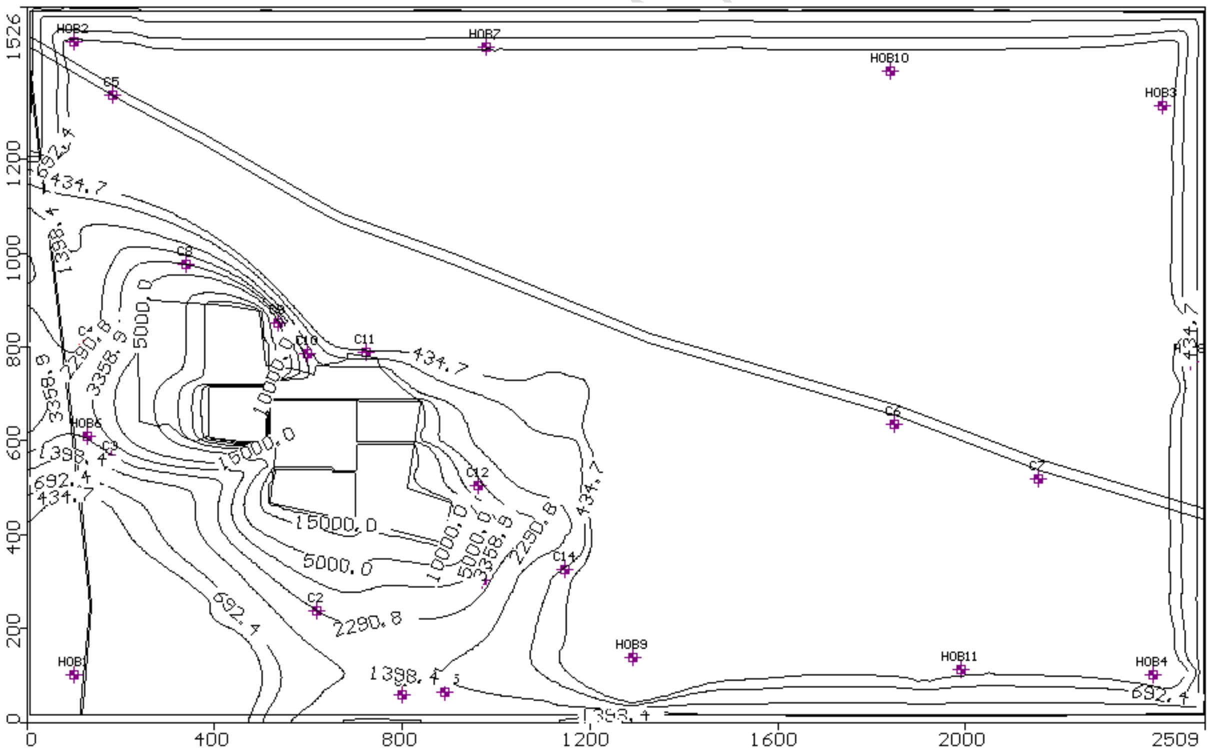
(a) December 2016



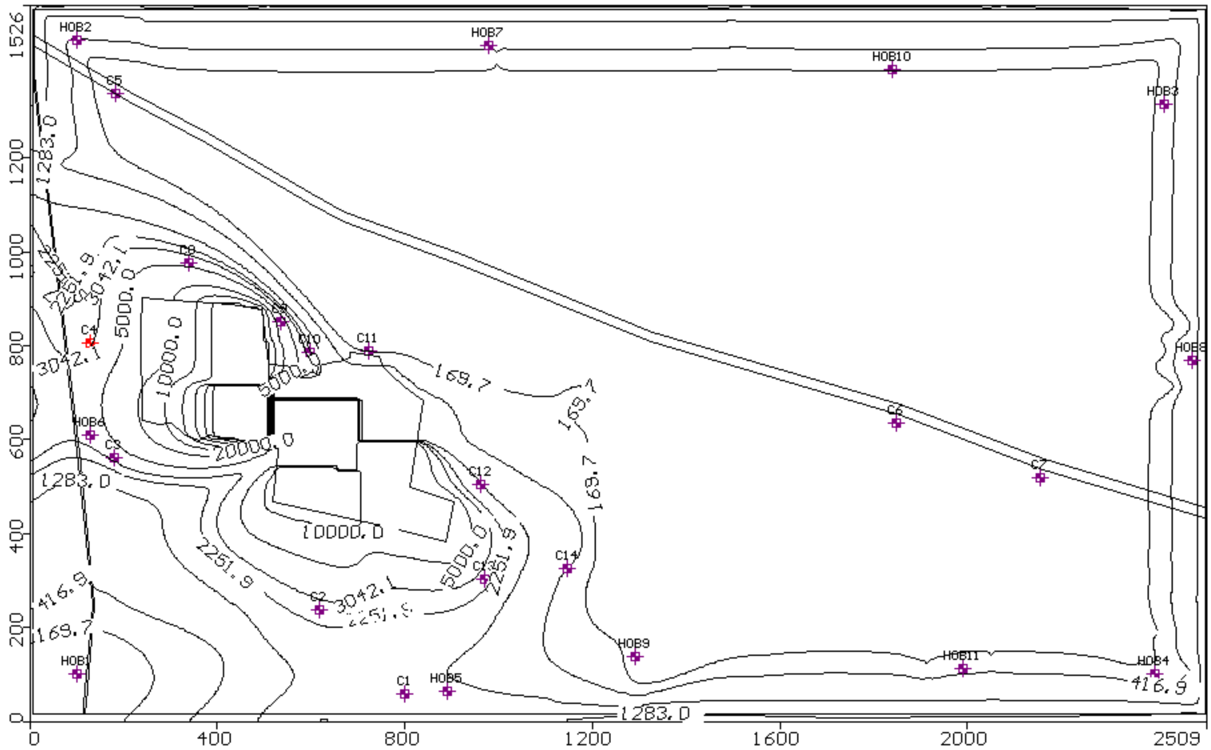
(b) December 2022

Fig. 17. Predicted Plume Movement (TDS Concentration in mg/l) for Scenario I

For the Scenario I (Fig. 17), the TDS leaching concentration from the open dumping site produced the gradual increase of TDS concentration in the surrounding observation wells. The wells located nearby the new dumping area were found to be more TDS contamination when compared to the old dumping area. The plume movement was detected towards the west and south east directions of the dumping area. The movement of plume reaches up to 250 m (December 2016) from the new dumping area along west direction and it is increased up to 300 m in December 2022. This may due to the constant concentration from the source. In the year 2010, the TDS concentration was observed as 1790 mg/l at well no. C8 then it was increased to 3461 mg/l in December 2016. Later, 3624 mg/l of TDS concentration was found in December 2022. The sudden increase in concentration from December 2010 to December 2016 may be due to the continuous leaching concentration from the open dumping site. The slight increase of TDS concentration from 2016 to 2022 indicated that the concentration reached the steady state at well no. C8. The same pattern of TDS concentration, such as the sudden increase from the year 2010 to 2016 and the slight increase from the year 2016 to 2022 was observed in all the surrounding observation wells.



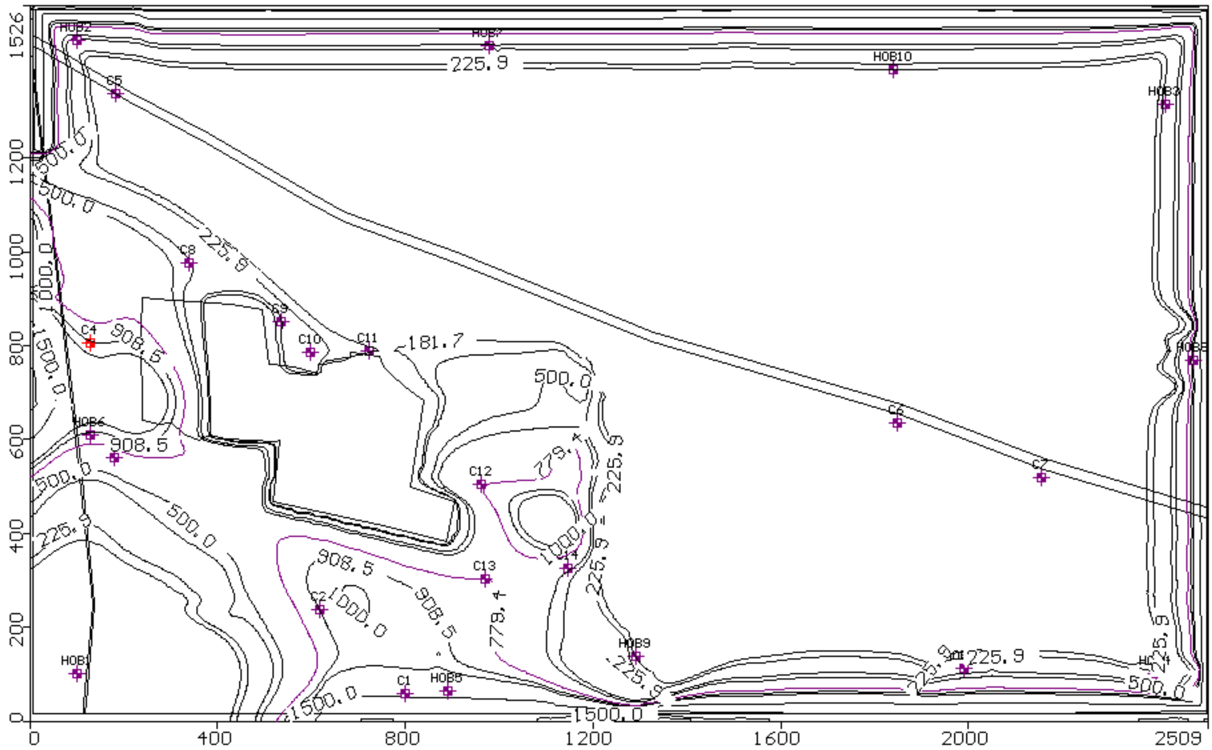
(a) December 2016



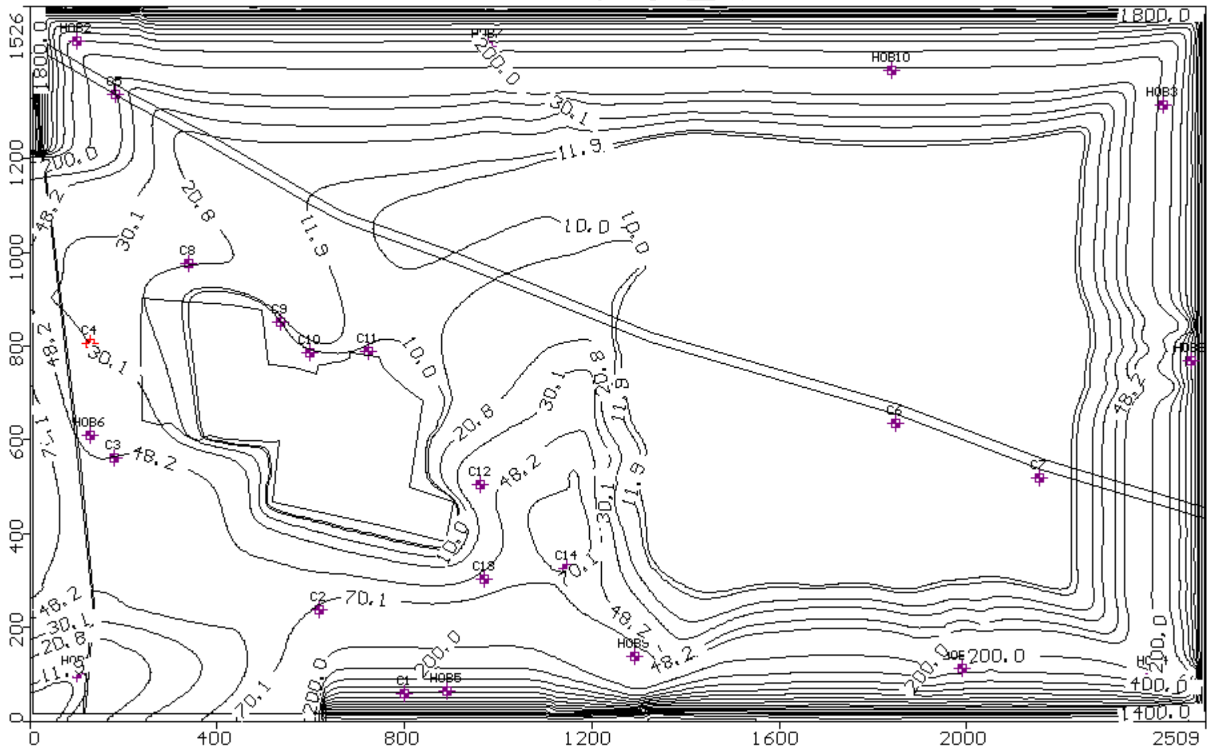
(a) December 2022

Fig. 18. Predicted Plume Movement (TDS Concentration in mg/l) for Scenario II

For the Scenario II (Fig. 18), the plume movement was increased gradually from the new dumping area along west direction whereas decrease in the movement of plume was observed (southeast) in the old dumping area. This may be due to the change in concentration in the source and change in the flow direction during the course of time. Initial plume movement (December 2010) from new dumping area indicated less spreading of TDS leaching concentration from the open dumping site. In the further sequence years (December 2016 and December 2022), the plume was widened when compared to initial plume movement with respect to distance and concentration around the study area. For the Scenario III (Fig. 19), the concentrations of TDS in all the observation wells were reduced in December 2022 when compared to December 2016. This is mainly due to the application of zero constant TDS concentration at the source from January 2014 onwards.



(a) December 2016

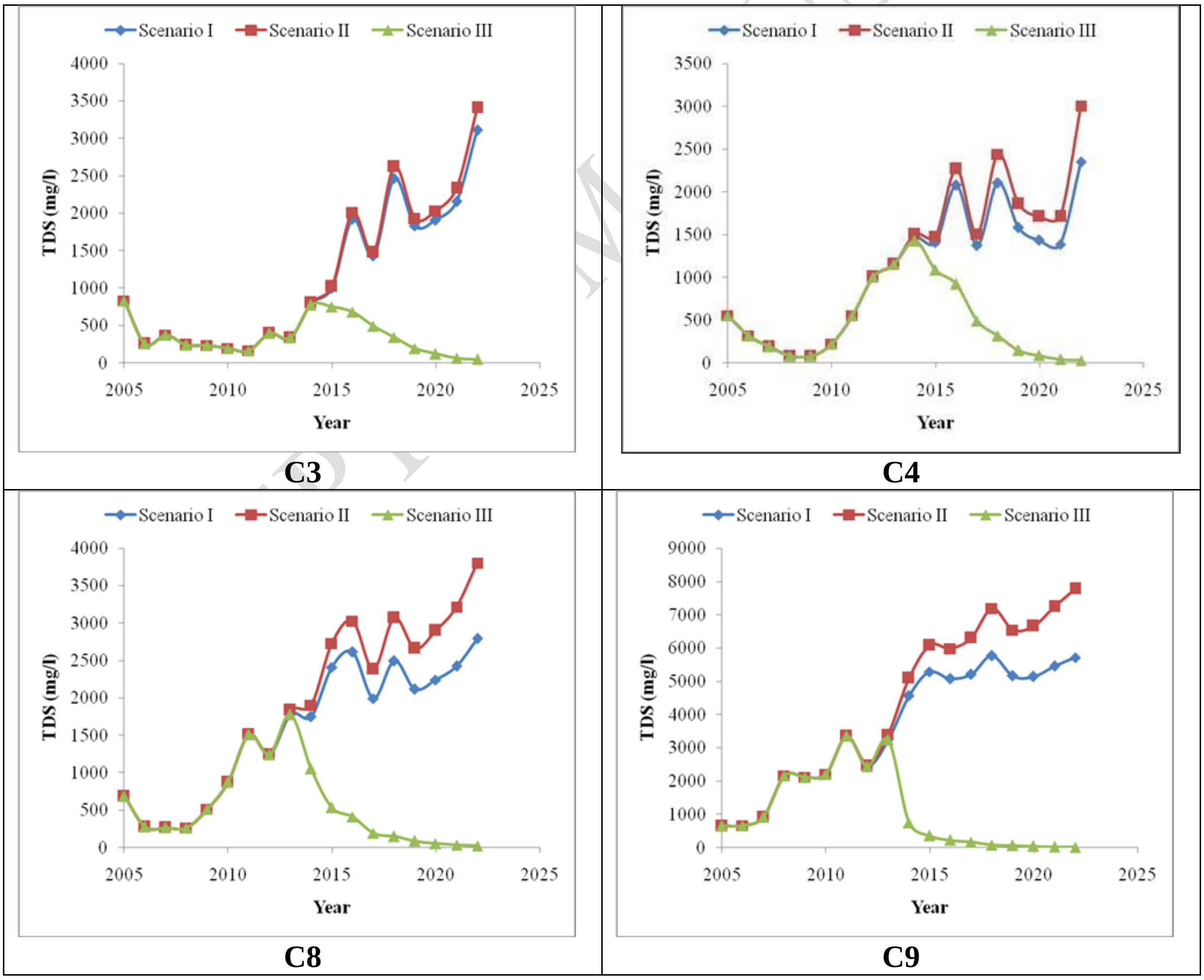


(a) December 2022

Fig. 19. Predicted Plume Movements (TDS Concentration in mg/l) for Scenario III

3.4.1 Comparison between Three Scenarios

To analyze the impact of three different Scenarios, the predicted TDS concentrations in the observation wells were compared and are shown in Fig. 20. As seen from Fig. 20, the concentration observation wells such as C3, C4, C8 and C9 indicates the gradual increase in the TDS concentration in Scenario II when compared to Scenario I. This is due to the continuous increase in leaching concentration from the new dumping area in Scenario II. In addition to that, these wells were located very near to the new dumping area. The predicted concentration in the observation wells C12 and C13 represented the increasing pattern in Scenario I, when compared to Scenario II. The reason may be due the decrease in leaching concentration from the source (old dumping area) in Scenario II. In addition to that these wells (C12 and C13) were located near to the old dumping area. By analyzing the results from Scenario – III for all the concentration observation wells, gradual decrease in concentration was observed from the year 2014 onwards. This is due to the application of zero TDS concentration from the source.



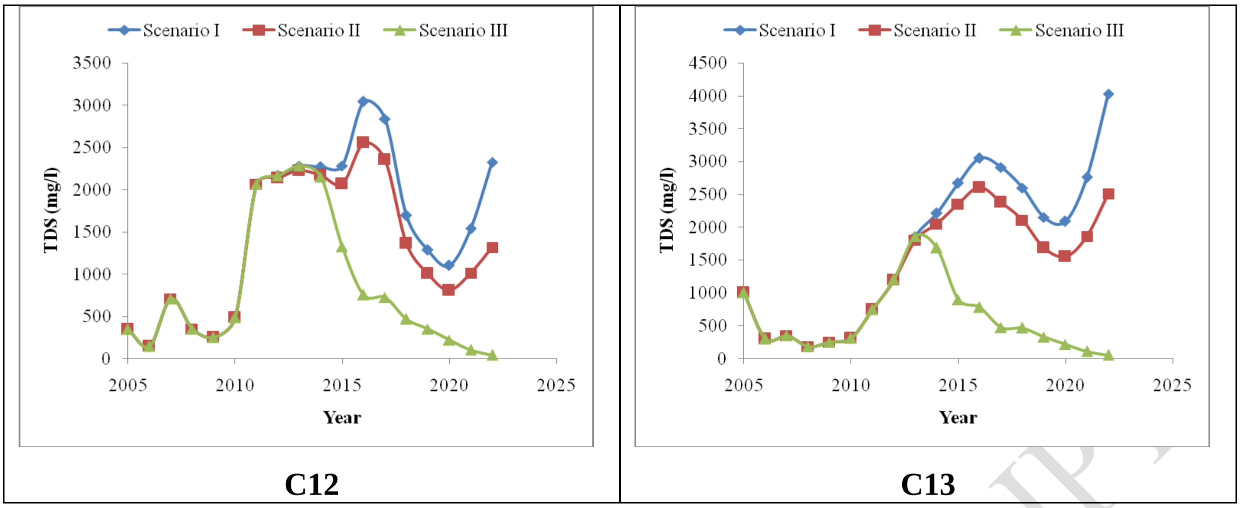


Fig. 20. Comparison of Three Different Scenarios

4. Remedial Alternatives

The concept of low permeability waste containment barrier is recommended in order to control the leachate migration from the open dumping site into subsurface system. The provision of biobarrier prevents the entry of leachate from the open dumping site and also it reduces the TDS Concentrations of the surrounding wells. The remediation measures cited by Kanmani et al. (2014), described the concept of biofilm accumulation in the sand column to control the leachate migration from the open dumping site into subsurface system. Four different combinations of column study were carried out using synthetic leachate as a substrate solution. Mixed and stratified mode of experiments with two different sizes (0.3 mm and 0.6 mm) of sand grains were used for column filling. Two columns were acting as a blank, the remaining two columns amended with mixed microbial cultures which were isolated from leachate. The column was operated with continuous synthetic leachate supply for 45 days. The results indicated that the highest hydraulic conductivity reduction occurred in the mixed sand microbial column with 98.8% when compared to stratified sand microbial column. The analysis of organic contaminants of the effluent leachate was also clearly reported that the mixed sand amended with microbes poses a suitable remedial measure when compared to natural and synthetic liners for controlling the leachate migration in the subsurface environment.

5. Conclusion

The three-dimensional groundwater flow model was developed for the present study area using visual MODFLOW (version 4.3). From the groundwater flow model calibration, fairly good visual comparison between the observed and simulated head is achieved at each observation well, with values differing by less than

1 m to 1.5 m. This is due to the variation in pumping pattern of the head observation well. In addition, consistent results are obtained for the hydraulic head distribution. From the groundwater flow model, it was found that the predominant groundwater flow direction from the open dumping site is towards west and southeast. It was also observed that, the increase in water level by 2.5 m above MSL from December 2010 (70.9 m above MSL) to December 2022 (73.4 m above MSL) around the study area. The developed groundwater flow and leachate transport model for leachate migration from an open dumping site can be effectively used to predict the leachate migration in the subsurface system. The wells located nearby the new dumping area was found to be more TDS contamination when compared to the wells located nearby old dumping area for both Scenario I and Scenario II. For Scenario III, the concentrations of TDS in all the observation wells were reduced in December 2022 when compared to December 2016. This is mainly due to the application of zero constant TDS concentration at the source from January 2014 onwards. Hence, the developed groundwater flow and leachate transport model can be effectively used for studying the leachate migration from the open dumping site into subsurface system.

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