Simulation of Flow & Transport processes of Groundwater aquifer using FEMWATER

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Abstract - *Due to excessive withdrawal of groundwater from the aquifers, contaminants present below the aquifer reaches at the well point because of more flow of groundwater towards the well. Thus, the concentration of the contaminants at the well locations increases. Some groundwater models are there to describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. Hence to know the concentration of contaminants at the well points and the transport of those contaminants, groundwater flow studies are required in detail. Though the water flow through the vadose zone is an important part of the hydrologic cycle but the modeling of flow and transport processes in this zone is a complex and computationally demanding task. Hence in this study the flow and transport processes of the contaminant concentrations are simulated for certain period to observe the pollutant distribution in the vadose zone.*

Key Words: Aquifers, Contaminants, Vadose zone, Hydrologic cycle.

1. INTRODUCTION

Generally, very little attention and efforts are given to the simulation of groundwater flow and transport processes within vadose zone by the Water Resources Engineers. But there is an urgent need for methods that can effectively simulate water flow through the vadose zone in large-scale hydrologic models to overcome some frequent simplification. For example, models that simulate surface and near-surface hydrology usually oversimplify the impact of vadose zone flow processes and rarely consider three-dimensional regional groundwater flow. Similarly, regional-scale groundwater models often simplify vadose zone flow processes by calculating groundwater recharge externally without proper consideration of changes in groundwater levels.

In this study, a three-dimensional finite element numerical groundwater model FEMWATER, has been used to simulate the flow and transport processes in a selected aquifer. The original version of FEMWATER was developed by *Yeh and Ward in 1980* and is currently being modified and maintained by the US Army Engineer Waterways Experiment Station. FEMWATER is a Saturated/unsaturated, density driven, coupled flow and transport model. FEMWATER is a public domain code that can be used with GMS, the U.S. Department of Defense graphical interface.

The execution of proposed methodology for FEMWATER is evaluated for an irregular boundary of two-dimensional illustrative study area (Fig 1). In this study area the flow and transport processes of the contaminant concentration are simulated for certain period of time to observe the pollutant distribution in the unsaturated zone. This illustrative study area is solved by using the conceptual approach available in FEMWATER, GMS.

2. Groundwater equations for FEMWATER

Two partial differential equations are required to solve the flow and transport processes of the contaminants in an aquifer and they are flow and transport equation. These are responsible for simulation of flow and transport processes in the aquifer which is simulated in FEMWATER.

2.1 Flow equation for FEMWATER

The governing equations for flow are basically the modified Richards equation. The three-dimensional flow equations for heterogeneous anisotropic medium can be written as,

$F(h)\partial h/\partial t=\nabla. [k(h). \nabla(h+z)] +q$ ……………………………….(i)

Where, F(h) is differential water capacity ($d\theta/dh$), θ is the Volume moisture content, h is height of hydrostatic pressure, t is time, k (h) – $k_r.k_s$ (hydraulic conductivity tensor), k_r is Relative hydraulic conductivity and k_s is Hydraulic conductivity tensor in saturation zone, z is Location height and q is the source element.

2.2 Transport equation for FEMWATER

The governing equations used in the FEMWATER model for transport are worked out based on the continuity of mass and flux laws.

$\Theta(\partial C/\partial t) +V.\nabla C-\nabla. (\Theta D.\nabla C) =0$ …………………………….....(ii)

Where, *V* is the discharge velocity vector (in Darcy flux), *C* is the material concentration in aqueous phase, *t* is time, *D* is the dispersion coefficient, α_T is the transversal dispersivity and α_L is the longitudinal dispersivity.

3. Overview of the study area

The practical applicability of the model is applied in Deepor Beel area which is situated in Guwahati, Assam. Deepor Beel (Beel means wetland or large aquatic body in Assamese) is located about 10 km southwest of Guwahati city is considered as one of the large and important riverine wetlands in the Brahmaputra valley of lower Assam, India. Fig 1 shows the study area of Deepor beel.

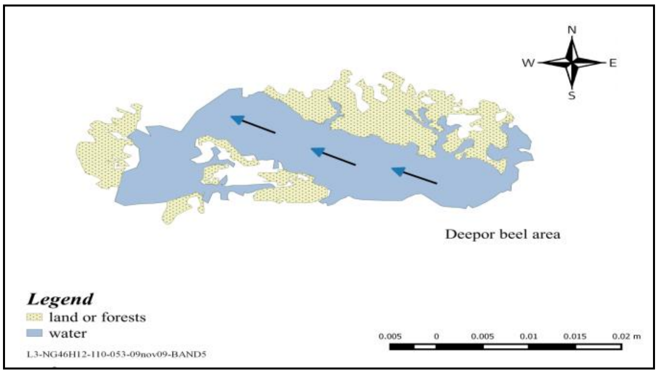

Fig 1: Study area of Deepor Beel

The execution of the proposed methodology is applied in the study area as shown in the Fig. 2, to show the field applicability of the model in FEMWATER. The size of the study area is about 13.513 km^2. The west, north and east sides have constant head boundaries, but the south side has no flow boundary. There are four pumping wells and four contaminant sources are considered in the study area designated as W1, W2, W3 & W4 and S1, S2, S3 & S4 respectively as shown in the Fig. 2. Four observations well locations are also considered in the model domain, which are designated as P1, P2, P3 and P4.

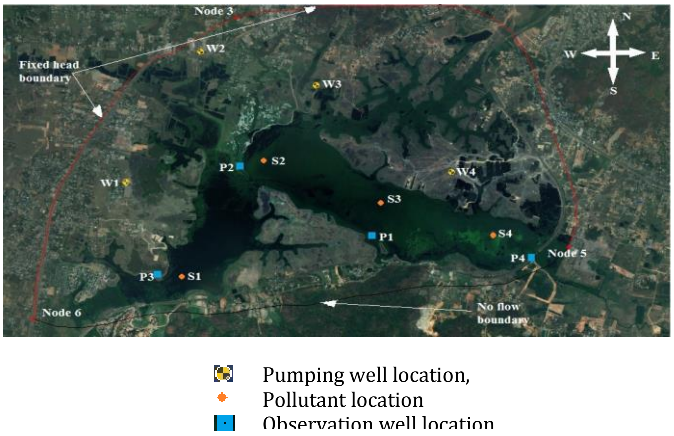

Fig. 2: Illustrative first study area

In this aquifer two materials are considered one is upper aquifer and another is lower aquifer. The upper and lower aquifers have hydraulic conductivities (K_{xx}) 3m/day and 9m/day respectively. Effective porosity (ŋ) for the upper aquifer is 0.46 and for the lower aquifer is 0.38 and longitudinal dispersivity is 40. The flow and transport simulations are made for 1000 days i.e. 2 years 8 month 27 days at constant 50 days time step and are active only for the first 11 stress periods.

4. Material Properties and considered data's

Different approaches were taken to describe the soil lithology within aquifers or materials. The material hydraulic properties for both material (upper aquifer and lower aquifer) are described in Table 1. The two materials are used to describe the single geologic realization within the vadose zone. For upper aquifer, silt is considered and for lower aquifer clay is considered.

Table-1 Material Properties used in flow simulation

Material Name	Hydraulic conductivity (m/day)	Longitudinal dispersivity	Maximum height above water table (m)	Effective porosity
Upper aquifer (silt)	3	40	2.5	0.46
Lower aquifer (clay)	9	40	1.8	0.38

4.1 Tracer Concentration for the first study area

The values of heavy metals found in the Beel water are very high with mercury recording values in the range of 12.4 µg/l – 139.9 µg/l. Some other metals that are also found in the Deepor beel, ranges in between 16.57 µg/l to 169.2 µg/l (National wetland conservation and Management Programme of the Ministry of Environment and Forests, 2008).

In this study a tracer is considered in the Deepor beel area to show the concentration distribution in the study area and the concentration values are considered in between 0.01657 mg/l - 0.1692 mg/l. The simulation is done for 1000 days for 20-time step at an interval of 50 days. As Vadose zone is the zone which is situated above the water table contained no groundwater. But during the rainy seasons due to excessive rainfall groundwater is also found in the unsaturated or vadose zone, hence this study is done when groundwater is found in the vadose zone also. Table-2 shows the concentration of four considered tracer sources of values ranging in between 0.01657 mg/l - 0.1692 mg/l. The values are considered to be active only for the first 11th time step after that the concentrations are inactive. Since the continuous pumping is done in the well locations so the pollutants are distributed in the entire groundwater aquifer hence at the tracer source locations the concentration after some time period may be almost zero. Therefore, the concentrations after 11th time step are considered as inactive i.e. the concentration values are zero.

Table -2 Tracer Concentration for the study area

Time Step	Tracer concentration (mg/l)			
	S1	**S2**	**S3**	**S4**
1	0.01657	0	0.0165	0
2	0.02547	0.06525	0.02155	0.01625
3	0.03741	0.01625	0.03523	0.0255
4	0.05541	0.0225	0.01264	0.01254
5	0.07885	0.03654	0.2583	0.03694
6	0.01565	0.06694	0.06992	0.04875
7	0.125	0.1112	0.08541	0.155
8	0.1472	0.1235	0.03654	0.1692
9	0.1657	0.1658	0.12236	0.1698
10	0.16	0.169	0.1688	0.16798
11	0	0.1682	0.165	0

4.2 Pumping values

The flow rates of water in the pumping locations as shown in the Fig. 2 are given in the Table-3.

Table-3 Flow rates of water in pumping locations

Time step	**Flow rate (m^3/d)**	**Time step**	**Flow rate (m^3/d)**
1	-3000	11	-4555
2	-3250	12	-3555
3	-4650	13	-4650
4	-4555	14	-3555
5	-3222	15	-3222
6	-3222	16	-3250
7	-3000	17	-4550
8	-3250	18	-4855
9	-4550	19	-3000
10	-4855	20	-3250

The flow rates are considered as transient condition as 20-time steps are considered from which the concentrations are active only for 11-time steps.

5. Results and Discussions of the study area

FEMWATER is used to compute pressure heads and total heads in the aquifer under transient-state conditions for the modeled area. FEMWATER is used to simulate flow processes for 1000 days at an interval of 50 days. The model consists of 903 numbers of total nodes with 3240 triangular elements forming a 3D mesh. Specified heads are assigned at three nodes of the fixed head boundary which is assigned automatically in the whole boundary (the red portion of Fig. 2) as flow boundary condition. Node number 6 and 3 are in the west and north side of the fixed head boundary as shown in the Fig. 2 and node number 5 is in the lower east side of the fixed head boundary. The specified heads at nodes 6, 3 and 5 are 130 m, 140 m and 80 m. After simulating the flow processes, FEMWATER is again used to solve the transport processes to observe the distribution of tracer concentration for the same time period. At every time step within the numerical model, flow and transport equations must be solved for every node within the model's finite element mesh.

5.1 Head Distribution in the aquifers by using FEMWATER

The output of the flow simulation results obtained the total head at every time step. Since transient pumping is used in the aquifers, the head distributions are different for different time period.

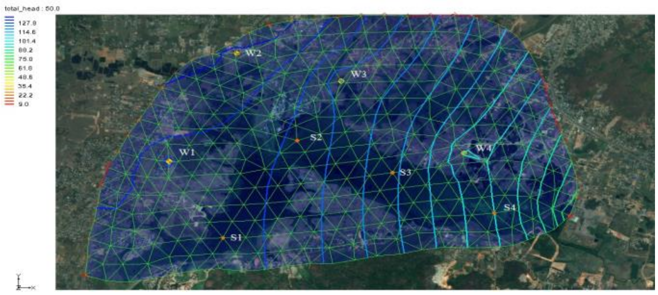

Fig. 3: Head distribution after 50 days

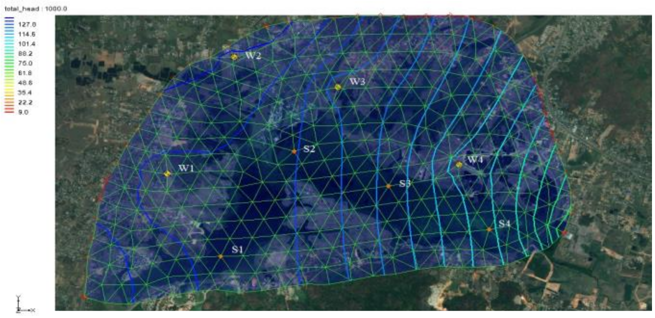

Fig. 4: Head distribution after 1000 days

The above figures show the head distribution in the aquifers by using finite element FEMWATER flow model after 50 days and 1000 days. It can be observed from the Fig. 3 and Fig. 4 that the head is more in the left side of the model and decreases towards the right side of the model. The head values are obtained at this time step near well 1 (W1), well 3 (W3) and near the tracer source 4 (S4) are 128.44 m, 120.71 m and 97.823 m respectively after 50 days and 129.23 m, 121.36 m and 98.73 m after 1000 days respectively. As the transient condition is used to simulate the flow process the head distributions are varied with every time step and this is due to the differences in the starting heads. The values in both the aquifer is almost same.

5.2 Distribution of Tracer Concentration

The transport simulation process is done for 20-time steps using transient state condition. The distribution of the pollutant at each and every time step is different. The four tracer concentrations are considered as point sources in the upper aquifer but after simulation it is distributed in the entire aquifer. So, by clicking at any point in the lower aquifer the concentrations can be read at that point in the FEMWATER model. The tracer concentration distribution is different from the previous steps depending on the concentration values.

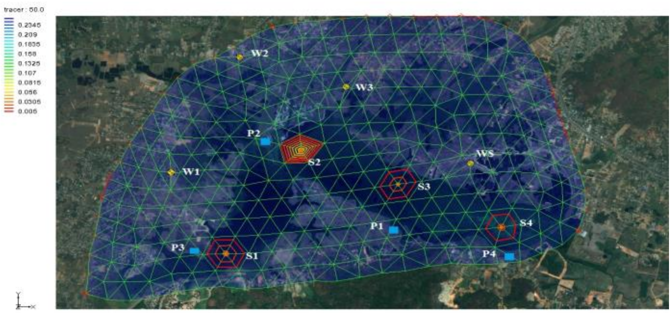

Fig. 5: 50 days point source contour

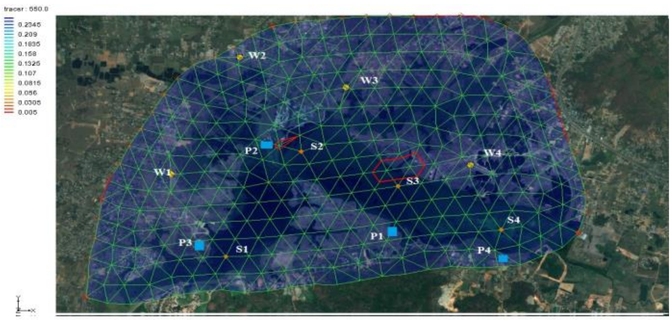

Fig. 6: 550 days point source contour

Fig. 5 & 6 shows the tracer concentration distribution after 50 days & 550 days in the upper aquifer. The pollutants in the aquifers are active up to 11th time step i.e. up to 550 days. Therefore, the tracer concentration distribution after 550 days shows that, the concentration is decreasing near the pumping wells. The concentration values after 50 days at observation well P1, P2 & P4 are 000012 mg/l, 0.00045 mg/l and 0.000019 mg/l. The concentrations attained at P1, P2, P3 & P4 are 0.00052 mg/l, 0.0060 mg/l, 0.000250 mg/l and 0.000946 mg/l respectively. The concentration values obtained after 550 days are higher than the vales obtained after 50 days time period.

As the concentrations from 11th time step is inactive so the distributions are moving away from their original location. The lower aquifer reaches very less concentrations than the upper aquifer. After this time step the concentrations are decreasing very slowly at the four-point source locations and they distributed in the entire aquifer

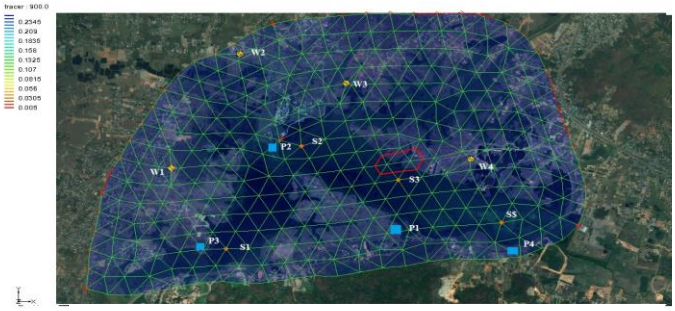

Fig. 7: 900 days point source contour

Hence the concentration attained after 900 days at P1, P2, P3 & P4 are 0.00046 mg/l, 0.0052 mg/l, 0.00025 mg/l and 0.000922 mg/l respectively. Breakthrough curves are prepared to observe the concentration trend after every time step at three observation wells.

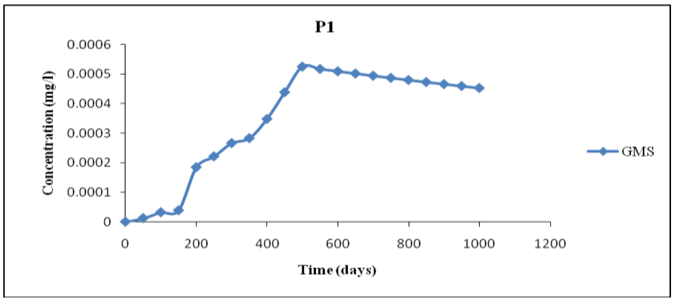

Fig. 9: Breakthrough curve at observation well P1

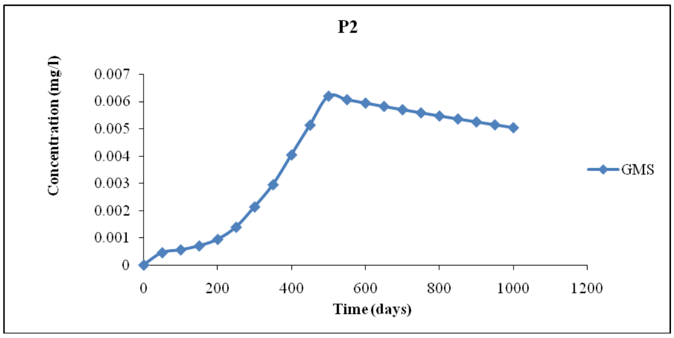

Fig. 10: Breakthrough curve at observation well P2

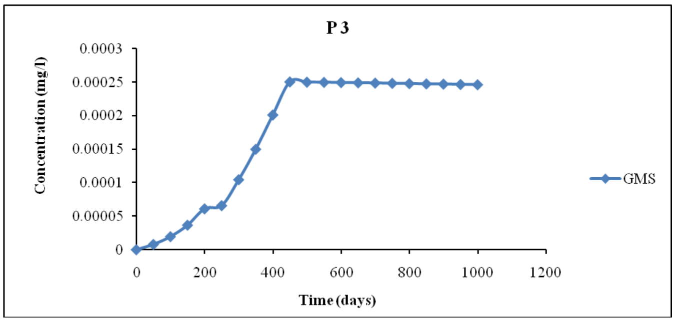

Fig. 11: Breakthrough curve at observation well P3

The tracer concentrations are distributed in the entire aquifer during the simulation period that can be observed at any time step at the observation wells P1, P2 & P3. As the tracer concentrations are active up to 11th time step i.e. 550 days, so the concentration reaches peak at 550 days and then it very slowly decreases and distributed in the entire aquifer. There are some non-continuations in the concentration distribution curve before 550 days; this is because the input values of tracer concentration were at some time step, decreases or increases. Non-continuation is also due to the concentrations coming from the nearby tracer source locations and overlap with each other then also may be the non-continuation of the concentration curve may occur.

6. Unsaturated curves generated in the FEMWATER model

The unsaturated curves or soil water characteristic curves are generated in the proposed FEMWATER model for the modeled area using the material properties which have shown in Table-1. Soil water characteristics curve i.e. Moisture content, Water capacity and Relative conductivity curves are obtained for the two aquifers. The curves are plotted as soil water characteristics i.e. Moisture content, Relative conductivity and water capacity against the pressure head.

The values of moisture content for lower aquifer are smaller than the values of moisture content for upper aquifer as the effective porosity values are considered smaller in lower aquifer. Moisture content for both aquifer values gradually increases with decrease in the pressure head. We can also say that more negative the pressure head lower the value of moisture content.

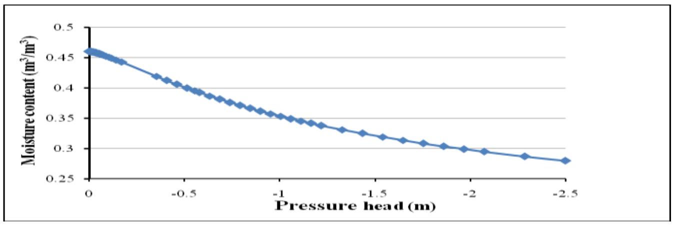

Fig. 12: Pressure head vs Moisture content Curve for the upper aquifer

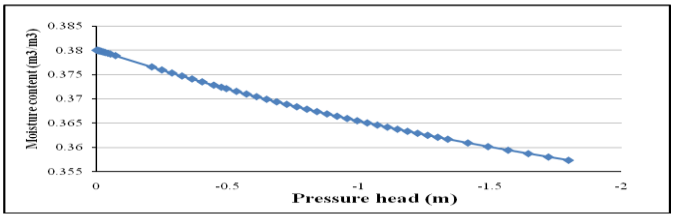

Fig. 13: Pressure head vs Moisture content Curve for the lower aquifer

From Fig. 14 & Fig. 15 it can be observed that, the values are ranging in between 0 and 1. As the Relative Conductivity ranging from 0.0 to 1.0, it expresses void spaces are only partly fluid-filled and only part of the total interconnected void spaces is connected by continuous fluid channels.

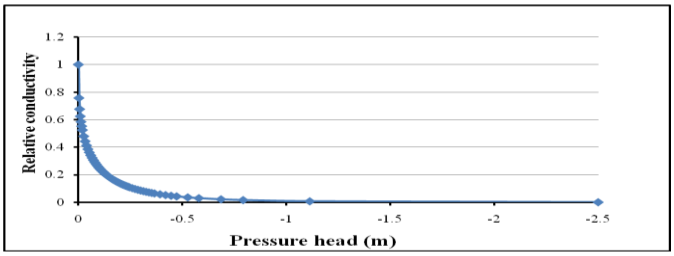

Fig. 14: Pressure head vs Relative conductivity Curve for the upper aquifer

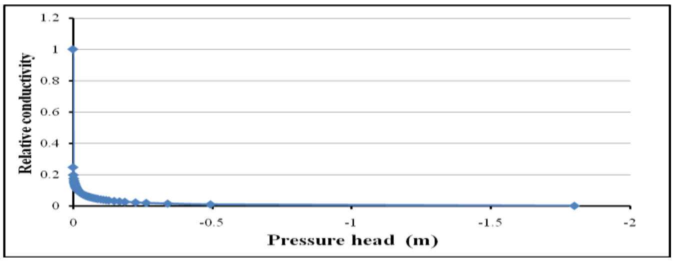

Fig. 15: Pressure head vs Relative conductivity Curve for the lower aquifer

Water capacity curve represents in Fig. 16 & 17, the variation of pressure head with respect to the slope of the moisture content curve. In this study the peaks in water capacity for the considered soil material, sand push the limits of model convergence as water capacity is more in the upper aquifer material.

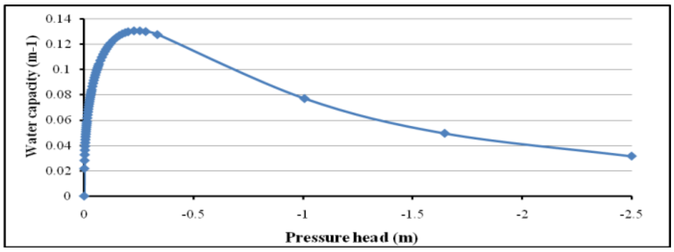

Fig. 16: Pressure head vs Water capacity Curve for the upper aquifer

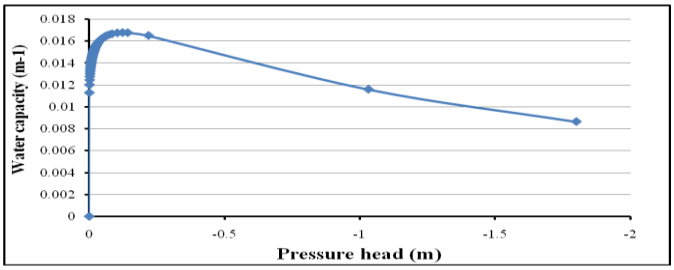

Fig. 17: Pressure head vs Water capacity Curve for the lower aquifer

7. Conclusion

In this study, the flow and transport processes of the contaminant concentrations are simulated for certain period of time using FEMWATER (GMS). To know the distribution of some tracer concentrations at the well locations or in the entire aquifer in the vadose zone of the Deepor Beel area, FEMWATER is very useful. Using this software Groundwater models can be easily made. This also helps to generate the soil water characteristic curves for the selected material properties. Using the transient pumping in the pumping wells it is possible to observe the tracer concentration in different observation well locations. The time concentration curves were prepared at some observation well locations to observe, how the tracer concentration is distributed in the vadose zone of the entire groundwater aquifer and their increasing or decreasing trend of the curve.

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