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Simulation of Flow and Transport Processes of a Confined Aquifer using Groundwater Modeling System applying Grid Approach

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Abstract

Throughout the world groundwater is an important source of water supply. Groundwater table is decreasing in many parts of the world due to overexploitation and unplanned pumping in the aquifer. Another problem in groundwater is extensive contamination due to various point and non-point sources. This current study presents a new simulation method by using the groundwater simulation software (GMS). This method proposes by linking user friendly commercial groundwater simulation software GMS with MATLAB for simulation of non-uniform aquifer. GMS is a complete program for building and simulating groundwater models. It is one of the most sophisticated groundwater modelling software through which we can simulate the flow and transport processes. The simulation packages MODFLOW and MT3DMS available in Groundwater Modelling System (GMS) are used to simulate the flow and transport processes in an aquifer. Two partial differential equations, the flow equation and the transport equation have been used to simulate both the flow and transport processes of the contaminants in the aquifer.

Keywords: Groundwater contamination; Non-uniform aquifer; Groundwater modelling system (GMS); Flow and transport processes; MATLAB; Simulation.

1. Introduction

Groundwater contamination has emerged as one of the Nation's primary environmental concerns. It is the occurrence, distribution and movement of contaminated water below the surface of earth that basically relates to water accumulation through generations by water infiltrating into the earth's crust from all natural and artificial water sources. The sources may be seen in any three phases of water forms which proves to be the basic necessity of the entire mankind making it utterly vulnerable to every possible causes of exploitation. Causes of exploitations are innumerable starting very first from excessive use of fertilizers and accumulation of toxic materials in all water sources. This never ending process leaves traces of some unidentified pollutant sources in an aquifer and pollution distribution takes place due to steady or transient pumping. Therefore, the pumping should be done in such a way that the entire aquifer does not dry up due to the continuous pumping.

Some famous yet efficient methodologies that have been put forwarded by some great people in time are of great importance with this discussion. The Galerian method of approximation in conjunction with the finite element method of analysis was used to simulate the movement of groundwater contaminants [7]. A nonlinear simulation-optimization model was developed to determine optimal strategies for contaminated groundwater remediation. The nonlinear programming algorithms available in MINOS (Modular In-core Nonlinear Optimization System) were used to solve the designed problem. The management model was solved both for steady and transient conditions [1]. The identification of the unknown groundwater pollution sources was studied by using linked simulation–optimization approach. The groundwater flow and transport simulators were linked to the nonlinear optimization model as an external module. The groundwater simulation model SUTRA (Saturated Unsaturated Transport) was linked with the optimization program MINOS. The computational efficiency of these models has been evaluated using hypothetical sources identification problems [3]. Artificial neural network (ANN) based methodologies, and a genetic algorithm (GA) based linked simulation optimization methodology was developed that would facilitate optimal identification for unknown groundwater pollution sources using concentration measurement data [10]. Three steps solution methodology was described to identify optimal dynamic monitoring network design and identification of unknown groundwater pollution sources. SUTRA (Saturated Unsaturated Transport) model was used for simulating the groundwater flow and transport processes [4].The methodology for optimal identification of unknown groundwater pollution sources was developed by linking flow and transport numerical simulation with classical nonlinear optimization [5]. GMS was linked with MATLAB-based optimization procedure for solving groundwater source identification problem [3].

In this study**,** a new methodology has been proposed by linking the most advanced groundwater simulation software GMS (Groundwater Modelling System) with MATLAB for simulation of non-uniform aquifer by using Grid approach. GMS is a complete program for building and simulating groundwater models. GMS contains numerous numerical models and support features for modelling the groundwater environment. The simulation packages MODFLOW and MT3DMS available in Groundwater Modelling System are used to simulate the flow and transport processes.Two partial differential equations, the flow equation and the transport equation have been used to simulate both the flow and transport processes of the contaminants in the aquifer. When GMS executes MODFLOW and MT3DMS, it saves input and output data in a number of flies in a modular pattern. Output data generated by MODFLOW is used by MT3DMS while solving transport model. So, for setting a MT3DMS simulation there should be a MODFLOW simulation. In this study, a MATLAB code is developed to open and change the input files of MT3DMS. This code can simulate the flow and transport processes in an aquifer for any arbitrary concentration source parameters.

2. Methodology

Two partial differential equations, the flow equation and the transport equation have been used to simulate both the flow and transport processes of the contaminants in the aquifer.

2.1. Groundwater Flow and Transport equation

A transient, two-dimensional, areal groundwater flow equation for a heterogenous, anisotropic and fully saturated aquifer given by [2] be written as-

$$\frac{\partial}{\partial x_i}\left(Tij\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial x_j} + Q - W \qquad (1)$$

Where, S is the storage coefficient; $T_{ij=}$ K_{ij}b is the transmissivity tensor (L^2T^{-1}); K_{ij} is the hydraulic conductivity (LT^{-1}); b is the saturated thickness of the aquifer (L); h is the hydraulic head (L); t is the time(T); Q is the pumping rate per unit area (LT^{-1}); W is the recharge flux per unit area (LT^{1}); x_i and x_j are the Cartesian coordinates.

The two-dimensional solute transport given by [6] be written as -

$$\frac{\partial(cb)}{\partial t} = \frac{\partial}{\partial x_i}\left(bDij.\frac{\partial c}{\partial x_j}\right) - \frac{\partial(bcv_i)}{\partial x_i} - \frac{c'W}{\eta} + \frac{c'Q}{\eta}$$
$$i, j = 1,2 \qquad (2)$$

Where, b is the saturated thickness of the aquifer (L); c is the concentration of the dissolved chemical species(ML^{-3}); D_{ij} is thecoefficient of hydrodynamicdispersion (second order tensor) (L^2T^{-1}); c' is the concentration of the dissolved chemical in a source or sink fluid (ML^{-3}); v_i is the seepage velocity in the direction x_i (LT^{-1}); ŋ is the effective porosity of the aquifer (dimensionless); Q is the pumping rate per unit area (LT^{-1}); W is the recharge volume flux per unit area (LT^{-1}).

2.2 Study area

The performance of the proposed methodology is evaluated for irregular boundary of two-dimensional illustrative study area. The confined aquifer of the study area has a size of 1.62km^2 (1.8 km × 0.9 km).The boundary of the aquifer is irregular and grid size is considered as 100m by 100m. There are 9 rows and 18 columns. The boundary condition of the aquifer is considered as time variant. Both north and south boundaries are no flow boundaries and east and west boundaries are fixed head boundary. Flow boundary condition is assumed to be constant at the east and west sides of the aquifer. At the west side of the aquifer, the head is varying from 100m to 97.5m. Similarly the hydraulic head at the east side is varying from 88m to 90.16m. Inside the aquifer, initial head is considered as 100m.This study is carried out for the illustrative study area (see figure.1)

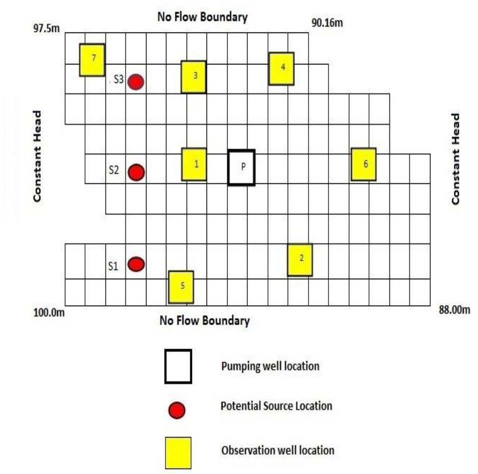

Figure 1. Illustrative Study Area.

There are three contaminant sources in the aquifer, which are designated as S1,S2 and S3 as shown in the Figure 1. The aquifer has horizontal hydraulic conductivity (Kxx) and vertical hydraulic conductivity (Kyy) of 20m/day. The effective porosity (ŋ) value of the aquifer is 0.3. The another parameter values of the aquifer are : longitudinal dispersivity(α_L)=20.0 m ;transverse dispersivity (α_T) = 9.6 m ; specific storage = 0.002 . A pumping well is located at the centre of the study area and firstly the rate of pumping is considered steady and then it is considered as transient. There are eight observation wells in the aquifer which are designated as 1,2,3,4,5,6,7.The flow and transport simulation are made for 2years using 8 stress periods of 3 months each. There are three (3) contaminant sources in the aquifer. At the time of simulating the transport sources, only two pollutants are taken as active and one is considered as inactive

The concentrations of the sources at different locations for the illustrative study area are given in the Table 1.

Table 1. Source flux for the illustrative study area.

Time Step	Source Flux (gm/sec)		
	S1	S2	S3
1	116.48	0	116.48
2	97.06	0	97.06
3	58.24	0	0
4	0	0	254.31
5	163.07	0	132.02

The different pumping rates of water in the pumping location are given in the Table 2.

Table 2. Pumping rate of water in pumping location.

Time step	Discharging rate (m^3/d)	Time step	Discharging rate(m^3/d)
1	120	5	115
2	130	6	125.95
3	118.75	7	148.95
4	135.70	8	159.60

2.3 Model Development by GMS :

Groundwater Modelling System (GMS) is the most efficient groundwater modelling software available. It is a complete program for simulating groundwater models. In this study, the flow and transport processes of a non-uniform aquifer can be observed by using the GMS. GMS contains two computer softwares, MODFLOW and MT3DMS for the flow and transport simulation of the non-uniform aquifer.GMS first runs MODFLOW and then it executes MT3DMS while solving the transport model. So for setting a MT3DMS simulation, there should be a MODFLOW simulation.After the execution of MODFLOW and MT3DMS, GMS saves input and output data in a number of files in a modular pattern. The input and output files of GMS are linked with MATLAB, to read the binary files produced by GMS. A code is developed in MATLAB to open and change the input files ofMT3DMS. Since binary head files cannot be opened in GMS, therefore, binary head file generated by MODFLOW can be opened in MATLAB and used to plot head contour. In this way, binary concentrations can also be opened in MATLAB and is used to plot contour for concentration of contaminants.

3.Results and discussions

3.1 Head distribution when there is Steady pumping by using MODFLOW.

Assuming the rate of steady pumping as Q_1=11500m^3/d and the recharge rate as 0.0009 m/d, the head distribution in the aquifer can be observed when there is a steady pumping (See Figure 2).

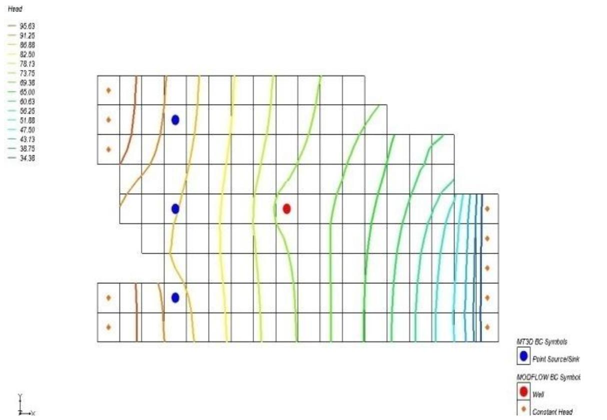

Figure 2. Head distribution during steady pumping

3.2 Pollutant distribution during transient pumping by using MT3DMS

A number of 2D transient transport simulation is performed using MT3DMS. The distribution of the pollutant at each and every time step is different from the previous step.It can be observed that the pollutant concentrations are moving towards the pumping well after 90 days of the concentration distribution (See Figure 2) due to continuous pimping of water from aquifer. Likewise, it can be observed that more and more pollutant concentrations are moving towards the well due to the continuous pumping after 180, 270, 360 days. Same situation has been observed as shown after 450 days (See Figure 3). It may be noted that the upto this period, the sources in the aquifer are active. The concentration distribution after 540 days (See Figure 4) shows that the pollutant concentration is decreasing near the pumping well. This is because the sources are considered as inactive now. Likewise after 720 days, it can be observed that the pollutant concentration slowly tends to disappear from the aquifer as the sources were not active for a longer period (See Figure 5).

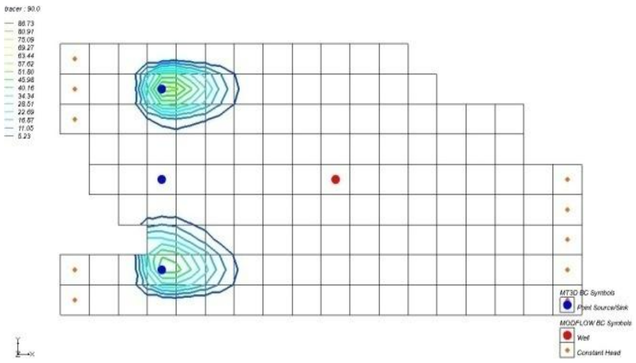

Figure 3. 90 days point source contour

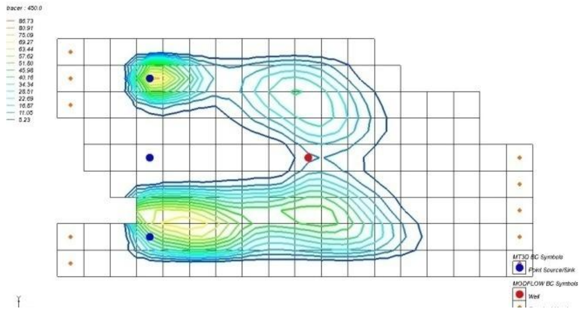

Figure 4. 450 days point source contour

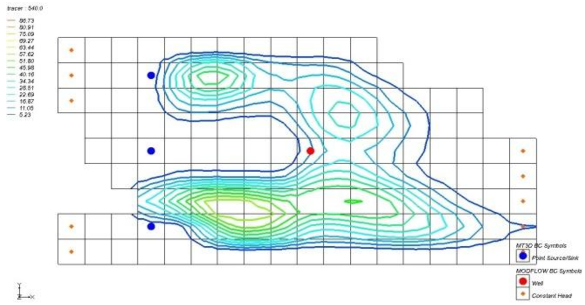

Figure 5. 540 days point source contour

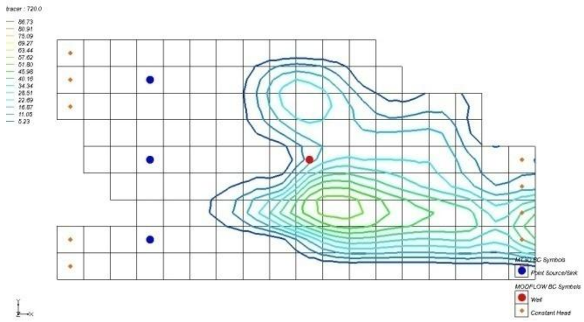

Figure 6. 720 days point source contour

4. Conclusion

In this paper, GMS has been proposed for the simulation of flow and transport processes of a non-uniform aquifer by using the user-friendly commercial software Groundwater Modelling Sytem (GMS). GMS is theefficient software platform for creating groundwater simulations. The two computer packages MODFLOW and MT3DMS available in GMS have been used in this methodology to simulate the flow and transport processes in the non-uniform aquifer. After linking GMS with MATLAB, the concentrations of the inactive pollutant can be read. The performance of the proposed methodology is evaluated for irregular boundary of two-dimensional illustrative study area.

The performance of this methodology is encouraging even when applied to complicated problem also. Further studies will be necessary to judge the full potential of the proposed methodology.

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