Impact Assessment of Hydrologic and Operational Factors on the Efficiency of Managed Aquifer Recharge Scheme

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Abstract: In this paper, groundwater flow models were created to assess the impact of hydrologic and operational parameters on the aquifer within the context of managed aquifer recharge project implementation. Flow /particle tracking models were used to track the movement of injected water during injection, storage and possible recovery. We used the software package COMSOL Multiphysics 4.3 and Visual MODFLOW to create the groundwater flow and transport models. This paper examines and compares the performance of both models. The simulation results show similar groundwater flow pattern in both models. Later on, COMSOL model was used to simulate different options of MAR project.

Keywords: Managed aquifer recharge, operational parameters, groundwater flow, particle tracing, COMSOL, Dhaka.

1. Introduction

Managed Aquifer Recharge (MAR) is the process of augmentation of the natural movement of surface water into subsurface by technique of construction, by surface spreading of water or by artificially changing natural conditions (Todd, 1980). To enhance the natural supply of groundwater, MAR is becoming increasingly important in groundwater resources management and particularly in situations where the conjunctive use of surface water and groundwater resources is considered (Asano, 1985). MAR has been practiced for a number of years in many countries (e.g., in Australia, the USA, Israel) and for a wide variety of water resource management purposes, e.g., for groundwater development in India (CGWB, 2000), rehabilitation of the coastal aquifer in Israel (Abbo and Gev, 2008), prevention and control of surface subsidence in China (Wang et al., 2010), wastewater reuse and storm water management in Australia (Thomas et al., 1997), and Aquifer Storage and Recovery in Arizona, USA (Lluria, 2011). In recent years, substantial progression has been achieved in the scientific understanding of MAR processes and the technologies associated with MAR have been increasingly extended and optimized. Basically, the selection of MAR technologies depends prevailing geological and hydrogeological condition of the area. Hence, it is always required to perform a pre-study before planning of MAR project.

In this study, cascade type recharge pit was considered for simulation. In this paper, groundwater flow models were created to assess the impact of hydrologic and operational parameters on the aquifer within the context of MAR project implementation. Flow /particle tracking and solute transport models were used to track the movement of injected water during injection, storage and possible recovery. We used the software package COMSOL Multiphysics® 4.2 and Visual MODFLOW to create the groundwater flow and transport models.

2. Study Area

Due to increased demands on groundwater accompanied by increased drawdowns (ca. 2-3 meters/year), technologies that use alternative water resources have been suggested for Dhaka City, Bangladesh. Preliminary studies show that managed aquifer recharge (MAR) would help in optimal use of available water resources and to reduce adverse effects of pumping in the Dupitila aquifer of the city. In this paper two potential approaches are considered to implement MAR using rainwater in Dhaka City. The approaches are: storm run-off harvesting and roof top rainwater harvesting combined with managed aquifer recharge. This study estimated that 20% of today's water demands could be met by rainwater harvesting. It is suggested, by Rahman 2011, that recharge trenches and pits would be the most appropriate MAR technique that can be implemented in most parts of the recharge area (ca. 277 km^2 out of 370 km^2). In case of a recharge trench, the lower parts (15 to 20 m) that are in direct contact with the aquifer can be backfilled with biosand filters (BSF) with a reactive layer containing metallic iron (Fe^0) to offer pre-treatment of the infiltrated water. Regarding water quality of the injected water, residence time of more than 6 months is recommended. As the distribution of pumping wells in the city is very dense, it is important to investigate the movement of the groundwater in the aquifer after injection. As a first step, this paper presents the preliminary results of the groundwater flow behavior under the water injection scenario. The flow behavior with in the recharge trench was not consider at this stage.

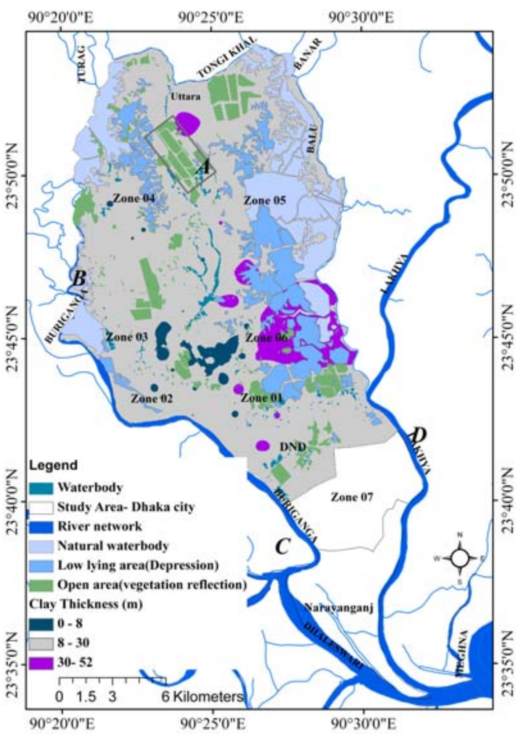

Figure 1: Study area showing Clay thickness, natural water bodies, lowlands, and wetlands in Dhaka City (based on data obtained from Sultana, 2009 and modified afterwards)

For examining the scenario, a place in the Dhaka City (See Figure 1 and 2) was selected where no pumping wells are functioning except one deep well. In this study, only upper aquifer was considered for simulation.

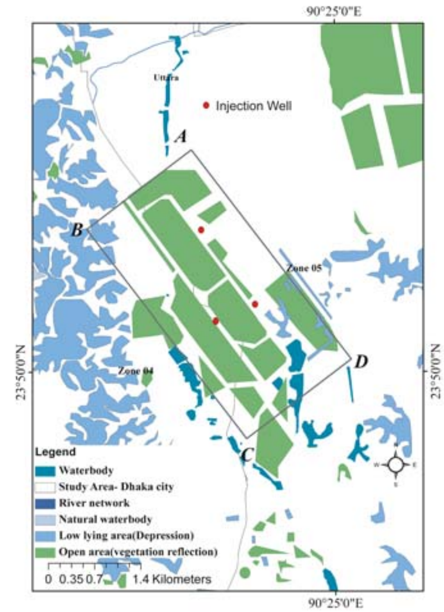

Figure 2: View of the model area with exemplary injection well location.

3. Methods and Model description

In this study two separate groundwater flow model were developed. We used visual MODFLOW and COMSOL Multiphysics®.

Visual Modflow is renowned software for groundwater flow and transport simulation. Visual Modflow is a complete and easy-to-use modeling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations. It is a finite difference model (Harbaugh and McDonald, 1996), which solves a system of equations describing the major flow and related processes in the hydrological system. The partial-differential equation of groundwater flow used in Visual Modflow can be represented by the equation 1 as shown below:

$$\frac{\partial}{\partial x}\left(K_{XX}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{YY}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{ZZ}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (1)$$

Where,

K_{xx}, K_{yy}, and K_{zz} = Values of hydraulic conductivity along the x, y, and z coordinate axes (L/T);

h = Potentiometric head (L);

W=Volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for

flow out of the ground-water system, and W>0.0 for flow in (T^{-1});
S_S = Specific storage of the porous material (L^{-1});
Visual Modflow uses rectangular grid to discretize the model domain.

Porous media and subsurface flow package that is included in COMSOL Multiphysics® (COMSOL AB, 2008) were used. Darcy's law was used to simulate the groundwater flow and particle tracing was used to demarcate the zone of influence of the recharge water. Darcy's law can be explained as follows:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\nabla.(\rho.u)=Qm \quad (2)$$

$$u=-\frac{\kappa}{\mu}\nabla p \quad (3)$$

Where,
u = Darcy velocity or specific discharge vector (SI unit: m/s);
κ = permeability of the porous medium (SI unit: m2);
μ = fluid's dynamic viscosity (SI unit: Pa·s);
p = fluid's pressure (SI unit: Pa)
ρ = density (SI unit: kg/m3);
ε = porosity,
*Q*m = a mass source term (kg/(m^3·s).
COMSOL uses triangular grid to discretize the model domain (Finite element).

Model set up:

The transient flow model involves a two-dimensional horizontal cross-sectional domain (4 km x 2 km). Boundary condition for flow is a time variable constant head at all boundaries. The groundwater level for the boundaries was obtained from the geostatistical analysis that was undertaken based on the observed data at the monitoring wells of Bangladesh Water development Board (BWDB). Figure 3 and Figure 4 shows the domain geometry in COMSOL and Visual MODFLOW, respectively.

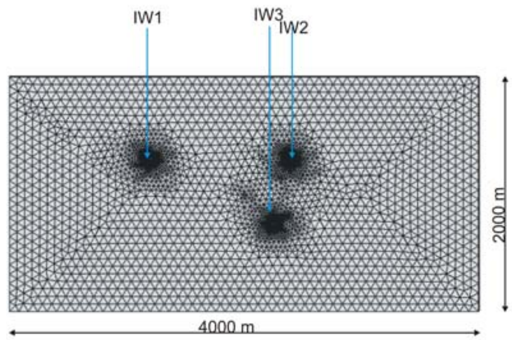

Figure 3: Model domain and mesh in COMSOL

In both modeling environment, effective Porosity, horizontal hydraulic conductivity were considered as 0.18 and 30 m/d, respectively. The model was considered as homogenous without any anisotropy. All the data were obtained from Institute of Water Modeling (IWM).

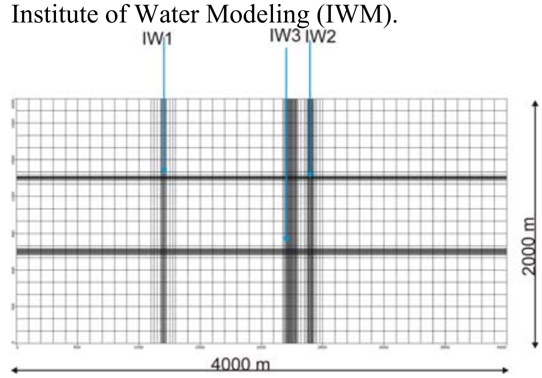

Figure 4: Model domain and mesh in Visual MODFLOW

4. Results and discussions

The models are simulated for one years (365days) without any injection scenario. Afterwards three injection wells were incorporated to each models and simulated. The groundwater level was observed for each simulation in a virtual monitoring well at position P (2000 m, 1000 m). Figure 5 shows the groundwater level comparison at COMSOL and Visual MODFLOW simulation, considering injection and no injection.

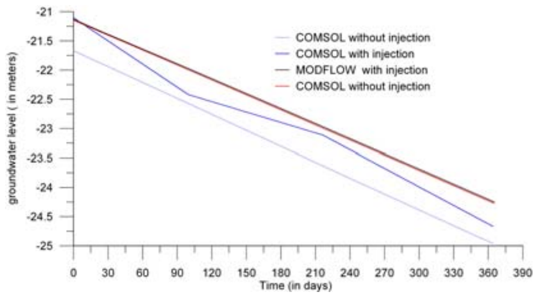

Figure 5: Comparison of GWL

The difference between two software simulations under without injection condition is much greater than with injection condition. The results for both scenarios in Visual Modflow are almost similar, whereas the difference in COMSOL simulation is prominent. This may indicate that the COMSOL model is more sensitive to any change in water injection than that of Visual Modflow. Besides these, the difference in using cell descritization, using of governing equations might play a role.

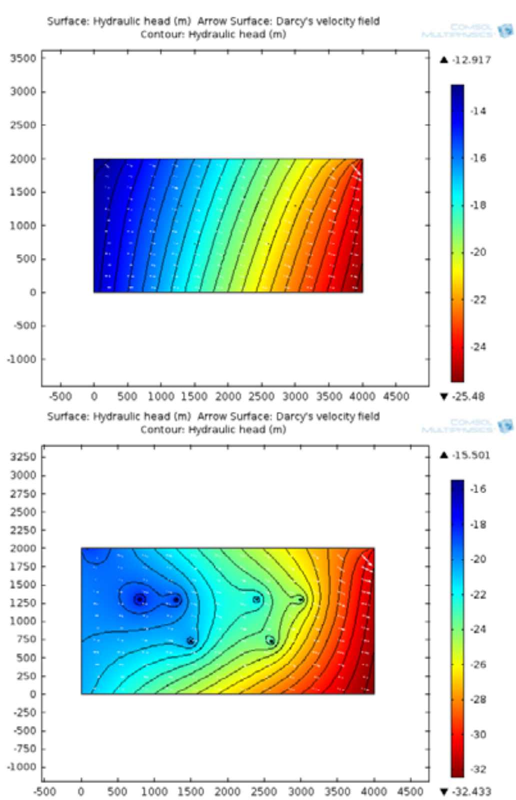

Figure 6: Groundwater flow direction (a) before injection (0 days) (b) after 2 years of injection

Figure 6a and 6b shows the groundwater level status after a long term simulation (2 years). Six injection wells were used. The result shows that more injection well is required to develop groundwater in the study area.

We used the COMSOL model in order to simulate further injection scenario. During MAR, it is recommended to recover the injected water after 180 days for water quality improvement. Particle tracing in fluid flow was used to estimate the distance for installation of injection well. Figure 7 shows the zone of influence for the injection well after after 5 years.

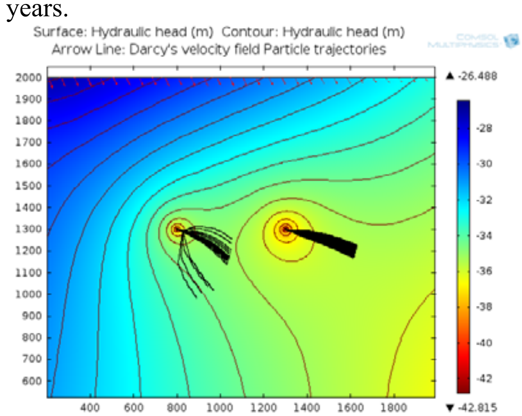

Figure 7: Zone of influence of the injected water in two injection wells at the study area

5. Conclusions and prospective

The overall aim of the study was to explore the feasibility of using COMSOL Multiphysics® for groundwater modeling under MAR implementation. Visual MODFLOW was also used for compare the COMSOL output. The two modeling software shows similar pattern of flow behavior but with significant difference in output. Further investigation is required to understand the clear difference.

Generic partial differential equation (PDE) solvers, provided by COMSOL, that are robust in handling coupled equations. Several models (1D, 2D, saturated and variably saturated etc) can be developed in the same platform using different model physics and can be combined easily. This flexibility is not available in Visual Modflow.

Another 1D flow and transport model using the Richards equation, included in COMSOL, will be created to assess the water quality changes during the injection of stormwater through the BSF filter. Heterogeneity will be included in the next step of saturated water flow simulation in COMSOL. It is also planned that both COMSOL models will be integrated to investigate the possible mixing of injected water with native water, to assess the development of clogging layers, considering physical and biological processes, and finally to optimise the height of the layers of the BSF column.

6. References

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