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Application of GIS and MODFLOW to Ground Water Hydrology- A Review

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ABSTRACT
Groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity. Due to over exploitation, the ground water systems are affected and require management to maintain the conditions of ground water resources within acceptable limits. With the development of computers and advances in information technology, efficient techniques for water management has evolved. The main intent of the paper is to present a comprehensive review on application of GIS (Geographic Information System) followed by coupling with MODFLOW package for ground water management and development. Two major areas are discussed stating GIS applications in ground water hydrology. (i) GIS based subsurface flow and pollution modelling (ii) Selection of artificial recharge sites. Although the use of these techniques in groundwater studies has rapidly increased since last decade the sucess rate is very limited. Based on this review , it is concluded that integation of GIS and MODFLOW have great potential to revolutionize the monitoring and management of vital ground water resources in the future.
***Keywords* -** GIS, Ground water management, MODFLOW, Recharge, Sub-surface modeling

I. INTRODUCTION

Sub surface water is natural resource in most countries, particularly for those in arid and semi-arid areas, due to its relatively low susceptibility to pollution in comparison to surface water (Jamrah et al., 2008). It is the source of freshwater available for all socioeconomic development. But the existence of groundwater is under great stress of degradation both in quality and quantity. Due to increase in population, lack of awareness among the people, and improper management of this valuable resource lead to depletion of potential and deterioration of the quality. Unfortunately the excessive use and continued mismanagement of water resources to supply ever increasing water demands to profligate users have led to water shortages, increasing pollution of fresh water resources and degraded ecosystems worldwide (Clarke, 1991; Falkenmark and Lundqvist, 1997; de Villiers 2000; Tsakiris, 2004). It presents a clear fact that water is finite and vulnerable resource and it must be used efficiently for present and future generations.

GIS has emerged as an effective tool for handling spatial data and decision making in several areas including engineering and environmental fields (Stafford, 1991; Goodchild, 1993).GIS provides a means of representing the real world through integrated layers of constituent spatial information (Corwin, 1996). Most GIS, can easily access overlay and index operations but cannot model groundwater flow and transport processes. However, coupling a GIS to process-based groundwater models can provide an effective tool for data processing, storing, manipulating, visualizing and displaying hydro geological information. Data used in groundwater modelling consists of four categories: (1) the aquifer system stress factor, (2) the aquifer system geometry, (3) the hydro geological parameters, and (4) the main measured variables (Gogu et al.,

2001). A well designed GIS database can significantly reduce the time required for data preparation, processing and presentation during the modelling process. Use of groundwater models in hydrogeology mainly includes the simulation of steady or transient sate groundwater flow, advection, hydrodynamic dispersion, and multi-component chemical reaction. In recent years, the use of GIS has grown rapidly in groundwater assessment and management research works. Lasserre et al. (1999) developed a simple GIS linked model for ground water nitrate transport in the IDRISI GIS environment. Visual MODFLOW is also an user friendly software that has ability to generate 3D visualization graphics and import GIS data. Xu et al. (2009) used MODFLOW 2000 (Harbaugh et al. 2000) coupled with GIS to simulate the groundwater dynamics. All of them vary both in space and time, thus adopting a Geographic Information System (GIS) in association with a model is helpful. Coupling GIS technology with a process-based groundwater model may facilitate hydro geological and hydrologic system conceptualization and characterization (Hinaman1993; Kolm1996; Gogu et al. 2001), thus also a proper adaptation of the groundwater flow model to the area under study (Brodie1998). In most of groundwater modelling softwares such as FEFLOW, MODFLOW, GMS (Groundwater Modelling System) there is an interface that links vector data through compatible GIS formats i.e. .shp, .lin, .dxf etc. and raster data formats i.e. .tif, .bmp, .img etc. Unlike surface water hydrology, the applications of GIS techniques in groundwater hydrology have received only cursory treatment and are less documented. In the present paper an attempt has been made to highlight coupling of GIS technology with MODFLOW as well as to present a state of the art review on the application of GIS techniques along with MODFLOW package in ground water hydrology.

II. Overview Of GIS Technology

GIS can be characterized as a software package that efficiently relates graphical information to attribute data stored in a database and vice-versa. GIS is used as a effective tool for developing solutions for water resources problems for assessing and mapping of ground water quality, understanding the natural environment and managing water resources on a required scale, assessing groundwater vulnerability to pollution, selection of artificial recharge sites, subsurface flow and pollution modelling.

Figure 1 shows the relationship between GIS and different types of information systems. At present, however, GIS not only represents the skills and procedures for collecting, managing, and using geographic information, but also entails a comprehensive body of scientific knowledge from which these skills and procedures are developed (Lo and Yeung, 2003).

III. OVERVIEW OF MODFLOW

MODFLOW is programmed under the FORTRAN 77 (American National Standards Institute 1978) language environment with the finite–difference method to describe the movement of groundwater flow. It was developed by McDonald and Harbaugh (1984) of US Geology Survey in 1984 and had been updated for three times including MODFLOW-88(McDonald and Harbaugh 1988), MODFLOW-96 (Harbaugh and McDonald 1996) and MODFLOW-2000 (Harbaugh et al. 2000). The newest version of MODFLOW-2000 could be compiled by FORTRAN language of Visual Studio program and general language of C could be used here.

3.1 COMPONENT OF VISUAL MODFLOW

The Visual MODFLOW is divided in three main sections such as input, run and output section. The input section of Visual MODFLOW is used to

1. Defining 3D finite difference grids,
2. Entering pumping well and observation well and attributes.
3. Defining soil properties zone, and
4. Assigning boundary conditions locations and attributes.

Visual MODFLOW is the most complete and easy to use modelling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations. Figure 2 shows various features and generation of model using Visual MODFLOW. With the combination of powerful analytical tools and logical menu structure, the software possesses the following major functions.

- easily dimension the model domain and select units,
- conveniently assign model properties and boundary conditions,
- run the model simulations,
- calibrate the model using manual or automated techniques, and
- Visualize the results using 2D or 3D graphics.

IV. Application Of GIS And MODFLOW In Ground Water Hydrology

4.1 BROAD SCENARIO

A review of GIS applications in hydrology and water management has been presented by several researchers during early nineties and mid-nineties such as Zhang et al. (1990), DeVantier and Feldman (1993), Ross and Tara (1993), Schultz (1993), Deckers and Te Stroet (1996), and Tsihrintzis et al. (1996). These reviews indicate that GIS applications in hydrology and water management are essentially in a modelling dominated context. Although the use of GIS in groundwater modelling studies dates back to 1987, its use for surface-water modelling has been more prevalent than for groundwater modelling because the available standardized GIS coverages are primarily of the land surface; few standardized coverages of hydro geologic properties are available (Watkins et al., 1996). Watkins et al. (1996) present an excellent overview of GIS applications in groundwater-flow modelling as well as discuss its usefulness and future directions. On the other hand, Pinder (2002) provides step-by-step procedures for groundwater flow and transport modelling using GIS technology.

Numerical models are capable of solving the more complex equations that describe ground water flow. These complex equations generally describe multi-dimensional ground water flow, solute transport and chemical reactions, although they are one dimensional numerical model. Tripathi et al., (2009) conducted a study to present the overall availability of groundwater in Chhattisgarh. Effort has also been made to suggest scientific methods for proper development and effective management of

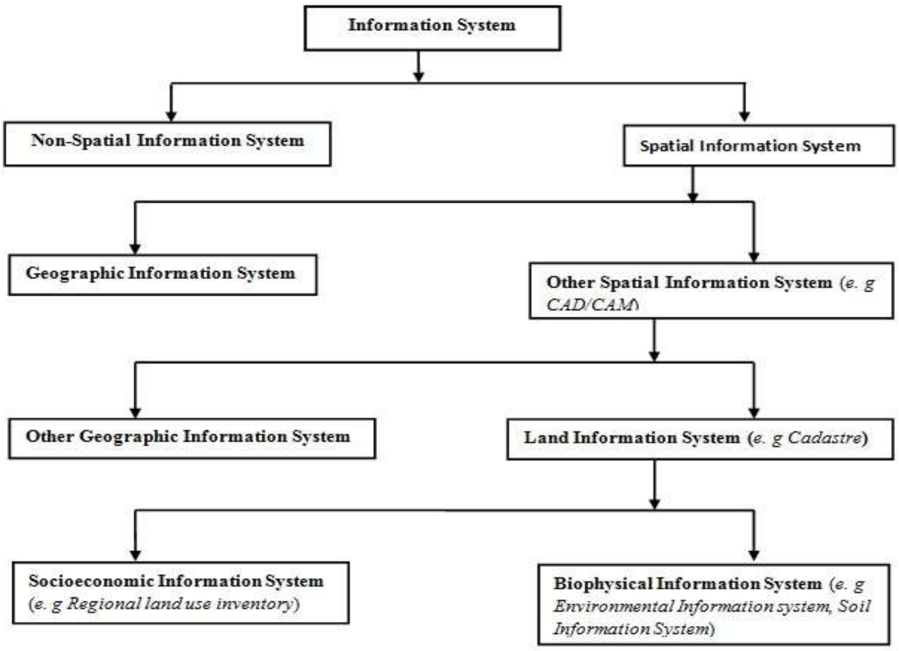

Fig.1 Typology of information systems (After Lo and Yeung, 2003)

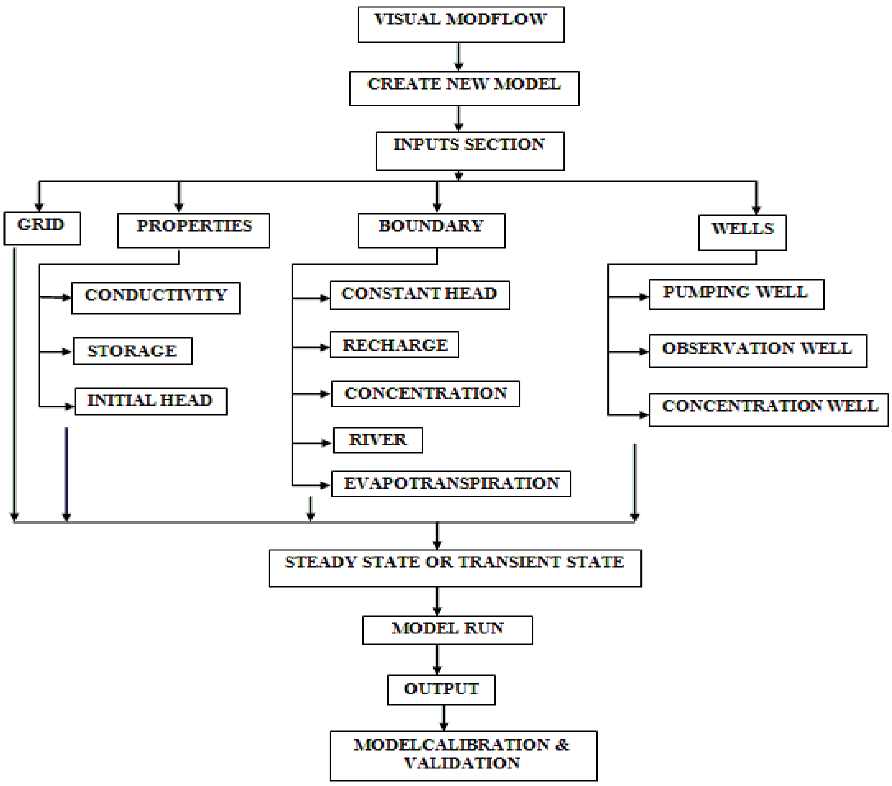

Fig. 2 Flowchart of various features and generation of model using MODFLOW

groundwater. Tripathi et al. (2009) conducted a study for groundwater assessment of a small watershed using Visual MODFLOW. The analysis was performed to know the impact of different flow and contaminant properties on hydraulic head, dispersion and chemical reaction in small ground water basin. The study had been performed for the Kurudih Nala Watershed adjoining the Patan block of Durg district in Chhattisgarh. Sekhar (2005) has adopted an integrated groundwater modelling approach for better assessment of water balance components. The model study shows that impact of pumping results in regional ground water flows influencing the hydro-geologic regime in the recharge zone of the sub basin. MODFLOW is calibrated assuming specified transmisivities for each of the zones obtained from several pump tests in the region. Madabhushi et al. (2006) has made an attempt to solve the problem of the ground water flow in porous media using a finite difference code called "MODFLOW". This code performs satisfactory in solving simple two or three dimensional problems; it takes a large computational effort when used to solve through layered soil strata with varying hydraulic conductivities. The modular structure of the code renders itself for the development of a parallelized code.

Based on this comprehensive literature survey the application of GIS technique and MODFLOW package in ground water hydrology to date have been characterized into two groups.

4.2 GIS-Based Subsurface Flow And Pollution Modeling: Model Development, Applications And Evaluation

Camp and Brown (1993) developed a GIS-based methodology for developing subsurface profiles from well-log data. They examined the accuracy and the reliability of well-logs with the help of geophysical logs and formation logs for each borehole from as many sources as possible. It was found that the geophysical logs were the most important and formed the nucleus of the GIS-well-log database. It was also demonstrated that any number of cross-sectional profiles or three-dimensional images of well-log data could be created and viewed interactively from this database. Furthermore, for each of the subsurface units, a GIS-MODFLOW interface was developed that computes the geo-hydro graphic parameters from the well-log database. It was concluded that a GIS-based interface provided a powerful method for overcoming data generation problems in groundwater-flow modelling.

Hinamann (1993) demonstrated the use of GIS for assembling input datasets for a FDM (Finite difference method) based three-dimensional groundwater flow model, MODFLOW through a case study in the middle Patuxent River basin of Howard County, Maryland. The model grids were developed with GIS. They considered various attributes such as model boundaries, regolith thickness, stream length, stream location, etc. After preparing the input layers using GIS, the output layers were prepared in a format which was suitable for the MODFLOW input. It was emphasized that the ability of GIS to change large sets of spatial data quickly and accurately enhanced the model calibration process.

Richards et al. (1993) used a numerical groundwater model, MODFLOW in a GIS environment using Arc Info software to optimize well-field design and to analyze aquifer stress problems in a coastal area of Santa Rosa County, Florida. They used GIS as a primary tool for the development of the model grids, in studying the performance of modeling procedure and the model analysis. They demonstrated that the model calibration became very quick and efficient using GIS tools. They concluded that GIS was well-suited to efficiently manage resource modeling projects by allowing data management, data analysis and graphic outputs within a single integrated software system. Model systems for specific modeling projects could also be developed very quickly and easily.

Lasserre et al. (1999) developed a simple GIS-linked model for nitrate transport using the IDRISI GIS software. They found that significantly less data are required for this GIS-linked model compared to the more classical hydro-geochemical model. They also linked this model with an unsaturated-zone transport model called Agri Flux for simulating water and nitrate fluxes leaving the root zone. The results indicated that the simulated nitrate concentrations were in good agreement with the measured values. Further, in order to compare the GIS-linked model with a more complete model, simulations were also performed using the standard software, MT3D-MODFLOW. The similarities between the results of these two models confirmed the validity of the developed GIS-linked model.

Boutt et al. (2001) presented an approach to examine potential relationships between land use-derived solutes and base flow surface water quality by estimating chloride concentrations in surface water due to road-salt transport through groundwater at the Michigan's Grand Traverse Bay Watershed (GTBW) using groundwater modeling and GIS. They developed a three-dimensional groundwater flow model of the GTBW using MODFLOW and incorporated Arc Info GIS software in the model which was beneficial for the model development and the analysis of model output as large amount of spatial data were required to execute the model. They reported that the developed geologically parameterized model offers a method to estimate spatially and temporally variable solute fluxes via groundwater to streams and lakes in the study area. A considerable legacy of land use influencing surface water quality was found in the area. It was concluded that this approach could also be used to examine the impacts of other land-use related solutes on base flow surface water quality.

4.3 SELECTION OF ARTIFICIAL RECHARGE SITES

Many workers in various parts of the world have followed different techniques for generation thematic maps on geology and hydrogeology integrated the data to select favourable areas for groundwater recharge (Weston and swain, 1979, Murakami, 1982, Sara et.al.1992). A limiting factor in developing artificial recharge of groundwater is site selection (Bouwer 2002). A lack of suitable sites often causes neglect of artificial recharge as a water management technique (Pyne 1995; Kalantari and Rangzan 2000; Abu-Taleb 2003).

Rezaei and Sargezi (2009) studied the effects of artificial recharge on the aquifer of Goharkooh Plain and specified the best location for the implementation of artificial recharge using MODFLOW model. The results showed that the aquifer response to artificial recharge was positive and the artificial recharge didn't have a destructive effect on the aquifer.

Chenini and Ben Mamou (2010) made use of GIS and numerical modelling in order to specify the proper location of artificial discharge and development of groundwater resources. MODFLOW code was used to estimate the effects of recharge on the piezometric behaviour of hydro geologic system and to manage groundwater resources in the studied area, as well.

The methodology adopted by researchers for the identification of ground water potential zones and for the selection of suitable sites for artificial recharge is explained in Figure 3.

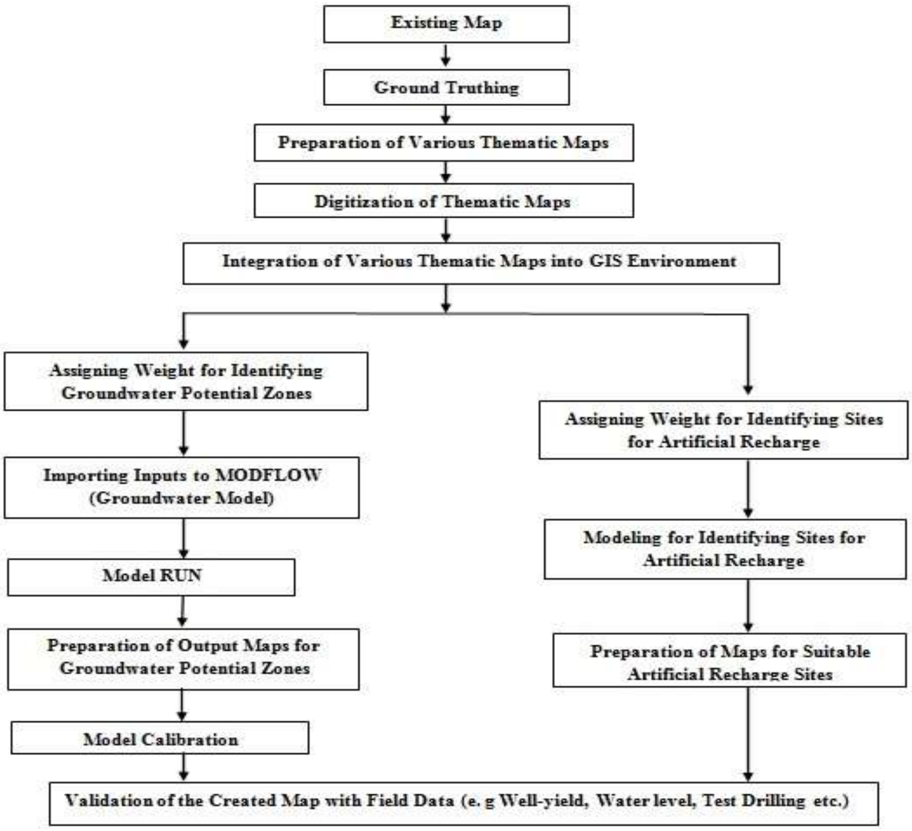

Fig. 3 Flowchart for evaluating and managing groundwater resources by coupling GIS with MODFLOW

V. CONCLUSIONS

Rapidly developing computer technology has continued to improve modelling methods in hydrology and water resource management. The present paper sufficiently highlights integration of GIS techniques and MODFLOW and presents a state-of-the-art review on the application of these two emerging coupling techniques in groundwater hydrology. The detailed reviews presented in this paper indicated that the current applications of GIS techniques in groundwater hydrology are limited to two areas: (i) GIS-based subsurface flow and pollution modelling, (ii) selection of artificial recharge sites. Considerable basic research and developments are indispensable in the future for enhanced and wide-scale applications of these two highly promising and economically viable integration techniques in groundwater hydrology. Rapidly expanding GIS technology will play a central role in handling the voluminous spatio-temporal data and their effective interpretation, analysis, and presentation, though such applications will raise some new problems.

Finally, it is concluded that Visual MODFLOW software has great potential to revolutionize groundwater monitoring and management in the future by providing unique and new data to supplement the conventional field data. The developed model would thus provides a decision support tool for evaluating better management options for sustainable development of land, surface and groundwater resources on micro as well as on macro levels in future.

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