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A review of visual MODFLOW applications in groundwater modelling

Hariharan V, Uma Shankar M
School of Civil and Chemical Engineering, VIT University,Vellore, Tamil Nadu-632014, India.

Email : mumashankar@vit.ac.in

Abstract. Visual MODLOW is a Graphical User Interface for the USGS MODFLOW. It is a commercial software that is popular among the hydrogeologists for its user-friendly features. The software is mainly used for Groundwater flow and contaminant transport models under different conditions. This article is intended to review the versatility of its applications in groundwater modelling for the last 22 years. Agriculture, airfields, constructed wetlands, climate change, drought studies, Environmental Impact Assessment (EIA), landfills, mining operations, river and flood plain monitoring, salt water intrusion, soil profile surveys, watershed analyses, etc., are the areas where the software has been reportedly used till the current date. The review will provide a clarity on the scope of the software in groundwater modelling and research.

1. Introduction

Visual MODLOW is a Graphical User Interface for the USGS MODFLOW. It is a commercial software that is popular among the hydrogeologists for its user-friendly features. The software is mainly used for Groundwater flow and contaminant transport models under different conditions. This article is intended to review the versatility of its applications in groundwater modelling for the last 22 years. Agriculture, airfields, constructed wetlands, climate change, drought studies, Environmental Impact Assessment (EIA), landfills, mining operations, river and flood plain monitoring, salt water intrusion, soil profile surveys, watershed analyses, etc., are the areas where the software has been reportedly used till the current date. The review will provide a clarity on the scope of the software in groundwater modelling and research.

Modular finite-difference flow model (MODFLOW) software was introduced by the U.S Geological Survey (USGS). As the name indicates, it uses finite-difference solving for groundwater flow and contaminant transport modelling. The software falls under the source code “free public domain software”. There are actively developed Graphical User Interfaces (GUIs) for MODFLOW available in the market. They are of commercial as well as non-commercial types.

Visual MODFLOW is a commercial Graphical User Interface for MODFLOW. It was introduced by the ‘Waterloo Hydrogeologic’ company in August, 1994. The main difference between MODFLOW and Visual MODFLOW is that MODFLOW uses input data in the form of text files which make it complex and time consuming. Whereas, Visual MODFLOW uses Excel files, Surfer grids, GIS and AutoCAD data as input files. This makes modelling user-friendly and consumes comparatively lesser execution time. Another advantage of the software is that it interprets the raw text and binary output files of MODFLOW by creating colour/contour maps and charts. With this, the model results can be easily analysed and interpreted better. Visual MODFLOW is available as two types- Classic and Flex. Both types are similar in all ways but the only difference is that the former uses a numerical approach while the latter uses a conceptual approach. The scope of this paper is to review the work that have been carried out in groundwater modelling using Visual MODLOW software since its inception till the present date. It will enlighten the reader with the versatility of the software and provoke confidence to carry out more studies in the future.

2. Groundwater Model development- The Big Picture

It is necessary to understand the steps common to all researchers involved in groundwater modelling, right from the beginning stages to the final model result interpretations. The simplified steps involved in groundwater model development using software are shown in Fig.1.

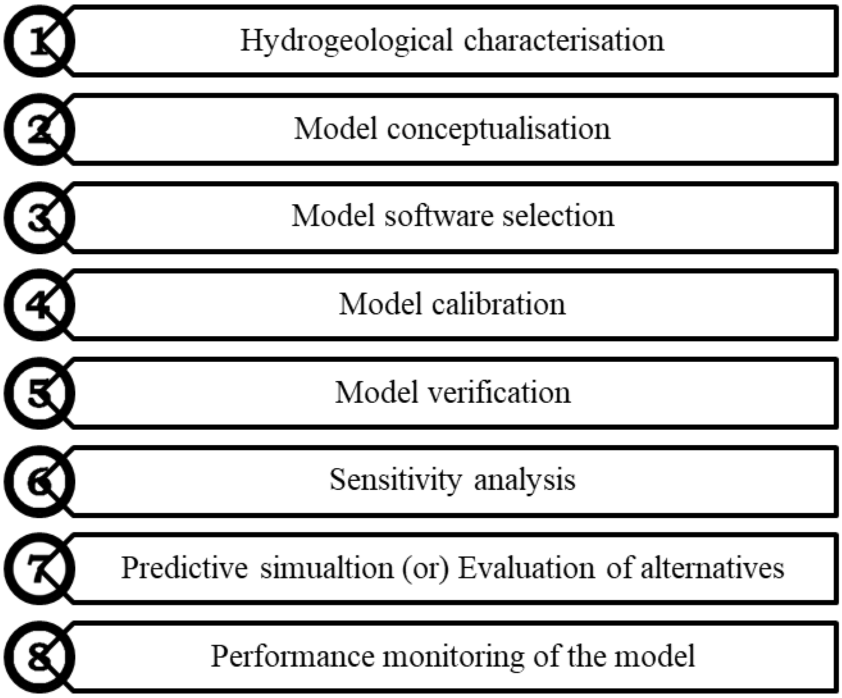

Figure 1. Groundwater model development Anderson & Woessner (1982)

3. Review of previous research

The review has been organised chronologically for better understanding. From the year of Visual MODFLOW release i.e., from 1994 to 2016, the different applications of the software in groundwater modelling have been analysed in depth and presented as follows.

Gburek (1999) [1] modelled the pollutant transport within a layered and fractured aquifer of an upland agricultural watershed in Pennsylvania, USA. The simulation results from a previous study by the same author (Gburek, 1998) on a groundwater flow simulation using Visual MODLFOW under springtime steady-state recharge was used as the basis for the study of areal-format water-shed flow paths.

Kuchling (2000) [3] modelled the groundwater flow and TDS plume transport arising from mining operations at Daivik diamonds project in Canada. Roadcap (2001) [4] simulated the effects of pumpage from a series of ten groundwater wells on a particular aquifer and its surrounding wells.

Rao (2001) [2] assessed the pollution of groundwater flowing downstream of an industrial site and modelled the flow and contaminants. Simulations were developed for 20 years (1977 to 1997) with data from previous records. The stream-aquifer interaction was found to be the reason for the faster migration of pollutants.

Jia (2003) [6] simulated the groundwater flow in the Luancheng county of Hebei Province, China to understand the groundwater level fluctuations. Kim (2003) developed a GIS based Pre- and Post-processing tool for Visual MODFLOW to manage input data for flow analysis.

Meriano (2003) [7] developed a groundwater flow model for a drainage basin in Canada. With their forecast they demonstrated the susceptibility of deeper aquifers to urban contaminants and suggested the importance of long term planning for water quality. Yunjie (2003) used Visual MODFLOW to simulate groundwater flow with the prevailing hydrogeological conditions at a sandstone-type uranium deposits.

Tiwary (2005) [8] modelled the migration of hexavalent chromium from chromite deposits of the Sukinda valley in Odisha, India. The path lines of migration of Cr^{6+} were simulated for 20 years. Bin (2005) applied well boundaries package of the software to simulate 23 faults (rocks) of compresso-shear and water-resisting types on the path of groundwater flow to study the effect of faults on the flow.

Hu (2006) [9] explores the application constraints with Visual MODFLOW in groundwater simulations. Yuan-fang (2006) studied the groundwater flow and levels around a river in China to ensure its quantity to meet the water demand of a city.

Yizhong (2007) simulated a two-dimensional unconfined groundwater flow and the migration of nitrate contaminant for a period of 42 years in Shijia Zhuang, China. Fei (2008) simulated the groundwater flow for a plain reservoir in Sheyang, China. They predicted the exploitable groundwater capacity with different water levels in the reservoir.

Rejhani (2008) [12] simulated a 2-D groundwater flow to study the overexploitation of groundwater and to analyse the aquifer response to various pumping strategies in the Balasore coastal basin, India. Five pumping scenarios were used for the simulation.

Zume (2008) [13] modelled the groundwater flow in the semiarid north-western Oklahoma, USA to assess the impact of exploiting groundwater on the streamflow depletion in the Alluvium and Terrace aquifer of the Beaver-North Canadian River in the north-western Oklahoma, USA. With the help of streamflow routing package of the software, changes induced by pumping on base flow and stream leakage were studied.

LIU (2009) [14] developed a three-dimensional seepage model of karst water and simulated the seepage flow field and the water level regime variation. The study was carried out to ensure the safety in coal mining. Mondal (2009) [16] developed a mass transport model for the migration of tannery effluent contaminants around a tannery industrial belt. It was reported that the migration phenomenon was affected mainly by advection rather than dispersion. The contaminant transport emanated from the tannery belt and moved towards eastern side of a river downstream.

Jovanovic (2009) [17] used Visual MODFLOW to calculate the spatial distribution of NOx concentrations in groundwater. The research work was to study the impact of nitrogen dynamics on land and ground at Riverlands Nature Reserve, South Africa. Saravanan (2010) studied the migration of leachate plume from the Kodungaiyur landfill in Chennai, India and simulated the transport of heavy metals for a period of 10 years.

Shi (2010) [18] applied Visual MODFLOW to evaluate the impact caused by the leakage of a sewage plant accident pool on groundwater. Ammoniacal Nitrogen (NH_3-N) migration from the accident spillage was simulated. Faghihi (2010) [22] predicted the reaction of an aquifer to different environmental stress scenarios in the Qazvin plain of Iran. Feng (2010) [20] predicted the groundwater depression funnel and variations in groundwater levels due to different exploitation extents.

Sarvarian (2010) [19] used Visual MODFLOW to identify capture zones for wells in Urmia plain, Iran. MODPATH package of the software was used for this work. Also, they determined the influence of injection wells of wastewater on capture zones of pumping wells.

Vandecasteele (2010) studied a catchment in Northern Ethiopia during the rainy season in 2006. They developed a groundwater flow model for the catchment with a perched water table. The soil water budget was calculated for the period 1995-2006.

Lei (2011) studied the seepage field along the centre line of an airport runway. Four different engineering conditions by excavating ditches were presented and simulated for the effect of floodwater on the groundwater seepage field on the runway. Yugen (2011) forecasted the water inflow impact in a bauxite mine in China. The forecast was used as a precautionary study to prevent water-in rush accident in the mine.

Saghravani (2011) [24] predicted the transport of phosphorus around a landfill in Malaysia for 10 years. Da (2011) built a model to simulate the pit dewatering process for a river delta region. The model result was suggested as a credible design reference for the construction of the dewatering scheme. Saravanan (2011) [21] modelled groundwater flow for textile effluent affected areas in Tirupur basin, India and demarcated the groundwater protection zones. These modelled zones were ranked and their need for keeping them pollution-free was stressed.

Varalakshmi (2011) [28] modelled the groundwater flow for a hard rock aquifer to determine the average input, output and the withdrawal levels of water in the aquifer system. Rao (2011) assessed the groundwater contamination around a dumpsite near TCCL at Ranipet, India. Migration of TDS and chromium plumes in the groundwater were simulated for 30 years.

Paramesswari (2012) [27] used Visual MODFLOW to prepare a pictorial representation of the geo-hydrological profile of their study area to represent the layers of soil in the study area. Liolios (2012) [29] modelled the fate and transport of Biochemical Oxygen Demand (BOD) for a horizontal subsurface flow constructed wetlands under Mediterranean conditions. Test runs were performed for various vegetation, porous media size, temperature and hydraulic retention time (HRT) conditions.

Xi-lian (2012) used the software to study the changes in groundwater flow field after the construction of a factory in Qufu city, China. Lead contamination was simulated for two different conditions created by the construction work. Haque (2012) modelled the recharge fluctuation rates of a groundwater source in Bangladesh. Also, they showed the reasons for groundwater shortage during dry seasons using modelling.

Ismail (2012) simulated the performance of a horizontal well to understand the optimum pumping rate that would safely achieve the desired drawdown in an area surrounding the horizontal collector well. Horizontal well hydraulic properties were assumed and a transient groundwater flow model was developed. Also, a steady-state model was built to predict the capture zone characterization.

Wang (2013) [32] used Visual MODFLOW as an Environmental Impact Assessment (EIA) tool. They ascertained the impact of soil and water conservation in weakening the surface run-off and strengthening the underground run-off using modelling. Rajamanickam (2013) [38] modelled the groundwater around the Amaravathi river basin of Karur District, Tamil Nadu to study the effect of discharging partially treated effluents from textile bleaching and dyeing units. Total Dissolved Solids (TDS) migration was simulated for 15 years under five different scenarios.

Kant (2013) [34] modelled the groundwater levels in the Sonar sub-basin in Madhya Pradesh. The aquifers situated in the alluvial plains of Madhya Pradesh were modelled to find the fluctuations in water levels. Beltran (2013) [33] used Visual MODFLOW with ArcGIS and Surfer to simulate the sub-surface water flow in and around a solid waste dumpsite in Mexico and modelled the migration path lines of contaminants.

Zhai (2014) [40] assessed the drainage of a limestone aquifer. The study was carried out in a mining area. The model result precisely identified the poor drainage condition in the eighth mining area and suggested remedial measures. Kumar (2014) [39] developed a groundwater flow model to quantify groundwater in Choutuppal Mandal, Andhra Pradesh. The water budget estimate was also made.

Parameswari (2015) [41] analysed the leachate migration from a dump yard at Perungudi, Chennai, India. The groundwater flow model was calibrated for transient conditions and chloride migration was simulated for 12 years. The model results were helpful to assess the contaminant’s influence on the water supply wells located downstream of the landfill. Guan (2015) predicted the groundwater level

decline downstream of a river basin under different conditions and found out the period during which overexploitation of groundwater was made.
Surinaidu (2015) [36] applied Visual MODFLOW to study groundwater seepage issues in subsurface tunnels. They created a three dimensional finite difference model with the help of inferences made from hydro-geo-morphological features and geological lineaments to investigate the groundwater seepages and then suggested solutions.
Qadir (2016) [43] studied the groundwater sustainability for agricultural activities near the Indus River in Pakistan. Water table depth maps and groundwater budget calculations were interpreted. The condition for the simulation was taken by considering the before and after scenarios of a river canal construction. The model results forecasted the continued drawdowns for the entire period of simulation (35 years).
Persson (2016) [44] modelled the transport of perfluorooctanesulfonic acid (PFOS) in groundwater at the old fire drill site of Bromma Stockholm airport in Sweden. They found that it would take approximately 570 years for the PFOS to be carried by groundwater from the site to the airport area.
Baharuddin (2016) [48] simulated the sub-drains' performance to investigate a water seepage problem at a Botanic park in Kuala Lumpur, Malaysia. The simulation was carried out for transient conditions and successfully determined the cause of water seepage issue in the area.
Nabil (2016) [45] modelled the effluents from a steel industry that pollute the Meboudja River in Algeria. Groundwater flow and mass transport model were simulated using Visual MODFLOW. Lee (2016) simulated the impacts of seasonal pumping on stream depletion. Visual MODFLOW was used to quantify stream aquifer interactions caused by the seasonal pumping of groundwater. Stream Depletion Factor (SDF) was found to be the reason for the seasonal variation of the stream depletion rate.
Park (2016) [49] undertook a feasibility study to determine the minimum embedded depth of vertical barrier to prevent possible contaminant leakage from an off-shore landfill. The study was successful.
Vijay (2016) [46] used modelling to assess the safe yield of groundwater withdrawal and quantified the future demand of water supply for the city of Puri, India, which is being subjected to constant sea water intrusion and continuous freshwater withdrawal due to pumping.
Steiakakis (2016) [47] studied the drought-induced impacts using Visual MODLFLOW. They investigated the combined effects of groundwater exploitation and climate variability on karst aquifers. Saline water intrusion was simulated using the SEAWAT package of the software. Suggestion to adjust the scheme of groundwater exploitation was recommended to prevent seawater intrusion.

4. Conclusions

It is evident from the review that the software has found applications in a variety of groundwater flow simulation settings. This shows an optimistic research potential with the software for the future. It is notable that the Middle East and the Asian countries (especially, China) have used the software comparatively more than other nations in modelling. The study of literature shows that the same research methodologies can be adopted for similar scenarios in other countries as well. Integrating other modelling software such GIS, SWAP, SWAT, etc., with Visual MODFLOW have been attempted in some studies. Such attempts add novelty to the research.

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