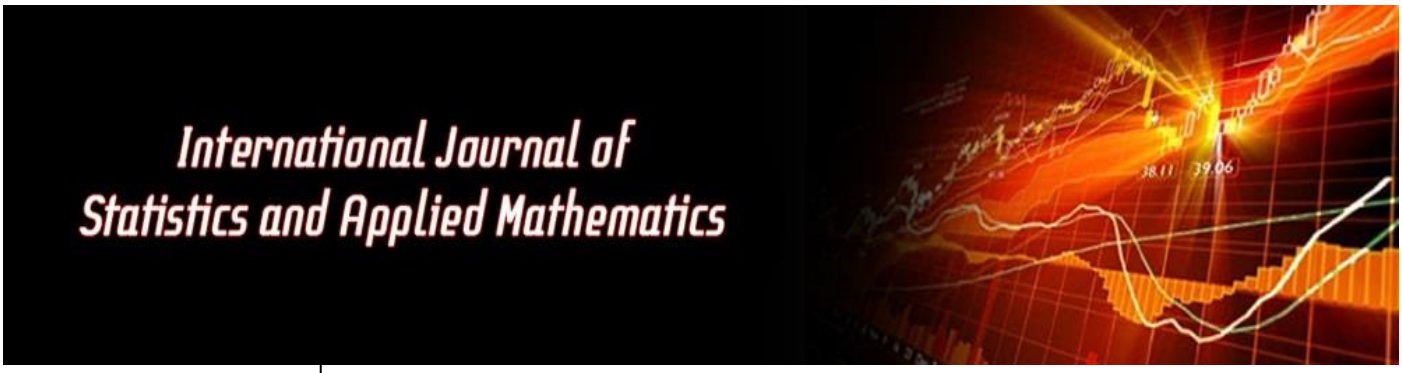

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A review of visual MODFLOW applications in groundwater flow and contaminant transport modeling

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Abstract
Visual MODFLOW is a software that combines industry-standard codes for groundwater flow and contaminant transport, essential analysis and calibration tools, and stunning 3D visualization capabilities in a single environment. It allows users to build models faster and more efficiently, handle large and complex data sets, and visualize model inputs and outputs in 2D, 3D and multi-view displays. Visual MODFLOW has been widely used for various applications such as delineating well capture zones, designing pumping well locations, determining contaminant fate and exposure pathways, simulating surface water-groundwater interactions, evaluating groundwater remediation systems, and assessing saltwater intrusion. This paper reviews some of the recent studies that have used Visual MODFLOW for groundwater flow and contaminant transport modeling in different settings and scenarios. The paper also discusses the advantages and limitations of Visual MODFLOW as a modeling tool, and provides some recommendations for future research and development. The paper aims to provide a comprehensive overview of Visual MODFLOW applications in groundwater modeling, and to highlight its potential for addressing complex hydrogeological problems.

Keywords: GIS groundwater modeling, quality modeling, visual modflow

Introduction
Groundwater modeling is a key factor for preserving the future availability and quality of natural water sources. Groundwater quality is essential for human health, social development, and environmental protection. For example, it affects drinking water safety, agricultural productivity, and climate change. Therefore, it is important to determine how much water supply there is in a specific research area and how to maintain its quality.

However, some regions face serious water problems because they use more freshwater than nature can replenish. In other regions, human activities contaminate groundwater. For instance, pollutants from domestic or industrial wastewater can seep into the water-bearing layer through the surface water bodies that are connected to it, such as ponds or reservoirs. The water-bearing layer's properties, such as its rock layers, minerals, water flow rate, thickness, yield, and storage capacity, also affect groundwater quality and quantity.

In order to model groundwater effectively, more data sets related to these properties are needed. Visual Modflow is an advanced software that can help visualize groundwater modeling based on the data inputs and the geographic information system (GIS) of the study area. This software is user-friendly and can be calibrated and validated with the available data to produce an accurate representation of the reality. It can also model groundwater flow and pollutant transport under different conditions. This paper will discuss how Visual Modflow can be applied in groundwater modeling.

Model design
To develop the groundwater flow model, the first step is to select the appropriate study area and set up the boundary conditions for flow. These assumptions are made when constructing the groundwater flow regions

1. No flow occurs across the boundaries, since they are in equilibrium.
2. Recharge of groundwater takes place from top layer of the catchment.

3. Since the catchment is closed collection point with a stream inlet, some outflow may take place.
4. Seepage from tanks in the study area is an added input to the catchment recharging system.
5. There will be downward leakage to the fractured zone.

Groundwater flow is a 3D flow in a porous media of constant media and density which can be expressed by a partial differential equation (Rushton and Redshaw, 1979).

$$\frac{\delta}{\delta x}\left\{Kxx\frac{\delta h}{\delta x}\right\}+\frac{\delta}{\delta y}\left\{Kyy\frac{\delta h}{\delta y}\right\}+\frac{\delta}{\delta z}\left\{Kzz\ \frac{\delta h}{\delta z}\right\}=Ss\frac{\delta h}{\delta t}\ \pm W$$

Where,

$\pm W$ - Volumetric flux which represents sources of water

h - Head in m

S_s - Specific storage

K_{xx},K_{yy},K_{zz}– Hydraulic conductivity of x,y and z coordinates based on multi-layer aquifer systems.

Visual Modflow

Visual Modflow Flex (VMOD Flex) is a graphical user interface for MODFLOW. The program also combines software's, such as MODFLOW-SURFACT, MT3DM and a 3Dmodel explorer. Visual MODFLOW supports man versions like MODFLOW 2000, 2005, NWT, MODFLOW-LGR, MODFLOW-SURFACT, and SEAWAT. The software is used widely by the hydro geologists, Groundwater Researchers to simulate groundwater flow and contaminant transport.

Mathematical models are techniques that are mostly used in the study of groundwater prediction. Mathematical models are commonly used to simulate the flow of groundwater and also used in the transfer of solutions and heat. It is necessary to know and understand the faults, potential causes of mistakes in numerical models to prevent model misuse (Fig. 1.).

This fully-integrated groundwater modelling environment allows us to:

1. To design the boundary grid, properties and their conditions graphically,
2. To visualize the Modflow input parameters in two or three dimensions,
3. To simulate the Groundwater flow, its path and pollution transport dynamics,
4. Assumptions are made to calibrate the model using WinPEST Automatically or by using manual methods, and
5. Visualize, Deliberate and interpret the modeling results in 3-Dimensional space using the Visual MODFLOW 3D-Explorer.

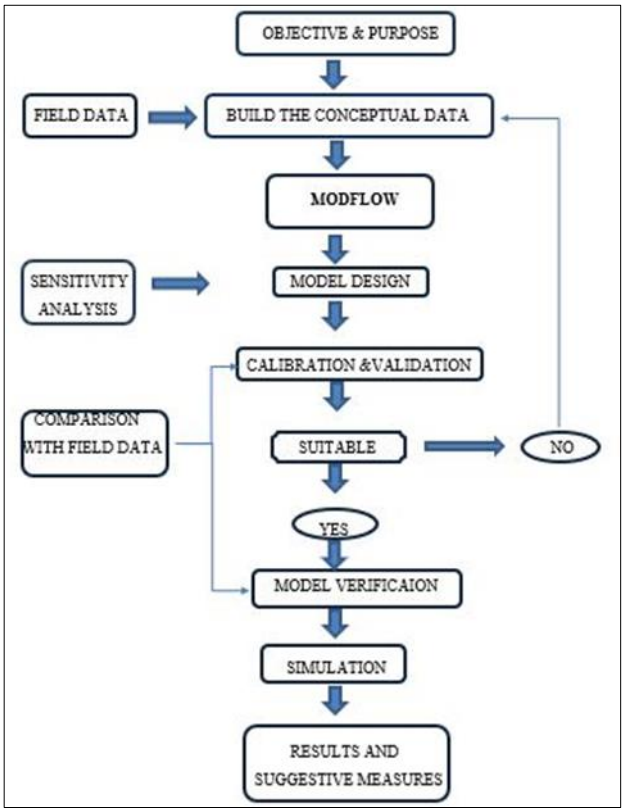

Fig 1: Flow chart of groundwater modeling

Review on Modflow and its applications

A research on groundwater flow modeling of the Yamuna-Krishi Interstream, part of the Ganga Plain, was performed in which the possible sites were found to be poorly maintained and adversely affected. The model's sensitivity to input parameters has been evaluated by adjusting the interest parameters over the values, measuring the model's reaction, and evaluating the RMSE of the simulated heads. These analyses showed that the model is most sensitive to hydraulic conductivity and recharge parameters. Three scenarios were considered to predict aquifer responses under varied conditions of groundwater abstraction [1].

A study on the ground water modeling using Visual Modflow in Tripura region since its one of the industrial hubs of Tamil Nadu and it's a prominent place where Industrial pollution is in dominant level affecting the environment. They examined the influence of industrial waste water on the level of groundwater content. The model boundary conditions and model grid configuration of the aquifer properties were analysed and the model was calibrated and validated. For a period of ten years (2021 to 2030), the validated model was

used to simulate water quality. They concluded that the simulated ground water quality was not suitable for both domestic as well as irrigation purposes. Current status of the Tirupur district will change when no injection of industrial effluent is made into possible action [2].

The study deals with the different challenges of calibrating the groundwater flow model using Modflow in Upper reach of a wash Basin in Ethiopia, where many bore wells are used for both domestic and industrial use. For several years, stagnant water levels have been obtained to calibrate a steady state model for groundwater modeling. They have done multiple calibrations for different combinations of boundary conditions and the aquifer parameters were also calibrated and the model was run to give the simulations for the upcoming years [3].

A functional hydrogeological model of the aquifer system of the for groundwater flow modeling, the hydrogeological data were combined, which was the basis for the model's development. The aquifer structure was modelled using MODFLOW-2005 mathematical modeling, which was further calibrated and an optimum numerical model displaying various flow paths in all the aquifer layers. The model was certified by comparing the observed and simulated heads. The result shows that in each of the aquifer layers, the general flow in the direction of west and south-west [4].

Statistical assessment of the water quality parameters in Sukhnag stream and have analysed the water quality in that stream and have statistically analysed the water quality data from February 2011 to January 2012. The parameters such as depth, transparency, temperature, pH, and conductivity were estimated on the spot while the rest of the parameters were determined in the laboratory using standard procedures. Data for physicochemical parameters of water samples were presented using descriptive analysis and correlative analysis. They concluded that the overall we observed significant degree of spatial and temporal variations in the concentration of water quality parameters using ANOVA ($P< 0.05$) and t-test ($P< 0.01$) analysis [5].

The groundwater potential using Modflow for Kalipat village, which has an average rainfall of 592 mm was studied. They have obtained the heads water table depths, drawdown, Head difference, velocity and path line of the study area and finally found the water balance for the proper planning and management of water resources in the study area using Modflow and found that the groundwater extraction outflow was more than the recharge inflow. They have also estimated the net recharge is 1568 cum and also the river leakage into the aquifer was higher. They have said simulated the head variation in the southern side was 132 m and the 141 m on the northern side [6].

The groundwater levels of coastal areas of Purba Midnapur, India using Modflow have been investigated and simulated. The consistency of the groundwater was simulated for the year 2012 and contrasted with the real field level results. The coefficient of correlation between such data was 0.56. The groundwater standard was then simulated for the period from 2019 to 2023 after calibration. They observed that, according to the simulation, the groundwater level was lowered to an average of 13.4 m in the southern part of the study area and 15.7 m in the northern part of the study area, and they concluded that the intrusion of sea water is taking place in the centre of the study area, which contributes to groundwater salinity [7].

The groundwater resources in Bangladesh using Visual Modflow and the modeling suggests that recharging happens largely due to infiltration at a low rate of rainfall and urban return drain, and in response to recharge and release, water levels fluctuate seasonally. Hydraulic relation between the river and the aquifer, showing the inflow beyond its limits from high river water levels. They suggested that the abstraction of groundwater rises every year to satisfy demand, adequate steps are important to maintain the capacity of the aquifer. Therefore, for the proper management and preservation of safe use of groundwater supplies, a comprehensive water law should be created [8].

The groundwater modeling is a tool to identify problems and helps in identifying the groundwater usage and understandings. A wide range of hydrogeological environments have been investigated using models. The first is model creation, which results in a software product, and the second is software application for a particular purpose. They came to the conclusion that models can be used as predictive tools, but that field monitoring is needed to validate model predictions. The correct method of reducing simulation errors is to apply good hydrogeological judgement and to validate the model simulation results [9].

The Modflow based groundwater evaluation and simulation in Mendha basin was studied. They have developed a grid or conceptual models for the purpose of modeling with the help of GIS. Their model was calibrated between 1998 and 2003, and between 2003 and 2005. They also simulated the groundwater situation for the draft and recharge for the 15-year period from 2006 to 2020. In the groundwater storage scheme, the water budget forecasts suggest a decline from 349.50 to 222.90 MCM, while groundwater abstraction indicates a rise from 258.69 to 358.74 MCM per annum [10].

A 3 D model Modflow with MT3D to model the surface and sub-surface water mixing in a delineated hypothetic zone was used. The Modeling results show that the adjective process is the key for the movement of groundwater. They also observed that the hypothetic exchange was found to be in the sinuous segments and that the flux values were lower with the zones' cross-section region being lower. They identified the hypothetic zone as subsurface areas within 10 days consisting of 10 percent surface water, so that we can quantify a three-dimensional volume using the model [11].

The groundwater quality in the Manas River Basin in China using visual Modflow and carried out water balance study. The flow model was developed for a depth of 300 m which have a lateral recharge of 3.57 × 109 m3 and total evaporation is about 1.81 × 108 cubic meter and the correlation coefficient between the observed and calibrated were 0.81, which clearly shows that the simulation was satisfactory. The simulation was conducted over a groundwater flow field of 24,120,240,300 days. The overall drawdown was 26.59 m and the drawdown rate was 0.15 m/d during peak pumping [12].

The fate and transport of Biochemical Oxygen Demand (BOD) for wetlands built under Mediterranean conditions was modeled for a horizontal subsurface flow were modelled. They Modeled the different transport scenarios and for different vegetation, porous media scale, temperature and Hydraulic Retention Time (HRT) conditions, test runs were conducted and models were evaluated [13].

The application of Visual Modflow and GIS in Thirukkazhukundram block in Tamil Nadu was studies. Long term water table trend and water table trend for individual wells for pre- and post-monsoon were drawn using 20 years (1991–2011) water level data. The time period from January 2000 to December 2011 was used for the calibration of the model and data of two years (2008-2010) were used for

simulation. As pointed out earlier the effectiveness of a model especially water related model mainly depends upon the availability and accuracy of the vast number of collateral data [14].

The development of a groundwater flow model using Visual Modflow for a steady state finite difference model for a study area consisting of 19 villages of Chotuppal Mandal of Nalgonda District was studied. The different parameters such as geology, hydrogeology, well inventory was analysed and the flow model was abstracted into two layers of weathered and broken aquifer structure and the parameters of the aquifer were assumed and the model was calibrated and the research region zone budgeting was performed and the simulation values were concluded within the good range of fit and was reliable [15].

The water quality of different water sources viz. wells, hand pumps and bore wells was studied in the rural areas of Sheopurkalan, Madhya Pradesh. Water samples were collected and studied throughout the monsoon, winter, and summer seasons. The values of Pearson's correlation coefficient (r) between several water quality parameters were investigated and reported. The study of the correlation coefficient (r) made it much easier to calculate some of the parameters without having to do it experimentally. Water should be treated before distribution and tested at regular intervals to monitor its quality, according to the recommendations [16].

The groundwater flow modeling of a micro-watershed in the upland area of East Godavari district, Andhra Pradesh was studied. The flow to be a steady state flow and analysed the input and output constraints in the basin and carried out the analysis of the water budget and found water losses in various ways, and the analysis of the water budget showed that the overall extraction of groundwater by pumping wells83.3 percent and evapotranspiration depletion is 5.7 percent of the overall recharge of groundwater in the basin, and 0.4 m/day was the highest velocity of groundwater flow. They concluded that, the southern part of the study region encountered tremendous stress and proposed crop rotation and the construction of many recharge infrastructure to resolve the impact of drought [17]. The modeling simulation of Amaravathi river basin of Karur District , Tamil Nadu using Visual Modflow and found that the 15-year simulated groundwater quality was divided into five scenarios as the research region consists of various garment areas, bleaching and dyeing units and found that the quality of groundwater would not be enhanced even though the effluent meets the discharge requirements for the next 10 years and concluded that when the units go for zero discharge, the quality of groundwater will be improved over a period of years [18].

The efficient groundwater management in Balasore and developed a 2D model and transport modeling by using Visual Modflow. The simulation model was calibrated and satisfactorily tested. Using the validated model, the groundwater reaction under established cropping conditions to five pumping scenarios was predicted. The findings of the sensitivity analysis shows that the aquifer system of Balasore is highly vulnerable to the surface river infiltration, drainage revive and interflow than the hydraulic vertical and horizontal conductivity and the specific storage of the particular study area. They concluded that, extraction of 100-150 percent in the upstream area and 50-75 percent in the downstream region of the second aquifer, it is possible that groundwater to ensure safe use of groundwater in the basin without taking any costly steps [19].

A research on numerical modeling to evaluate the potential effects of pumping and recharge implications for sustainable groundwater management in Mahanadi delta. They composed a quasi-three-dimensional model of a top unconfined and bottom confined aquifer. The findings of the stratigraphy review showed that the thickness of the unconfined aquifer ranges between 3.4 and 46.5 m, while the confined aquifer differs between 3.1 and 80.3 m across the basin with a confining layer of between 2.1 and 60.0 m thickness. Future hydraulic head forecasts (2012-2031) suggest that there is a small decline in hydraulic head pattern in all types of aquifers during the pre-monsoon seasons of 2019-2021 and 2029-2031 years, under current conditions of groundwater abstraction and recharge [20].

Gundal Subbasin in Kabini River Basin for which a two-dimensional model was used for an unconfined aquifer with the support of Remote Sensing and Geographic Information System. The thematic layers of the study area are integrated in GIS to produce a composite zonation layer of aquifer parameters. The model boundary is assumed to be a no flow boundary. During the base flow, the maximum volume of water above the river bed was found to be 0.75 m during the month of October and no flood was observed from February to June. Further validated by groundwater chemistry studies, the findings of groundwater modeling illustrate the effect of pumping contributing to local groundwater flows impacting the hydrogeological organization in the recharge area [21].

A groundwater flow model for simulating the escalating groundwater pumping in Punjab due to intensive pumping was developed. The study was used to identify the groundwater prone zones and the quantity of groundwater exploited by using Modflow. The study area was analysed and the different scenarios were assumed based on the groundwater uptake as constant throughout the study period, groundwater uptake was increased based on the historic trend of globalization and by adjusting the canal water supplies. Hence found that canal water utilization showed a good management strategy to increase the Groundwater level and to avoid depletion of groundwater of the study area [22].

The hydrogeological and groundwater simulation experiments to measure the groundwater inflows into the coal mines at various mining levels using Modflow, AP, with the geological logs of 183 bore wells for an area of 5.33 square kilo meter. Based on the topographic maps, the boundary conditions were allocated. The results were achieved through trial-and-error method by adjusting the hydraulic conductivity and recharge rates.it also included to plan optimal groundwater pumping and the possible locations to dewater the groundwater for safe mining at different mine development stages [23].

The study compared the Sabarmathi river, Khari River and its surrounding well water levels and modelled the water flow regime and flow direction beneath the ground surfaces and also concluded that visual MODFLOW is very effective on to simulate the groundwater flow, aquifer water level, well distribution, specific yield of the aquifer and its distribution. The model also gave a similar result as that of the observed values which gives the model high accuracy [24].

Conclusion

Visual Modflow is a useful and reliable tool for groundwater modeling, as the reviews show. It is easy to use and produces realistic results that match the natural processes and the available data. However, there is still room for improvement in the quality, validation and accuracy of modeling, especially by using more data and less assumptions. Future modeling

could also benefit from integrating and coupling different software packages, such as FEFLOW, SWAT and SEAWAT. Moreover, Visual Modflow could be enhanced by developing web-based applications and updating data output formats to make it more compatible with advanced and holistic studies of groundwater dynamics.

References

1. Ahmed, Izrar, Rashid Umar. Groundwater flow modeling of Yamuna-Krishna inter stream, a part of central Ganga Plain Uttar Pradesh. Journal of Earth System Science. 2009;118(5):507-523.
2. Arumugam K, Karthika T, Elangovan K, Sangeetha RK, Vikashini S. Groundwater Modeling Using Visual Modflow in Tirupur Region, Tamil Nadu, India. Nature Environment and Pollution Technology, 2020;19(4):1423-1433.
3. Berehanu B, Ayenew T, Azagegn T. Challenges of groundwater flow model calibration using Modflow in Ethiopia: With particular emphasis to the upper awash river basin. Journal of Geoscience and Environment Protection. 2017;5(3):50-66.
4. Bhandari R, Pathak D. Groundwater Flow Modeling in Chitwan Dun Valley Nepal. Journal of Institute of Science and Technology. 2019;24(2):30-38.
5. Bhat SA, Meraj G, Yaseen S, Pandit AK. Statistical assessment of water quality parameters for pollution source identification in Sukhnag stream: an inflow stream of lake Wular (Ramsar Site), Kashmir Himalaya." Journal of Ecosystems; c2014.
6. Bhatu H, Kapupara P, Gohel J, Dadhaniya H. Study on Groundwater Potential using MODFLOW for Kalipat Village, Indian Journal of Pure and Applied Biosciences. 2020;8(3):539-544.
7. Chakraborty S, Maity PK, Das S. Investigation, simulation, identification and prediction of groundwater levels in coastal areas of Purba Midnapur, India, using Modflow. Environment, Development and Sustainability. 2020;22(4):3805-3837.
8. Haque MAM, Jahan CS, Mazumder QH, Nawaz SMS, Mirdha GC, Mamud P, *et al*. Hydrogeological condition and assessment of groundwater resource using visual Modflowmodeling, Rajshahi city aquifer, Bangladesh. Journal of the Geological Society of India. 2012;79(1):77-84.
9. Kumar CP, Singh S. Concepts and modeling of groundwater system. International Journal of Innovative Science, Engineering and Technology. 2015;2(2):262-271.
10. Kushwaha RK, Pandit MK, Goyal R. MODFLOW based groundwater resource evaluation and prediction in Mendha sub-basin, NE Rajasthan. Journal of the Geological Society of India. 2009;74(4):449-458.
11. Lautz LK, Siegel DI. Modeling surface and ground water mixing in the hyporheic zone using MODFLOW and MT3D. Advances in Water Resources. 2006;29(11):1618-1633.
12. Li X, He X, Yang G, Zhao L, Chen S, Wang C. Study of groundwater using visual MODFLOW in the Manas River Basin, China. Water Policy. 2016;18(5):1139-1154.
13. Liolios KA, Moutsopoulos KN, Tsihrintzis VA. Modeling of flow and BOD fate in horizontal subsurface flow constructed wetlands. Chemical engineering journal. 2012;200:681-693.
14. Needhidasan S, Manoj N. Application of Visual MODFLOW and GIS in Groundwater Modeling. International Journal of Civil Engineering (IJCE). 2013;2(3):41-50.
15. Pradeep Kumar GN, Anil Kumar P. Development of groundwater flow model using visual MODFLOW. International Journal of Advanced Research. 2014;2(6):649-656.
16. Prajapati R, Mathur R. Statistical studies on the ground water at the rural areas of Sheopurkalan, Madhya Pradesh. Journal of Ecotoxicology & Environmental Monitoring. 2005;15(1):47-54.
17. Prasad YS, Rao YRS. Groundwater flow modeling of a micro-watershed in the upland area of East Godavari district, Andhra Pradesh, India. Modeling Earth Systems and Environment. 2018;4(3):1007-1019.
18. Rajamanickam R, Nagan S. Groundwater quality modeling of Amaravathi river basin of Karur district, Tamil Nadu, using Visual Modflow. International Journal of Environmental Sciences. 2010;4(2):91-108.
19. Rejani R, Jha MK, Panda SN, Mull R. Simulation modeling for efficient groundwater management in Balasore coastal basin, India. Water Resources Management. 2008;22(1):23-50.
20. Sahoo S, Jha MK. Numerical groundwater-flow modeling to evaluate potential effects of pumping and recharge: Implications for sustainable groundwater management in the Mahanadi delta region, India. Hydrogeology Journal. 2017;25(8):2489-2511.
21. Sekhar M, Rasmi SN, Sivapullaiah PV, Ruiz L. Groundwater flow modeling of Gundal sub-basin in Kabini river basin, India. Asian Journal of Water, Environment and Pollution. 2004;1(1-2):65-77.
22. Shakoor A, Arshad M, Ahmad R, Khan ZM, Qamar U, Farid HU. Development of groundwater flow model (MODFLOW) to simulate the escalating groundwater pumping in the Punjab, Pakistan. Pakistan Journal of Agricultural Sciences. 2018;55(3):629-638.
23. Surinaidu L, Gurunadha Rao VVS, Srinivasa Rao N, Srinu S. Hydrogeological and groundwater modeling studies to estimate the groundwater inflows into the coal Mines at different mine development stages using MODFLOW, Andhra Pradesh, India. Water Resources and Industry. 2014;7:49-65.
24. Vanar APH, S Langalia, B Zolapara, P Mehta. "Analysis of Groundwater Recharge Estimation Model by Visual MODFLOW. IJRAR-International Journal of Research and Analytical Reviews (IJRAR). 2019;6(2):91-98.