J. Res. Technol. Eng. 5 (4), 2024, 128-135

Journal Of Research Technology & Engineering
www.jrte.org

Groundwater Flow Modelling in a Tributary Catchment of the Badulu Oya River, Sri Lanka

*K.S. Dhanushka, A.M.A.N.B. Attanayake

Faculty of Applied Sciences, Uva Wellassa University of Sri Lanka
*ksdhanushka02@gmail.com

Received:07 Aug 2024; Revised:25 Aug 2024; Accepted: 15 Sep 2024; Available online: 10 Oct 2024

Abstract: This study investigates the regional groundwater flow patterns in the Rambukpotha Oya micro catchment within the Badulu Oya basin by integrating Geographic Information System (GIS) techniques with numerical groundwater flow modeling. Despite the lack of previous studies on the groundwater flow system in this micro catchment, the research utilized existing data and information to build a comprehensive groundwater model. GIS was employed for preprocessing hydrogeological data and creating various data layers of the study area, which were then imported into groundwater modeling software for simulation. MODFLOW-NWT, coupled with ModelMuse for the graphical user interface, was used to conduct the flow simulations. The study generated regional groundwater flow patterns and examined their sensitivity to variations in recharge rates, evapotranspiration, and hydraulic conductivity. The results, presented through detailed graphical representations, provide valuable insights for future groundwater management and research in the Rambukpotha Oya micro catchment.

Keywords: Catchment, GIS, Groundwater, modeling, Modelmuse

1 Introduction

Sustainable management of groundwater resources is crucial for the long-term development of natural water supplies. A comprehensive understanding of groundwater flow systems is essential for effective groundwater resource management, development, and future consumption planning, as well as for addressing various groundwater-related issues.

Groundwater flow systems can be classified as regional, local, intermediate, or a combination thereof, depending on the topography and geometry of the drainage basin. Regional groundwater flow systems, which encompass large areas with substantial water storage capacities, are characterized by significant distances between recharge and discharge areas. Typically, recharge zones are situated in topographically high regions, such as mountain ridges, while discharge areas are located at the bottoms of major drainage basins.

A catchment, also known as a drainage basin or watershed, is a land area that collects water from the surrounding landscape. The size and structure of a catchment can vary widely, influenced by factors such as topography, drainage patterns, hydro-climatic conditions, and geology. Small streams, or tributaries, often feed into larger bodies of water, including rivers and lakes. Large catchments generally consist of several smaller tributary catchments. In tropical climates, such as that of Sri Lanka, catchment dynamics are primarily driven by rainfall and sediment inputs, with outputs including water evaporation, deposition, and runoff. Rainfall on mountain ridges typically flows into a common outlet, such as a river or lake, while some water infiltrates the ground, contributing to regional subsurface flow along the topographic gradient.

Understanding groundwater flow presents significant challenges due to its non-visibility. Groundwater flow models serve as tools to represent and predict groundwater behavior. These models can range from analog and physical scale models to numerical simulations, aiding in the prediction of groundwater flow patterns. Due to the complexity and variability within regional groundwater systems, laboratory-scale models often require simplifications that can introduce uncertainty. Numerical models, which use mathematical equations to create simplified representations of complex groundwater systems, offer a practical solution for simulating three-dimensional regional groundwater flow in heterogeneous and anisotropic environments [1]. These models are instrumental in analyzing and predicting regional groundwater flow patterns effectively.

Bandulu Oya, a right bank tributary of the Mahaweli River—the longest river in the country—originates from the Namunukula mountain range. This system includes over 20 micro-catchments that converge into the main river, resulting in a dendritic drainage pattern. For this study, the focus is on the Rambukpotha Oya micro-catchment, which is situated at an elevation ranging from 680 to 1,380 meters above mean sea level and spans an area of 20.8 km^2 [2].

Groundwater plays an increasing role in Sri Lanka, benefiting small farmers by allowing them to plant more crops and reducing the impact of water shortages during the dry season. The Badulu Oya catchment is an agriculture-dominated catchment, especially for tea, paddy, and vegetable cultivation. And also, it is the catchment dwellers' major source of drinking, domestic, and irrigation water. Therefore, it is essential to have continuous availability of quality water throughout the year. However, in the dry season, this area is subjected to water scarcity problems. Therefore, establishing a regional groundwater model is a very useful tool for understanding the regional groundwater system, groundwater resource management, and planning for future water consumption in the Rambukpotha catchment area.

The primary objective of this study is to develop a preliminary regional groundwater flow model for the Rambukpotha Oya microcatchment by integrating Geographic Information Systems (GIS) with numerical groundwater flow modeling. This research aims to construct a numerical groundwater flow model based on available data pertaining to the study area under steady-state conditions, accurately representing the physical characteristics of the aquifer and incorporating relevant hydrological processes. To achieve this main goal, several sub-objectives have been established: first, to analyze existing literature and maps related to the study area; second, to explore innovative groundwater modeling methods that integrate GIS techniques for examining subsurface flow patterns within the catchment area; and third, to develop a regional conceptual hydrogeological framework that will facilitate the construction of a numerical groundwater flow model for the selected tributary catchment of Badulu Oya.

2 MATERIALS AND METHODS

2.1 Preliminary useful data collection

Different types of data and information from many sources are required for hydrological studies. Preliminary useful data/information such as morphology of the catchment, geology of the terrain, stream network, soil types, topography features, rainfall, and land use were collected. The gathered data/information needed to be analyzed and combined. The study was based on available maps of the study area. A previous research project by [2] obtained data layers for the geology, land use, soil types, slopes and stream network of the entire Badulu Oya catchment. The obtained shape file layers were clipped out and customized using QGIS 3.2.0 software to generate different thematic layers Rambukpotha Oya microcatchment.

2.2 Governing equation for three-dimensional groundwater flow

In groundwater modeling, simplification using mathematical equations is usually based on a set of assumptions. Assumptions typically consist of the geometry of the model domain, the properties of groundwater flow, and the heterogeneity or isotropy of the porous medium [3].

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)-Q=S_s\frac{\partial}{\partial t} \quad (1)$$

Where,
Kxx, Kyy, Kzz- Hydraulic conductivity along the x, y, and z coordinate axes(L/T)
h- Potentiometric head (L)
Q-Volumetric flux per unit volume (sources/sinks) (T-1)
SS-Specific storage of the porous material (L-1)
T-Time (T)

Equation (1) was solved for three-dimensional groundwater flow in a saturated, homogeneous and isotropic aquifer with Darcian flow using finite differential method. Other key assumptions are that the flow is incompressible and the mass of the system is conserved. In the homogeneous groundwater basin, key properties of geologic formations such as hydraulic conductivity, specific storage, layer thickness are same at all locations. In contrast, the hydraulic properties vary spatially within natural porous media. This is termed heterogeneity. In the isotropic porous medium, the geometry of the voids is uniform in all directions and hydraulic conductivity is independent of the direction of measurement at a point.

To solve the groundwater flow equation, the MODFLOW-NWT model code was used to translate physical systems into mathematical equations using the finite deferential method. The USGS developed a graphical user interface called Modelmuse [4] that is capable of storing input data independently of the grid. It allows the user to discretize the model domain by changing grid size, layering, and another model features as needed. And also, Modelmuse allows running model code and visualizing and analyzing model output results. Groundwater flow simulation was performed using MODFLOW-NWT and Modelmuse version 4.3. The groundwater flow was simulated in steady state conditions. At steady state the amount of water flowing into the system (inflow) is equal to the amount flowing out of the system (outflow). And also, hydraulic head only changes with space and it is independent with time within the model domain.

2.3 Model development

A summary of the model input parameters is described under this subsection.

2.3.1 Solver

MODFLOW-NWT is a computer program which is designed to solve groundwater flow equations using the newton solver method with two asymmetric matrix solver options. The MODFLOW-NWT was used with the Upstream Weighting Package (UPW) by adjusting the maximum number of outer iterations to 1000.

2.3.2 Model Extension

Model extension was defined by importing the selected catchment boundary shape file into the Modelmuse. The grid cell size was set to 100. The cells within the catchment shape were activated, and other cells were inactive in the model domain.

2.3.3 Layer definition

The model included two major lithological layers, named upper aquifer and middle aquifer and layer types are convertible and confined respectively. The thickness of the convertible layer and the confined layer were set to 20m and 500m respectively.

2.3.4 Topography

A gridded Digital Elevation Model (DEM) is made up of uniform, regularly spaced grids that contain elevation data for each grid. The extracted DEM file including topography data was imported and overlaid to insert the topography into the model. The elevation data was directly set to the model top.

2.3.5 Boundary condition

Boundary conditions represent the processes along the boundaries, which include physical and hydraulic features such as surface water bodies, geological structures, and groundwater divides. Aquifer hydrogeological conditions and the purpose of the modelling affect the selection of boundary condition [5]. The shape file of the stream network was imported to model muse as a single multiple object and it was set to the model top. Drain, Evapotranspiration, and Recharge packages were activated as boundary conditions in Modelmuse.

2.2.6 Run the model

The fig.1 shows the top, front, side and three-dimensional view of discretized model domain. All required parameters and conditions were set to the model to run the model. The model was run and model results were imported to visualize and analyze properly. Two different models were constructed to compare model results.

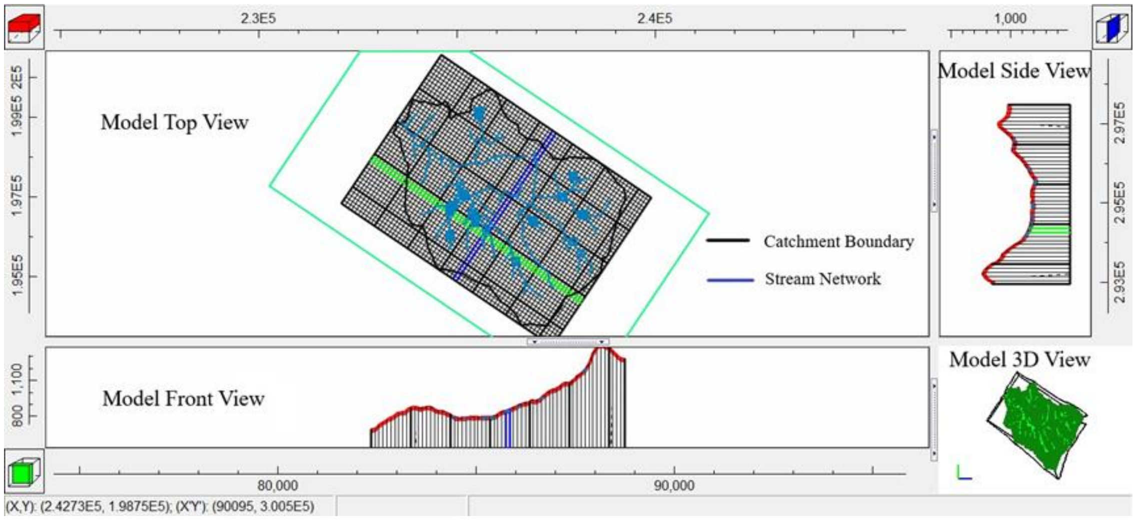


Fig. 1. The software interface of the discretized model domain

3 RESULTS AND DISCUSSION

The fig. 2 shows the total in is equal to total out within the model domain. Recharge was added as inflow in to the system and added inflow flowed out as drains and evapotranspiration from the system. Therefore, change in the volume stored in the groundwater system is zero. And also, zero of percent discrepancy indicates that the system is under the mass conservation. The summary of the output justifies that model calculations for steady-state groundwater flow are acceptable. The same way was followed for the model 02 to justify the model calculations.

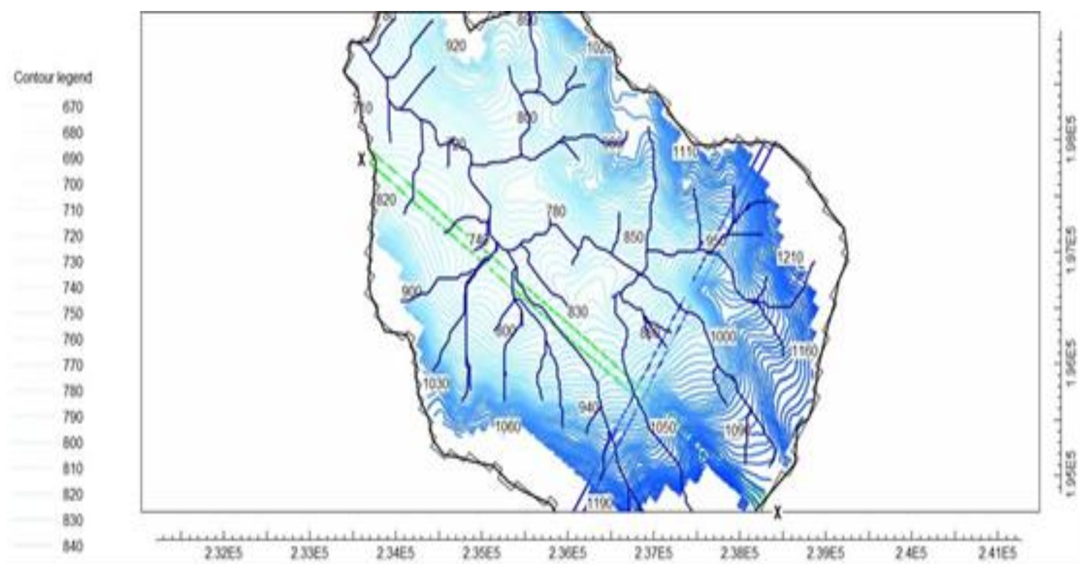
```
1
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
             STORAGE    =          0.0000             STORAGE    =          0.0000
       CONSTANT HEAD    =          0.0000       CONSTANT HEAD    =          0.0000
              DRAINS    =          0.0000              DRAINS    =          0.0000
            RECHARGE    =          0.9946            RECHARGE    =          0.9946
         ET SEGMENTS    =          0.0000         ET SEGMENTS    =          0.0000

            TOTAL IN =             0.9946            TOTAL IN =             0.9946

         OUT:                                     OUT:
         ----                                     ----
             STORAGE    =          0.0000             STORAGE    =          0.0000
       CONSTANT HEAD    =          0.0000       CONSTANT HEAD    =          0.0000
              DRAINS    =          0.9827              DRAINS    =          0.9827
            RECHARGE    =          0.0000            RECHARGE    =          0.0000
         ET SEGMENTS    =      1.1899E-02         ET SEGMENTS    =      1.1899E-02

           TOTAL OUT =             0.9946           TOTAL OUT =             0.9946

            IN - OUT =        -1.0014E-05            IN - OUT =        -1.0014E-05

 PERCENT DISCREPANCY =            -0.00     PERCENT DISCREPANCY =            -0.00
```

Fig. 2. Summary of the model output results of model 01

Fig.3 illustrates the hydraulic head contour map for Model 01, showcasing the intricate variations in groundwater flow patterns within the study area. The contour lines represent different hydraulic head levels, with closely spaced lines indicating a steep gradient and, consequently, a rapid groundwater flow. The map also features directional arrows that indicate the primary flow pathways, demonstrating how groundwater moves from elevated regions toward lower areas, ultimately discharging into the stream network.

Notably, the areas of highest hydraulic head, typically found in the upland regions, serve as significant recharge zones, where precipitation and surface water infiltrate the ground. As groundwater flows downhill, it converges toward the streams, suggesting a vital connection between the groundwater system and surface water bodies. This interaction is critical for maintaining streamflow, particularly during dry periods.Understanding these flow dynamics is essential for effective groundwater management and conservation efforts. By identifying recharge areas and flow paths, water resource managers can better predict how land use changes, such as urbanization or agriculture, may impact groundwater availability and quality in the region.

Fig. 3. Top view of the model 01



The shape of the water table generally follows the surface topography. Fig.4 shows the selected cross-sectional area of Model 01, where the water table contours provide a detailed representation of groundwater elevation. The contour lines, spaced at regular intervals, illustrate variations in groundwater depth, with closer lines indicating steep gradients and wider spacing showing gentle slopes. The highest contour line values in the region correspond to areas of elevated terrain, suggesting groundwater recharge zones, while lower values appear in depressions, pointing to potential discharge areas.

Groundwater flow, as inferred from the map, moves perpendicular to the contour lines, flowing from areas of high elevation to lower elevations.The water table follows the surface topography closely, showing a dynamic interplay between the region's landforms and groundwater flow patterns.

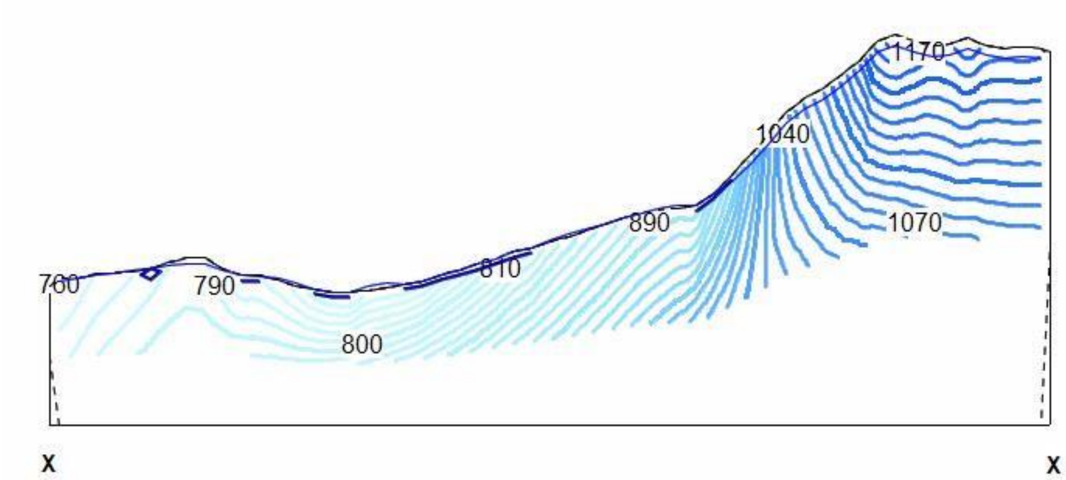


Fig. 4. Model 01 cross section X-X

In model 02, lower recharge rates and reduced hydraulic conductivity values were applied compared to models 01. As illustrated in Fig.5, the top-view representation of model 02 reveals that the entire model domain is characterized by denser subsurface contouring. This increased contour density indicates a greater degree of spatial variability in hydraulic head, likely due to the lower permeability and recharge conditions. In contrast, models 01 exhibits more widely spaced contours, reflecting higher hydraulic conductivity and recharge rates, which allow for more uniform groundwater flow across the domain.

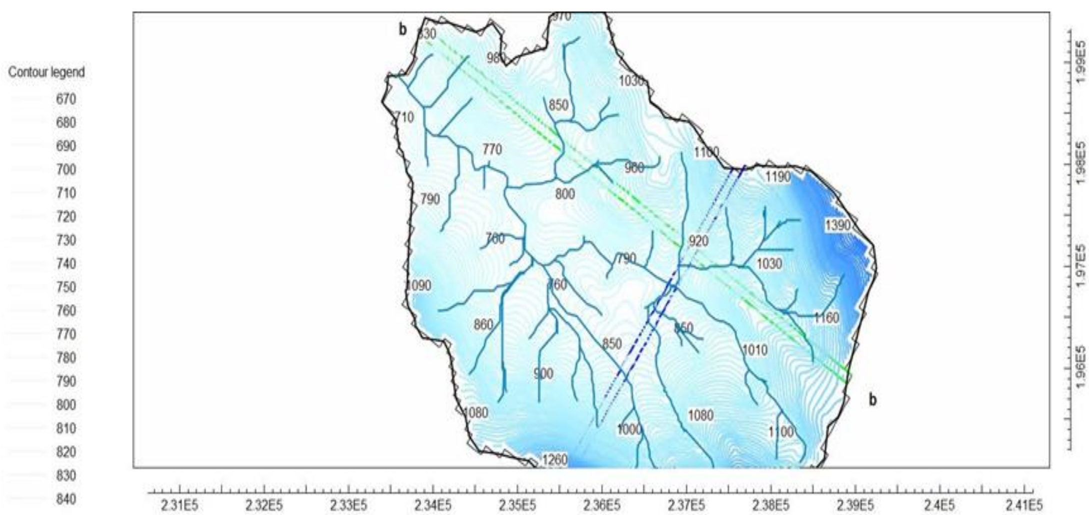


Fig. 5. The top view of model 02

In the cross-section view of model 02 (Fig.6), the calculated water table extends above the ground surface in certain areas. This suggests the potential for water to seep onto the surface, as theoretically indicated by the model. Such results are likely due to the combined effects of lower hydraulic conductivity and reduced recharge values, which slow down subsurface drainage, allowing the water table to rise to a point where it exceeds ground elevation. This scenario may represent conditions where surface ponding, saturation, or even overland flow could occur, particularly in low-lying areas or regions with limited permeability. These findings highlight the sensitivity of groundwater models to parameter changes and their impact on surface and subsurface hydrological processes.

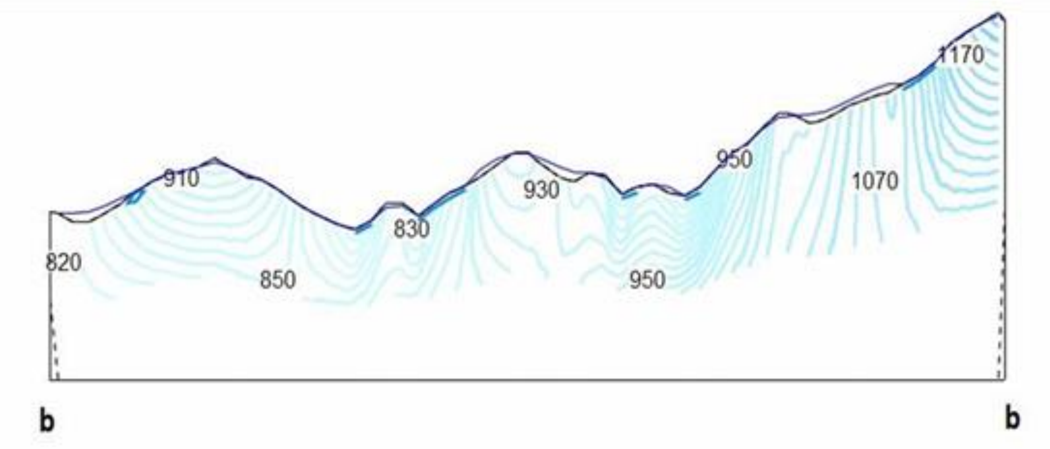


Fig. 6. Model 02 cross section b-b.

4 Conclusion

The hydraulic contour maps were simulated for the regional groundwater basin in one of the selected microcatchments of Badulu Oya to understand and study the regional groundwater flow patterns. In groundwater modelling, calibration and validation processes are necessary to avoid uncertainty in model results. Model calibration is the iterative process of comparing model results based on estimated input values and measured field values. The process attempts to match field conditions such as boundary conditions, sources and sinks and the selected values of model input parameters, within some acceptable range. The calibration process continues until the model is validated. Therefore, this study should be developed further. However, the generated preliminary groundwater flow patterns can also be used to understand the complex groundwater flow field to apply the knowledge for groundwater management, development, construction of new wells and future groundwater consumption in the Rambukpotha Oya microcatchment area.

Acknowledgment

The authors gratefully acknowledge the support given to this research from Uva wellassa University of Sri Lanka.

References

[1] Y. Zhou, W. Li, "A review of regional groundwater flow modeling," Geoscience Frontiers, vol. 2, Apr. 2011, doi.org/10.1016/j.gsf.2011.03.003

[2] G.N. Rajapaksha, "Morphometry, climate variability, land use diversity in the Badulu Oya catchment, and their influence on surface water resources", Master thesis, Dept. of Applied Earth Sciences, Uva Wellassa Univ.,2020.

[3] Kumar, C. P. (2004). Groundwater Flow Models, https://www.academia.edu/171259/Groundwater_Flow_Models, (accessed 19th April 2022)

[4] R.B. Winston, R.B., ModelMuse- A graphical user interface for MODFLOW–2005 and PHAST: U.S. Geological Survey Techniques and Methods 6–A29, 52 p., available only online at https://pubs.usgs.gov/tm/tm6A29, (accessed 19th April 2022).

[5] M. Kirubakaran, J.C. Johnny, and S. Samson, "MODFLOW based groundwater budgeting using GIS: A case study from Tirunelveli taluk, Tirunelveli district, Tamil Nadu, India". Journal of the Indian Society of Remote Sensing, Vol. 46, Feb. 21,2018, doi.org/10.1007/s12524-018-0761-7.