Cureus Journal of Engineering

Open Access Original Article

Application of Geomodeller in Production of Enhanced Lithological Map for Groundwater Exploration

Received 04/21/2025
Review began 05/14/2025
Review ended 06/13/2025
Published 06/20/2025

DOI: https://doi.org/10.7759/s44388-025-05364-4

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Abstract

Lithology is one of the major controlling factors considered in groundwater potential mapping. The factor is considered because it controls the recharge rate from rain water that forms groundwater table. Lithology has always been derived from geological maps of a region through digitization of different units constituting the geology of the area. However, developed geological map excludes unconsolidated material within which groundwater aquifers are developed. The aim of the study was to develop the protocol for deriving lithology thematic maps within soil, laterite, saprolite, and granite in Tochi watershed for use in groundwater potential mapping. The method utilized data derived from borehole drill logs, the geology map of Uganda for extraction of unique features, and a Digital Elevation Model (DEM) to develop input data required by Geomodeller 3.2.0 software. From the 3D model of Tochi watershed generated, transverse and longitudinal sections were created to gain insight into subsurface lithological arrangement through visual interpretation. In order to develop a thematic map of mentioned lithology, point elevation data of 3D lithological boundary surfaces were exported in excel format for further analysis in ArcGIS. A Triangular Irregular Network (TIN) was generated from the imported data of individual stratigraphic units. The TIN was converted to DEM followed by reclassification into four lithology thematic maps namely; very high, high, low, and very low. The result revealed that soil formed patches mainly at lowland areas exposing laterite to the topographic land surface due to erosion and deposition regimes. Laterite occupied the slopy section within the watershed and also does not exist as a continuous series. The same trend applies to saprolite whose exposure to the land surface is exhibited at the foothills of hilly areas. Granite was exposed to land surface at the highest elevation within the watershed and formed more less a continuous series. From the thematic maps developed, highest groundwater potential was exhibited in lowland areas where strike slip fault exists. The potential reduced with increase in elevation. The finding shows that the developed protocol, which is user friendly can enhance the development of lithological map from groundwater drill logs using the Geomodeller tool. The map can be used to clearly identify groundwater recharge zones for effective management of the groundwater resource.

Categories: Environmental and Sustainable Engineering, Environmental Engineering and Sustainability, Water Resources Engineering
Keywords: unconsolidated material, hydrogeology, watershed, lithostratigraphic unit, groundwater potential, hydraulic properties, subsurface strata

Introduction

The ever-increasing demand for groundwater for household, industrial, and agricultural uses exerts enormous pressure on the dwindling resource [1,2]. Compounding on the increased demand is the challenge of pollution affecting its suitability for use [3-5]. Management of the resource involves the use of groundwater potential maps to protect recharge zones guaranteeing water table replenishment and pollution control through controlled activities within vulnerable regions [6,7]. Use of such maps also minimizes incidences of drilling dry wells thus avoiding unnecessary cost. Groundwater potentials are identified using models broadly classified as statistical, hybrid, and machine learning [8]. The approach relies on the identification of contributing factors influencing groundwater recharge rate, which is a pathway through which groundwater is replenished. Commonly used factors include land use, rainfall, soil type, slope, geomorphology, lithology, lineament, and drainage density. Thematic maps are prepared for each of the factors indicating respective groundwater potential. The prepared maps are then integrated in GIS software to produce overall groundwater potential map. A lithology thematic map is developed from the existing geological maps or toposheets through digitization of spatial rock boundaries [9-13]. The map developed is ranked to produce lithology map of area under study. The major consideration in ranking is the ability to transmit infiltrated water based on textural characteristics of the formation. Despite the wide dependence on geology map in production of lithology thematic map, geology map assumes uniform textural characteristics of geological material in the vertical direction. The assumption has resulted in the representation of a single layer of lithology thematic map within the unconsolidated region of geological

How to cite this article
Joachim B, Geoffrey O, Denis N, et al. (June 20, 2025) Application of Geomodeller in Production of Enhanced Lithological Map for Groundwater Exploration. Cureus J Eng 2 : es44388-025-05364-4. DOI https://doi.org/10.7759/s44388-025-05364-4

formation. Unconsolidated materials and their textural characteristics are also not adequately represented on geology map because they are considered as near-earth surface materials affected by recent processes such as erosion, deposition, and weathering. In terms of geological time, little meaningful information can be derived from recently formed materials. From hydrogeology perspective, unconsolidated geological materials are groundwater aquifers particularly in Tochi watershed and well development continue to take place within the region. Furthermore, litho-stratification exists within the unconsolidated region with varying porosity and permeability as is evident from lithology description section of borehole drill logs. The variation in hydraulic properties within the unconsolidated zone alters recharge rates and the spatial distribution of groundwater within Tochi watershed [14]. In addition, Tochi watershed has experienced increasing dependence on groundwater sources [15], massive tree cutting for energy needs, and agricultural land expansion to meet increasing population demand [16]. Such uncontrolled activities affect groundwater recharge thereby negatively impacting on groundwater table. Although 3D hydrogeology models based on statistical approach have been used to predict groundwater potential [17-20], its use as a means of production of lithology thematic map has not been reported. Protocol based on 3D model is important because it considers variations in porosity and permeability existing among different lithological units known to affect groundwater recharge and their spatial distribution. The outcomes from such approach are several lithological units of more less uniform textural characteristics which is in sharp contrast with output generated from geology map. When used in groundwater potential mapping, lithology map prepared using the approach results in improvement of prediction accuracy. In this study, several lithological maps are produced relying on drill log data using 3D structural models for use in groundwater potential mapping. 3D models are simple to construct and rely on readily available data. 3D model also plays important role in the conceptualization and visualization of the subsurface strata fundamental in development of numerical models. From the substrata generated, individual groundwater recharge potentials are estimated for management applications and resources estimation in mining industry. Hydrogeological processes can also be explained through observation of lithostratigraphic unit arrangement.

Materials And Methods

Materials

The study gathered raw data from different sources and analyzed them to produce the required result. First, geological map of Uganda for year 2008 (scale 1:1000000) was obtained from Uganda Geological Survey department. The map was used to identify location of strike slip fault within the watershed as well as provide geological formation existing within the watershed. ArcGIS/ArcSWAT in combination with preexisting shape files of Uganda, borehole spatial location, and Digital Elevation Models (DEMs) (30 m resolution) were used to generate study area map. Geomodeller software was used to produce lithology thematic maps. The software was chosen because of its (1) ability to implicitly develop and isolate sub-lithology units of relatively uniform porosity and permeability based on drill log data and (2) ability to represent lithological surfaces in 3D thereby aiding identification of recharge zones. Such representation is not easy to perform in 2D models as it would require generation of several sections to identify recharge zones. DEM obtained from United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/) are utilized by the Geomodeller software in grid format as the topographic land surface required during 3D model generation. Another important input required for thematic map development is borehole drill logs. The log contains wealth of data on spatial location, estimated lithology change depth, pump test, and water quality. A total of 52 drill logs were obtained from the districts of Omoro (21 logs) and Oyam (31 logs). Drill log data period ranged between March 2003 and December 2016. Borehole drill logs were selected for use because the data adequately approximate depth at which lithology changes within the unconsolidated zone. Screening was performed on drill log to eliminate unrequired data and identify water strike depth which formed groundwater table level. Inspection was also performed on geology map of Uganda to identify dip angel of the strike slip fault for use in Geomodeller as well as any other unique feature of importance. The process ensured input data used by Geomodeller software was of good quality. The logs acquired were considered adequate because of good spatial coverage of the watershed (Figure *1*). In addition, the watershed also has overall elevation range of only 168 m implying a relatively flat area with less complex geology generally consisting of sedimentary deposits [21]. Based on the above observations, generated layers of lithological units through interpolation of borehole data provide good estimate of sub-lithological units within the watershed. In complex geologic formation, more drill log data is required to adequately represent lithology partitioning. As an example, 173 drill logs were used by [22] to produce satisfactory result with low misfit between model result and borehole depth over a catchment area of 7812.8 km^2 and vertical depth of 2 km. Finally, QuillBot and Grammarly were used during the writing process to check for Grammer and Artificial Intelligence.

Study area

Tochi watershed covers approximately 2206.7 km^2 (Figure *1*). It is bounded within the zone 36N, 402516.1 m East, 313538.38 m North, and 459743.92 m East, 239269.02 m North. Major soil units within the watershed are Haplic Alisols, Haplic Ferralsols, Eutric Gleysols, and Albic Plinthosols with a unimodal type of rainfall received [23]. The geology consists of the Neoarchaean rock deposit formed between 2500Ma and 2800Ma as the parent material [24]. Rock deposits are respectively overlaid from top to bottom by Metagabbro, Gneissic granitoids of Uganda Neoarchaean, and the Amuru Group (consisting of granite and granodiorite). A strike slip fault also exists within the watershed.

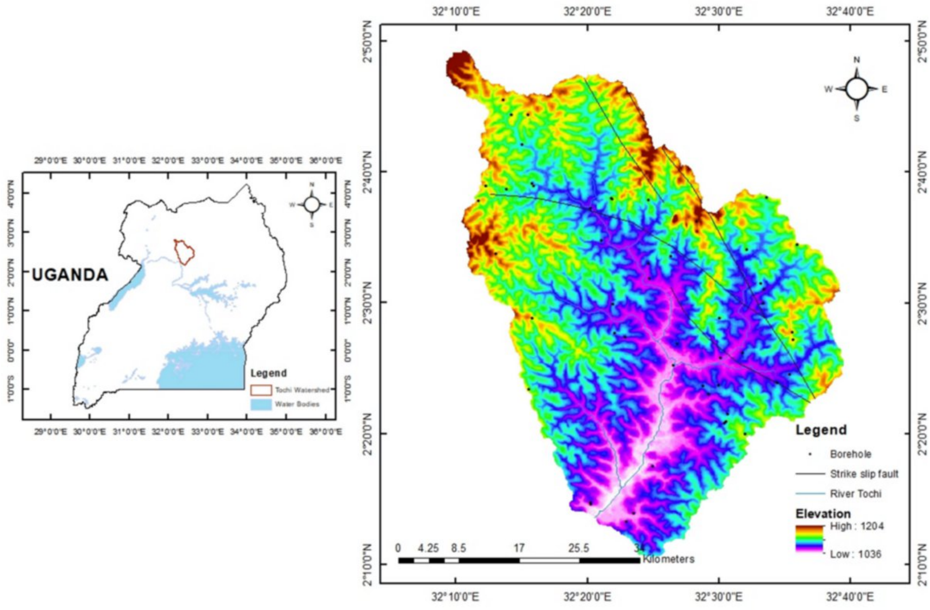

FIGURE 1: Location of Tochi watershed

Method

Database Development

From the drill logs obtained three different databases were prepared in Excel (Collar table, Geology table, and Survey table). The databases are stored in comma separated value (csv) format for use as input in Geomodeller software. Collar table was prepared by extracting information on borehole name, latitude, longitude, elevation, and maximum depth of drill hole (67 m). The depth is arrived at by adding a working allowance of 2 m on top of deepest borehole depth of 65 m drilled within the watershed. The depth of 67 m guided by DEM elevation was used to set the minimum elevation of 920 m and maximum elevation of 1204 m as vertical scale range within Geomodeller software. The maximum drill hole depth in combination with latitude and longitude within which the watershed lies provides the specification for 3D grid box generation. Geology table contains information on borehole name and vertical depth where lithology changes with corresponding sub-lithology name. Such data were extracted from lithology section of the drill log and populated into the database. In instances where borehole drillers did not record name of the geological material, the reported color and texture of the geological material was used to deduce the name of the parent geological material. Survey table also contains information on borehole name, dip angle of the lithology (900), and maximum borehole depth (65 m). The information was populated into the database for use in Geomodeller software.

Development of Lithology Thematic Map

Thematic map preparation in Geomodeller software begins by setting boundaries for 3D structural geometry generation. The boundaries were set as Latitude to longitude with vertical elevation as minimum and maximum. DEM was imported into the software in grid format to provide topographic land surface. Collar table, geology table, and survey table were also imported into the software. The imported databases provided the structural elements required to generate the 3D model of the watershed. Stratigraphic unit pile was defined respectively from top most layer toward groundwater table as soil, laterite, saprolite, granite, and saturated zone using onlap relationship. Next, interpolation is performed on the same borehole lithology boundaries in 2D. This formed the basis upon which different stratigraphic units are separated. The generated 2D datapoints are projected onto the third plane during simulation to provide the 3D model of Tochi watershed in accordance with Equation (1).

$$m(x) = \sum_{j=1}^{j} \sum_{k=1}^{k} m_k \beta_k^j(x) \qquad (1)$$

Where m(x) = aquifer thickness, j or k = number of nodes, B = interpolating function on the grid. The function defines the geometric structure of the parametrization.

Next, the geology map of Uganda was clipped to boundary of study area, strike slip fault digitized and incorporated into the 3D model generated using a dip angle of 90°. Section tool was used to create transverse and longitudinal section through Tochi watershed (Minakulu to Oyam district headquarters and Keyo hill toward Kamdini respectively). The aim was to provide more insight into geology arrangement within the unconsolidated zone through visual interpretation. In order to develop thematic map for each sub-layer generated from the 3D model, the bottom interface between each stratigraphic unit was exported as point data in comma separated value format (csv) for further analysis in ArcGIS. Triangular Irregular Network (TIN) was developed from imported data using the 3D analyst toolbox. The TIN was converted into a DEM for each individual subsurface. On the basis that water flow from high elevation to low elevation, regions with the lowest elevations receive and store more water and as such exhibit high water potential. The concept formed the basis for reclassification. Reclassification was performed using four class intervals (very high, high, low, and very low) to generate lithology thematic maps for soil, laterite, saprolite, and granite. The choice for use of four classes was based on low elevation range of 168 m which could not justify use of more classes.

Results

Section through unconsolidated geological material is presented in Figure *2*. A depression exists in the middle portion of the section. This is where most water collect whether surface or groundwater due to low elevation and it coincides with region where strike slip fault exist. Patches of soils are mainly located at lowest elevation and are of greater thicknesses especially in downstream regions. With exception of granite that forms a continuous series, soil, laterite, and saprolite also exist as patches at different regions within the watershed. Most aquifers within the watershed are found predominantly within granite stratigraphic unit followed by saprolite at some geographic locations. Laterite exists along the slopy section (between highest and lowest elevation) within the watershed and are exposed to the topographic land surface. At highest elevation, granite exists and is exposed to the land surface. There is a general decrease in elevation from Keyo hill toward Kamdini. Granite strikes the topographic surface around Keyo hill with great thickness with reduced elevation toward the outlet. At the lowest elevation, granite exhibits low thickness in comparison to higher elevations. In terms of contribution of sub-lithological units to groundwater occurrence in groundwater potential mapping, high groundwater potential is exhibited at lowest elevations (Figure *3*). As elevation increases, the depth to groundwater reduces, thus resulting in very low groundwater potential.

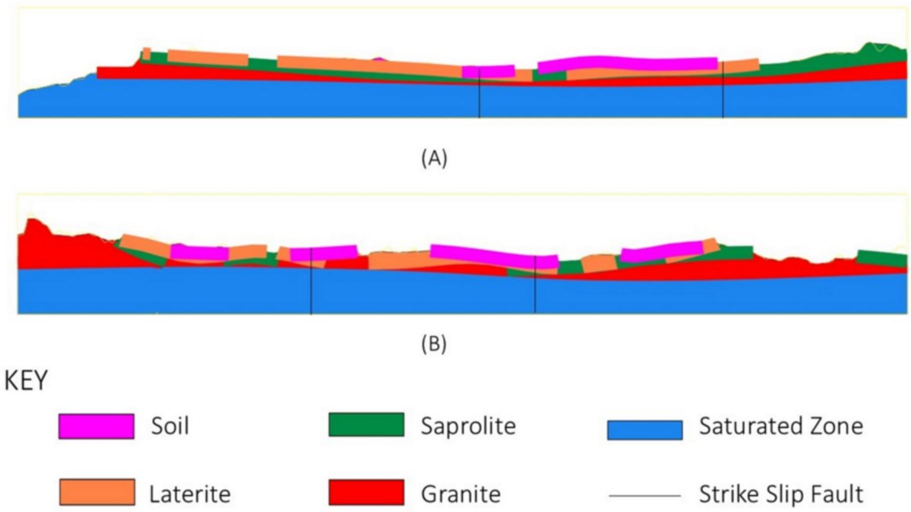

FIGURE 2: Lithostratigraphic section (A) across Tochi river (Minakulu to Oyam district headquarters through Tochi irrigation scheme), (B) along Tochi river (Keyo to Kamdini)

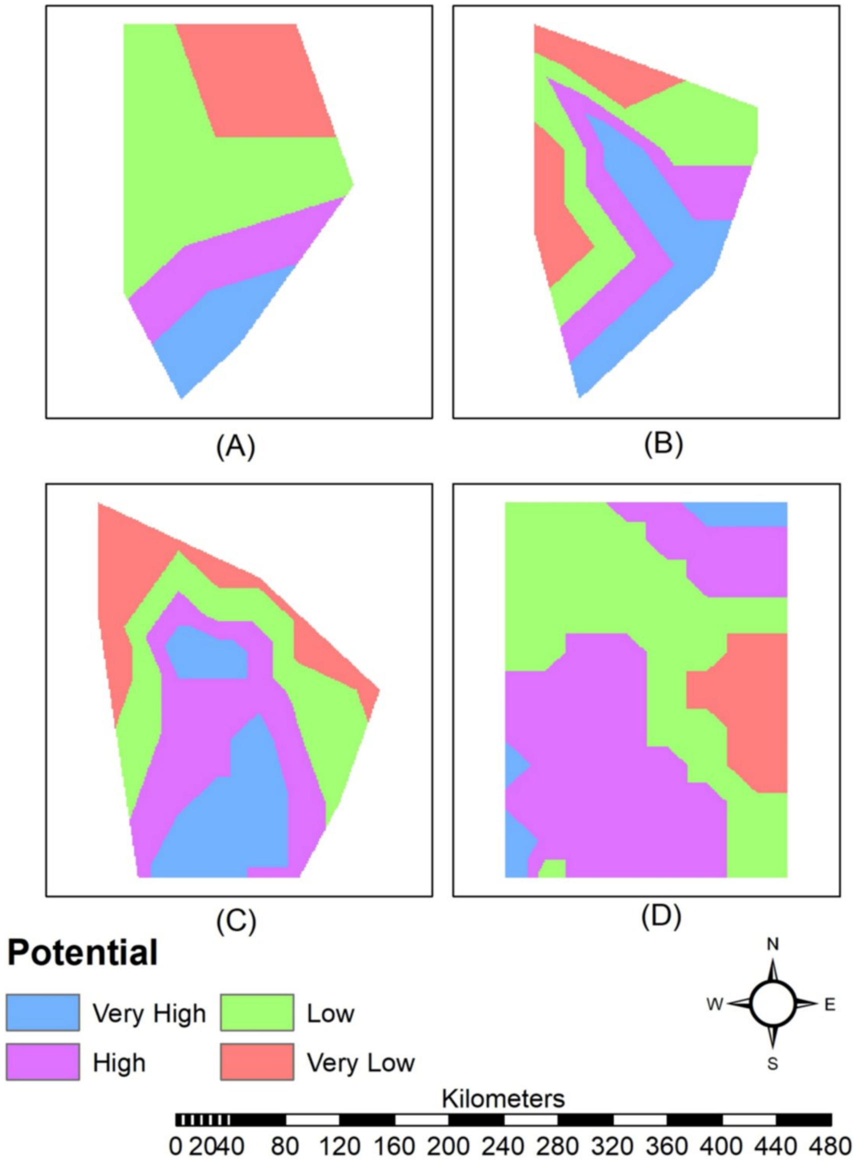

FIGURE 3: Lithology thematic maps (A) soil, (B) laterite, (C) saprolite, and (D) granite

Discussion

Soils located in low elevation areas are probably the result of natural erosion processes amplified by anthropogenic activities causing more sediments to be deposited in those areas. Such processes resulted into exposure of laterite to the topographic land surface. Despite the deposition, some of the soils are exported outside the catchment through stream networks. Existence of high soil moisture at lowland areas as opposed to upland areas could have also accelerated weathering process within this zone resulting into thick soil pile within the zone. Loss of topsoil may result in lowering of soil productivity for agricultural purposes at some locations within the watershed due to sediment and nutrient export out of the watershed through rainfall surface runoff [25,26]. Wetland encroachment has also been attributed to the existence of fertile soils in lowland area [27]. Agricultural activities result into drying up of riparian vegetation thus affecting aquatic ecosystem [28]. The mixed nature of lithostratigraphic units indicate different erosion and deposition of unconsolidated materials within the catchment to an extent that saprolite is exposed to land surface at some location. From hydrogeological perspective, each regime has different porosity and permeability thus affecting groundwater movement differently [29,30]. At higher elevation, erosion has resulted into exposure of granite to the topographic land surface. Groundwater movement from higher elevation to lower elevation has resulted into high water table in low elevation areas. The movement is encouraged by the high porosity and permeability of the unconsolidated materials deposited. Despite granite having low permeability, in Tochi watershed, the geological material is considered perched due to the existence of strike slip fault allowing water to percolate through it. Recharge through the medium could also be influenced by existence of localized recharge zones existing within the watershed. The existence of strike slip fault within the lowland areas acts as a sink draining groundwater collected in the lowland areas. Such observation may attempt to explain the dry season fluctuation of surface water within wetland as opposed to wetland encroachment causing drying and shrinking of riparian vegetation. However, due to the absence of pumping test data for extended period of time, the effect of faulting on hydrogeology within the watershed cannot be adequately explained [31]. In terms of groundwater potential mapping, regions with low elevation are accorded high groundwater potential and this coincides with the location where high groundwater table occurs (Figure *2*). The potential follows a decreasing trend as elevation increases. Several studies on groundwater potential mapping have also utilized lithology map [32-35]. The reclassification approach utilized the knowledge on differences in textural characteristics and elevation differences existing within the watershed to deduce groundwater potential for a given lithology. The rationale behind production of lithology thematic map is in agreement with the method employed in this study. However, the study developed four different lithology thematic maps namely soil, laterite, saprolite, and granite as opposed to a single thematic map developed from geology map [36]. The maps are produced on the basis of differences in textural characteristics observed during drilling operations. Due to such considerations, the method introduces refinement in lithology thematic map generation for use in groundwater potential mapping.

Conclusions

The study developed lithology thematic maps for soil, laterite, saprolite, and granite for use in groundwater potential mapping using Geomodeller software. Result indicated that soil existed mainly in lowland areas. Laterite predominantly occupied slopy sections within the watershed with granite being close to land surface at higher elevation. Groundwater potential maps developed indicated very high potential at low elevation and very low potential at higher elevation. The study provides useful result for identification of recharge zones within the watershed. Strike slip fault existing at low elevation is a sink draining away groundwater within the watershed. The effect may manifest through shrinking of wetland buffer zones as opposed to wetland encroachment as has been attributed by several research findings. However, the hydrogeology within strike slip fault is not well known and is a subject for further research. Agricultural land productivity is anticipated to reduce due to loss of topsoil from the erosion process. Pollution of groundwater sources is possible especially in lowland areas where high water table exists.

Future Scope

Continuous loss of topsoil due to anthropogenic activities results into depletion of nutrients required by plants. Therefore, there is need to manage this process to retain land productivity within the watershed. This can be achieved through designed land use planning to manage the watershed. There is also need for more research into hydrogeology within strike slip fault. This will create more knowledge on dry season surface water fluctuation within lowland areas often attributed to wetland encroachment.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Bongomin Joachim, Openy Geoffrey, Byakatonda Jimmy, Nyeko Martine

Acquisition, analysis, or interpretation of data: Bongomin Joachim, Nono Denis, Labeja Richard Louis, Nyeko Martine

Drafting of the manuscript: Bongomin Joachim, Nono Denis, Byakatonda Jimmy, Labeja Richard Louis, Nyeko Martine

Critical review of the manuscript for important intellectual content: Bongomin Joachim, Openy Geoffrey, Nono Denis, Byakatonda Jimmy, Labeja Richard Louis, Nyeko Martine

Supervision: Openy Geoffrey, Nyeko Martine

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they

have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Acknowledgements

Great thanks go to the districts of Gulu, Nwoya, Oyam, Omoro, and Apac for providing the borehole drill logs upon which the study was built. Thanks also go to the management of the Uganda Meteorological Authority for providing meteorological data. Great thanks go to my family members for the moral support offered during the course of the study.

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