Civil and Environmental Engineering
Vol. 19, Issue 1, 39-47, DOI: 10.2478/cee-2023-0004

DETERMINATION OF THE HYDROLOGICAL AND MORPHOMETRIC CHARACTERISTICS USING GIS

Sahar I. M. ABD ELRAHMAN[1,*], Ibrahim M. Ibrahim ATAALMANAN[1]

[1] Surveying Engineering Department, Sudan University of Science and Technology, Khartoum, Sudan.
[*] corresponding author: engsaharesmail@gmail.com

Abstract

This paper was conducted to determine the hydrological and morphometric characteristics of the Wad Ramli region, Sudan. The Digital Elevation Model (DEM) was obtained and then processed within the ArcGIS 10.8 program. Hydrological analysis tools were used to determine the hydrological characteristics, and then the quantitative analysis was done to deduce the morphological characteristics. The water flow direction, water streams, stream orders, order 4 watershed, and all water basins were obtained. The best location for the dam's water storage was determined. It was found that the water is flowing normally, the basin is asymmetrical, and the area has low terrain.

Keywords:

Geographic Information Systems (GIS);
Digital Elevation Model (DEM);
Hydrological analysis;
Dam best site;
Morphometric analysis.

1 Introduction

Global and local issues are intertwined in the complicated, multi-layered problem of climate change [1]. Both scientific and practical contexts frequently use hydrological studies. For instance, they are utilized in operational contexts for flood predictions, water resource evaluations, and other environmental management, but they might be useful in scientific investigations to comprehend hydrological processes [2]. To fully comprehend watershed behavior, a hydrological cycle study necessitates a careful investigation of the relevant parameters [2]. Several correlated random variables' joint behavior can be used to describe hydrological occurrences [4]. The hydrologic model is an international problem. The results show strong heteroscedasticity and autocorrelation in an area where the seasonal variance in rainfall is significant, which makes the problem much more challenging [5]. Over the past three decades, hydrological models have advanced greatly in terms of their increased complexity and wide range of applications, including flood prediction, rainfall-runoff modeling, and the study of land use and climate change scenarios [6]. For monitoring the effects of the changing climate and researching the dynamics of the distribution of water resources, global hydrological models are essential [7]. Understanding the spatiotemporal characteristics of hydrological components is essential for identifying climatological, biological, and hydrological processes affected by environmental change as well as for managing potential water challenges [7]. Because of human activities such as the growing worldwide population, changing land use, water pollution, and climate change, water is an essential resource for sustainable economic and social development [9]. Despite advancements in the representation of many processes, hydrological models are still unsure. Their unpredictability is caused by the model's structure, parameters, and input and calibration data [10]. Large uncertainties from a variety of sources, such as model variables and input/output data with observational uncertainty, can impact simulations from hydrological models [11]. The lengths and intensities of both hydrological and meteorological phenomena are crucial factors, and these factors are often connected [12].

Morphometry is the measuring and quantitative analysis of the dimensions, shapes, and configurations of the landforms on Earth. Several quantitative techniques have been developed to comprehend the development and behavior of drainage patterns [13]. Understanding the drainage basin's geo-hydrological behavior through the channel network's morphometric analysis is essential. This analysis also communicates the catchment's current climate, geology, geomorphology, and structural antecedents [14]

Geographic Information Systems (GIS), a collection of computerized tools for processing, analyzing, storing, retrieving, and displaying geographically connected spatial data as well as their characteristics, can be used to solve flood problems [15]. Today, more effective methods of GIS have been implemented to improve the watershed and the characteristics of the drainage basins [16].

1.1 Research objectives

This study was conducted to determine the hydrological and morphometric characteristics of the Wad Ramli region and benefit from them to reduce the physical and human disasters that the area is exposed to each autumn and also to choose the best site to set up a water storage dam, where this area is one of the areas affected by the floods and the consequent loss of lives and property.

1.2 Previous studies

Gaurav Singh and Singh (2022) [17] in their study used the free Copernicus DEM 30 m open-source to determine the geomorphometric and topo-hydrological parameters of the Betwa River Basin. They concluded that the basin has a roughly elongated shape, less flow of water is available, relative relief is less, and a weak drain system.

Ma et al (2018) [18] using satellite remote sensing data, linked routing, and surplus storage, studied hydrological modeling in the Shehong basin from 2006 to 2013. The findings demonstrate that the humid Shehong basin primarily experiences summer rains (from May to September). In the period 2010 - 2013, compared to the period 2006 - 2009, there is a notable rise (+ 52 %) in drainage and a less notable rise (+ 18 %) in rainfall.

The authors agreed with previous studies in the study of hydrological and morphometric characteristics, but their study was more comprehensive, detailed, and clear, and relied only on geographic information systems.

2 Materials and methods

Since the study is detailed about the determination of the hydrological and morphometric characteristics, many operations were implemented to achieve the desired results.

2.1 Study area

Wad Ramli, Fig. 1, is a large village located north of Khartoum Bahri on the eastern bank of the Nile, about 75 km from the city of Khartoum. Throughout the ages, it has played a prominent role and had wide participation in Sudanese affairs, as it was established 570 years ago. It is bordered on the east by the Khartoum refinery; on the north by the village of Quri; on the south by the village of Wausi; and on the west by the Nile River. Among the neighborhoods of Wad Ramli, Al-Jaaliyn, Al-Dhananab, Hilat Al-Haj, Hilat Al-Sidr, Hila Ali, and Woodmanofli, most of its residents are from Al-Jimyaab, Al-Jaaliyn, Al-Mahas, Al-Shayqiah, and Danagla. Due to the location of the village, which is located on the banks of the Nile River and its fertile muddy lands, agriculture is the main occupation of the population. The Wad Ramli agricultural project is one of the oldest agricultural projects in Sudan.

In the past, the area was far from the course of the Nile, but due to the demolition, the Nile included the valleys that separated it from it, and the Nile moved east, and the distance separating the houses from the Nile became only about 300 - 400 m. In recent years, the village has been affected both humanly and materially by floods every autumn.

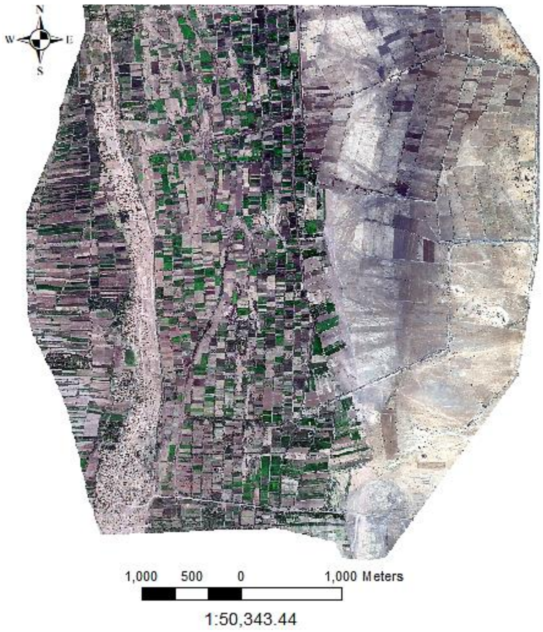

Fig. 1: Wad Ramli satellite image (Global Mapper 22.0).

2.2 Data and software

The data used in the study is a digital elevation model for the Wad Ramli region, which was obtained from the USGS website with a spatial resolution of 30 x 30 meters [19]. The digital elevation model is one of the basic components of GIS and the basis on which to infer the characteristics related to the topography of valleys, where it represents the terrain and topography of the Earth's surface in a raster format.

The Global Mapper 22.0 program was used to obtain a satellite image of the study area, and then the ArcGIS 10.8 program was used to determine the hydrological and morphometric characteristics of the Wad Ramli region. Global Mapper is a powerful geographic information system application that combines a full range of software solutions for spatial data processing and provides access to several formats used in the world of GIS and engineering. A geographic information system is software that enables the management and analysis of geographic data by visualizing geographic statistics through the layering of maps, such as trade flows or climatic data. It is used to conduct and deliver ground-breaking research by numerous academic institutions and departments, including those in the humanities and sciences. Numerous governments and private/commercial organizations throughout the world also use it.

2.3 Procedures

The work was divided into three steps:

- digital elevation model processing,
- hydrological analysis,
- morphometric analysis.

2.3.1 Digital elevation model processing

After the DEM was obtained from the USGS website, it was processed in three ways:

• Firstly, we converted the coordinate system from the geographic to the metric system using the Project Raster tool.

• Secondly, we processed the anomalous values that are too high or too low compared to the values around them using the Fill tool.

• Finally, we used the Mask Function and Elevation Void Fill Function tools to process gaps, which are empty spaces that do not contain values.

2.3.2 Hydrological analysis

A hydrological analysis is an automated method for determining the drainage network, as it is useful in all aspects of planning for areas with drainage networks, especially if the planning aims to confront the danger of floods, reserve water for agriculture or feed the underground reservoir.

A shapefile for the Wad Ramli region was created from the satellite image and by which the study area was extracted from the processed DEM. The water flow direction from each cell to the adjacent cells was obtained.

The streams were determined by knowing the water accumulation, i.e. the number of cells or the amount of water that flows into each cell. The resolution of the streams was increased. It is controlled by a certain value, where the lower this value, the higher the accuracy, and in return, the larger the file size, and there is no fixed value. The obtained streams file was converted from a raster file to a vector to become a layer of polylines defining the streams of the study area.

The stream orders were determined. Four stream orders were obtained, where stream order 4 is the highest. The stream orders were converted from the raster format to the vector format, to be dealt with, and then the resulting vector layer was dissolved by the grid code field. A symbology was made for the resulting layer, where the thicker lines indicate the highest stream order.

A point shapefile was created with the same metric coordinate system and in it was created a point located at the end of a stream order 4, and by it and the flow direction layer, the water basin which affects this point was determined. To study this water basin morphometrically, it was converted from a raster file to a vector, and thus a polygon layer was obtained. Only the stream orders located inside this basin were extracted and then symbolized.

All the water basins in the study area were determined, where there are two main basins and many sub-basins on the sides of the study area. The water basins raster file was converted to a polygon layer to be used in the morphometric analysis.

The water basin with the biggest area of the vector water basins layer was selected and then exported in a separate layer. Through this layer, the stream orders within it were extracted and then symbolized.

The best location was determined to construct a dam to collect the water inside it, to reduce the risk of floods and make use of the water collected in other seasons. This was done by creating a point shapefile with the same metric coordinate system and in it was created a point representing the location of the proposed dam at the end of the highest stream order in the biggest water basin.

2.3.3 Morphometric analysis

Morphometric analysis is a type of analysis that deals with the phenomena of the Earth's surface, based mainly on numbers. All the standard basin characteristics that result from taking specific measurements of the water basins and the morphometric characteristics of the water basins are directly related to natural factors such as the geological structure, climate, and vegetation cover.

The morphometric analysis was performed on the two vector layers for the water basin with the biggest area and the extracted stream orders inside it.

In the morphometric analysis, drainage density, bifurcation ratio, relief ratio, basin texture ratio, form factor, stream survival constant, ruggedness value, and stream frequency were determined.

The drainage density means the degree of branching and spread of the river network within a specific area. It is the result of dividing the sum of the lengths of the water streams by the area of the drainage basin. The drainage density indicates the nature of the surface water runoff in the basin, which is affected by factors such as climate or the terrain of the area. If the drainage density is high, it means that the water flows normally, and if it is low, it indicates that some obstacles impede the flow of water.

The bifurcation ratio is the ratio between the number of streams of one order and the next order, and the ratio in the basins usually ranges between 3 - 5 and it is a reflection of the climatic, terrain, and geological conditions of the study area. The bifurcation ratios close to the mentioned limit are evidence of the similarity of the basin’s climatic and structural properties, and any high and low from the mentioned limit is evidence of the basin’s asymmetry from the natural aspects or that there is a tectonic or structural activity in the basin.

The relief ratio is the ratio between the highest and lowest points of the basin to the actual length of the basin. It is one of the extremely important topographical features of the basin, as the higher the ratio indicates that the course of the stream passes through an area with high terrain and indicates an increase in the transfer of sediments; the lower the ratio indicates that the terrain decreases in the stream.

The basin texture ratio is the ratio of the number of streams in the basin to the perimeter of the basin. It relies on several elements, including climate, especially rainfall, natural vegetation cover, rock composition, soil type, degree of infiltration, and terrain.

The form factor can be obtained by dividing the area of the basin by the square of the basin length. The decrease in the quotient indicates the small area of the basin to its length, which indicates that the form of the basin is close to the triangle form.

The stream survival constant is calculated as an algebraic invert of the drainage density, where the larger the value of the output for all basins of the study area, this indicates the expansion of the basin area at the expense of water channels of limited length.

The roughness value is the product of multiplying the drainage density by the height difference between the highest and lowest points, divided by the length of the basin. The low value indicates that the streams run in areas of low terrain, and the high value is when the terrain increases or the lengths of the streams increase at the expense of the basin area.

The stream frequency is the ratio of the number of water streams of all orders for the given basin to the area of the basin. In the case of calculating the stream frequency for all basins of the study area, if the results converge, they indicate the normality of the rock homogeneity over which the water streams flow.

3 Results, analysis, and discussion

To perform the hydrological analysis, the digital elevation model was processed within the ArcGIS 10.8 program in the WGS 1984 UTM Zone 36N coordinate system.

The DEM of the study area was extracted using the shapefile created based on the satellite image of the study area.

The water flow direction was obtained, where the result shows that the cells bearing the color 1 have water flow in the east direction, 2 in the southeast direction, 4 in the south direction, 8 in the southwest direction, 16 in the west direction, 32 in the northwest direction, 64 in the north direction, and 128 in the northeast direction.

The flow accumulation was determined and is the product of the number of cells that flow into each cell, and then the resolution of these streams was increased using the value > 100. The vector layer of streams was obtained.

The stream orders were determined and converted into a vector format. The result was dissolved by the grid code field and symbology was done where it is noted that there are four orders, the highest of which is the 4, Fig. 2.

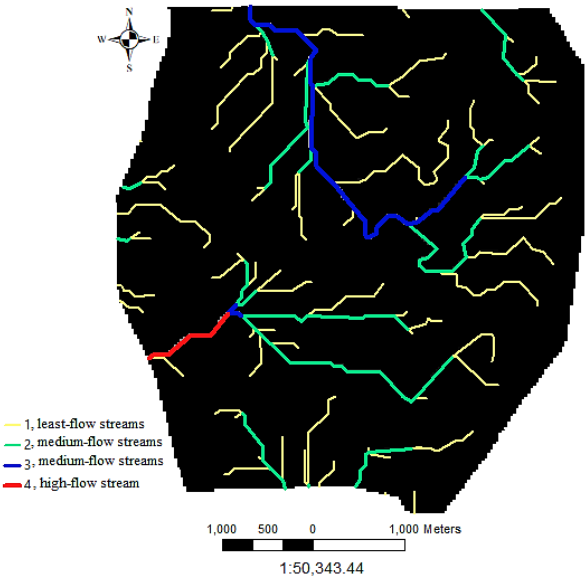

Fig. 2: Stream orders. It was found in the study area that there are four stream orders, where the number 1 indicates the streams that have the least water flow, and so on until we reach the number 4, which is the stream that has the highest water flow.

The watershed for order 4 was determined through the shapefile of the point at the end of the fourth-order stream. This basin was converted into a vector layer and then the stream orders that fall inside it were extracted and symbolized, Fig. 3.

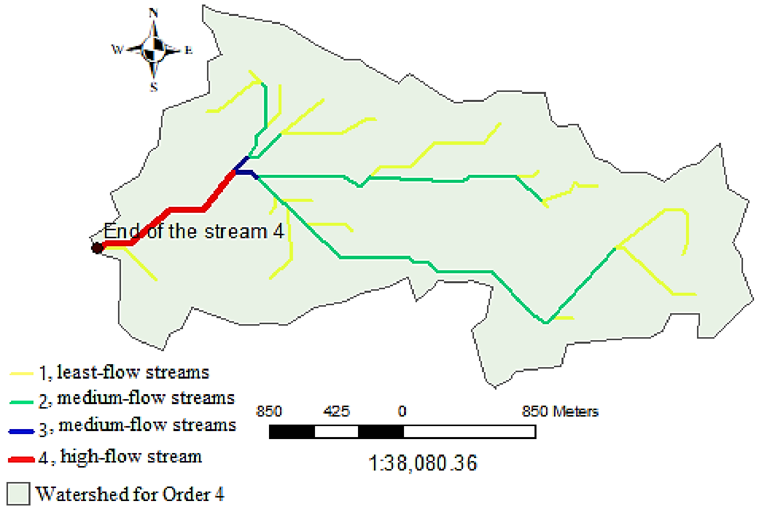

Fig. 3: Basin of the order 4. The watershed in which the highest stream flows.

All the water basins, Fig. 4, within the study area where there were two main basins and many sub-basins were obtained and then converted into vector format to be used in the morphometric analysis.

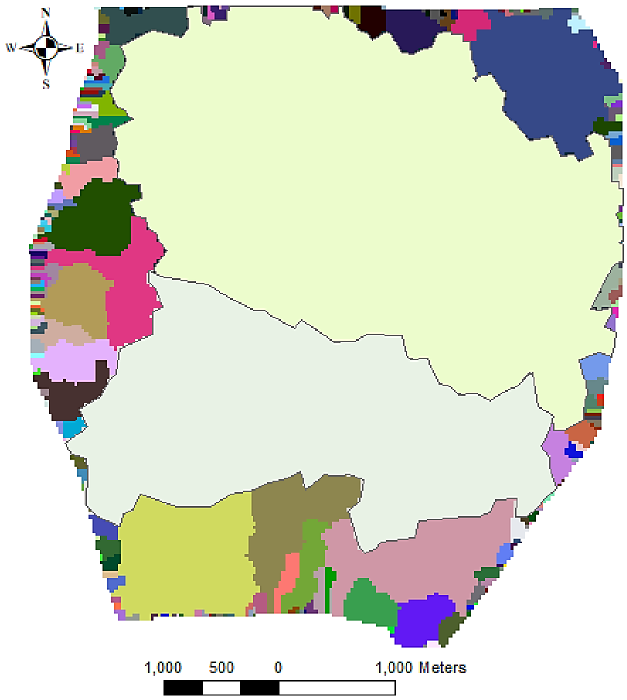

Fig. 4: Basins of the study area. It was determined two main basins in the study area and several secondary basins that were shared with the neighborhood.

The biggest water basin was exported in a separate layer and from this layer were extracted the stream orders within it and symbolized.

To conserve the water that collects in the autumn and to benefit from it, as well as to reduce the risk of floods, the best site for the proposed dam was determined, into which the biggest water basin flows and it is located at the end of the highest stream order in the basin, Fig. 5.

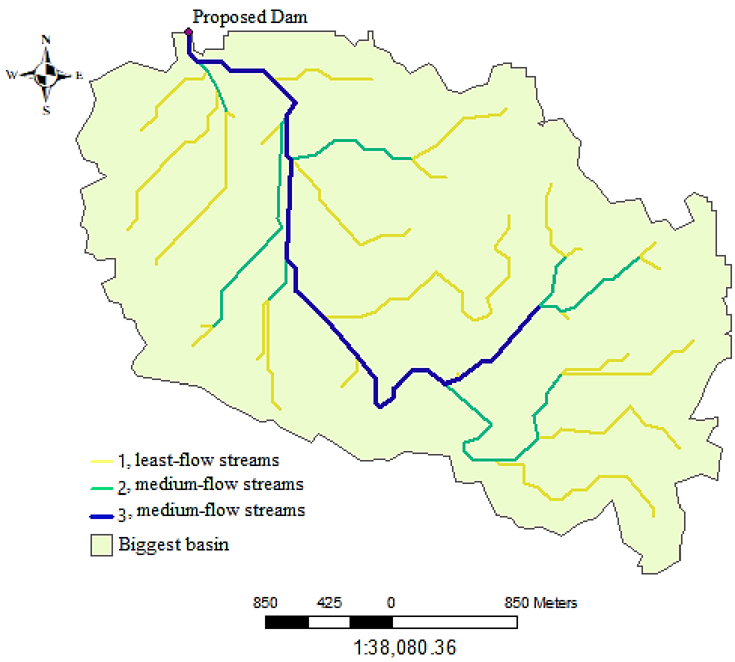

Fig. 5: Best site of the proposed dam. The best location of the proposed dam was determined in the study area, where the largest amount of water flows into it.

Many morphometric characteristics were determined based on the biggest water basin and extracted stream orders layers obtained from the product of the hydrological analysis.

To find out the drainage density, from the attribute table of the stream orders layer, the length sum of the water streams in kilometers was obtained, and from the water basin layer, the drainage basin area was known in square kilometers. It was found that the drainage density is 2.603 km/km^2, which indicates that the water flows normally.

From the stream orders layer, the number of streams for the first and second order was known, and it was found that the bifurcation ratio is 1.9, which indicates that the asymmetries of the basin from a natural perspective or that the basin is experiencing tectonic or structural action.

The digital elevation model of the water basin under study was extracted from the total study area, from which the difference in height between the highest and lowest points in meters was known. A relief ratio of 0.003 was obtained through the height difference and length of the water basin taken in meters. The result indicates that the stream's terrain is descending.

By knowing the number of streams and the water basin perimeter in kilometers, it was found that the basin texture ratio is equal to 2.814 km. This shows the average of the streams regardless of their placement within the water basin.

Using the length and area of the water basin obtained, the form factor was calculated and found to be equal to 0.440, which highlights the basin's tiny area compared to its length.

The stream survival constant was obtained, which is an algebraic invert of the drainage density, and found that it is equal to 0.384 km.

By knowing the drainage density, the height difference between the highest and lowest points, and the basin length, it was found that the roughness value is 0.008, which shows that the streams flow in low-lying places.

It was found that the stream frequency is equal to 4.787 stream/km^2 by dividing the number of streams by the basin area.

Thus, many hydrological and morphometric characteristics were easily determined by performing some procedures within the ArcGIS 10.8 program, which are difficult to obtain manually. This reflects some of the many benefits of GIS in various fields.

4 Conclusion

The hydrological and morphometric characteristics of the Wad Ramli region were determined by applying many procedures within the ArcGIS 10.8 program. After the DEM of the study area was processed, the water flow direction and water streams were obtained, and then:

1) The stream orders were derived and found to be four orders, where order 4 is the one with the highest water flow, Fig. 2.

2) The watershed was determined into which the order 4 stream flows, Fig. 3.

3) All the water basins in the study area were obtained where there are two main basins and many sub-basins shared with neighboring regions, Fig. 4.

4) The best site for the proposed dam was determined to be at the end of the biggest water basin, which is used to conserve water and reduce the risk of floods, Fig. 5.

The morphometric analysis of the biggest water basin and stream order inside it was performed and the following was determined:

1) The drainage density is 2.603 km/km^2. This shows the water is flowing normally.

2) The bifurcation ratio is 1.9, which indicates the basin’s asymmetry from the natural aspects or that there is a tectonic or structural activity in the basin.

3) The relief ratio is 0.003, which shows that the terrain decreases in the stream.

4) The basin texture ratio is 2.814 km. It shows the average of the streams in the water basin, whatever their order.

5) The form factor is 0.440, which indicates the small area of the basin to its length.

6) The stream survival constant is 0.384 km, which is an algebraic invert of the drainage density.

7) The roughness value is 0.008, which indicates that the streams run in areas of low terrain.

8) The stream frequency is 4.787 stream/km^2. It is the number of streams divided by the basin area.

References

[1] VOON, K. L. – TAN, K. W. – CHIN, K. S.: Assessment of the Flood and Drought Occurrence Using Statistically Downscaled Local Climate Models: A Case Study in Langat River Masin, Malaysia. Civil and Environmental Engineering, Vol. 18, Iss. 1, 2022, pp. 221-233, doi: 10.2478/cee-2022-0021.

[2] KAVESTSKI, D. – CLARK, M. P.: Ancient numerical daemons of conceptual hydrological modeling: 2. Impact of time stepping schemes on model analysis and prediction. Water Resources Research, Vol. 46, Iss. 10, 2010, pp. 1-27.

[3] VOLPI, E. – FIORI, A.: Design event selection in bivariate hydrological frequency analysis. Hydrological Sciences Journal, Vol. 57, Iss. 8, 2012, pp. 1506-1515.

[4] SHEN, Z. – CHEN, L. – CHEN, T.: Analysis of parameter uncertainty in hydrological and sediment modeling using GLUE method: A case study of SWAT model applied to Three Gorges Reservoir Region China. Hydrology and Earth System Sciences, Vol. 16, Iss. 1, 2012, pp. 121-132.

[5] SONG, X. – ZHANG, J. – ZHAN, C. – XUAN, Y. – MING, Y. – CHONGGANG, X.: Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications. Journal of Hydrology, Vol. 523, 2015, pp. 739-757.

[6] WERTH, S. – GUNTNER, A.: Calibration analysis for water storage variability of the global hydrological model WGHM. Hydrology and Earth System Sciences, Vol. 14, Iss.1, 2010, pp. 59-78.

[7] MA, J. – SUN, W. – YANG, G. – ZHANG, D.: Hydrological analysis using satellite remote sensing big data and CREST model. IEEE Access, Vol. 6, 2018, pp. 9006-9016.

[8] ZHU, Y. – DUAN, P. – ZHANG, S. – SUN, B.: Spatiotemporal analysis of hydrological variations and their impacts on vegetation in semiarid areas from multiple satellite data. Remote Sensing, Vol. 12, Iss. 24, 2020, pp. 1-19.

[9] VILAYSANE, B. – TAKARA, K. – LUO, B. – AKKHARATH, I. – DUAN, W.: Hydrological stream flow modelling for calibration and uncertainty analysis using SWAT model in the Xedone river basin, Lao PDR. Procedia Environmental Sciences, Vol. 28, 2015, pp. 380-390.

[10] MOGES, E. – DEMISSIE, Y. – LARSEN, L. – YASSIN, F.: Sources of hydrological model uncertainties and advances in their analysis. Water, Vol. 13, Iss. 1, 2020, 23 p.

[11] PIANOSI, F. – WAGENER, T.: Understanding the time-varying importance of different uncertainty sources in hydrological modelling using global sensitivity analysis. Hydrological Processes, Vol. 30, Iss. 22, 2016, pp. 3991-4003.

[12] WONG, G. – VAN, L. H. – TORFS, P.: Probabilistic analysis of hydrological drought characteristics using meteorological drought. Hydrological Sciences Journal, Vol. 58, Iss. 2, 2013, pp. 253-270.

[13] ALTAF, F. – MERAJ, G. – ROMSHOO, S. A.: Morphometric analysis to infer hydrological behaviour of Lidder watershed, Western Himalaya, India. Geography Journal, 2013, pp. 1-15.

[14] HAJAM, R. A. - HAMID, A. - BHAT, S.: Application of morphometric analysis for geo-hydrological studies using geo-spatial technology: A case study of Vishav Drainage Basin. Hydrology Current Research, Vol. 4, Iss. 3, 2013, pp. 1-12.
[15] CHRISTOPHER, O. – IDOWU, A. – OLUGBENGA, A.: Hydrological analysis of Onitsha North East drainage Basin using geoinformatic techniques. World Appl Sci J, Vol. 11, Iss. 10, 2010, pp. 1297-1302.
[16] GAURAV, S. V. - SINGH, S. K.: Analysis of geo-morphometric and topo-hydrological indices using COP-DEM: a case study of Betwa River Basin, Central India. Geology, Ecology, and Landscapes, 2022, pp. 1-28.
[17] MAXWELL, C. – NJOKU, C. – NWAKUBA, N. – EZEDOZIE, P. – OKORAFOR, O.: Global mapper 15.0: A comparative software tool in the design of open channel drainage systems. Poljoprivredna tehnika, Vol. 46, Iss. 3, 2021, pp. 61-73.
[18] DAVILA, H. S. – TRINIDAD, J. G. – FERREIRA, H. E. J. - CAPETILLO, C. F. B. – AVILA, H. M. D. – ESCARENO, J. C. – LETECHIPIA, J. O. – ROVELO, C. O. R. – BALTAZAR, E. A. L.: Effects of the Digital Elevation Model and Hydrological Processing Algorithms on the Geomorphological Parameterization. Water, Vol. 14, Iss, 15, 2022, pp. 1-25.
[19] https://earthexplorer.usgs.gov/.

.