OPEN ACCESS
Saudi Journal of Civil Engineering
Abbreviated Key Title: Saudi J Civ Eng
ISSN 2523-2657 (Print) |ISSN 2523-2231 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com/journal/sjce/home

Original Research Article

Watershed Modelling, Using the Geographical Information System (GIS) Approach (Federal University of Technology Owerri, Imo State Nigeria as Case study)

Ukachukwu O. C[1*], Dike B. U[1], Nganya K. C[1], Eberechukwu, T.E[1]

[1]Department of Civil Engineering, Federal University of Technology Owerri, Imo state, Nigeria

DOI: https://doi.org/10.36348/sjce.2024.v08i07.003 | **Received:** 29.07.2024 | **Accepted:** 04.09.2024 | **Published:** 14.09.2024

***Corresponding author:** Ukachukwu O. C
Department of Civil Engineering, Federal University of Technology Owerri, Imo state, Nigeria

Abstract

In a typical watershed area such as the Federal University of Technology, Owerri, Nigeria, watershed modelling is essential for the sustainable management of water resources, protection of ecosystems and more. In this study, we will be creating a watershed model for FUTO, this study will also cover other aspects such as estimating the depression-less flow direction, delineating the flow accumulation, extracting realistic drainage network using the Strahler's stream order method and we will also delineate the watershed's boundary and identify possible outlets / pour points, using the digital elevation model (DEM) gotten from Alaska satellite facility used as a main data source in combination with the PC version of ArcGIS software (ArcMap 10.7) and then we extract the hydrologic information from the DEM in ArcGIS using Hydrology tools. The estimation of depression-less flow direction is done by filling the digital elevation model (DEM). This includes performing fill on sinks to ensure proper delineation of basins and streams. If the sinks are not filled, a derived drainage network may be discontinuous. After the DEM has been filled, then we can now move on to delineating the flow accumulation in the study area. The results shows that by using watershed function in ArcGIS for watershed flow direction and accumulation in FUTO can be determined. The results also shows the drainage network that was extracted by Strahler's method, showing different orders of streams and it also shows the watershed boundary and pour point / outlets along the Otamiri River which the watershed drains into. This work simply shows the applicability of GIS as a tool of watershed delineation and drainage extraction.

Keywords: FUTO, Otamiri River, Digital Elevation Model, Depression-Less Flow Direction, Watershed Boundary Delineation, Pour Points, Outlets, Flow Accumulation, GIS, ArcMap 10.7.

1.0 INTRODUCTION

A watershed is the upward region that provides concentrated drainage, or flow, usually water, to a common exit. It may comprise smaller watersheds known as subbasins or it may be a portion of a bigger watershed. Drainage divides are the lines separating watersheds. The location on the surface when water exits a region is known as the outflow or pour point. It is the lowest point on a watershed's border.

A model is a simplified representation or simulation of a system, process, or phenomena found in the real world. Various elements of engineering projects and systems can be better understood, analyzed, predicted, and optimized by using models. A model is an artificial abstraction that captures the key features of a complicated system or idea while leaving out the details that are unimportant to the analysis or problem at hand.

A watershed model is a representation or simulation of the processes that occur within a watershed, watershed models take into account factors such as precipitation, evaporation and the movement of water through various land uses. These models are valuable tools for managing bwater resources, assessing the impact of land development and making informed decisions about land and water management practices.

A digital elevation model (DEM) is a critical dataset that provides information about the elevation or topography of the terrain within the watershed's boundaries. Typically, satellites, drones, and aircraft gather remotely sensed data that is used to create DEMs. Due to the diversity of DEM source data, it is possible, for example, to fill in data gaps where there is limited data accessible over remote locations. Automatic DEM extraction from stereo satellite scenes enables the use of data from satellite sensors with a resolution of 5–10 m, such SPOT-5.

Estimating depression-less flow direction by filling the DEM, as stated earlier, digital elevation models are approaches to describe the terrain surface in a way, that computers can display them and use them to calculate additional information, e.g. terrain slope, exposure, flow direction etc. An alternative name for them is digital terrain models (DTM). The surface may have both plant and man-made components like buildings. A DEM devoid of depressions is a fundamental prerequisite for a good flow accumulation analysis. Smaller sinks in particular in nature fill with water and continue to cause surface runoff. The accumulation halts in the flow route analysis, and a new path with a fresh accumulation cascade begins. As a result, the true catchment area of a location and the flow accumulation process are underestimated. You must "fill" these types of sinks in your DEM in order to create continuous flow paths, which will close the gap and get you closer to reality.

Using the Watershed tool, one can outline a watershed from a DEM by calculating the flow direction. Using the flow direction tool, a raster depicting the flow direction was initially made in order to identify the contributing area. Next, we can supply the sites for which we want to calculate the catchment area. These locations could be structures like dams or stream gauges, for which we want to calculate the contributing region's characteristics. The result is a raster of the watersheds, and it is necessary to specify a flow accumulation raster and the threshold value, or the minimum number of cells that make up a stream.

Extracting realistic drainage networks is a crucial task in fields such as hydrology, geomorphology, and environmental science. The Strahler Method is one approach used to extract drainage networks from digital elevation models (DEMs) or topographic data. It helps in representing the hierarchical structure of river systems in a way that reflects the natural flow paths of water. The Strahler Method aims to mimic the natural behavior of rivers by representing their branching patterns and hierarchy. The Strahler method assigns stream orders based on the concept of network complexity. By assigning stream orders based on network complexity, hydrologists and geomorphologists gain a systematic way to study and describe river systems. This classification method helps in capturing the inherent hierarchy of river networks and their contributions to the larger watershed dynamics.

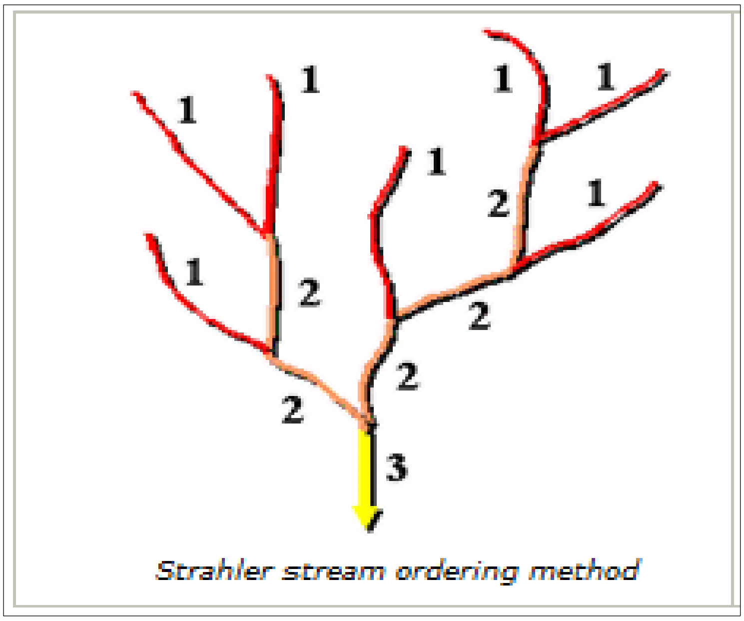

Figure 1.0: Strahler stream ordering method

It is useful for various applications such as watershed delineation, flood modeling, and understanding river basin dynamics. However, it is important to note that the Strahler Method might not capture all local variations and can be sensitive to the resolution and accuracy of the DEM data used.

Watershed boundary delineation is the process of identifying and mapping the geographic boundaries that define a particular watershed. In the context of hydrological connectivity, the process of delineating watershed boundaries involves analyzing the flow patterns, stream networks, and flow convergence points. Specialized software is often used to simulate how water moves through the landscape and to identify the areas where flow paths diverge or converge.

Watershed pour point is a location within a watershed where surface runoff converges and flows into a common outlet, to identify pour points, one can use digital elevation models (DEMs) and geographical information system (GIS) software to locate areas where water flow accumulation. The identification of pour-points or outlets is a crucial step in watershed delineation, as it marks the point where water exits a particular watershed area. Geographical analysis involves the use of various techniques, tools, and data sources to locate and define these points accurately.

Mohan P. Pradhan, M. K. Ghose and Yash R. Kharka Department of CSE, SMIT Sikkim India in 2012, did a study on automatic association of Strahler's order and attributes with the drainage system. This work implements procedures that efficiently associates order with the identified segments and created a repository that stores the attributes and estimates of different segments automatically. Implementation of such techniques not only reduced both time and effort as compared to that of manual procedures, it also improved the confidence and reliability of the results.

Nahida Hameed Hamza Alqaysia and Mushtaq Abdulameer Alwan Almuslehi in 2016, did a study on the delineation of the watersheds basin in the Konya City and modelling by geographical Information system, in this study 3768 catchment watersheds delineated automatically by using basin function of the hydrology toolbox.

Imas Sukaesih Sitanggang and Mohd Hasmadi Ismail in 2011, did a study on the simple method for watershed delineation in Ayer Hitam forest reserve using geographical information system and were able to get both the flow direction and flow accumulation of the watershed area using GIS.

2.0 MATERIALS

The materials used for this study are:

i. ArcGIS Software (ArcMap 10.7)
ii. Digital Elevation Model (DEM)
iii. Hydrological Data

3.0 METHODS

Method for estimating depression-less flow direction by filling the digital elevation model (DEM):

Step A: Import the digital elevation model into the software.

Step B:

Perform fill operation on the DEM using fill tool to balance out voids and inconsistencies in the DEM. The fill tool uses the equivalents of several tools, such as Focal Flow, Flow Direction, Sink, Watershed, and Zonal Fill, to locate and fill sinks. The tool iterates until all sinks within the specified limit are filled. As sinks are filled, others can be created at the boundaries of the filled areas, which are removed in the next iteration.

Step C:

Estimate the flow direction using the D8 flow model. There are eight valid output directions relating to the eight adjacent cells into which flow could travel. This approach is commonly referred to as an eight-direction (D8) flow model and follows an approach presented in Jenson and Domingue (1988).

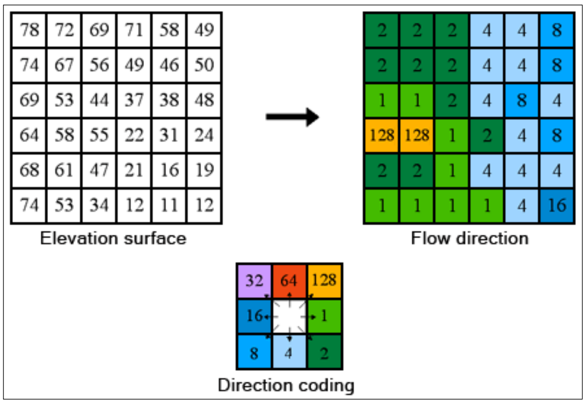

Figure 3.0: The coding of the direction of flow

Step D: Calculate the direction of flow by the direction of steepest descent, or maximum drop, from each cell. This is calculated as follows:

$$maximum\ drop = \frac{change\ in\ z - value}{distance\ x\ 100}$$

Step E:

Allocate flow direction codes to each cell for example, if the direction of steepest drop was to the left of the current processing cell, its flow direction would be coded as 16.

Step F: Save the output / result as raster file.
Method for delineating the accumulation of flow

Step A: Import the output file of the filled DEM.

Step B:

Condition the raster, the Con tool allows you to control the output value for each cell based on whether the cell value is evaluated as true or false in a specified conditional statement.

Step C: Input 0 as false to denote areas which do not accommodate water.

Step D: Input 1 as true to denote areas that accommodate water.

Step E: Save the output as raster file.

By calculating the total weight of all the cells that flow into each downslope cell in the output raster, the Flow Accumulation tool determines the accumulated flow. In the event that no weight raster is given, each cell is given a weight of 1, and the number of cells that flow into each cell is indicated by the value of cells in the output raster.

Method for extraction of realistic drainage network using the Strahlar method

Step A: Input stream flow direction raster file and flow accumulation raster file.

Step B: Covert the stream flow direction and flow accumulation from a raster file to a vector file using the "stream to feature" tool.

Step C:

Assign orders 1-7 to denote the various magnitude of every stream by the use of Strahler method in the watershed. The most used stream ordering technique is the Strahler approach. This technique, however, does not account for all links and can be sensitive to the addition or removal of links because it only grows in order at crossings of the same order.

Method for delineation of the watershed boundaries and identification of pour-points / outlets

Step A: Compute the flow direction and input it alongside the drainage network raster into the watershed tool.

Step B: To determine the contributing area, a raster representing the direction of flow must first be created with the Flow Direction tool.

Step C:

Provide the locations you wish to determine the catchment area for. Source locations may be features, such as dams or stream gauges, for which you want to determine characteristics of the contributing area. In this case, our catchment area is the Otamiri river. Therefore, a flow accumulation raster must be specified as well as the minimum number of cells that constitute a stream (the threshold value).

Step D: The output is a raster of the watersheds.

Step E: The pour points can be identified on the watershed raster (model) as the cell that accumulates the highest amount of water.

4.0 RESULTS: The flow direction model without depressions

The flow direction from each cell to its neighbor with the steepest downslope is modeled by the D8 flow method. An integer raster with values ranging from 1 to 128 is the result of using the D8 flow direction type in the Flow Direction tool. Below are the values for each direction away from the center:

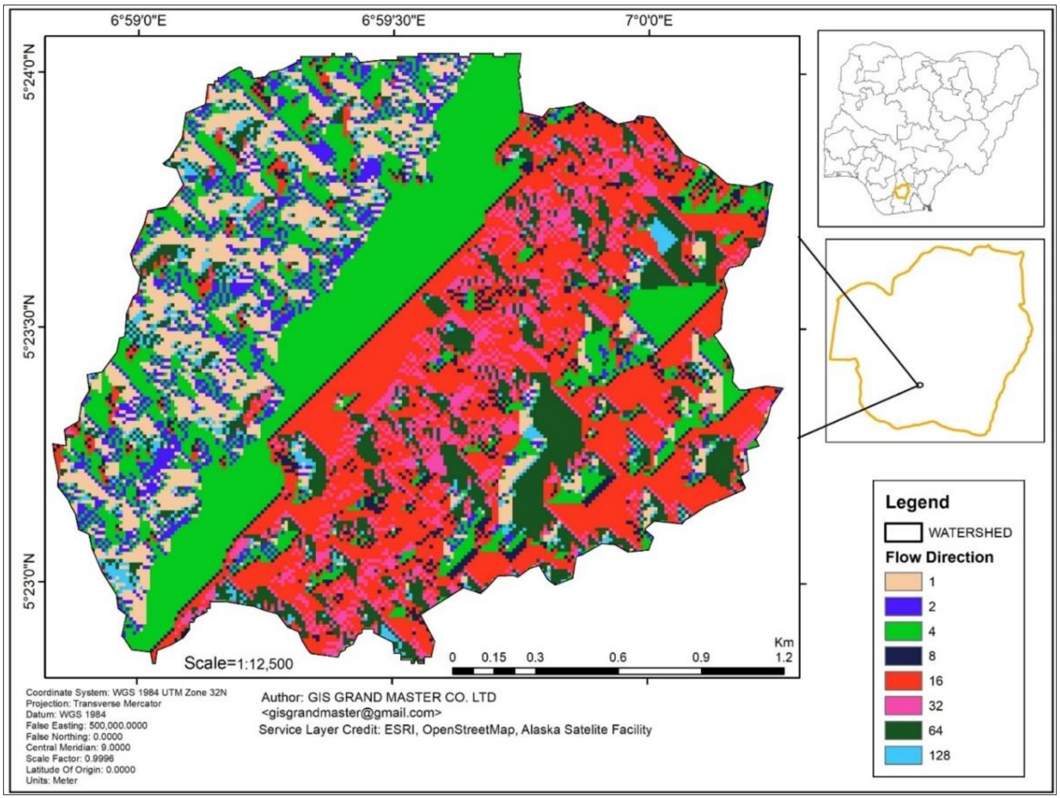

Figure 4.0: Flow accumulation map of study area

The flow direction talks about the direction of flow. The figure below shows where water will flow since we have agreed that there are different heights. We performed this, using the D8 algorithm. The D8 algorithm shows the flow in a particular pixel in 8 different directions. The D8 algorithm can be found in the tool box of the ArcMap GIS software.

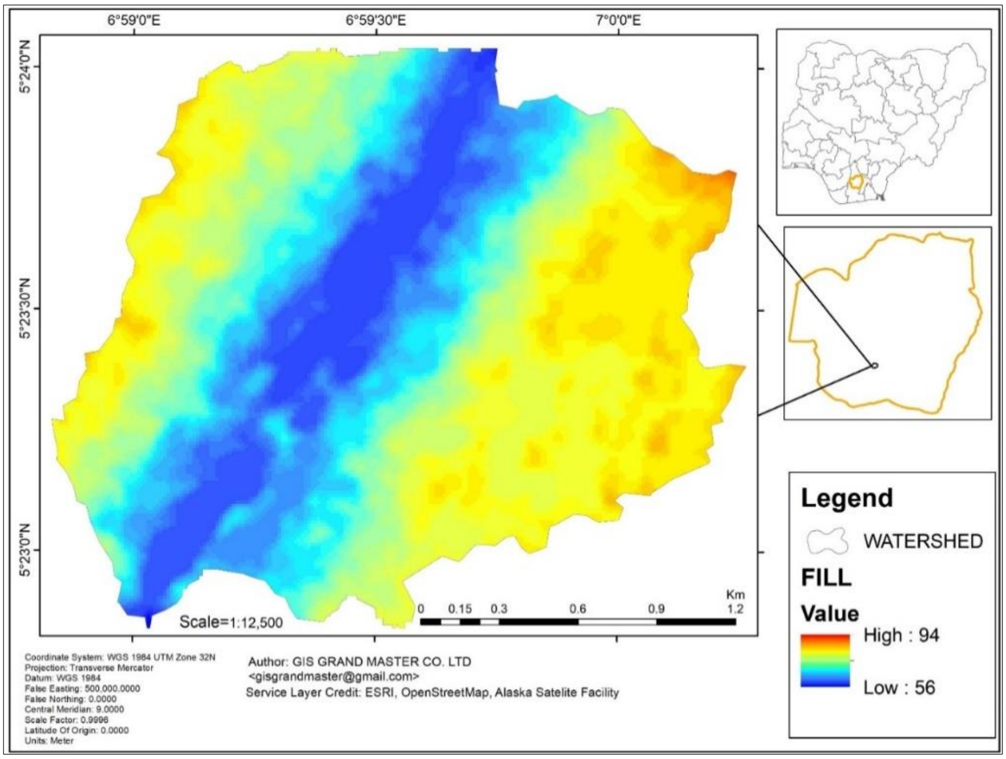

Figure 4.1: Fill map of study area

The flow accumulation model

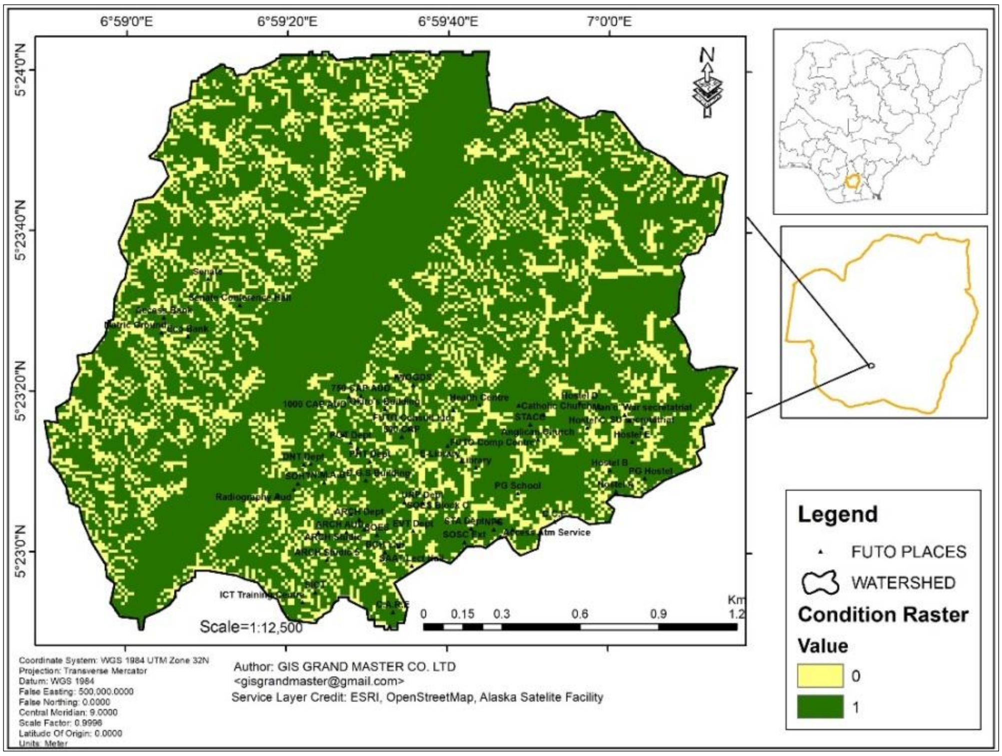

Figure 4.2: Conditioning flow accumulation in the watershed

Below is the flow accumulation condition raster for this research.

The flow accumulation condition raster above resulting in the flow accumulation map is shown below:

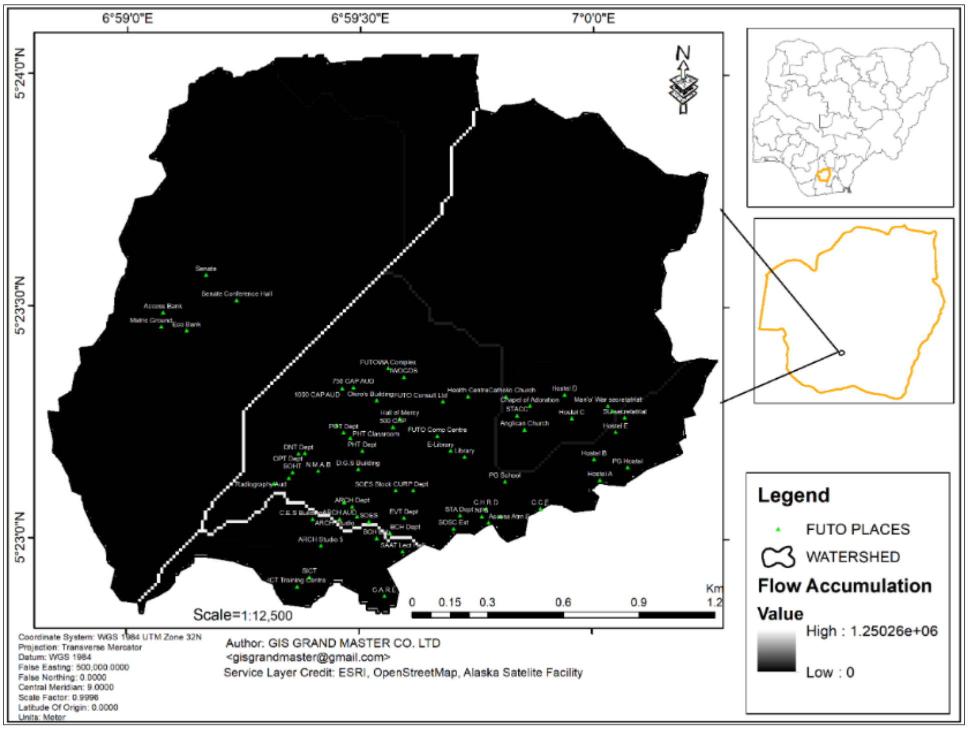

Figure 4.3: Flow accumulation map

The drainage network / stream order:

After getting the flow accumulation, we then got the drainage network, showing the order of streams within the watershed, and the result is shown in the next page.

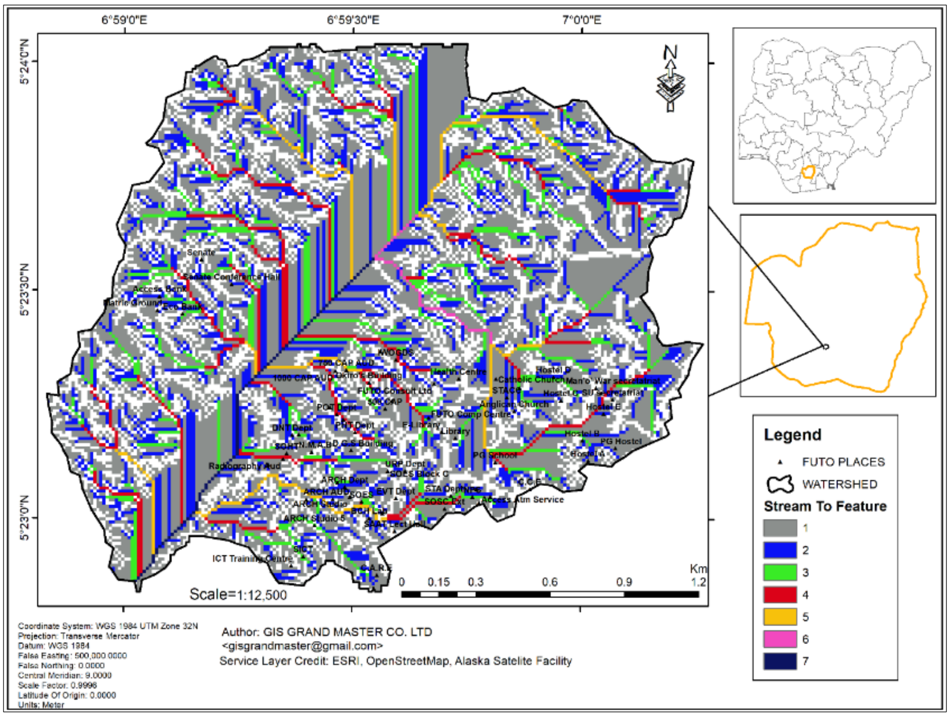

Figure 4.4: Stream order / drainage network

The watershed boundary and identified pour points

After we have gotten the different stream orders, and streams of smaller intensity removed, the water shed map in the next page is called out. It also shows the pour point, which is the point with the highest accumulation.

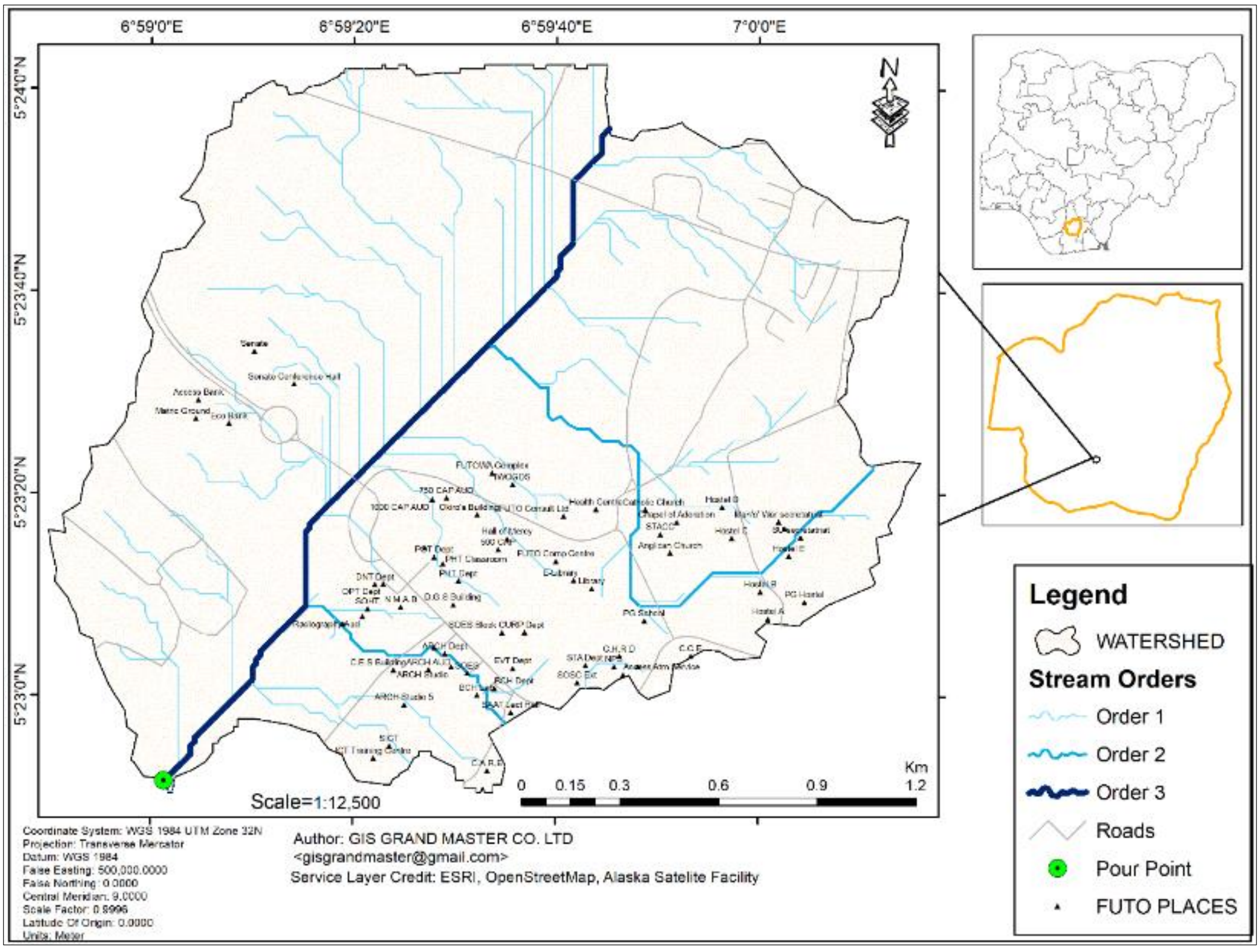

Figure 4.5: The watershed model

5.0 RESULTS DISCUSSION: The depression-less flow direction model

The map in figure 4.0 shows that the areas with a magnitude and direction of flow in real life, below is an explanation of the respective magnitudes and their direction of flow:

i. Areas with magnitude 1 flows in the East direction.
ii. Areas with magnitude 2 flows in the South-east direction.
iii. Areas with magnitude 4 flows in the South direction.
iv. Areas with magnitude 8 flows in the South-west direction.
v. Areas with magnitude 16 flows in the West direction.
vi. Areas with magnitude 32 flows in North-west direction.
vii. Areas with magnitude 64 flows in the North direction.
viii. Areas with magnitude 128 flows in the North-east direction.

Next, the flow accumulation raster data is integrated in the software to now show the cells that accommodate more water across the study area, and their direction of flow. The depression-less flow direction map of the watershed, seen in figure 4.1 shows the areas within the watershed and their respective heights, as we all know, water flow from a place of elevation to a place of depressions. This study area has a highest Fill value of 94, meaning that the areas within that point of value are elevated surface and a low of 56, meaning that areas around that value are depressed surface.

The flow direction simply talks about the direction of flow. We performed this, using the D8 algorithm. The D8 algorithm shows the flow in a particular pixel in 8 different directions. The D8 algorithm can be found in the tool box of the ArcMap 10.7 software. Recall Nahida Hameed Hamza Alqaysia and Mushtaq Abdulameer Alwan Almuslehi in 2016, in their study on the delineation of the watersheds basin in the Konya City and modelling by geographical Information system, used this same D8 algorithm to get their flow direction.

The flow accumulation model

In figure 4.2, the attached condition raster file of the flow accumulation within the watershed shows us two distinct features on the legend, 0 and 1. Where we already stated in the methods to input the conditions that:

i. Input 0 as false to denote areas which do not accommodate water.
ii. Input 1 as true to denote areas that accommodate water.

But the problem with the raster file is that it is not too easy to understand so there was a need to then apply the "stream to feature" tool as stated in 3.0 to then get a more understandable and readable map. The output is shown in figure 4.3, the places with high of (1.25026e+06) are areas that accumulate more water and those of low (0) shed water into the high accumulation areas meaning they do not hold water. Recall Imas Sukaesih Sitanggang and Mohd Hasmadi Ismail in 2011, in their study on the simple method for watershed delineation in Ayer Hitam Forest reserve using geographical information system were able calculate the flow accumulation layer from the flow direction layer by the same steps as stated in this study.

As seen from the legend, in figure 4.4 we have stream orders of 1 to 7 meaning that stream order 1 has lower current but stream order 7 has the highest current as Strahler explained. The only problem with this map is that it shows streams of every order, therefore making it difficult to read and understand, so then to get the watershed itself, we employ the methods as stated in 3.0. Recall Mohan P. Pradhan, M. K. Ghose and Yash R. Kharka Department of CSE, SMIT Sikkim India in 2012, in their study on automatic association of Strahler's order and attributes with the drainage system, Implemented Strahler method which associates order with the identified segments and created a repository that stores the attributes and estimates of different segments automatically. Implementation of the Strahler's order method makes it easier for the streams to be read, reducing the amount of orders of stream from over 128 to just 7 steam orders and these streams can furthermore be reduced to allow for easy interpretation of the model.

DISCUSSION ON THE WATERSHED BOUNDARY AND IDENTIFIED OF POUR POINT

The output of the method in 3.0 is now our watershed model, showing only three stream orders and the pour point as seen in figure 4.5. The boundaries between watersheds are termed drainage divides. The outlet, or pour point, is the point on the surface at which water flows out of an area. It is the lowest point along the boundary of a watershed, and in this study we were able to identify only one pour point as shown above, we can also see the flow of water through the various places and departments in FUTO. This model also shows that the stream order 3 is the Otamiri River which serves as the drainage basin of FUTO as a watershed.

6.0 CONCLUSION

In this research, we estimated the depression-less flow direction, delineated the flow accumulation, we also extracted a realistic drainage network and we were able to create a model of the watershed, FUTO using the digital elevation model (DEM) gotten from Alaska satellite facility used as a main data source in combination with the PC version of ArcGIS software (ArcMap 10.7).

The results of this research as documented in section 4.0, helps us to see how water flows from different parts of the watershed area and shows the stream network in the watershed area which is the different departments and places in FUTO as shown in figures 4.0 to 4.5 and how the watershed contributes water into the Otamiri River flowing through FUTO. This study can also help in decision making for environmental growth.

REFERENCES

- Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association, 34*(1), 73-89.
- Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1999). Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of hydrologic engineering, 4*(2), 135-143.
- Imas Sukaesih, S., & Mohd Hasmadi, I. (2011). The simple method for watershed delineation in Ayer Hitam forest reserve using geographical information system.
- Jenson, S. K., & Domingue, J. O. (1988). "Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis." *Photogrammetric Engineering and Remote Sensing, 54*(11), 1593–1600.
- Mishra, S. K., & Singh, V. P. (2011). A review of drought concepts. *Journal of hydrology, 403*(1-2), 157-175.
- Mohan, P., Pradhan, M. K. G., & Yash, R. (2012). *Kharka Department of CSE, SMIT Sikkim India*. Automatic association of Strahler's order and attributes with the drainage system.
- Molina-Navarro, E., Gómez-Plaza, A., Martínez-Pérez, A., & Hernández-Hernández, M. (2017). A review of decision support systems for water resources management. *Journal of Hydrology*.
- Nahida Hameed, H. A., & Mushtaq Abdulameer, A. A. (2016). Delineation of the watersheds basin in the

Konya *City and modelling by geographical Information system*.

- Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and water assessment tool theoretical documentation version 2009*. Texas Water Resources Institute.
- Nengwang, C., Huancheng, Li., & Lihong, W. (2009). A GIS-based approach for mapping direct use value of ecosystem services at a county scale: Management implications.
- Vijay, K. T.(2014). A GIS-based model, Soil Conservation Service Curve Number (SCS-CN).