2024 Scienceline Publication

Journal of Civil Engineering and Urbanism

Volume 14, Issue 3S: 199-205; September 25, 2024

ISSN-2252-0430

DOI: https://dx.doi.org/10.54203/jceu.2024.20

Effects of Resampled DEM on Watershed Characteristics and Prediction of Sediment Load in Oyun Watershed, Kwara, Nigeria

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RESEARCH ARTICLE

PII: S225204302400020-14

Received: June 25, 2024

Revised: September 02, 2024

Accepted: September 05, 2024

ABSTRACT

Understanding the terrain and its impact on watershed characteristics, streamflow, and sediment loading is crucial for effective water resource management. This study investigates the influence of resampled Digital Elevation Models (DEM) on the prediction of watershed characteristics, streamflow, and sediment loading upstream of Oyun River Watershed, Nigeria. Various DEM resolutions, ranging from 30-meter to 90-meter, were analysed to assess their effects on hydrological predictions. To delineate the watershed, a DEM of 90-meter resolution was sourced from the space Shuttle Radar Topography Mission (SRTM), and the ASTER global DEM data sources. The 90-meter resolution was resampled to four different resolutions which are 75-meter, 60-meter, 45-meter, and 30-meter resolutions. The watershed and streamline were delineated, and the hydrologic simulation was performed using Soil and Water Assessment Tool (SWAT). The research findings revealed that changes in DEM resolution had a negligible impact on streamflow predictions within the Oyun River Watershed. However, a noticeable impact was observed in the prediction of sediment concentration. The 90-meter resolution DEM yielded the lowest predicted sediment concentration, measuring 2.28 mg/l, while the 30-meter resampled DEM produced the highest value at 5.21mg/l. Similarly, the sediment yield (SYLD t/ha) exhibited considerable variation across the different DEM resolutions, with the 90-meter DEM demonstrating the lowest value of approximately 528.90 t/ha, and the 30-meter DEM registering the highest at 2145.57 t/ha. Overall, this research highlights the necessity of careful DEM selection in hydrological modelling to ensure a comprehensive understanding of watershed dynamics, particularly in regions where sediment transport and water quality are of paramount concern.

Keywords: DEM, Hydrological Modelling, Nigeria, Sediment Loads, Watershed

INTRODUCTION

Accurate prediction of streamflow, sediment concentration and yield in a river catchment is essential for sustainable management of water resources at the watershed level. To achieve this, hydrological modelling is necessary, and the application of Geographical Information Systems (GIS) combined with Digital Elevation Model (DEM) has significantly improved this process. Digital Elevation Models (DEMs) play a pivotal role in understanding and modelling terrain characteristics, which have far-reaching implications for various fields, including hydrology, geology, environmental science, and engineering. DEMs are digital representations of the Earth's surface, capturing elevation data at discrete points in a grid format. They are instrumental in depicting topographic features, such as mountains, valleys, and river basins, which are essential for a range of applications.

However, one common challenge associated with the use of DEMs in hydrological modelling is their spatial resolution, which refers to the size of each grid cell and, consequently, the level of detail they can capture. In many cases, DEMs are derived from remote sensing data sources, such as satellite imagery or airborne LiDAR (Light Detection and Ranging), and the chosen spatial resolution may not fully capture local topographic variations or fine-scale features. To address this limitation, researchers often employ resampling techniques. Resampling involves altering the spatial resolution of a DEM by aggregating or disaggregating data points. By doing so, researchers can enhance the level of detail in specific regions or reduce computational demands for large-scale analyses. The selection of an appropriate resampling technique is a critical decision in DEM processing, as it directly impacts the accuracy and reliability of subsequent analyses Digital Elevation

To cite this paper: Adeogun AG, Mansur AW and Mohammed AA (2024). Effects of Resampled DEM on Watershed Characteristics and Prediction of Sediment Load in Oyun Watershed, Kwara, Nigeria. *J. Civil Eng. Urban.,* 14 (3S): 199-205. DOI: https://dx.doi.org/10.54203/jceu.2024.20

Models (DEMs) are essential tools for studying land surface processes and modelling the flow of water and sediment in river catchments (Viglione et al., 2013). DEMs provide a digital representation of the elevation of the land surface, typically at a spatial resolution ranging from several meters to several kilometres (Dávila-Hernández et al., 2022; Badamasi et al., 2022). DEMs can be used for a wide range of applications, including terrain analysis, land use planning, environmental monitoring, and hydrological modelling (Tang et al., 2009). The development of DEMs has revolutionized hydrological modelling by providing a detailed and accurate description of the topography of river catchments (Wu et al., 2013).

Based on the foregoing, it is common to resample DEMs to a coarser resolution to reduce computational requirements (Dixon and Earls, 2009; Choi et al., 2015; Muthusamy et al., 2021). Resampling involves averaging or aggregating elevation values over larger grid cells, which can result in a loss of fine-scale terrain details (Badamasi et al., 2022). However, high-resolution DEMs can also pose computational challenges due to their large file size and processing requirements. Therefore, it is essential to carefully consider the effects of DEM resolution on the accuracy of predictions and to use appropriate methods to account for errors introduced by resampling.

This research investigated the effects of various resolutions by resampling of an existing DEM. The study's specific goal was to use DEM, GIS, and SWAT to model the drainage pattern and predict the flow and sediment loadings on river catchment in Nigeria. Some challenges and opportunities of using SWAT to predict basin water characteristics within a river catchment could be identified through the application of SWAT for hydrological modelling and prediction of flow and sediment loadings.

MATERIALS AND METHODS

Description of the Study Area

The study area is Oyun River Basin, which has a terrain elevation of 259 meters above sea level and can be found between latitudes 90. 501 and 80. 241 North and Longitudes 40. 381 and 40. 031 East. The river Oyun, which starts near Ila Orangun in Osun State of Nigeria at an elevation of 465.003 m above the sea level, flows for about 80 kilometres to the northeast and converges with river Asa in Kwara State. The area of Oyun in Kwara State is located southeast of Ilorin and is known for its open and undulating terrain, rocky outcrops, and varying slopes in the northwestern portion. It is a region of Nigeria's grass plains that is mostly used for farming with only a small section of forest reserve. River Oyun is a major water source for Offa town and its neighboring areas, and it also supplies raw water for the University of Ilorin, Ilorin water supply scheme. Figure 1 shows a map of the Oyun River basin, which includes a network of rivers and catchment areas.

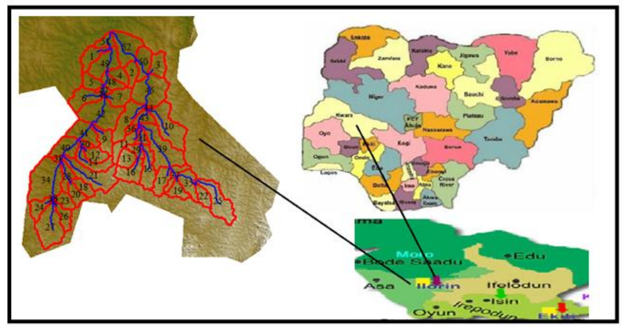

Figure 1. Map of Nigeria showing the location map of the study area.

Model Selection and Description

The model used in this study is the soil and water Assessment Tool, SWAT (Neitsch et al., 2005). The selection of SWAT for this study was based on many reasons. For instance, SWAT is an existing software that is available for free on SWAT website. Also, based on past studies, it has been confirmed as an efficient tool in the modelling of hydrological processes (Adeogun et al., 22; Adeogun et al., 2015; Adeogun et.al, 2014; Betrie et al, 2011). The SWAT model originated from the collaborative efforts of the U.S. Department of Agriculture – Agriculture Research Service (USDA-ARS) and operates on a continuous time basis as a conceptual model. Its integral components encompass weather patterns, hydrological processes, erosion and sedimentation dynamics, plant growth mechanisms, among others. Within the agricultural realm, it accounts for variables like fertilizers, crops, tillage methods, grazing, and even the incorporation of point source loads (Neitsch et al., 2009).

Model Input Data

The basic spatial input datasets used by the model include the Digital Elevation Model (DEM), Land use/ cover data, soil data and weather data. Digital elevation model used in this study is of resolution 90 m x 90 m and was obtained from online database developed by United State Department of Agriculture (CGIAR, 2012). The DEM (Figures 2 to 6) provides the basis for watershed delineation into sub-basins. The Land use map (Figure 7) used for the modelling was downloaded from the Global Land Cover Characterization (GLCC) database and has a spatial resolution of 1Km and 24 classes of landuse representation (GLCC, 2012). The digital soil data for the study was extracted from harmonized digital soil map of the world (Harmonized World Soil Database (HWSD) produced by Food and Agriculture Organization of the United Nations, Rome (Nachtergaele et al., 2009). Meteorological data necessary to run the SWAT model was obtained from Nigerian Meteorological Agency (NIMET) station based in Ilorin, Kwara State. The data collected includes daily precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. The weather variables for driving the hydrological balance within the watershed were for a period of 19 hydrological years i.e. (January 1, 2001, to December 31, 2019).

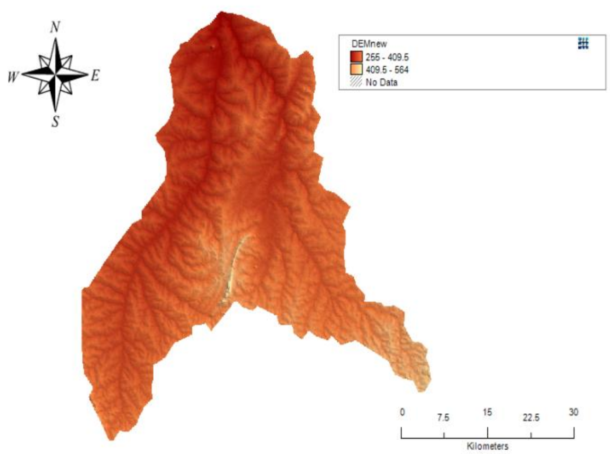

Figure 2. DEM of 90 m resolution of the study area.

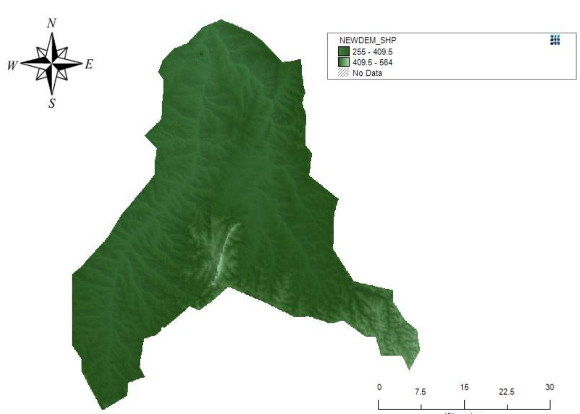

Figure 3. DEM of 75 m resolution of the study area.

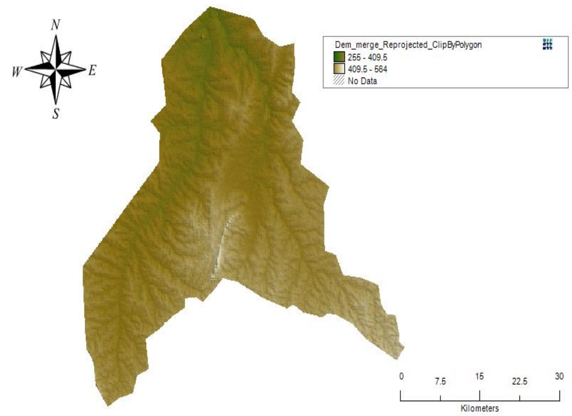

Figure 4. DEM of 60 m resolution of the study area.

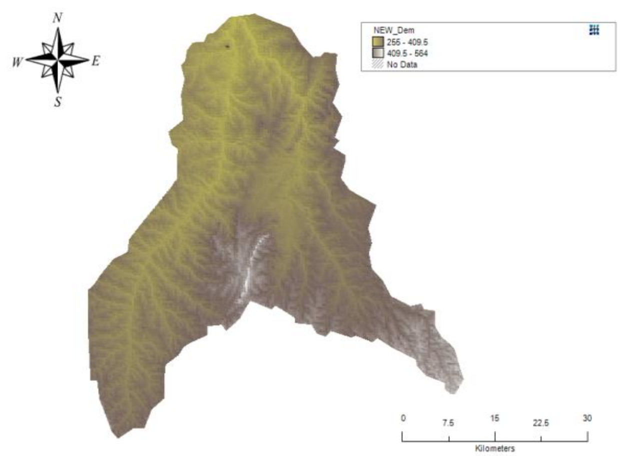

Figure 5. DEM of 45m resolution of the study area.

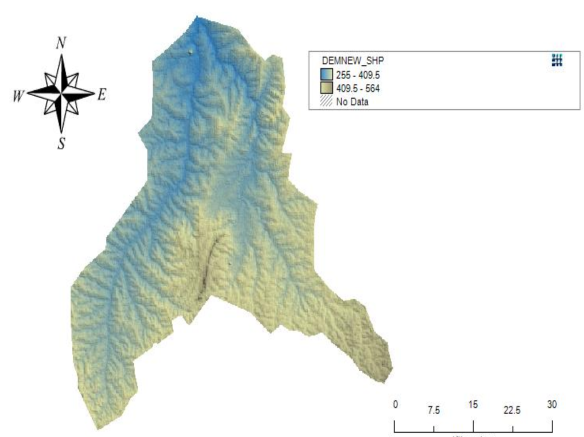

Figure 6. DEM of 30 m resolution of the study area.

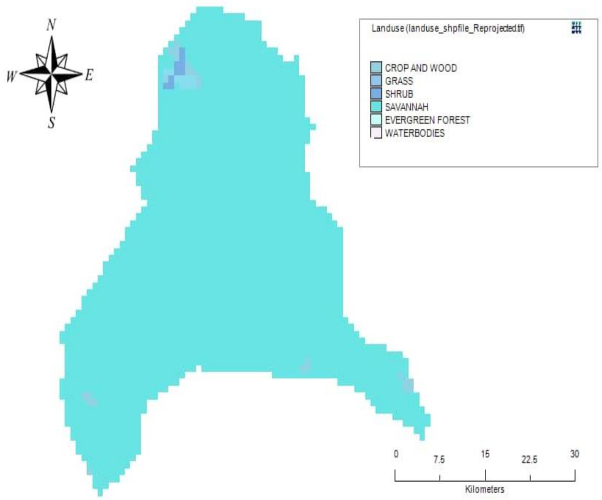

Figure 7. Landuse map of the study area.

Watershed delineation into sub-basins and Hydrologic Response Units (HRUs)

The delineation of the watershed was achieved using reprojected DEM of the study area. A total of 55 sub-basins were created in the watershed and was subdivided into 59 hydrologic response unit (HRUs) for all the resampled DEM and the watershed was delineated automatically. The HRU is the smallest spatial unit needed for running the hydrological model. Figure 8 shows the delineated subbasins of the study area for all the resampled DEM.

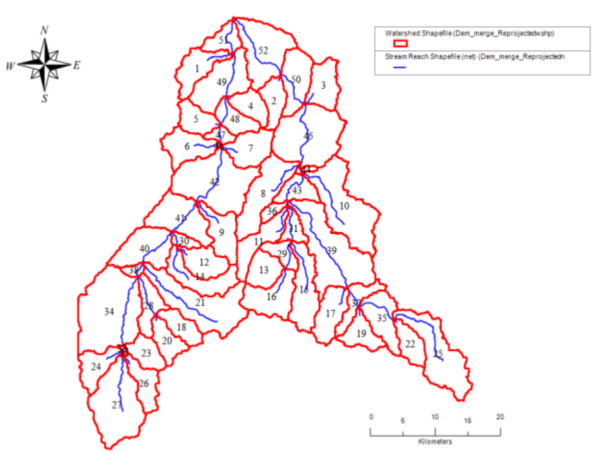

Figure 8. Watershed Delineation and Hydrological Response Unit (HRU)

SWAT Setup and Run

SWAT was executed using the Soil Conservation Service (SCS) Runoff Curve Number method for estimating surface runoff from precipitation. The SCS curve number method is a rainfall-runoff model that was designed for computing excess rainfall (direct runoff). This method assumes an initial abstraction before ponding that is related to curve number. The daily weather was prepared and imported into the model. The resampled DEM of resolution 90 m, 75 m, 60 m, /45m, 30m were used in turn in conjunction with other spatial and temporal data for the prediction of flow and the sediment loadings. The simulation period is from 01 January 2001 to Dec 31, 2019. All the necessary files needed to run SWAT were written, and the appropriate selection of weather sources done before running the SWAT executables.

RESULTS AND DISCUSSION

Effect of DEM Resolution on Watershed Characteristics

The analysis of the effect of DEM resolution on watershed characteristics revealed a clear relationship between DEM resolution and watershed area (check Table 1 for details). As the DEM resolution becomes finer (smaller), the calculated watershed area generally decreases. For instance, the 30-meter DEM resolution results in the smallest watershed area, while the 90-meter resolution yields the largest. This trend suggests that higher resolutions capture finer details of the terrain, resulting in the identification of smaller, more defined watersheds. In essence, higher resolution DEMs provide a more accurate representation of the landscape's intricacies, allowing for the delineation of smaller drainage areas. The study also examined the number of sub-basins across different DEM resolutions. Interestingly, the number of sub-basins remains relatively consistent across the various resolutions, with only minor variations. This finding indicates that the delineation of sub-basins is less sensitive to changes in DEM resolution compared to watershed area. While higher resolutions offer greater detail in terrain representation, they do not significantly impact the overall number of sub-basins. This suggests that sub-basin delineation may be less influenced by the level of detail in the elevation data.

The analysis of cumulative stream length provides insights into how DEM resolution affects the representation of stream networks within watersheds. It is observed that as DEM resolution becomes finer, the cumulative stream length generally increases. This phenomenon can be attributed to the improved accuracy in depicting the elevation data at higher resolutions. Finer resolutions allow for a more precise identification of stream channels and, consequently, lead to longer cumulative stream lengths. Therefore, researchers aiming to analyse stream networks in detail should opt for higher-resolution DEMs to ensure accurate results. The assessment of average slope values across different DEM resolutions indicates a notable trend. Lower DEM resolutions tend to produce slightly higher average slope values, which signify steeper terrain representation. Conversely, higher DEM resolutions result in slightly lower average slopes, indicating a smoother representation of the terrain. This trend highlights the importance of considering DEM resolution when assessing the steepness of a landscape. Coarser resolutions may exaggerate slope values, while finer resolutions provide a more realistic depiction of the terrain's gradient.

Effect of Resampled DEM on the prediction of Stream Flow

At the outset, the lowest predicted average annual stream flow value observed was 2229.91m³/s. This value was obtained using a lower resolution of 90 m by 90 m for the hydrological modelling process. However, when the DEM resolution was adjusted to a finer level of 75m, the maximum predicted stream flow value increased to 2345.14 m³/s. This suggests that refining the resolution of the DEM can lead to higher predicted stream flow values. Further experimentation with resolutions of 45 m and 30m resulted in a relatively stable range of predicted stream flow values. At a resolution of 45m, the stream flow values remained consistently between 2341.29 m³/s and 2344.19 m³/s, while at 30 m resolution, a similar stability was observed. This stability in the predicted values implies that reducing the DEM resolution beyond 60 m might not significantly impact the stream flow predictions.

Similarly, for average monthly predicted flow, the lowest predicted value of 185.83 m³/s was obtained using a coarser DEM resolution of 90m by 90m. However, upon refining the DEM resolution to 75m, this value increased to its peak at 195.43 m³/s. It was noticed that there was a remarkable consistency within the range of 195.11 m³/s to 195.10 m³/s. This consistency emerged at even finer resolutions, specifically 45 m and 30 m respectively. The steadfastness in values across these resolutions implies that modifications to the DEM resolution below the 60 m threshold bear minimal impact on the projected stream flow values pertaining to the river. The study's findings align with prior research conducted by Ghaffari (2011) and Arega et al. (2015), both of which concluded that DEMs resolutions have a notable influence on predicted runoff, sediment yield, and stream flow values. This emphasizes the importance of considering DEM resolution's impact on hydrological processes, underlining the need for optimizing DEM resolution to ensure accurate measurement and prediction of stream flow. Table 2 provides more details information about predicted flow and sediment by each of resampled DEM.

Table 1. DEM resolutions and watershed characteristics in the study area

DEM	Sub-basins	Cum. Stream length (m)	Average slope
90 m	55	287,136	0.17
75 m	53	288,276	0.16
60 m	53	289,765	0.16
45 m	53	291,283	0.17
30 m	53	292,110	0.17

Table 2. Details information on predicted flow and sediment by each of resampled DEM

S/N	DEM(m)	Av. Annual Flow(m3/s)	Monthly sedcon(mg/l)	Sed.Yld(t/ha)
1	90 x 90	2229.9	19075.0	528.9
2	75 x 75	2345.1	41986.9	1926.1
3	60 x 60	2338.0	40537.3	1965.1
4	45 x 45	2341.3	42181.2	2080.0
5	30 x 30	2341.2	43437.2	2145.6

Effect on the Prediction of Sediment Concentration and Sediment Yield

The results highlighted the significance of DEM resolution on sediment concentration measurements. Among the various resampled DEM resolutions, it was the 30m resolution that stood out, recording the highest predicted sediment concentration value of 521,246.94 mg/l. This finding underscored the substantial influence of DEM resolution on sediment concentration measurements. Further analysis unveiled a direct correlation between predicted sediment concentration and DEM resolution. This correlation was consistent throughout the resolution range, with the 90 m resolution revealing the lowest sediment concentration of 228,899.70 mg/l, as indicated in

Table 2. The sediment yield values varied significantly between different DEM resolutions. For instance, the 90 m resolution DEM yielded the lowest sediment yield value of approximately 528.90 t/ha, while the 30m resampled DEM demonstrated the highest value of 2145.57 t/ha. This discovery held crucial implications, suggesting that the precision of sediment yield estimates is greatly influenced by the DEM resolution chosen.

Table 2 provides a comprehensive glimpse into the monthly predictions across various resampled DEM resolutions, unveiling crucial insights into the interplay between DEM resolution and key hydrological metrics. Predicted flow values serve as a vital indicator of water movement, representing the volume of water traversing a specific river point over a given time frame. In parallel, sediment concentration values quantify the quantity of suspended sediment particles within the water column, measured in milligrams per liter (mg/l).

Additionally, sediment yield values encapsulate the mass of sediment transported across a unit area, expressed in tons per hectare (t/ha). Upon analysis, a consistent trend was observed with the finer DEM resolutions yield marginally higher predicted flow values and sediment concentration levels. This trend follows logically, as finer resolutions capture complex terrain details more comprehensively, thereby enabling more accurate simulations of flow dynamics and sediment transport processes. The parallel increase in sediment yield values with finer DEM resolutions signifies that the heightened detail enables the modeling of sediment transport with greater precision. As the resolution becomes finer, the model can account for smaller variations in terrain, enhancing its ability to estimate sediment transport across the landscape.

CONCLUSIONS

Based on the outcome of this study, the following can be concluded:

i. The SWAT model's analysis revealed significant variations in streamflow, with Subbasin 51 having the highest streamflow and Subbasin 23 the lowest. This emphasizes the need for tailored management strategies considering local factors and watershed characteristics to effectively address water resource challenges.

ii. As the Digital Elevation Model (DEM) resolution became finer, shifting from 90m x 90m to 30m x 30m, there was a consistent increase in predicted sediment concentration, indicating that finer resolutions provide a more detailed representation of terrain and hydrological features, leading to higher sediment concentration predictions.

iii. Moreover, there was a consistent trend of increasing values in both sediment yield and concentration as the DEM resolution decreased, implying that finer resolutions better capture localized terrain variations and hydrological features, resulting in elevated sediment predictions.

In conclusion, this study provided significant contributions to the understanding of sediment-related dynamics in relation to DEM resolution. The intricate relationship between sediment concentration, sediment yield, and DEM resolution has far-reaching implications for water resource management, erosion control, and environmental planning.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Acknowledgements

The authors would like to acknowledge the management of the Kwara State University, Malete, Nigeria for creating a conducive environment to conduct this research.

Authors' contribution

A.G. Adeogun: Conceptualization, methodology, writing original manuscript, review and editing.

A.W. Mansur: data collection, Model analysis.

A.A. Mohammed: Review, editing and validation of model.

Competing interests

The authors declare no competing interests in this research and publication.

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