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Dam Sedimentation Assessment: A Case Study of Opa Dam, Ile-Ife, Osun State, Southwest Nigeria

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ABSTRACT: Small reservoirs are mainly utilized for domestic purposes, livestock watering, fishing and irrigation. Due to their importance in water resource provision, planning and management, there is a need to know the capacity and useful life of reservoirs for harvesting the optimum quantity of water. Traditional techniques of estimation of the reservoir capacity and sedimentation such as inflow-outflow technique, hydrographic survey, integrated bathymetric survey are uneconomical, clumsy, tedious, involve enormous manpower, and lack of equipment. GIS and remote sensing technique has provided new opportunity to compute the loss of storage capacity and sedimentation in Opa dam in Ile-Ife, Osun State, Nigeria. Satellite imageries covering the study area were acquired for 2002 and 2022; Landsat 2002 (ETM+) and Landsat 2022 (OLI/TIRS) to determine the extent of shoreline changes during the period of 20 years. The imageries were processed using ERDAS IMAGINE 2014 and AcrGIS 10.8 for land use/land cover and the Normalized Difference Water Index (NDWI), the reservoir's shoreline extractions from the NDWI using slicing and reclassification operations. The results of this study show a decrease in the surface area of the dam between 2002 and 2022, from 40.1 to 22.50 hectares. The surface area of associated farmland/shrubs, secondary/re-growth forest and built-up changed from 187.47 to 148.42, 51.86 to 63.45 and 139.10 to 163.98 hectares respectively, between 2002 and 2022. The storage capacity of Opa dam in 2022 is estimated to be 1,232,444.05 m^3. The loss in reservoir gross capacity due to sedimentation for a period of 44 years since the time of impoundment in 1978 with initial capacity of 2.81 Mm^3 was estimated to be 1,577,555.95 m^3, which translate to 56.14 % gross capacity loss and 35,853.54 m^3 capacity loss per year. If the current trend persists, it suggests that Opa dam may be filled up in the next 44 years from 2022, however the useful capacity of the dam may be lost much earlier than projected.

KEYWORDS: Satellite imagery, NDWI, GIS and Remote Sensing, Reservoir, Sedimentation

1.0 INTRODUCTION

Reservoir is one of the credible hydraulic structures mainly made for storage of water so that this stored water may be used for human life in various aspects. But when the Soil is eroded due to rainfall and wind, resulting in sediment movement into watercourses by flood and storm waters. Increased reservoir sedimentation as a result of accelerated erosion from farmland and bare surfaces in the interfluvial area around dams has been identified as an endemic problem throughout the tropics, particularly in southwestern Nigeria, dams in Ede, Ile-Ife, Ado-Ekiti, Owo and Asejire, have been cited, Adediji, 2012. The main consequence of severe reservoir sedimentation is a reduction in water supply to the communities that the dams were built to serve. As a result, there is an urgent need to monitor the reservoir dynamics in order to ensure a continuous supply of water in adequate quantity and quality to the communities for which they were designed.

Dam based reservoirs are known as the temple of any modern country (Alsdorf et al., 2007), which is continuously suffering by deposition of sedimentation. Various types of problems due to sediment deposition in channels or reservoirs are, increased stream beds, greater flood heights, throttling of navigation channels and reduction of storage capacity of reservoirs (Alsdorf et al., 2007). Reservoirs, sea & rivers become a natural means for storage of transported sediment or eroded soil (Carvalho, 1990; Petkovsek et al., 2014). There are various agents like climate change, deforestation, vegetation, topography, grazing, inappropriate techniques of tillage, an imprudent agriculture and anthropogenic land use practices, which accelerate the high flow eroded sediment into the streams or river (Amore et al., 2004; Chandran, 2006). The main objectives of reservoir are flood control, supply of water for industrial and domestic purposes, irrigation, hydropower, fisheries and

maintenance of minimum flow in river etc, which is continuously lacking behind, reducing economic life and effective storage capacity, due to fast deposition of sediment (Ne et al., 2011).
However, the conventional techniques for quantifying reservoir sedimentation are cumbersome, inconvenient, expensive and time consuming. Furthermore, prediction of sediment deposition profiles using mathematical models requires large amounts of data which are rarely available. As a result, the potential for using remote sensing techniques has attracted considerable attention in recent years, hence this study.

1.1 Aim and Objectives

The aim of this study is to assess sedimentation of Opa Dam Ile-Ife, Osun State, Nigeria, between 2002 and 2022, using remotely sensed data and GIS. The specific objectives are to:

i. identify water and non-water features in the study area using NDWI;
ii. determine change in surface area of Opa Dam between 2002 and 2022.
iii. estimate the storage capacity of Opa Dam in 2022;
iv. estimate the reservoir capacity loss of Opa dam due to sedimentation since the time of impoundment in 1978.

2.0 MATERIALS AND METHODS

2.1 The Study Area

The Opa Reservoir catchment extends from the Obafemi Awolowo University campus to Osu in Atakumosa and constitutes the study area. The study area is approximately 68km^2 in area. The area lies between latitudes 7"27N and 7'35" and longitudes 4"30'E and 4"40'E. The dam and the associated reservoir were built on the Opa River within the confines of the University estate in 1978. The reservoir on the Opa River was approximately 2.5km long and 0.5km at its widest point. It had a total impounded volume of 2.81 million m^3 of water on completion (Capital Project and Development Unit, OAU, Ile-Ife) when it was impounded in 1978. It provides treated water to the University Community and supports recreational fishing. The reservoir has successfully reduced flooding incidences downstream of the dam. The dam spillway is 25m wide and 55m long. Ile-Ife is the hosting community of the dam it has two local government areas, namely: Ife central and Ife East as shown in Figure 1. Ife central and Ife East LGAs have a population of 644,373 according to 2006 population census.

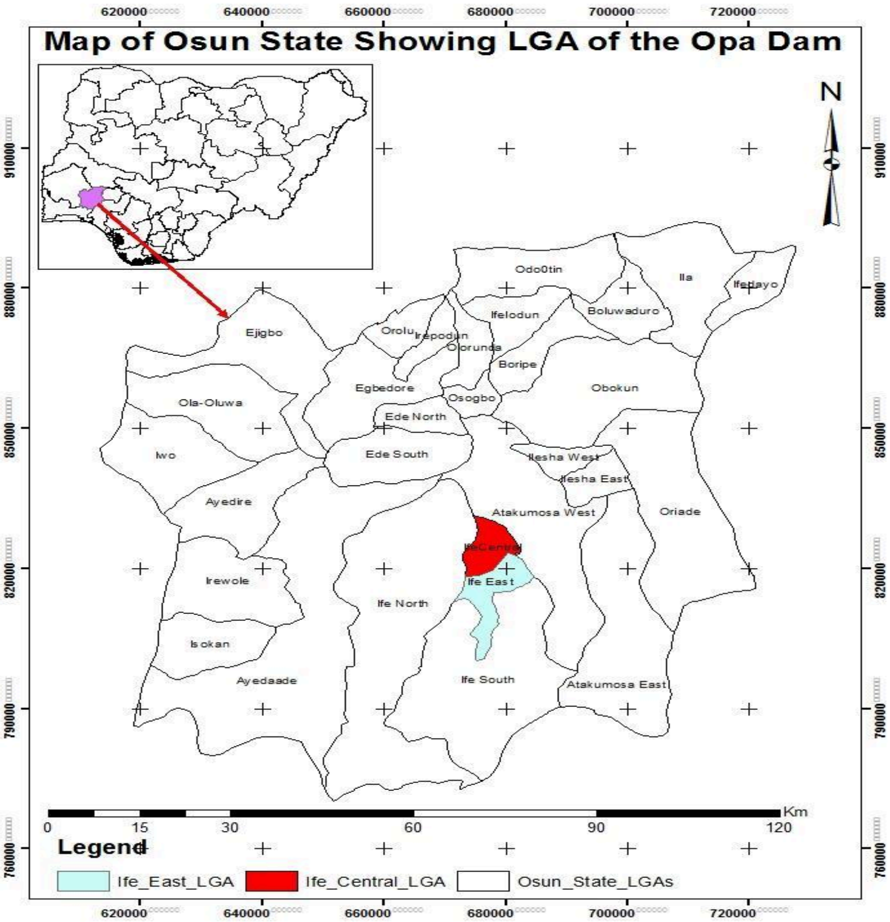


Figure 1: Map of Osun State showing the LGAs of Opa Dam

2.2 Data Sources and Collection

In the course of the study, only secondary data were used. The data required for running the various steps for the simulation model were obtained from different sources. Most of the sources are at the national scale but the study area regional shape file was used to clip the data so they can be used for the region.

1. Nigeria Administrative map shape file
2. Landsat 2002 (Enhanced Thematic Mapper Plus) ETM+ of 30 m spatial resolution acquired from the USGS website for land use/land cover mapping.
3. Landsat 2022 (Operational Land Imager) OLI/TIRS of 30 m spatial resolution acquired from the USGS website for land use/land cover mapping.

2.3 Data Processing Procedure

Satellite images used in this study are described in Table 1. Data processing procedure involves the various steps which are used in the production of the topographic map of the study area, satellite images processing and the subsequent map production using geospatial techniques. Figure 2 shows the flowchart for the method adopted in this study. The datasets belong to Landsat Collection 1—Level 1 corrected data, which have the highest radiometric and positional quality and are suitable for time-series analysis. The spatial resolution of all Landsat scenes is 30 m. Figures 3 and 4 show stacked images band 5,4,3, of Landsat 2002 and 2022.

Table 1: Raster and Vector Data for the Study and their Sources

s/n	Data Type	Date of Production	Path/Row	Resolution/Scale	No of Bands	Source

1	Landsat ETM+	Feburary 07, 2002	190/055	30 m	7	Google Earth Engine (GEE)
2	Landsat OLI/TIRS	January 26, 2022	190/055	30 m	10	Google Earth Engine (GEE)

2.4 Colour composite creation

The spectral bands of Enhanced Thematic Mapper plus (ETM+) scanner were:

Band 1 0.45 – 0.52µm Blue
Band 2 0.52 – 0.60 µm Green
Band 3 0.63 – 0.69 µm Red
Band 4 0.76 – 0.90 µm NIR
Band 5 1.55 – 1.75 µm SWIR
Band 7 2.08 – 2.35 µm FIR
Band 6 10.40 – 12.50 µm TIR

In this study, bands 5, 4 and 3 which corresponded to shortwave infrared (SWIF), near infrared (NIR) and Red bands were combined for each of the images to obtain false colour composite (FCC) images suitable for better visual interpretation.

2.5 Creation of Area of Interest (AOI)

In Erdas Imagine 2014, the entire scenes of the Landsat 2002 and 2022, were submapped and the Opa Dam was clipped in rectangular shape with other land features like vegetations and built-ups enclosed in the area of interest. Figures 5 and 6 showed the created area of interest.

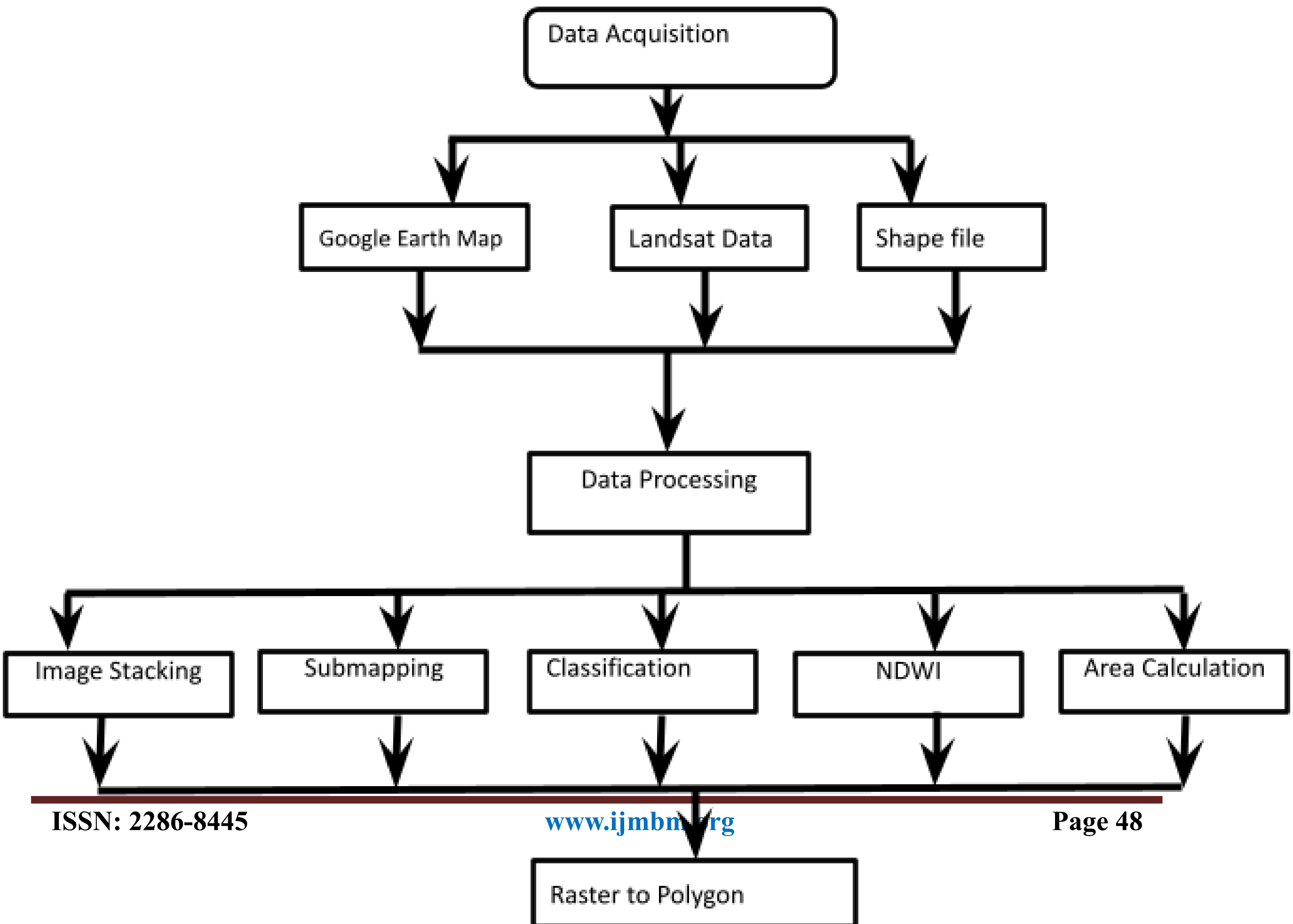


Figure 2: Methodology flowchart

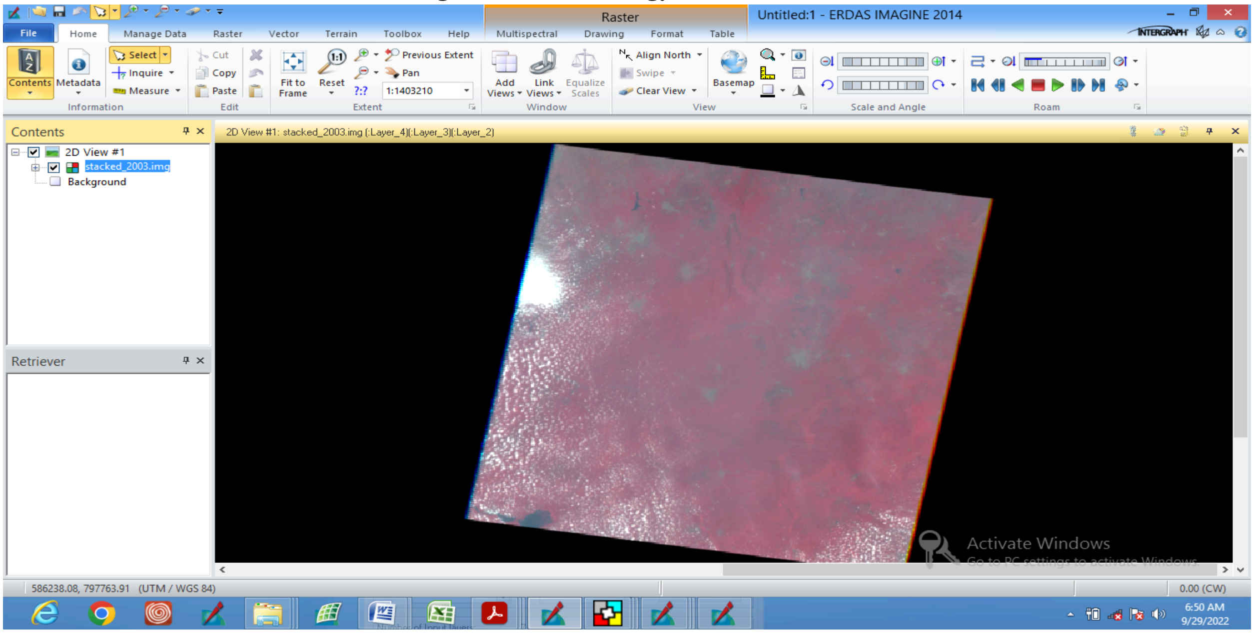


Figure 3: Landsat 2002 of Path 190 and Row 55 of bands 5,4,3 stacking

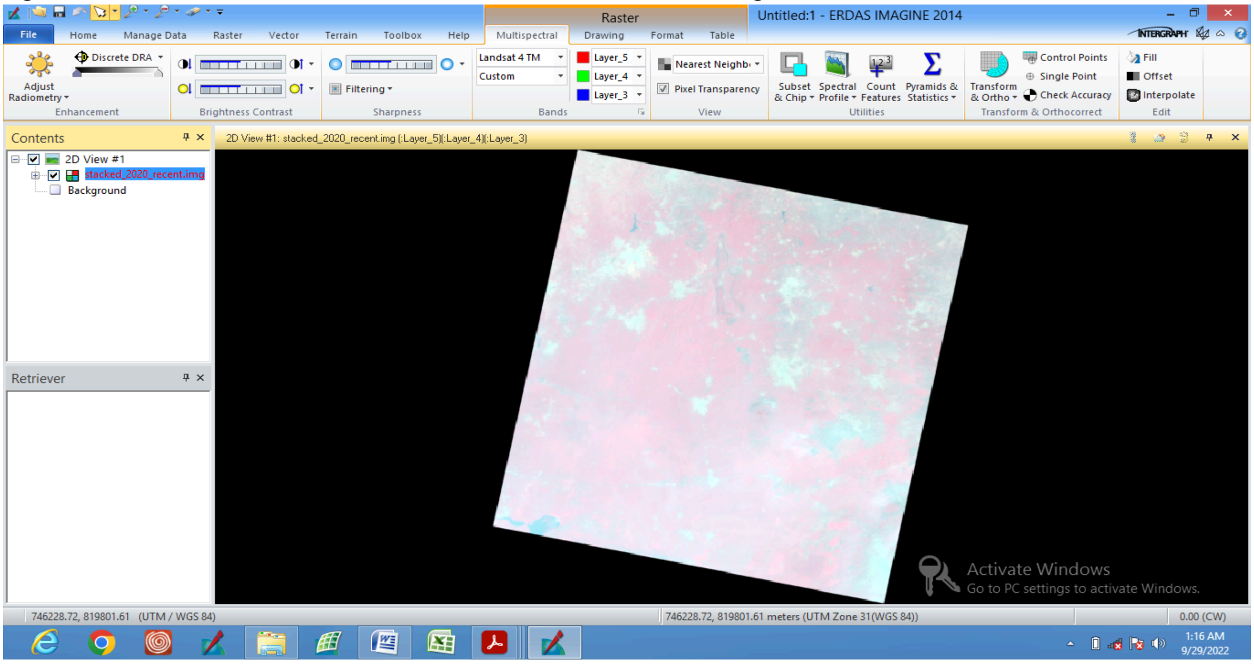


Figure 4: Landsat 2022 of Path 190 and Row 55 of bands 5,4,3 stacking

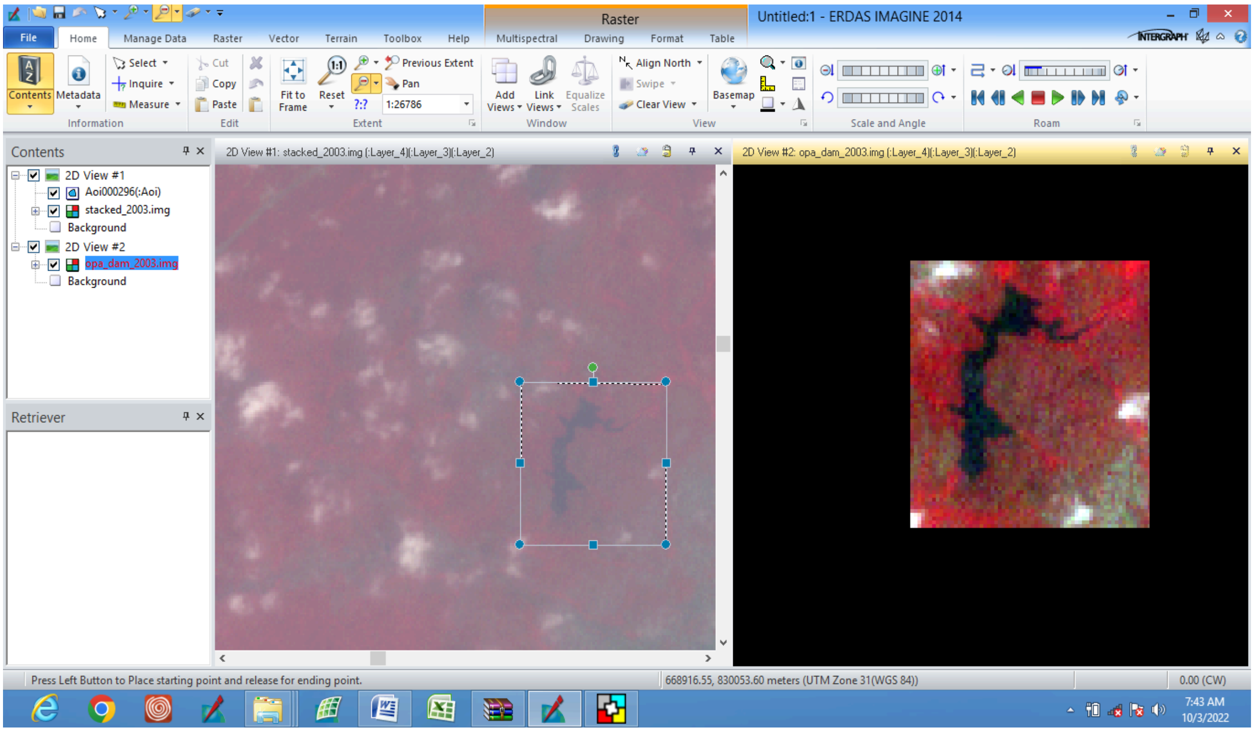


Figure 5: Opa dam clipped from Landsat 2002

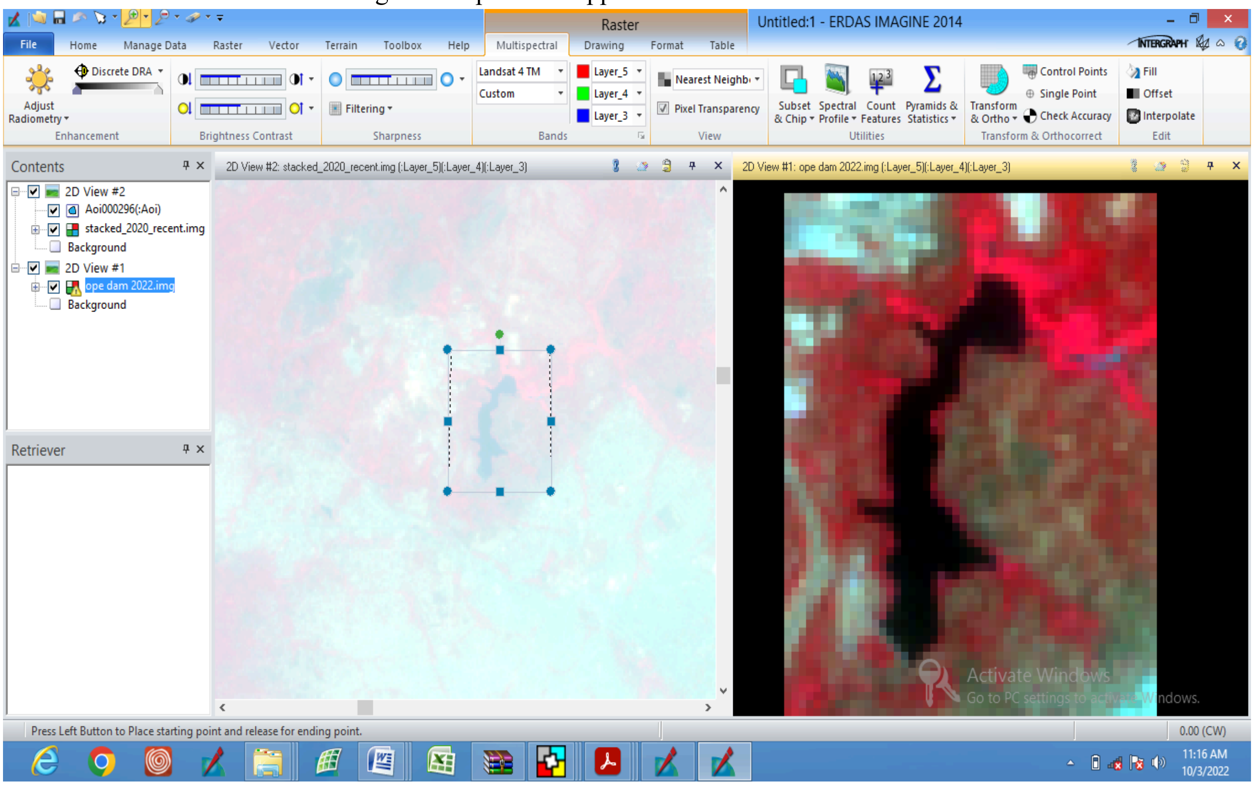


Figure 6: Opa dam clipped from Landsat 2022

2.6 Remote Sensing (RS) Analysis

The special spectral reflectance remote sensing (RS) property of water was used to differentiate between water and other surface materials around the water. A multiple RS indices algorithm based on supervised classification was used in ERDAS IMAGINE 2014, to identify the surface water coverage area of Opa Dam in 2002 and 2022. The spectral indices measurements acquired from Landsat ETM+ and OLI were analyzed by the algorithm that trains the randomly chosen samplings to construct a binary decision tree, and finally decodes this in order to classify the surface water and other features around it, Figures 7 and 8 for Landsat 2002 and 2022, respectively. The algorithm was fully implemented and run on the Erdas Imagine platform.

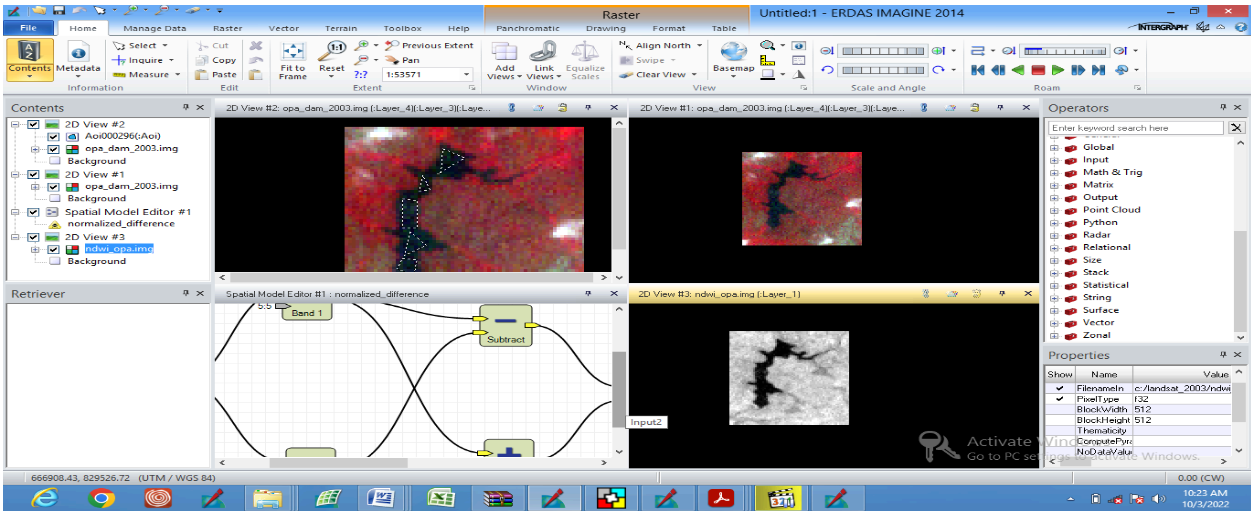


Figure 7: NDWI analysis of Landsat 2002 in Erdas Imagine

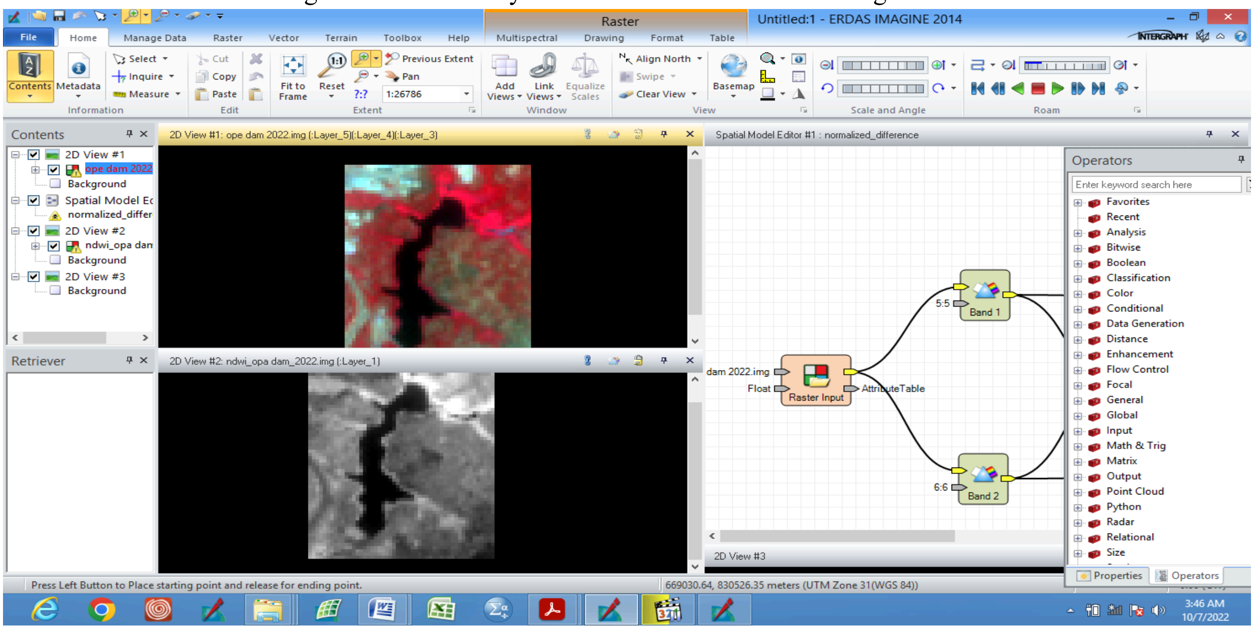


Figure 8: NDWI analysis of Landsat 2022 in Erdas Imagine

2.7 Normalized Difference Water Index (NDWI)

The visible region of the spectrum (0.4-0.7 µm) shows the transmittance of water significant and the absorption and reflectance are low. As a result, water features have positive values and are enhanced. Vegetation and soil features usually have zero or negative values and are suppressed McFeeters, 1996. The normalized difference water index (NDWI) was used to identify the water pixels in the images. The Normalized Difference Water Index (NDWI) was first suggested by McFeeters 1996, to detect surface waters in wet land environments and measure surface water dimensions. The NDWI for TM and ETM sensors can be representing as:

$$NDWI = \frac{band_2 - band_4}{band_2 + band_4}$$

Or

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

Where

$band_2$ = Green band

$band_4$ = Near Infrared (NIR) band

The MNDWI method suggested by Xu, 2006 has been commonly used and is a powerful index that can extract water bodies Ji et al., 2009 & Lu et al., 2011. It is expressed by

$$MNDWI = \frac{band_2 - band_5}{band_2 + band_5}$$

Or

$$MNDWI = \frac{Green - SWIR}{Green + SWIR}$$

Where

$band_2$ = Green band

$band_5$ = Shortwave Infrared (SWIR) band

The resulting values representing the water features have positive values because of their higher reflectance in band 2 than in band 5, and non-water features have negative NDWI values Xu, 2006. A threshold value for MNDWI (simply a value of zero) can be set to segment the MNDWI results into two classes (water and non-water features).

2.8 Image Classification

The images were classified in Erdas Imagine 2014, using supervised classification method. Figures 9 and 10 show the images obtained during supervised classification of the images, signature editor was used to create the training sites for the image classification. Four classes were created which include; Opa Dam, Built-up, Farmland/Shrubs and Secondary Re-growth forest.

2.9 Surface Area Calculation

The surface areas (hectares) of the Dam, Built-up, Farmland/Shrubs and Secondary/Re-growth were calculated in Erdas Imagine 2014. Figures 11 and 12 showed the images obtained during the surface areas calculations.

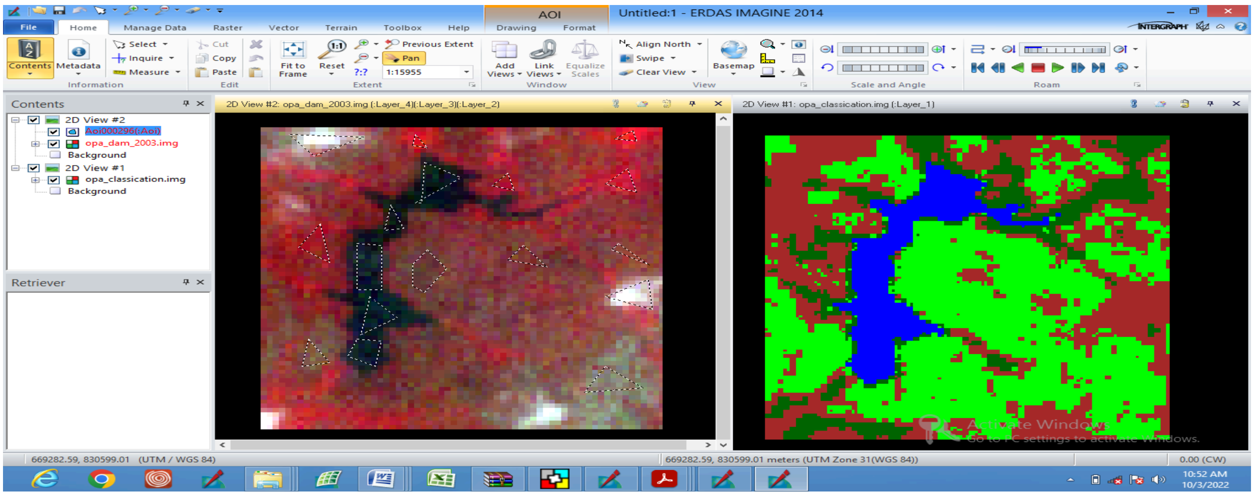


Figure 9: Classified clipped Image of Landsat 2002

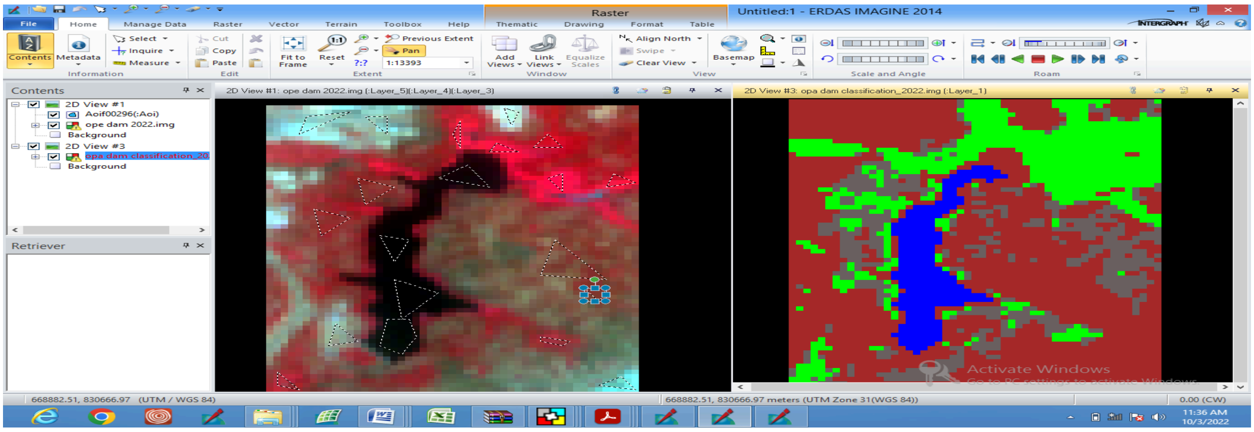


Figure 10: Classified clipped Image of Landsat 2022

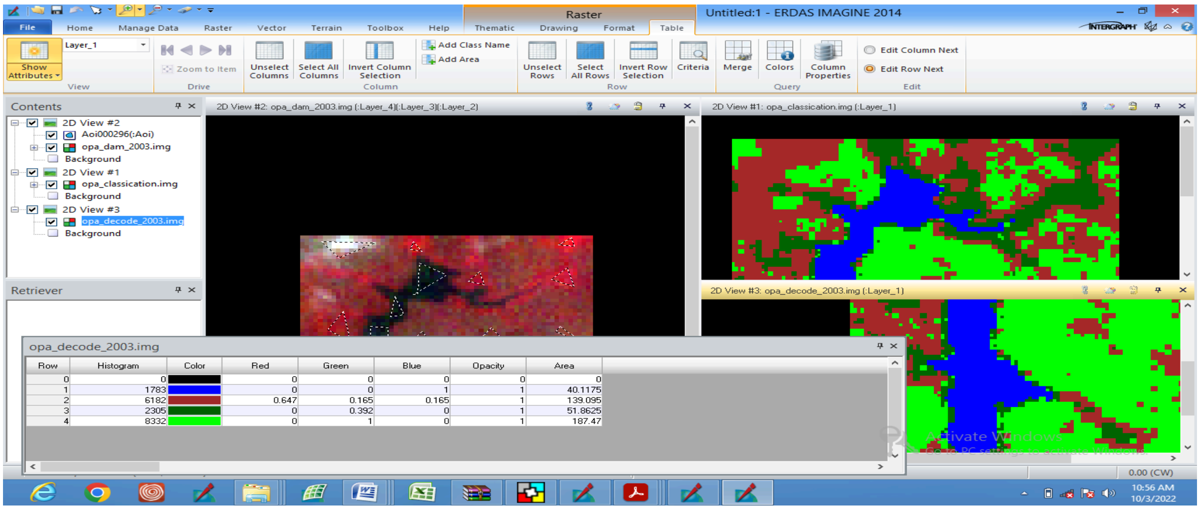


Figure 11: Calculation of Opa Dam surface area in Erdas Imagine 2014 for Landsat 2002

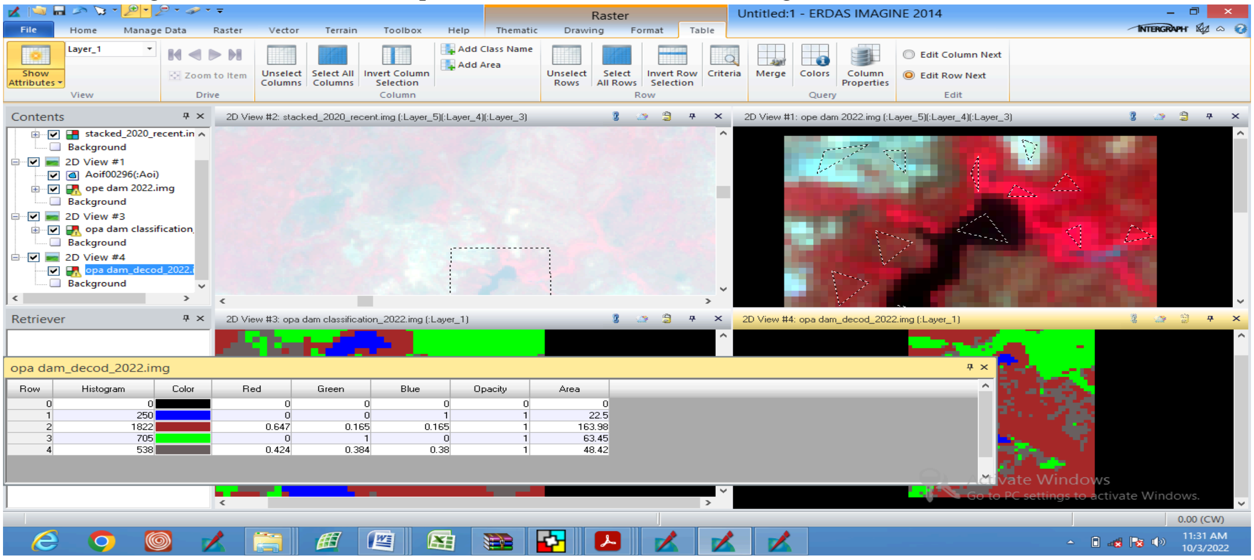


Figure 12: Calculation of Opa Dam surface area in Erdas Imagine 2014 for Landsat 2022

2.10 Spectral Profile of Supervised Classification of Landsat Images

The spectral profiles of the four classes (Opa dam, Built-up, Farmland/Shrubs and Secondary/Re-growth forest) in the processed Landsat images of 2002 and 2022 were obtaied in Erdas Imagine 2014 to produce the reflectance of each class as the electromagnetic radiation in form of light incident on them. Figures 13 and 14 show the output of the spectral profiling of the classified images.

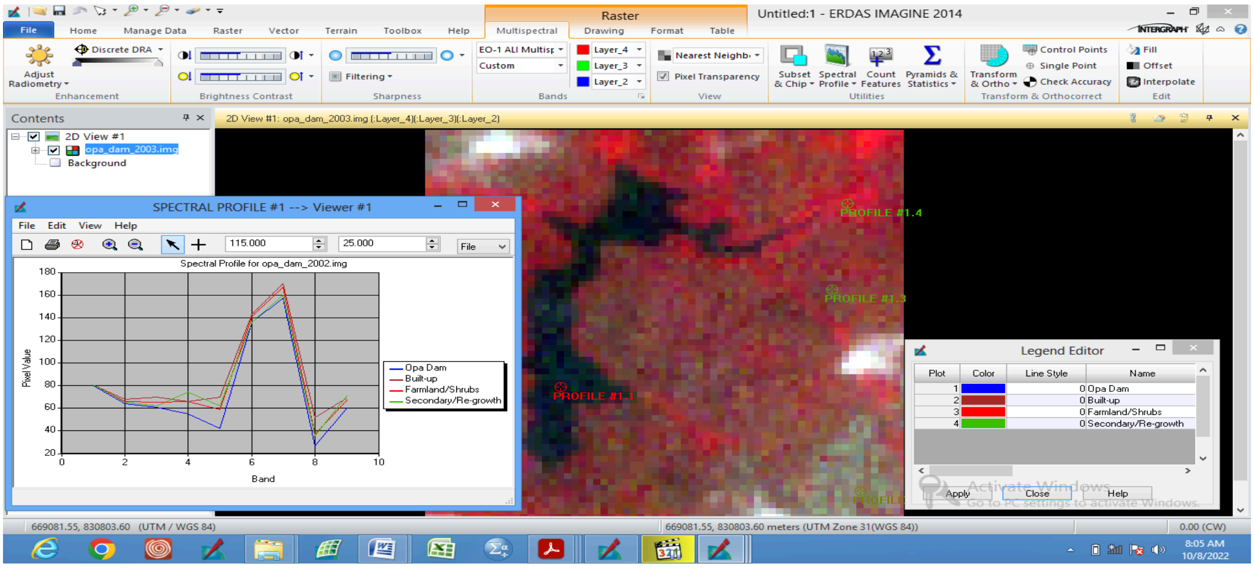


Figure 13: Spectral Profile supervised classification of Landsat 2002

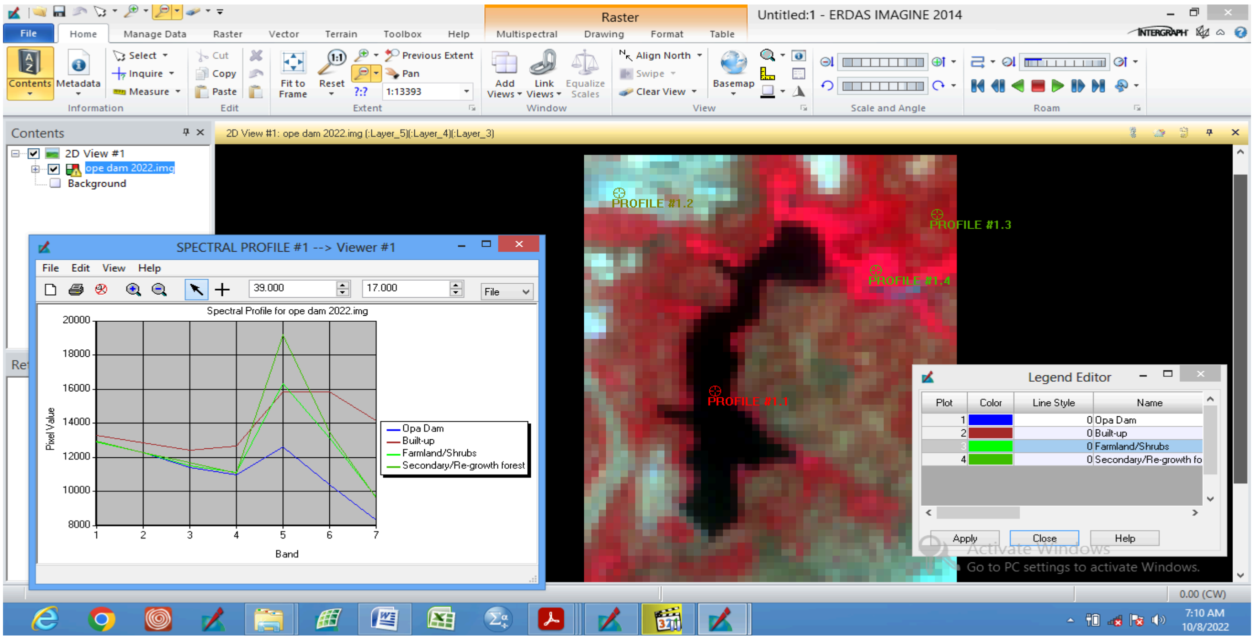


Figure 14: Spectral Profile supervised classification of Landsat 2022

2.11 Calculation of Opa dam/reservoir capacity

After finalizing the water body areas for all the images by slicing of the NDWI and MNDWI images, the histograms are analysis and the water pixels in each image are recorded. The water body area at any water level or elevation is obtained by multiplying the number of water pixels by the size of one pixel. A generalized Area-Elevation curve for reservoir, Figure 15, adopted from Asha and Mohammed, 2019, was used to estimate the storage capacity of Opa dam between 2002 and 2022. The reservoir capacity between two consecutive reservoir elevations (ΔV) was computed using the trapezoidal formula as adopted by Elvis et al., 2016; Dadoria and Tiwari, 2017:

$$\Delta V = \frac{\Delta H}{3}\left(A_1 + A_2 + \sqrt{A_1 X A_2}\right)$$

Where

A_1 = surface area (hectares) of Opa dam in 2002

A_2 = surface area (hectares) of Opa dam in 2022

ΔH = difference in elevation (m) of Opa dam between 2002 and 2022

To calculate the capacity of Opa dam in 2002 and 2022, the surface area for each year was obtained from NDWI and MDWI analysis of the images, and their respective elevations have been obtained from the original elevation-area-capacity curve, (Asha and Mohammed, 2019; Dadoria and Tiwari, 2017). Figure 4.4 shows the elevation-area curve for reservoir used in this study.

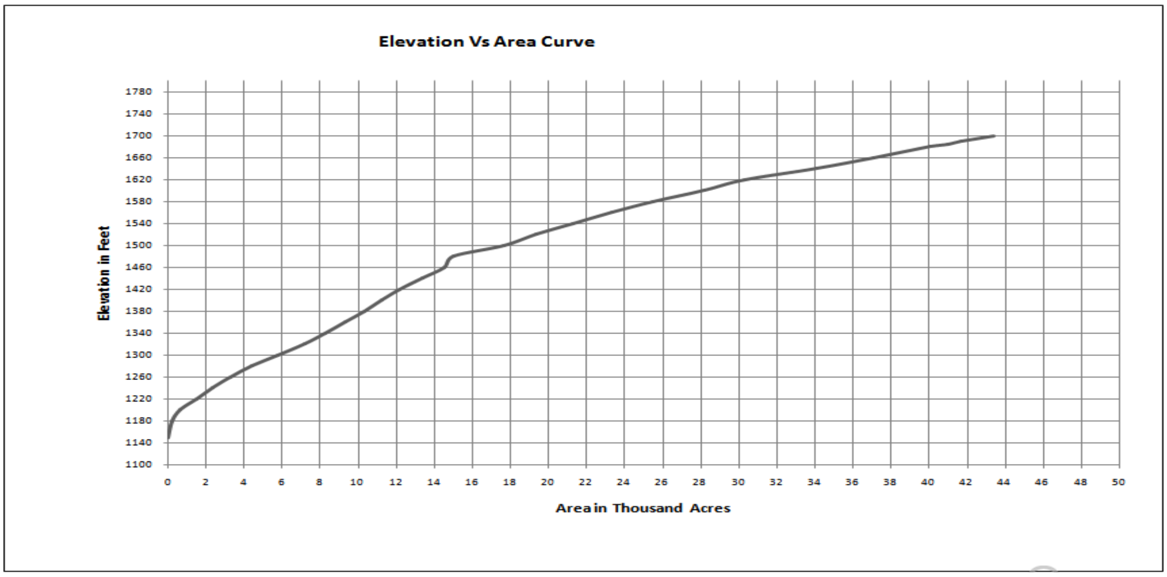


Figure 15: Area-Elevation curve for reservoir (Source: Asha and Mohammed, 2019)

2.12 Change Detection Calculation

Change detection model was used to determine variation in the surface area of the dams between 2002 and 2022. The parameters adopted include: change per interval year, percentage change per interval year, change per year, and percentage change per year, as adopted by (Adeoye and Ayeni, 2011). The mathematical expressions for these parameters were presented below.

i. Change per interval year (ΔP) = $P_n - P_o$
ii. Change per year (ΔP_i) = $(\Delta P)/n_i = (P_n - P_o)/n_i$
iii. % change per interval year ($\%\Delta P$) = $(P_n - P_o)/P_o$ X 100
iv. % change per year ($\%\Delta P_i$) = $[(P_n - P_o)/P_o$ X $100]/ n_i$

where,
P_n = value of land use/land cover at the current year
P_o = value of land use/land cover at the previous year
n_i = years difference between the current year and previous year

3.0 RESULTS AND DISCUSSION

3.1 Surface area of Opa Dam and other land use/land cover around it

The total surface areas under consideration were 418.55 hectares and 398.35 hectares for 2002 and 2022, respectively, as shown in Table 2. The surface area of Opa dam greatly decreased from 40.12 hectares to 22.50 hectares between 2002 and 2022, there was slight decline in the surface area of the farmland/shrubs from 187.47 hectares to 148.42 hectares, between 2002 and 2022. The results obtained in this study revealed that there was a slight increase in the area covered by secondary/re-growth forest and built-up from 51.86 to 63.45 hectares, 139.10 to 163.98 hectares respectively, between 2002 and 2022. The surface areas of Opa dam and its surrounding were compared in Figure 16. The maps of Opa dam and its surrounding in 2002 and 2022 were presented in Figures 17 and 18, respectively.

Table 2: Surface area (hectares) of the Dams and other Land use/Land cover

Land use/Land cover	Surface Area (hectares)	
	2002	2022
Opa Dam	40.12	22.50
Built-up	139.10	163.98
Farmland/Shrubs	187.47	148.42
Secondary/re-growth forest	51.86	63.45
Total	418.55	398.35

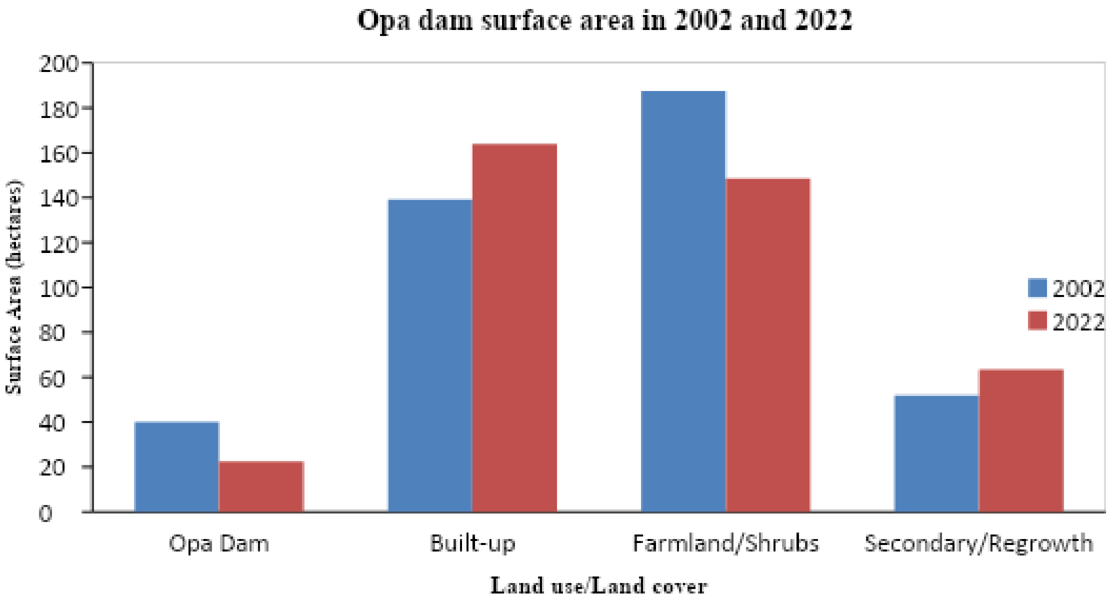
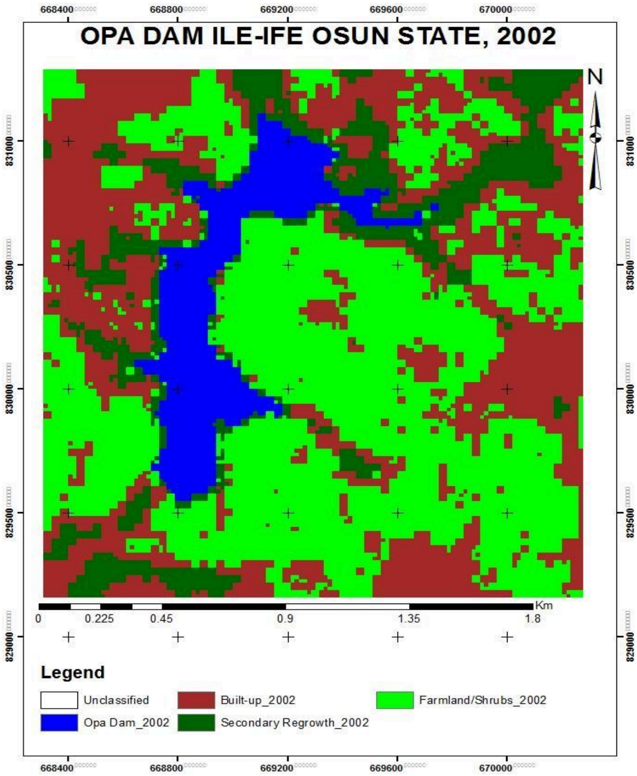


Figure 16: Comparison of surface area of Opa dam and its surrounding in 2002 and 2022

Table 3: Change in Surface area of Opa Dam between 2002 and 2022

Year	Coverage area (hectares)	Change per interval year	% change per interval year	Change per year	% change per year
2002	40.12	--------	--------	--------	--------
2020	22.50	17.62	43.92	0.881	2.20



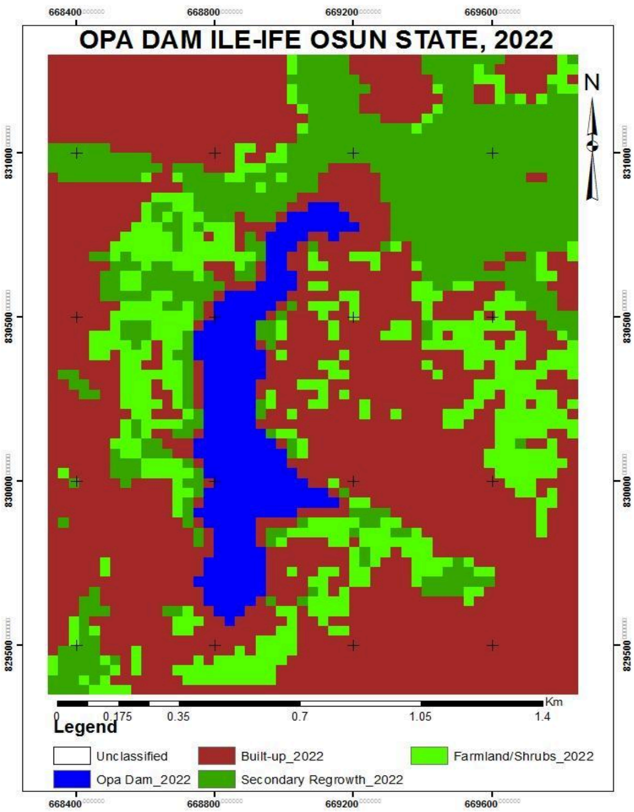


Figure 17: Opa dam and its surrounding in 2002 Figure 18: Opa dam and its surrounding in 2002

3.2 Change in Surface area of Opa Dam between 2002 and 2022

The changes that occurred in the surface areas of Opa dam were estimated using the change detection model adopted by (Adeoye and Ayeni, 2011). Change in the surface area of Opa dam is presented in Table 3, the coverage area (hectares) of the dam decreased by 17.62 hectares over the period of 20 years with decrease per year being 0.881 hectares. The percentage change over 20 years was estimated to be 43.92 % and the percentage change per year was 2.20 %.

4.3 Opa Dam/Reservoir Capacity computation

Opa dam capacity was computed using the trapezoidal relation and its storage capacity in 2022 was estimated to be 1,232444.05 m^3, lost in its capacity due to sedimentation from the time of impoundment 1978 to 2022 (44 years) was estimated to be 1,577,555.95 m^3 with percentage reduction of 56.14 % of the initial capacity of 2.81 million m^3 when it was impoundment. The results obtained in this study corroborate the findings of Adedeji 2012, who reported the volume capacity of Opa dam as 1,496,623.0 m^3 with volume and mass of deposited sediment of 1,313,377 m^3 and 575t/km^2/yr in 2012 with the reduction of 46.67 % of the initial capacity of 2.81 million m^3 as at the time of impoundment in 1978.

4.0 Conclusion and Recommendations

This study presents assessment of Opa dam/reservoir sedimentation between 2002 and 2022, using remotely sensed data and GIS, with the aim of determining the storage capacity of the dam, land use/land cover around the dam, and the volume of sediment deposited within the time of study. Opa dam declined in surface area from 40.12 to 22.50 hectares between 2002 and 2022, with 43.92 % over 20 years and 2.20 % per year. The surface area of the farmland/shrubs also declined from 187.47 to 148.42 hectares between 2002 and 2022, while there was a slight increase in the surface area of secondary/re-growth forest from 51.86 to 63.45 hectares between 2002 and 2022, similarly, the area covered by built-up had increased from 139.10 to 163.98 hectares between 2002 and 2022. The storage capacity of Opa dam in 2022 is estimated to be 1,232444.05 m^3, with percentage reduction of 56.27 % of the initial capacity of 2.81 million m^3 as the time of impoundment in 1978, and the volume of deposited sediment was estimated to be 1,567,555.95 m^3. If the current trend persists, it suggests that Opa dam may be filled up in the next 44 years from 2022, however the useful capacity of the dam may be lost much earlier than projected. This study thus recommends base on its findings that; there should be anti-erosion measures before any dam is constructed to prolong the life span of any proposed dam/reservoir. In the case of the Opa reservoir, the university authority should urgently take measures to clear hydrophytes and other water weeds which have colonized the area around the periphery of the reservoir if its life span is to be prolonged. Deforestation for structure construction should be discouraged around the dam to prevent increase run-off into the dam and thus reduce the rate of sedimentation.

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