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ASSESSMENT OF SATELLITE DERIVED BATHYMETRY

A Case Study of Mindu Dam

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B.Sc. Geomatics

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A Case Study of Mindu Dam

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A Dissertation Submitted to the Department of Geospatial Sciences and Technology in Partially Fulfilment of the Requirements for the Award of Science in Geomatics (BSc. GM) of Ardhi University

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Ardhi University dissertation titled "**Assessment of satellite derived bathymetry, a case study of Mindu Dam**" in partial fulfillment of the requirements for the award of degree of Bachelor of Science in Geomatics of the Ardhi University.

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Date………………….........	Date……………………….

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I, KAPINGA, JULIANA R hereby declare that, the contents of this dissertation are the results of my own findings through my study and investigation, and to the best of my knowledge they have not been presented anywhere else as a dissertation for diploma, degree or any similar academic award in any institution of higher learning

…………………………

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DEDICATION

I dedicate this work to my parents and family instilled in me the desire to learn and made sacrifices so I would have access to high quality education from an early age and the constant love and support. Also, this work is dedicated to my close friends who have always supported me throughout my study years even on the tough days.

ABSTRACT

Bathymetry information plays a significant role in planning near-shore structure activities such as, fishing, dredging operation, oil drilling, aquaculture and in determination of underwater topography used to generate hydrographic charts for safe navigation. Traditionally bathymetry relied on the hydrographic conventional methods such as lead line, single beam echo sounder and Multibeam echo sounder which are expensive, consumes a lot of time and not effective on shallow waters and other dangerous environments. Thus, these limitations prompted the need for a better technique that would minimize these limitations. Thus, the new technique Satellite Derived Bathymetry (SDB) that provide bathymetry information from satellite images but it is limited to shallow waters. This study was aimed to assess the performance of Sentinel 2 satellite optical image on deriving bathymetry of Mindu dam, a shallow water source of less than 10m.

Band ratio model developed by Stumpf (2003) presented in equation 2.1 was used to derive depths from Sentinel 2 image. This model uses a set of points with known depths from the sounding technique and band ratio extracted from satellite imager to derive depths in this study. Pre-processing was performed to improve the quality of the image and resample all bands to the same resolution, followed by processing of image which involved land and water separation that involved masking out the land leaving the aquatic area only, correction for sun-glint to remove scattering effect of sunlight, determination of the model parameters used to derive depths from the image and lastly derivation of bathymetry using blue and green bands. Arc map tools were used to generate bathymetry maps, snap software was used to process the image and the extraction of the band ratio, surfer was used to grid bathymetry data and perform statistical analysis of the data, and Microsoft excel was used in perform mathematical operations involved in this study.

The derived depths were then assessed and compared to the sounding data to obtain the difference between the two data sets which were then analyzed statistically having a mean value of 0.26, standard deviation of 0.947 and root mean square 0.982. Considering the standards of EOMAP 87.01% of the derived depths fall within the acceptable range of 0 to 1m. Therefore, from the results obtained in this study considering the depth variation at different points, the technique can be used to derive depths over optically shallow waters

Keywords: Depth variation, in-situ data, Sentinel 2 imagery, Satellite derived bathymetry.

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ACRONYMS AND ABBREVIATIONS

AOI	Area of Interest
EOMAP	Earth Observation and Environmental Services
ESA	European Space Agency
GPS	Global Positioning System
IOH	International Hydrographic Organization
LIDAR	Light Detection and Ranging
NOAA	National Oceanic and Atmospheric Administration
SDB	Satellite Derived Bathymetry
USGS	United States Geological Survey

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Bathymetry, the underwater topography, is a fundamental property of oceans, seas, and lakes. As such it is important for a wide range of applications, like physical oceanography, marine geology, geophysics and biology or the administration of marine resources (Hell, 2011). Bathymetry information is very useful and significant for a wide number of reasons particularly in terms of aiding safe navigation for boats, ships and other vessels as it helps to identify if the water is too shallow for passage or deep enough by providing navigational charts and seafloor profiles. This information also facilitate dredging activities and maritime infrastructure works by depicting the seabed conditions through contours. And again, bathymetry data is of great use in land development projects such as urban planning, bridge building and housing (Hinds, 2022). Bathymetry information can be obtained from different hydrographic surveying techniques that are either conventional or remote sensing.

Conventional hydrographic surveying methods such as multibeam echosounder and light detection and ranging (LIDAR) technologies have been widely used to obtain bathymetry information. However these techniques often have limitations such as the echosounders are often have narrow coverage, the vessels for mounting the equipment are expensive to hire and have trouble navigating shallow water areas, while LIDAR technology which provides relatively accurate bathymetry information and has a high resolution is too expensive for many applications (Quoc & Khanh, 2019). Thus, many hydrographic offices do not have the resources to conduct frequent hydrographic surveys using techniques therefore alternative methods should be used. Due to the development of science and technology optical remote sensing imagery can provide valuable information on water bodies as an alternative technique known as the Satellite Derived Bathymetry.

Satellite Derived Bathymetry (SDB) is relatively a new survey remote sensing technique acquisition technique method which uses high resolution multispectral satellite imagery for depth determination especially for shallow water areas. It’s founded on the analytical modeling of light penetration through the water column in visible and infrared bands. This technique is potentially an important low-cost source of a large number of spatial information including hydrographic data of different shallow water bodies (Leder & Leder, 2020). Thus, it's a promising technique that can be used to carryout frequent hydrographic surveys to monitor water depth as it is cost effective and covers a large area, it's also less time consuming and data is available freely or sometimes purchased at affordable prices depending on the resolution of the data required.

Dam water refers to the water collected and stored behind a dam, which is a barrier constructed across a river or a stream. Port water refers to the water found in ports, which are facilities where ships can load and unload cargo and passengers. Port water is different from dam water in the sense that port water is generally saline or brackish as it is influenced by sea water while dam water is typically freshwater since it originates from upstream sources such as rivers or rainfall.

The maximum water depth mapped by Satellite-Derived bathymetry is similar to the maximum penetration depth of sunlight. Since this varies by season and location, a global depth statement is not appropriate. There are several mapping depths that have been analyzed from different parts of the world: Red sea (20-30m), Gulf region (5-15m from north to south), Mediterranean Sea (20-30m), Baltic sea (2-15m from north to south), Caribbean Sea (20-30m), US West coast (5-15m), Pacific region (20-30m). Uncertainties associated with derived depths are a combination of internal model uncertainties such as the sensitivity of the sensor and external uncertainties such as the effect of tides. With ideal scenarios and on-site information, the uncertainty of Satellite derived depths is 0.5m. Without access to on-site information the uncertainty is typically between 0.5m to 1m.(EOMAP, 2020).

Studies have been conducted in different parts of the world to assess its performance on shallow waters and most based on coastal waters such as ports. In Tanzania, research was conducted by Saule, (2022) on "Determination of Satellite Derived Bathymetry using Sentinel 2" using band ratio model which was developed by Stumpf to derive bathymetry information from the satellite image of Dar es salaam port and Malindi port. From the result obtained in the study, it shows that Satellite derived bathymetry provide the good result depends on the water clarity that enable the penetration of the electromagnetic radiation in the water. Result shows that Satellite Derived Bathymetry can be used to monitor sea level rise and changes in the coastal feature, reconnaissance tool for planning in the shallow areas and updating the chat (Saule, 2022).

As most studies have covered coastal areas thus there's a need to assess the performance of this technique with different type of water which have different characteristics such as lakes, rivers or streams. Thus, this research focuses on the assessment of Satellite Derived Bathymetry on dams particularly Mindu dam as it's a fresh water source which is located in the Ngerengere River about 6 km south-west of Morogoro with 0 to 10m depth. As the most important water supply for domestic, commercial, and industrial uses in Morogoro, Mindu dam requires frequent hydrographic surveys to monitor water level changes and the limitations of conventional techniques makes it difficult to conduct frequent surveys. Thus, assessing the performance of this technique on Mindu dam is essential as an alternative and cost-effective technique.

1.2 Statement of the research problem

Obtaining bathymetry data using conventional hydrographic surveying methods such as the use of acoustic sensors that requires specialized operating vessels is well established technique that allows for high accuracy to be achieved. It is also a very expensive technique and requires careful calibration of the sensors and long processing time of the data acquired and can be difficult to be applied in very shallow water or inaccessible areas, the method is also time-consuming, with limited coverage in providing bathymetry information of different water bodies. Again, bathymetric surveys based on Laser Imaging Detection and Ranging (LiDAR), which, in shallow water, may suffer from transient water turbidity and are affected by the difficulty of separating surface, water column and bottom reflections. To overcome these limitations satellite derived bathymetry has been utilized as an alternative method especially for depth determination of shallow waters and it is an indirect new revolution of bathymetry survey techniques. Due to the fact that most studies have focused more on the assessment of the performance of this technique on coastal areas thus there is a need to assess its performance on dams which have different characteristics from the ocean waters. Thus, the study considers Mindu dam as a case study to derive bathymetry information.

1.3 Research Objectives

1.3.1 Main Objective

The main objective of this research is to assess the accuracy of Satellite-Derived Bathymetry using sounding data at Mindu dam.

1.3.2 Specific Objectives

i. To derive bathymetry information of Mindu dam using Sentinel 2 image.
ii. To assess the derived bathymetry information of Mindu dam using the available in-situ sounding data.
iii. To generate bathymetry map for Mindu dam from the obtained derived depth.
iv. To perform statistical analysis and derive the accuracy limitations.

1.4 Significance of the study

By assessing the performance of satellite derived bathymetry as a better and cost-effective method thus its validity will make it possible to conduct frequent hydrographic surveys of shallow waters and other challenging environments that that conventional techniques are difficult to implement such as on moving waters or on water sources inhabited by dangerous animals such as crocodiles in rivers. And also monitor water levels on not only Mindu dam so as the dams efficiently fulfill their purposes.

1.5 Beneficiaries

i. Hydrographic surveyors

They will be able to use this as an alternative method to conduct frequent hydrographic surveys of shallow water and inaccessible areas at relatively low cost as it requires no mobilization of people nor equipment, within a short period of time and with big coverage, thus easy monitoring of the water levels of the dam and other shallow fresh water sources.

ii. Fishermen

The generated bathymetry could be a useful method for fishermen and mariners for safety transportation and avoid possible hazard. Also, Bureau of fisheries would be used bathymetry information for guidance in the development, improvement, management and conservation of the habitat of the present fisheries.

iii. Morogoro Municipality

As Mindu dam is a reservoir for domestic and industrial use for the Morogoro municipality and also serves for irrigation and flood control downstream therefore if the assessment of this technique proves to be valid then it can be used as an alternative way to monitor the sustainability of the dam for the municipal in meeting its primary goal.

1.6 Description of the Study Area

This study was carried out in Mindu dam located in Morogoro. It's a primary dependable source of fresh water supply and fresh water fishery in Morogoro urban and peri-urban areas (Mgedela , et al., 2009). It's a dam located in Wami Ruvu Basin, with estimated area of 3.8 km^2 (Ngoye & Machiwa, 2004).

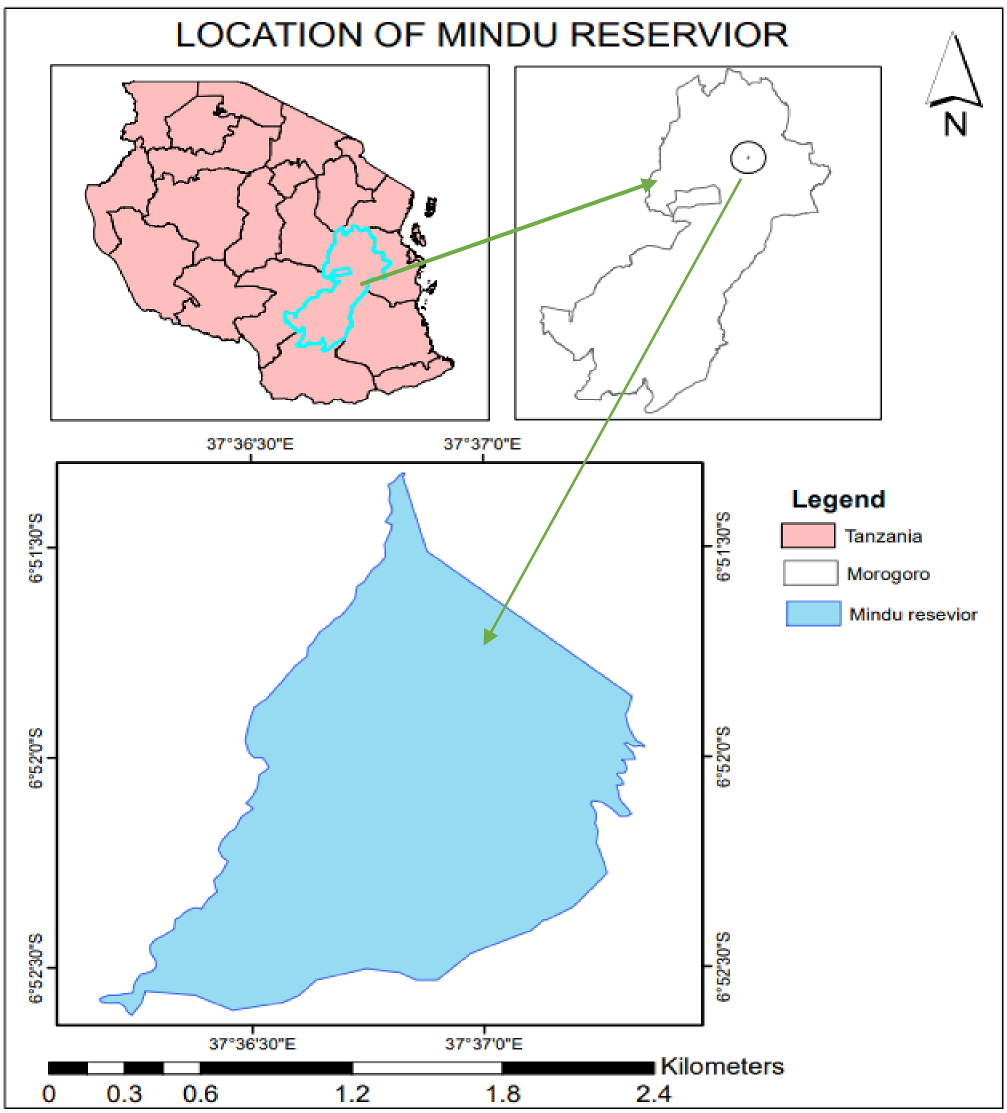

Figure 1.1 Geographical location of the study area.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

This chapter gives brief description of what has already been done by other researchers on Satellite Derived Bathymetry and a summary of the research explaining other methods that can be used and points out the advantages of each technique and deeply explains the models used to derive bathymetry information of different water bodies

2.2 Concept of Bathymetry

Bathymetric surveys are a type of hydrographic surveys designed to ascertain the depth of a specific water body (the measurement of the depths of water bodies from the water surface) particularly important in aiding safe navigation and dredging activities, and supporting different land projects (Hinds, 2021). Bathymetric surveys are generally conducted with a transducer which transmits a sound pulse from the water surface (usually attached to a boat) and records that same signal when it bounces from the bottom of the water body.

Traditionally, Bathymetric surveys are conducted using an echo sounder attached to a survey boat and as the boat moves across the water, the echo sounder will generate electrical signals which are then converted to soundwaves by an under-water transducer. These soundwaves bounce off features under water and this echo is then identified by the echo sounder and the distance to the identified feature is calculated. Bathymetric survey systems rely on highly accurate GNSS(GPS) systems to link each measured distance to a particular depth of the surveyed area (Hinds, 2021).

2.3 Bathymetric surveys methods

This section includes different methods that can be used to obtain bathymetry information from the earliest methods to latest methods pointing out the advantages and disadvantages of each method/technique.

2.3.1 Lead lines

Eighteenth century sailors used lead lines to measure the depth of the water when they were at sea. The lead line was a simple device that was made up of a long length of rope tied to a lead weight at one end. The line was marked every six feet. One sailor would throw the weighted end of the line overboard while the other counted the marks as it went out (Beta, 2018). Once the weight hit the bottom of the sea, the depth was calculated and recorded. Again, Lead lines are ropes or lines with depth markings tied to a lead weight attached at regular intervals. These lines are lowered and the line is used for determining the depth of water when sounding manually, generally, in depths of less than 50 meters (Selva , et al., 2013).

The advantage of this method is that it can be used in situations where use of electronic sounding would be impractical, impossible, or give faulty results. Lead line sounding is especially suited for the underwater investigation of rock or concrete placement; on the slopes of jetties, groins, and revetments; and near bulkhead construction. In such areas, echo sounding may be inaccurate or contaminated with noise from side echoes. Also, for silty bottoms containing “fluff” that would give questionable echo-sounding readings, a lead line may be required in a construction contract.

As a disadvantage this method it takes too much time and after all does not yield accurate value (Parente & Vallario, 2019). Hydrographic information uses increase frequently which lead to the modern methods based on specialized software, expert, operating vessels and equipment.

2.3.2 Sounding Pole

Also known as the sounding rod made of seasoned timber 5cm to 10cm diameter and 5m to 8m length. A lead shoe of sufficient weight is connected at bottom to keep it vertical. Graduations are marked from bottom upwards. Hence the readings on the rod corresponding to water surface is water depth (Neenu, 2018).

This method has similar advantage like lead lines, they are useful in certain situations in which an electronic echo sounding system is not practical or accurate. For example, areas with dense bottom vegetation or irregular jetty stone may give false signals electronically and must be sounded by hand. Next to instrumental leveling, a sounding pole is perhaps the most accurate hydrographic measuring device in shallow water depths. It is especially suitable for subsurface rock and concrete placement. Its light weight is useful in fluff areas where free-fall penetration must be minimized. Its uses are generally restricted to depths not exceeding 15 to 20 ft.

2.3.3 Echo sounding

Sometimes known as depth sounding is the use of sonar for ranging, normally to determine the depth of water(bathymetry). It involves transmitting acoustic waves into water and recording the time interval between emission and return of a pulse, the resulting time of flight along with the knowledge of speed of sound in water, allows determining the distance between sonar and target. This information typically used for navigation purposes or in order to obtain depths for charting purposes. There are two different kinds of echo sounders that can be used known as;

2.3.3.1 Single beam Echo Sounder

This instrument employs transmission of ultrasonic beam towards the bottom and then by measuring the time interval required for the beam to reflect and travel back to the transducer, the depth is determined. It produces consistent high-resolution vertical bed profile (Selva , et al., 2013). It measures a single depth value in a unit of time and directly below the ship/boat by previously defined profiles. Compared to multibeam echo sounder its advantage in data collection is in lower equipment prices and easier processing of data collected but it’s not intended for recording broad band underwater floor (Sijeg, Cavric, Maric, & Barada, 2019). It produces consistent high-resolution vertical bed profile.

2.3.3.2 Multibeam Echo Sounder (MBES)

Multibeam technology was originally developed in the 1960s for deep water mapping and was then further extended to shallow water applications. Multibeam echo sounders have then become more popular over the last few years. It is simple to operate and provides better resolution and increased floor coverage (Selva , et al., 2013). Multibeam systems are fan-beam acoustic systems consisting of a number of narrow single beam transducers mounted in close proximity and focused at equally spaced angles form a location under the survey boat. The time it takes for the sound waves to reflect off the seabed and return to the receiver is used to calculate the water depth. This echo sounder measures multiple depth values at the same times, covers larger surfaces and thus produces an actual morphological model of the sea bottom without using the interpolation method. Given the possibility of collecting more data in shorter period, there are disadvantages such as the high equipment cost and the more demanding data processing (Sijeg, Cavric, Maric, & Barada, 2019).

2.3.4 Side Scan Sonar

Also, sometimes known as side imaging sonar or bottom classification sonar and it's a sonar category that is used to efficiently create an image of large areas of the sea floor. Side-scan sonars can be operated from small vessels in water depths down to about 2 m.

Side scan uses a sonar device that emits conical or fan shaped pulses down the seafloor across a wide angel perpendicular to the path of the sensor through the water, which may be towed from a surface vessel or submarine, or mounted on the ship's hull. The intensity of the acoustic reflections from the sea floor of this fan shaped beam is recorded in a series of cross-track slices. When stitched together along the direction of motion these slices form an image of the sea bottom within the swath (coverage width) of the beam (Hagemann, 1958).

Side scan sonar may be used to conduct surveys for marine archeology, in conjunction with seafloor samples it is able to provide an understanding of the difference in material texture type of the sea bed. This technique is also used to detect debris items and other obstructions on the seafloor that may be hazardous to shipping or to seafloor installations by the oil and gas industry. In addition, the status of pipelines and cables on the seafloor can be investigated using side-scan sonar (Rusby, et al., 1973).

The advantage of this technique is that it has a high resolving detail, can be operated from very small vessels, can be used in very shallow water and small objects (dm range) can be detected with this technique.

Its disadvantageous in the sense that there is no penetration below the seabed, no precise geo-referencing, not suited for detection of most Stone Age sites and no 3D bathymetry.

2.3.5 Airborne laser systems

The Airborne laser systems are based on extensive field experiments and theoretical research and simulations. The first operational systems did not appear until the mid-1980s, the laser bathymetry concept was first conceived, and systems proposed in the 1960's. They offer both an alternative and a complement to survey with acoustic systems. This system composes of a laser scanning system, global positioning system and an inertial measurement unit (Selva , et al., 2013).

LIDAR (Light Detection and Ranging), is a system for measuring the water depth. A series of short pulses of blue-green laser light along with infrared pulses are projected simultaneously form the aircraft into the reservoir (Eren, Pe'eri, Rzhanov, & Ward, 2018). The surface and the bottom of the reservoir reflect the blue and green laser light whereas the infrared pulse is scattered by the water surface. The time delay between the surface and bottom reflections are then used to calculate the reservoir depth.

These systems have very efficient and have very high speed compared to the traditional acoustic systems. Also, the speed is not dependent on the water depth as it is in acoustic systems. Laser systems give good coverage, close to full coverage, in extreme conditions of temperature, where acoustic systems may produce poor quality data. They also provide good coverage and can be used in places where it is not possible to take boats. Safety is also a major advantage of laser systems. But water clarity is the primary constraint of LIDAR. LIDAR has been successful at collecting bottom data through as much as 40-meter depths of clear water. In less clear waters, LIDAR data collection has been successful at depths of two to three times the visible depth. It is very sensitive to suspended material and turbidity of water. One major factor is that the initial and operational cost of airborne systems are substantially higher (Selva , et al., 2013).

2.3.6 Airborne Electromagnetic Systems

Airborne electromagnetic systems have been in development for over 50 years. And this system was further developed for mapping floor formations in shallow water.

In the beginning, the airborne electromagnetic system technology was used for detecting the ore bodies which are buried beneath a conductive ground. Later, due to the advance of technology have allowed the use of electromagnetic induction principles for mapping seafloor formations in shallow water. Advances in this technology have allowed the use of electromagnetic induction principles for mapping seafloor formations in shallow water (Smith, Annan, & Gubins, 1997).

The method has some of the same advantages as that of air borne laser systems, including high speed of data acquisition as compared to the traditional acoustic systems and they also provide good coverage and can be used in areas, where it is not possible to take boats. Since they use low frequencies, they can also be used for operating over thick ice. The initial cost here is high as compared to the acoustic systems. Also, the system is at present, for reconnaissance purpose only. In the range of 0–40 m of water, the representative difference between the interpreted depths and the charted depths is about 2 m (Selva , et al., 2013).

2.3.7 Photo-bathymetry

Aerial photography is commonly used to delineate the boundaries of reservoirs and, are many a times very useful in reconnaissance, planning of hydrographic surveys, and creation of a qualitative description of the floor rather than by mans by which to determine the water depth.

Aerial pictures are digitally processed to extract various information form the image. Digital image processors have the ability to correlate light intensity with depth. However, this is function of the material in suspension, clarity of water and also on the reflective properties of the bottom surface. Thus, a local calibration should be undertaken to account these variations (Selva , et al., 2013).

2.4 Bathymetry survey by using satellite imagery

Deriving bathymetry information from satellite imagery is the most recent developed method of surveying shallow waters. In contrast to other bathymetric survey methods, this method requires no mobilization of persons nor equipment, provides rapid and access to bathymetric data and saves costs. Optical satellite data can be an efficient alternative for bathymetric derivation in shallow and clear coastal waters, providing temporal and spatial continuity (Phinn, et al., 2005). Time series of satellite imagery allow studying the long-term changes of the water levels of these water sources.

2.4.1 Earth Observation Sensor for Satellite Derived Bathymetry

Bathymetric information can be generated from multispectral satellite datasets acquired from different multispectral sensors, namely the Worldview 2, Planet Scope, and the Sentinel 2 (Argyriou, et al., 2022). This study uses Sentinel 2 to derive bathymetry information.

2.4.2 Sentinel 2 Overview

It was launched as part of the European Commission's Copernicus program on June 23, 2015, was designed specifically to deliver a wealth of data and imagery. The Sentinel 2 mission carries a passive sensor which means it observes objects and features of the earth's surface using external energy sources such as the sun light. It is formed by the constellation of two twin satellites, Sentinel 2A and Sentinel 2B passing at the polar orbits meaning that they complete full circles around the earth passing always from north to south poles and they are phased at 180◦ to each other carrying a multispectral instrument with 13 spectral bands (Webinar, 2021).

Table 2.1 Spectral bands of Sentinel 2 image *(ESA, 2017)*.

Spectral band	Center wavelength (nm)	Band width (nm)	Resolution (m)
Band 1 – Coastal aerosol	443	20	60
Band 2 – Blue	490	65	10
Band 3 – Green	560	35	10
Band 4 – Red	665	30	10
Band 5 – vegetation red edge	705	15	20
Band 6 – vegetation red edge	740	20	20
Band 7 – vegetation red edge	783	115	20
Band 8 - NIR	842	20	10
Band 8a – vegetation red edge	865	20	20
Band 9 – water vapor	945	20	60
Band 10 - SWIR	1375	30	60
Band 11 - SWIR	1610	90	20
Band 12 - SWIR	2190	180	20

The spatial resolution varies based on the spectral band as listed in the table above. At the equator, Sentinel 2 has a revisit time of 5 days. All Sentinel mission data can be downloaded through Copernicus Open Access Hub and USGS Earth Explorer.

2.4.3 Principal Mechanism of Satellite Derived Bathymetry

The principle of deriving the water depth from multispectral images is that the light penetration of a water column with different wavelengths which is a function of the characteristics of the seawater (Zhongqiang, et al., 2022). The spectral radiance received at an optical sensor over optically-shallow waters is a function of atmospheric transmittance, sea surface reflectance, scattering and absorption in the water column, and substrate reflectance. A typical multispectral sensor contains several channels. Each channel captures a broad (70–150 nm wide) spectral range. Collectively, the channels span the visible through infrared portions of the electromagnetic spectrum. Light transmittance through the water column varies as a function of wavelength.

The spectral range of sunlight that penetrates seawater to appreciable depths is typically between 350 nm Satellite Remote Sensing to Assess Nautical Chart Adequacy 295 (ultraviolet-blue) and 700 nm (red), depending on the water clarity depth (Mobley , Zhang, & Voss, 2003). Sunlight at wavelengths greater than 700 nm (near infrared) has very low transmittance in seawater. As a result, these water areas are observed as very dark in the near-infrared (800–900 nm), making them useful in delineation of the land/water boundary in coastal regions (Freire, 2017). In the visible bands that penetrate the water column, an exponential attenuation of radiance as a function of both depth and wavelength provides the fundamental principle for depth estimation. In order to retrieve depth information, correction for spectral contributions from the water column, atmospheric effects, and sea surface reflections are applied to the spectral imagery (Abd-Eleahman, et al., 2022).

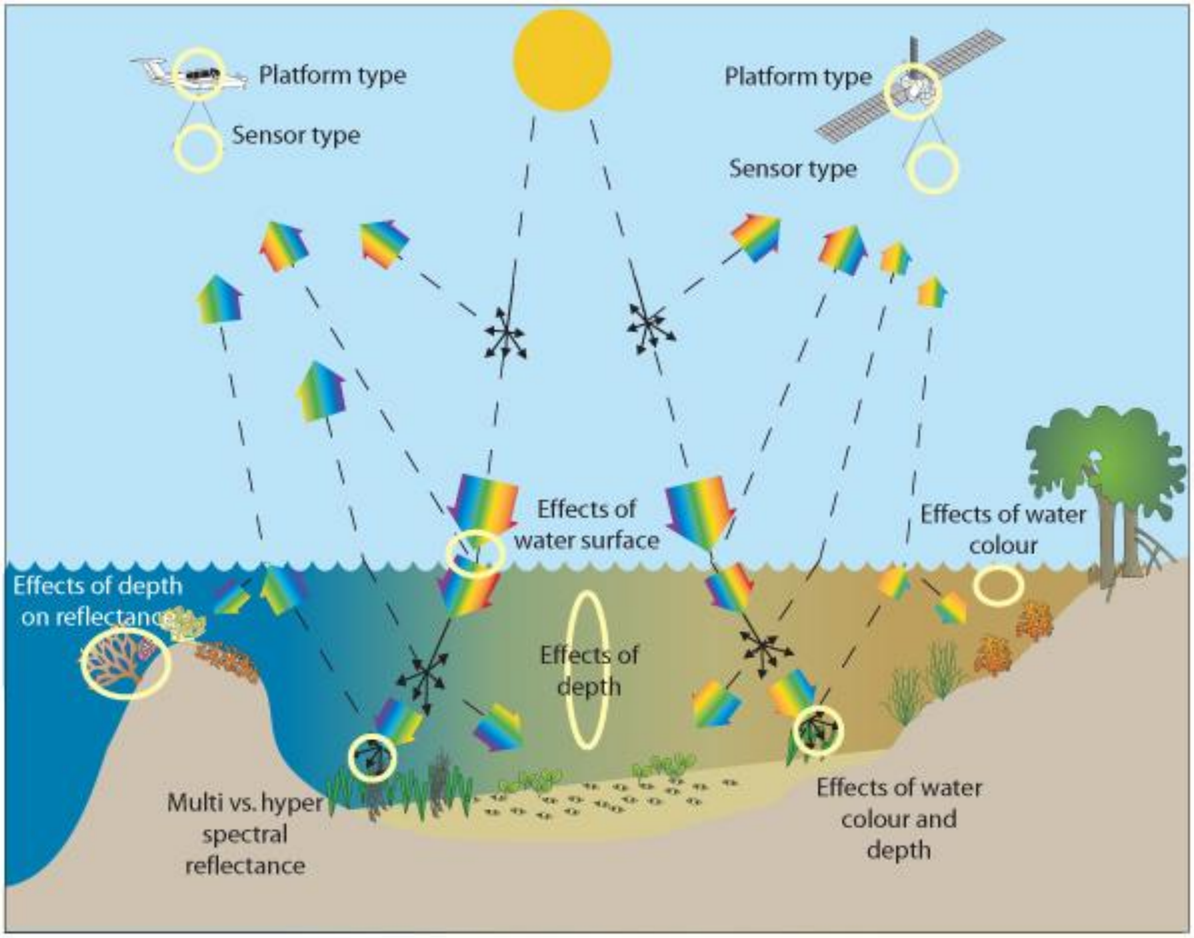

Figure 2.1 Remote sensing of a water body *(Sciences, 2019)*.

2.5 Models used in deriving bathymetry

The derivation of bathymetric information from optical remote sensing data can be generally divided into two methodologies or models; empirical model and physics-based model inversion approaches. Both methods make use of the physical concepts of light transmission through water, such as the assumption that light is attenuated exponentially with depth (Paul, et al., 2019). The difference between the two models is that the empirical methods rely on known bathymetry data points to estimate unknowns through regression whereas model inversion methods more tightly constrain these unknowns and attempt to derive bathymetry information from each pixel of the image (Brando, et al., 2009). Physics based approaches can be applied without known bathymetry points but are more challenging to implement and computationally demanding thus empirical approaches remain a common and more practical method for deriving bathymetry information from optical remote sensing data (Dekker, et al., 2011).

2.5.1 Empirical Model

Empirical modelling assumes that the total reflectance is primarily related to water depth and the secondary to water turbidity (Sagawa, Yamashita, Okumura, & Yamanokuchi, 2019). These methods purely rely on the statistical estimators derived from in-situ data. The empirical algorithm is developed using a training dataset of in-situ observation and the reflectance of suitable bands from satellite imagery. The model establishes a relationship between the satellite image's spectral reflectance values and water depth. The method relies on in-situ measurements or reference data to calibrate the relationship between the image and bathymetry. There are three approaches used in the derivation of bathymetry information using this model. The linear regression model (LRM) using log-transformed bands or log-transformed band ratios originally developed by (Lyzenga D. , 1981) and (Stumpf, 2003) and recently revisited by (Caballero, 2019) for Sentinel-2A/B applications. The switching model (SM) and the cluster-based regression model (CBR) (Geyman & Maloof, 2019).

2.5.1.1 Ratio Transform Algorithm

(Stumpf, 2003) designed a ratio transformation method for shallow water bathymetry estimation. This model is principally based on the concept that light weakens exponentially at water depths and shows an albedo effect on the substrate, and will be minimized using two bands to obtain water depth. Thus, according to this model, different spectral bands will weaken at different depth levels. Therefore, the ratio between the two spectral bands will vary in obtaining water depth data (Freire, 2017). The ratio is given by the following equation;

$$Z = m_1 \frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))} - m_0 \quad \text{……}2.1$$

Where, m_1 is the tunable constant to scale the ratio to depth

n is the fixed constant for all areas to ensure the ratio remains positive under all values

R_W is the reflectance of water for bands of the ratio and in our case the blue and green bands.

m_0 is the offset for depth of zero meters.

Z is the derived depth

m1 is gaining and m0 is offset.

2.5.1.2 Linear Transform Algorithm

The reflectance transformation of the bottom of the water using natural logarithms will linearize the effect of depth. In theory, each type of bottom water is represented by a parallel line, where the gradient is the ratio between the attenuation coefficients in each band. The single band algorithm used to calculate the water depth according to (Lyzenga D. R., 1985). Linear transform algorithm is given by

$$Z = a_0 + a_1 X_1 + a_i X_i \qquad \text{2.2}$$

Where, Z is the depth value

a_0, a_1, and a_i are the coefficient determined through regression analysis

X_1 and X_i are the reflectance value of each band/channel.

2.5.2 Analytical Model

Analytical model is purely based on the manner of light penetration in water. Development of this model requires a number of optical properties of water over near-shore region such as absorption coefficient suspended and dissolved materials, attenuation coefficient, scattering coefficient, backscatter coefficient, bottom reflectance, and others (Ashphaq, Srivastava, & Mitra, 2021).

These kinds of models generally termed as a radiative transfer model. The radiative transfer model involves the inherent assumption of a reflective bottom, an appropriate level of water quality, and shallow water less than 30m.with limitation of derive bathymetry which need a precise input parameter related to atmospheric effect. Another limitation of analytic approach is simultaneous collection of field data to image acquisition (satellite pass) for modelling accurate water (Leder , et al., 2023).

This method computationally complex and execution are difficult as there are no atmospheric correction methods that provide accurate water reflectance for shallow and/or optically complex coastal waters. In analytical method three techniques are used to determine the water depth, first forward modelling, inverse modelling techniques or look-up tables (LUT) based on forward & Inverse modelling techniques or combination of any of three methods.

2.5.2.1 Forward and Inversion Modelled

Forward modelling techniques are used majorly to serve three functions; explain, predict or model inversion of problem in consideration. Models explain relationships between physical parameters and remote sensing parameters or derived parameters like. Model simulations are used to explain certain phenomena from actual satellite images. Certain phenomena observed in the actual data but can't be explained through the model, provides the prospect to modify the model to predict the phenomena more precisely (Zhongqiang, et al., 2022).

2.5.2.2 Look-Up Table (LUT)

LUT technique refers to a large database containing spectral signatures, known constituent concentrations' water-leaving radiance, IOPs, bathymetry, and seabed properties. The spectral signatures of satellite images and LUT database are assessed to find the nearest match for all the parameters under consideration (Dekker, et al., 2011). The analytical method applied to RTE by Mobley, (1994) resulted in the first LUT technique 'Hydro light' using forward modelling of remote sensing reflectance (Mobley , Zhang, & Voss, 2003).

LUT techniques have been effectively used for SDB estimation and water constituent determination, however the result of derivation depends on precision of LUT database, whether it contains IOP/AOP, benthic substrate spectral signature and bathymetry as in the geographical area of the imagery. researcher suggested that the safe use of analytical algorithms demands validation of the underlying approximations and quantification of their impact (Ashphaq, Srivastava, & Mitra, 2021).

2.5.3 Combined Model

The model based on a combination of analytical and empirical model which suggested by many authors in order to overcome the demerits of both models. Among SDB models, combined model is popular and has been widely applied (Lyzenga D. R., 1985). These models are physically based algorithm and the predictor can be analytically derived from a radiative transfer model. Calibration depth is used to calculate the attenuation coefficient of each spectral band. The empirically derived parameters/coefficients by a comparison of spectral radiance with measured depths are related to the inherent optical properties of the water and the bottom. Calibration depth is needed for such models and can estimate reliable SDB even from low quality water regions. These models are faster and needed less prior knowledge of spectral properties of the water and rapid processing can be expected.

2.6 Review from other studies

As the most recently developed method of surveying shallow waters with several advantages over the conventional methods such as; the method doesn't require mobilization of persons or equipment, provides rapid access to bathymetry data and saves costs. Satellite-Derived bathymetry makes operations in shallow water more effective and reduce project risks. These advantages and due to the fact that the maximum water depth mapped by Satellite-Derived bathymetry is similar to the maximum penetration depth of sunlight and it varies by season and location, a global depth statement is not appropriate thus, this prompted researchers from different parts of the world assess the accuracy at which this technique can be used as an alternative method in obtaining bathymetric information especially for shallow water sources with various characteristics such as the coast, lakes, rivers, streams and dams.

El-sayed (2018), conducted research on assessing the performance of the two satellite (Landsat 8, and Sentinel-2A) for shallow water depth extraction using computational method. The first objective of this research was to assess the estimated depth of the bottom of the Al Manzala Lake in Egypt by using the remote sensing of satellite imagery. The second objective is to study the effect of different satellites data as an input to the Stumpf model and give the best results.

The results of his research showed that the compatible satellite that derived bathymetric mapping was able to offer a fast, flexible, efficient, and economically advantageous solution to map the underwater topography. It is also proven to be more cost effective, less labor intensive, and time saver method of acquiring bathymetry comparing to the conventional sonar sounding surveys not only this but also it allows significant repetitions of bathymetry mapping over broad area. Moreover, the results show that the Sentinel-2A is far superior to Landsat-8.

Argus (2022), conducted research on "Mapping bathymetry and shallow water benthic habitats in inland and coastal waters with Sentinel-2" and concluded that Sentinel-2 data quality and availability have increased the opportunities to monitor hard to reach coastal areas that have both ecological and commercial value. Sentinel-2 mission, with Sentinel-2A and Sentinel-2B registering data at 10 m of spatial resolution and a nominal revisit time of 5 days may not guarantee that cloud-free images can be received in less than a week, particularly in Baltic Sea area, where a high percentage of cloud coverage has often compromised the results obtained. Thus, it may be concluded that Sentinel-2 is suitable for bathymetry and habitat mapping on optically complex inland and coastal waters. The depths at which this can be done are shallower than in clear oceanic water, but the results are still very valuable for coastal managers, monitoring agencies, researchers and in other fields.

Saule (2022), in Tanzania also conducted research to determine and validate the bathymetry information derived from Sentinel-2 using the band ratio model of Dar es salaam port and Malindi port and in her findings, she concluded that Satellite derived bathymetry provide the good result depends on the water clarity that enable the penetration of the electromagnetic radiation in the water. Result shows that Satellite Derived Bathymetry can be used in monitor sea level rise and changes in the coastal feature, reconnaissance tool for planning in the shallow areas and updating the chat and recommended that another researcher may base his/her research on the determination of Satellite Derived bathymetry using other models that does not required training data such as linear model and compares the performance of this model in Both environment of Dar es Salam Port and Malindi Port or the researcher may base on more accurate satellite mission that might provide better accuracy such as World viewer 2 and other commercial satellite mission that provides high resolution images or the researcher may base on different environment such as lakes, river and assessing it performance in those areas.

From the researcher’s recommendations, this research is aimed at assessing the validity of this research on a different environment that has different characteristics and different from the ports using the same approach and compare the results obtained from both findings.

CHAPTER THREE

METHODOLOGY

3.1 Overview

This chapter gives a description of the methods and materials that were adopted in this study for the collection, processing, analysis and presentation of data in order to achieve its stated aim and objectives.

3.1 Data collection

Cloud free Sentinel 2A image of Mindu dam was downloaded from Copernicus Open Access Hub website on the same season that sounding was conducted so as to prevent effects of sedimentation or dredging on the depth that could lead to errors in the derived depths. The details of the satellite data acquire are shown in Table 3.1 below;

Sensor	Date of acquisition	Bands used	Resolution of bands used	Source
Sentinel 2A	27/03/2022 to 31/03/2022	Band 2 – Blue Band 3 – Green Band 4 – Red Band 5 – Near Infrared (NIR)	10m	Copernicus website

The blue and green visible bands are selected in this region because they provide higher water penetration whereas, Blue bands can penetrate up to 30m, green band can penetrate up 10m, red band can penetrate up 5m and near infrared which can penetrate up to 0.5m and is used for distinguishing water from land (Sagawa, Yamashita, Okumura, & Yamanokuchi, 2019).

Sentinel 2 image was selected for this study because it is a free data source providing high resolution optical images with a swath width of 290km with 13 spectral bands that guarantee consistent time series, showing variability in surface conditions and minimizing any artifacts introduced by atmospheric variability and also to compare the results obtained on the dam and coastal areas derived from the same type of image (Wei, Zhao, Lu, & Fu, 2021).

Figure 3:1 Sentinel 2A image containing Mindu Dam.

The echo sound bathymetric data of Mindu dam were collected from 27^{th} to 31^{st} of March, 2022 basing on the mean level but the depths were obtained from direct observations from the echo sounder and the GPS connected to the vessel providing the location of the depth points in terms of eastings and northings thus each point having both the position and the depth data, and were to be used for calibration to derive the coefficients and constants used in the determination of depths from the satellite image and to assess the derived depth were obtained from Mr. Method Gwaleba, Ardhi University.

3.2 Data processing

It is section that gives detailed description of how each data set was utilized, the processes that were followed to yield the required information and the mathematical equation involved and the software that were used in processing of data. Processing stages involved different stages including data pre-processing, spatial registration and subset, land mask (land and water separation), sun-glint correction, dark-object atmospheric correction and finally empirical bathymetry.

These stages were completed using different software to pre-process the raw data, to process including bathymetry derivation and validation of the obtained information. The processing software include; Snap Software was used to perform resampling of the image to a 10m resolution since all the bands used in this study are of 10m resolution and also used in the extraction of the band ratio used in regression analysis and the derivation of depth from the optical satellite image, Microsoft excel software was used to perform mathematical operations involved in the study and arrange the sounding data in the format that can be processed by other software, Golden Surfer software was used to grid the Sounding bathymetry data into a manageable size and perform statistical mathematical operations involved in the study and, ArcMap software was used to generate bathymetry maps of Mindu reservoir.

3.2.1 Data pre-processing

The first step before actual processing that refers to the manipulation or cleaning of data before it is used in order to ensure or enhance performance and minimize possible errors. As there are several factors affecting state of the atmosphere such as haze and clouds, affecting the water column such as sedimentation, turbidity and variable optical properties thus generally affecting the sensing capabilities of different sensors imposing different errors to the images captured and therefore pre-processing of the images is important to correct or minimize image distortions resulting from image systems, sensors and observing conditions to enhance the image so as to yield proper results (Bose, et al., 2017).

This pre-processing often includes atmospheric correction, but in this case the image downloaded is of the level-2A product which provides atmospherically corrected surface reflectance images free from atmospheric disturbances. The atmospheric corrected image seems more clearly, especially on shallow water areas, with the application of this correction has proven to increase the contrast of the image (Makarau, et al., 2008). Also, tidal correction for the satellite image downloaded while for the sounding data gridding was done to have the data in a manageable size due to the large amount of data. This process was performed using the ArcMap software for the image and surfer was used to grid the sounding data.

3.2.2 Spatial registration and subset

This stage involves resampling of all bands into the same spatial resolution it is basically commanding the software to take the size of one band and resample all other bands into the same size and in our case the blue band was used to resample all other bands of the image that has 13 bands into 10m resolution because it is the resolution that the bands used to derive the bathymetry information have which are the blue, green, red and Near Infra-Red bands.

From the resampled image the area of interest was identified and extracted as presented in the figure below;

Figure 3:2 Sentinel 2 image after subseting the Mindu Dam.

3.2.3 Land Mask

Generally, masks are used to exclude certain pixels from the image processing or when computing image statistics. And, land masking involves masking the land pixels from the image so as to keep only the aquatic areas, thus a land mask was created and then applied to our four bands of interest and in turn separating the land area from the water area. Band 8 was used to create the land mask in this study due to the fact that it has the best contrast in reflectance for discriminating land from water. The expression for masking out the land pixels from the water pixel values is presented as;

If B8 > 0.27 then NaN else 1

Whereas the expression can be explained as, if the band 8 has values more than 0.27 they are termed as NaN (No data values) else 1. The created land mask was the applied to the blue, green, red and NIR bands since they are the bands used to derive the bathymetry information. When this was performed all the areas with land appeared black while the water area appeared white as shown in the figure below;

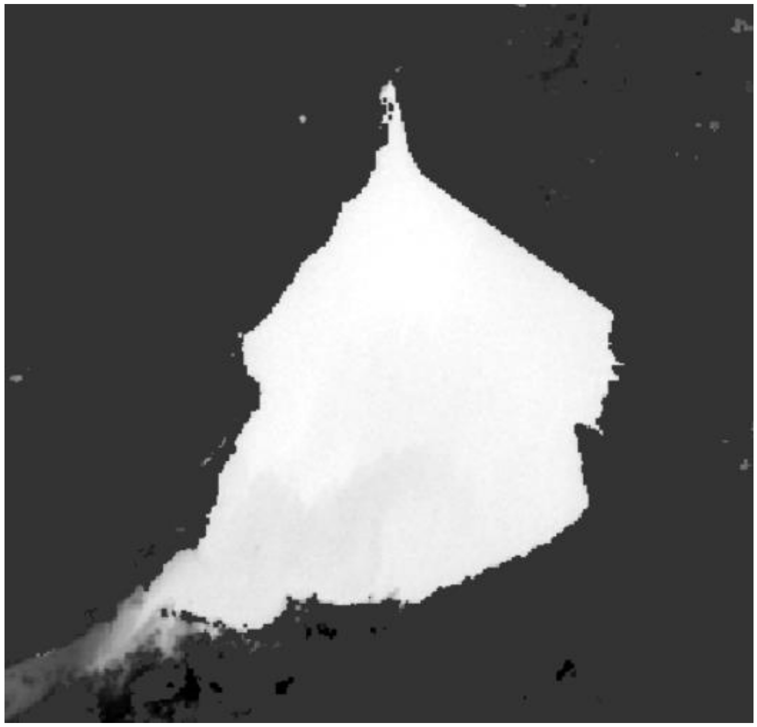

Figure 3:3 Sentinel 2 image after land mask of Mindu Dam.

3.2.4 Sun-glint Correction

Sun-glint is a common phenomenon in satellite images and it refers to the specular reflection of the sun on water surfaces thus the water leaving reflectance cannot be observed easily due to the reflection of the direct sunlight on the air-water interface in the direction of the satellite. When looking at satellite imagery, bright areas mainly over water bodies may be seen as gleam or sparkle and this effect is the sun glint, and its where sunlight is reflected off the surface at the same angle that the sensor views it (Kay, Hedley, & Lavender, 2009). Thus, the removal of this effect is necessary if the amount of sun-glint prevents the visibility of the bottom of the water source (Webinar, 2021). There are several methods that can be used to remove sun-glint but in this study the method developed by (Hedley, Harborne, & Mumby, 2005) that describes the linear relationships between Near-Infra Red and visible bands using linear regression analysis based on the sample obtained by creating some polygons setting some standard areas as samples so that it reads some pixels and use them to apply to the rest of the image pixels. The equation below describes the sun-glint correction;

$$R_i^* = R_i - b_i(R_{NIR} - Min_{NIR}) \quad \text{......3.1}$$

Where, R_i is the reflectance from visible band i and for this study the reflectance of already masked band 2, band 3 and band 4 were used.

b_i is the regression slope obtained from performing regression analysis of the three masked bands of interest an example shown below;

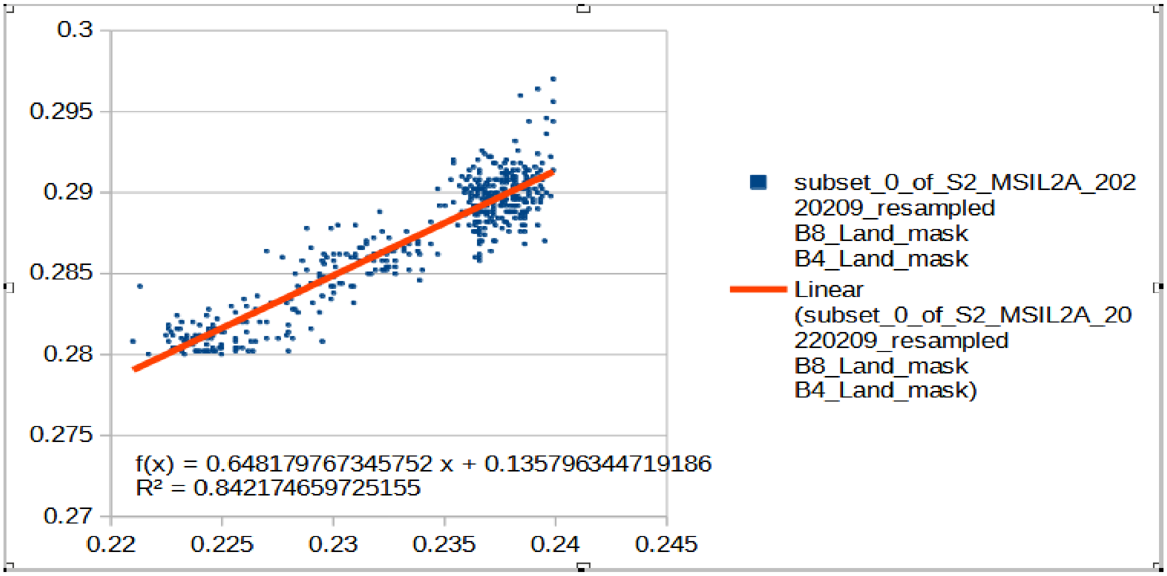

Figure 3.6 Regression analysis of the band

From the figure 3.5 the regression slope is the coefficient of X which is different for all the three bands thus when correcting for the sun glint each band will use its corresponding regression slope.

R_{NIR} is the Near-Infra Red band value and this study made use of the already masked band 8(Near Infra-Red).

Min_{NIR} is the minimum Near-Infra Red value of the sample

All the above parameter values were obtained from the analysis of the image.

3.2.5 Dark-Object Atmospheric Correction

It is an empirical atmospheric correction method which assumes that the reflectance from dark objects includes a substantial component of atmospheric scattering and therefore it needs to be subtracted (Webinar, 2021). The band 2 and band 3 were used in this last stage before the derivation since these two bands will also be used in the band ratio technique to derive the bathymetry information from the image. Dark object atmospheric correction process is performed by subtracting the minimum value of the blue and green band deglint obtained from the histogram of the deglint bands an example shown in the figure blow;

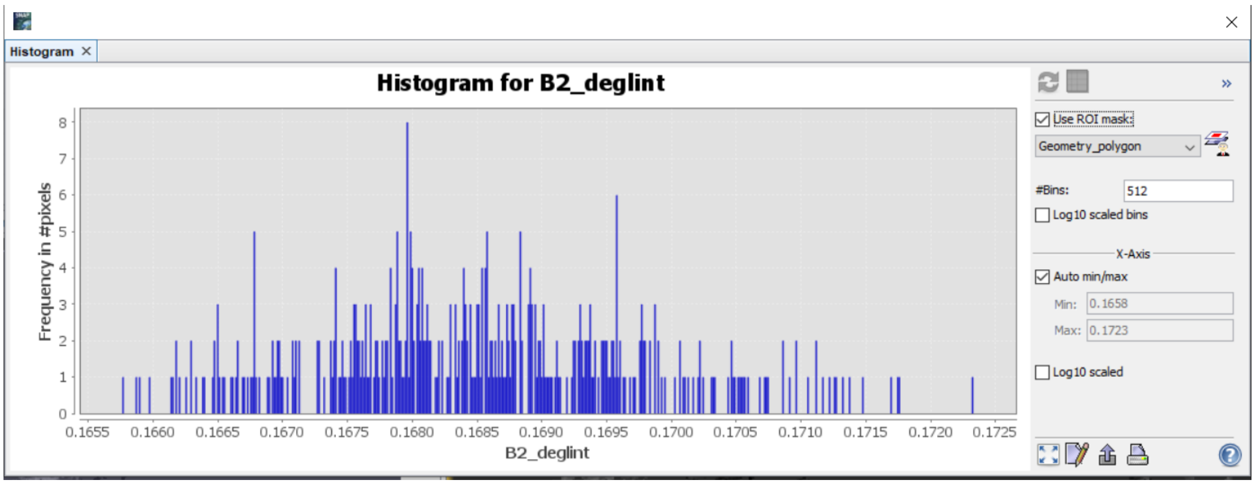

Figure 3.7 Minimum and maximum value of the band 2 deglint.

3.2.6 Empirical Bathymetry

The final stage in data processing that involves the derivation of bathymetry data and in this study the bathymetry information was derived by making use of the Band Ratio Model developed by (Stumpf, 2003) as presented in equation 2.1. This model bases on the principle that each band has a different absorbing level of water and this diversity level theoretically will produce the ratio between bands. This ratio then will generate a simultaneous change when the depth changes, and in this study the ratio was applied for the red and blue bands. This model also makes use of the sounding data which has a set of points with known depths by training the data to obtain constants used to derive the bathymetry information from the image.

3.2.6.1 Derivation of the band ratio

The band ratio was derived using the green band and blue band due to the fact that the blue band has high reflectance. And the bands used have been corrected for any type of error and the equation 2.1 was used to calculate the band ratio from the Sentinel 2 image.

The fixed value of n in the equation above is chosen to assure both that the logarithm will be positive under any condition and that the ratio will produce a linear response with depth and mostly ranges from 500 to 1500.

3.2.6.2 Determination of Gain(m1) and offset(m0)

A subset of the field data in this case the sounding data is selected to create a training dataset. The extracted band ratio values from the satellite imagery were then paired with the corresponding water depth measurements and linear regression of the band ratio against depth was performed to obtained the gain and offset parameters an example depicted below;

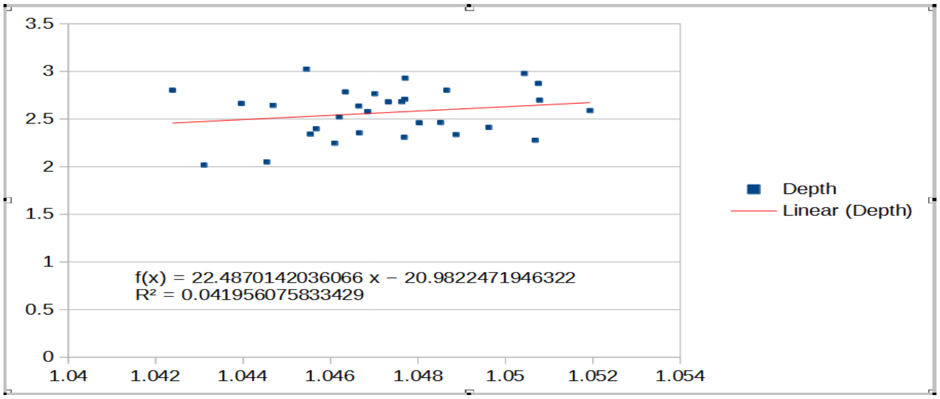

Figure 3.8 Determination of m0 and m1

From equation 2.1 and the equation in figure 3.8 m1 is 22.487 and m0 is 20.982.

3.2.6.3 Derivation of satellite bathymetry

Bathymetry information was derived using the band ratio equation 2.1 and due to the fact that the in-situ data measurements had many values a number of points were selected to derived and validate the derived depths.

CHAPTER FOUR

RESULT, ANALYSIS AND DISCUSSION

4.0 Overview

In this section, the results obtained from the research methodology and the validation technique used to verify the derived bathymetry information are presented and interpreted.

4.1 Data Processing and Result

4.1.1 Satellite Derived Bathymetry of Mindu reservoir

Before the derivation of the bathymetry information using the band ratio model the model Parameters were computed between the raster value of the blue and green band ratio with the sounding data of the reservoir using different values of n. The results are as shown below;

Table 4.1 model parameters for SDB when n is 1

Parameter	**Value**
n	1
m0	9.831892
m1	-5.102997

The m0 and m1 parameters were obtained from the linear regression of the band ratio values and some of the known depths.

After the determination of the model parameters the Stumpf model was used to derive the depths of the remaining points that were not used for training and the results showed that for most points the technique did not perform well because the difference between the derived bathymetry information and the known depths was big, and performed well at few points.

Some sample points are presented in the table 4.2;

Table 4.2 consists of some sample points and their corresponding derived bathymetry information and the difference with the known depths.

Table 4.2 Sample of the xtracted points of SDB for mindu reservoir

SN	**Longitude**	**Latitude**	**Depth**	**SDB(m)**	**Diff(m)**
1	37.6072779	-6.87315132	2.44296431	2.166909	0.27605
2	37.6072803	-6.87233464	2.75082875	3.011627	0.26080
3	37.609995	-6.86635353	4.65383419	4.661371	0.00754
4	37.6167286	-6.86963976	4.0021701	4.004436	0.00226
5	37.614835	-6.87153988	2.85758306	2.652433	0.20515
6	37.6129516	-6.86990106	4.17048931	4.200396	0.02990
7	37.6148405	-6.8696343	4.2963828	4.328951	0.03256
8	37.6151102	-6.86963508	4.31430124	4.328561	0.01425
9	37.6167325	-6.86827863	5.12078751	5.126686	0.00589
10	37.6121512	-6.86690424	5.1883514	4.909576	0.27878
11	37.6108033	-6.86662811	5.04334237	5.045987	0.00264
12	37.6132427	-6.86255176	6.40670981	5.751597	0.65511
13	37.6105241	-6.86989402	3.24767618	3.191569	0.05611
14	37.6159186	-6.86990964	3.72561204	3.722669	0.00294

4.1.2 Statistical analysis of the bathymetry information of Mindu reservoir

Using the gridded points statistical analysis was performed for the two sets of data considering different values of n to determine which value will provide more accurate results as n is a fixed value chosen to assure both that the logarithm will be positive under any condition and that the ratio will produce a linear response with depth. The results are as presented below;

Table 4.3 Statistics of the Satellite Derived Depths when n is 1

Point	Number value	Mean(m)	Maximum(m)	Minimum(m)	Standard Deviation(m)
SDB	1552	4.264	6.253	-1.889	0.649

Table 4.4 Statistics of the echo sounding depths when n is 1

Point	Number value	Mean(m)	Maximum(m)	Minimum(m)	Standard Deviation(m)
Echo-sounding depth	1552	4.856	7.763	1.539	1.536

For n = 10

Table 4.5 statistics of satellite derived depths when n is 10

Point	Number value	Mean(m)	Maximum(m)	Minimum(m)	Standard Deviation(m)
SDB	2528	4.390	7.965	-1.337	1.525

Table 4.6 Statistics of the echo sounding depths when n is 10

Point	Number value	Mean(m)	Maximum(m)	Minimum(m)	Standard Deviation(m)
Echo-sounding depth	2528	4.656	7.769	1.444	1.638

For n = 100

Table 4.7 statistics of satellite derived depths when n is 100

Point	Number value	Mean(m)	Maximum(m)	Minimum(m)	Standard Deviation(m)
SDB	1565	4.331	5.181	-10.265	0.775

Table 4.8 Statistics of the echo sounding depths when n is 100

Point	Number value	Mean(m)	Maximum(m)	Minimum(m)	Standard Deviation(m)
Echo-sounding depth	1565	4.875	7.763	1.539	1.542

For n = 1000

Table 4.9 Statistics of the echo sounding depths when n is 1000

Point	Number value	Mean(m)	Maximum(m)	Minimum(m)	Standard Deviation(m)
SDB	1565	4.151	7.6	-8.805	0.0.357

Table 4.8 was used for comparison with table 4.9 since they have the same number of points for the derived bathymetry and the echo sounding depths. From the tables 4.3 – 4.9 above shows the comparison of different statistical analyses with different values of n and when n was 10 the results obtained were at a better accuracy than other values of n.

4.1.3 Satellite Derived Bathymetry map of Mindu reservoir

Referring to the third objective of this research a bathymetry map was generated using the derived bathymetry information derived using n as 10 as it provided results approximately the same as the depths from the echo sounding technique as validated using the statistical analysis of the two data sets seen in the figure below;

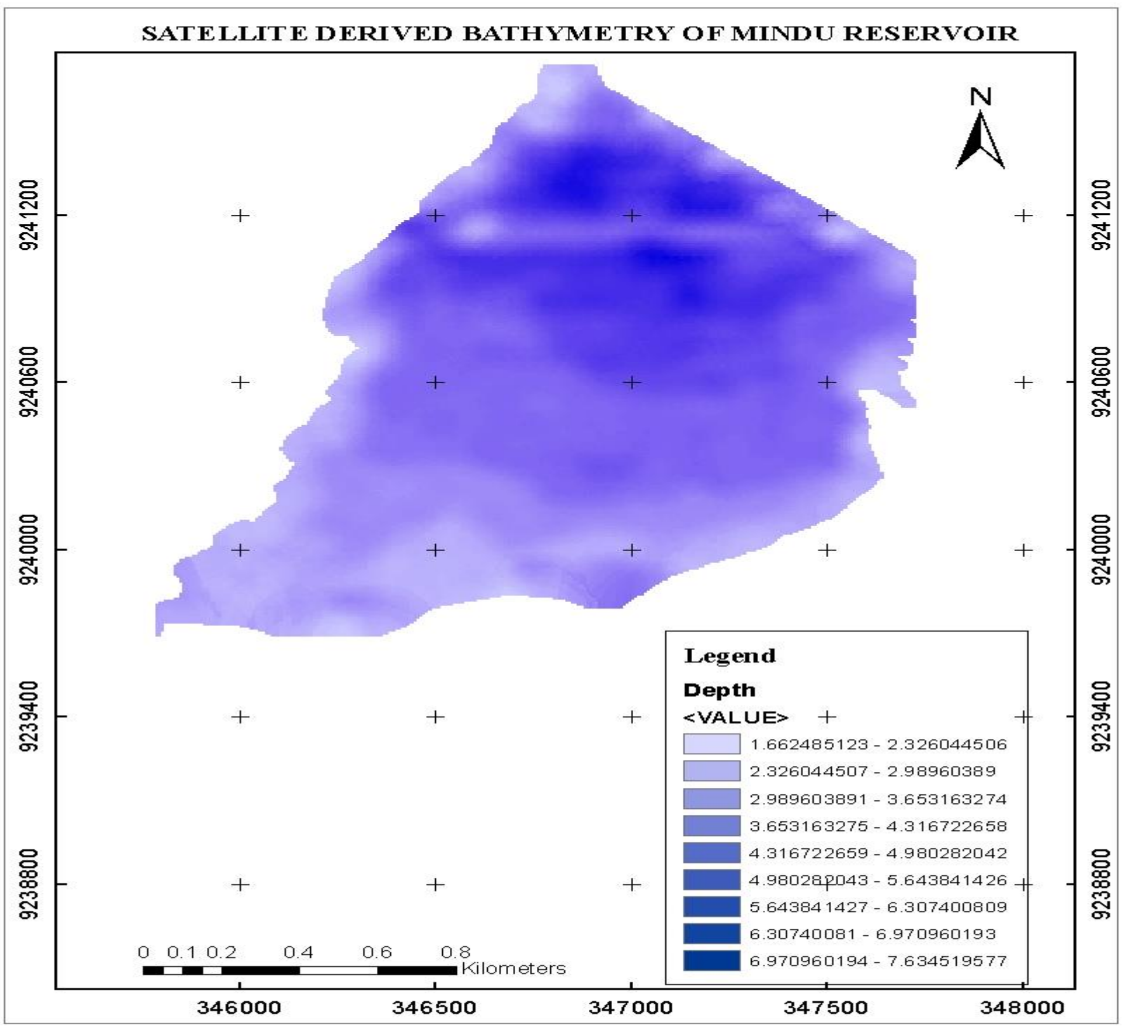

Figure 4.1 Satellite Derived Bathymetry of Mindu reservoir

4.1.4 Echo-sounding bathymetry map of Mindu reservoir

The bathymetry points from echo-sounding technique were gridded to a manageable number of almost 2500 points and then extracted using the surfer software to be used in this study. From the tables 4.3 to 4.9 showing the statistical analysis of the two data sets, its clearly reflected that using n = 10 the satellite derived technique provided results for all the gridded points and therefore the same echo-sounding depths will be used to generate the bathymetry map of Mindu reservoir and then compare the two maps basing on their color variation. The echo-sounding bathymetry map is as presented below;

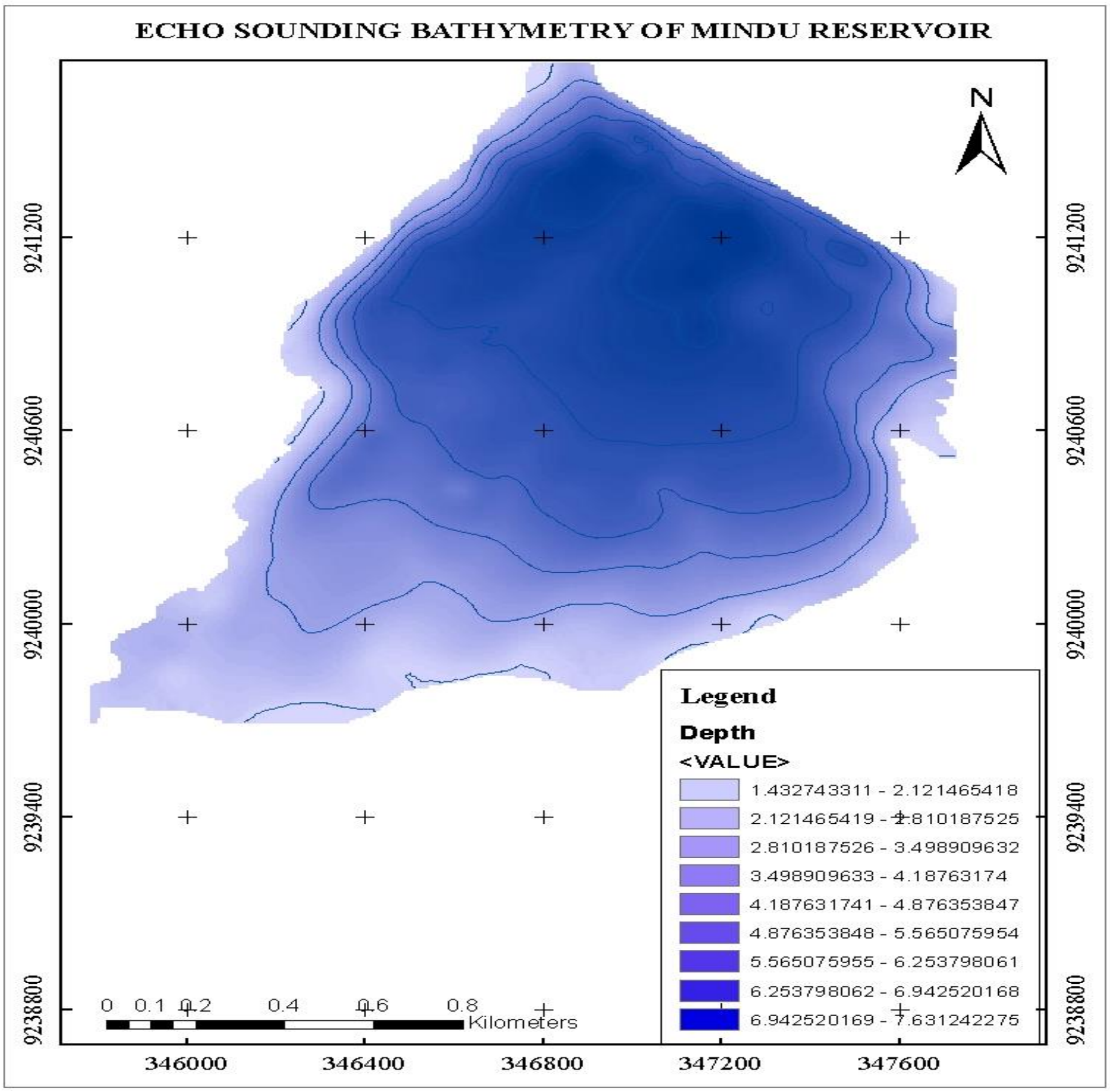

Figure 4.2 Echo-sounding bathymetry of Mindu reservoir

4.2 Discussion of the result

4.2.1 Model Parameter

The model parameters were obtained through linear regression by plotting the depth values against the band ratio pixel values, as the Stumpf model states the ratio of the blue and green band was derived using different values of n and plotted against some few points with known depths to obtain the linear regression equation and with each different value of n the model parameters were also different as presented in the tables below;

Table 4.10 model parameters when n is 10

Parameter	**Value**
N	10
m0	21.708
m1	-11.738

Table 4.11 model parameters when n is 100

Parameter	**Value**
N	100
m0	5.387
m1	-0.573

Table 4.12 model parameters when n is 1000

Parameter	**Value**
n	1000
m0	4.104
m1	0.083

With different values of the parameters the depths derived were also varying depending on the parameters used to derive the bathymetry information.

4.2.2 Comparison of the Results

The results were compared using the bathymetry information derived when n is 10 since it provided more approximate derived depths. The derived depths were derived using the same position as that of the sounding data that was used for validating the derived bathymetry information by comparing the two depths of the same point and analyzing the depth difference between the two data sets. The same point positions were used so as to minimize the effect that could result from using a different position that could result into a large difference in depth. Also, the image used was of the same season as the season when sounding data were collected so as to remove the effect of dredging if by any chance took place and other seasonal factors as this technique has an accuracy that varies by season and location.

The table 4.13 below shows the statistical analysis of the difference between the two data sets.

Table 4.13 statistical analysis of the depth differences

Point	**Difference**
Number of values	2528
Sum	657.984
Minimum(m)	-4.780
Maximum(m)	7.312
Mean(m)	0.260
95% confidence interval (m)	0.037
99% confidence interval (m)	0.048
Variance	3.233
Standard deviation	0.947
Root Mean Square	0.982

The depth variation calculated at each position was then plotted on a map and how this variation can be depicted from the map indicating areas with small, medium or large variations in depth according to the map legend.

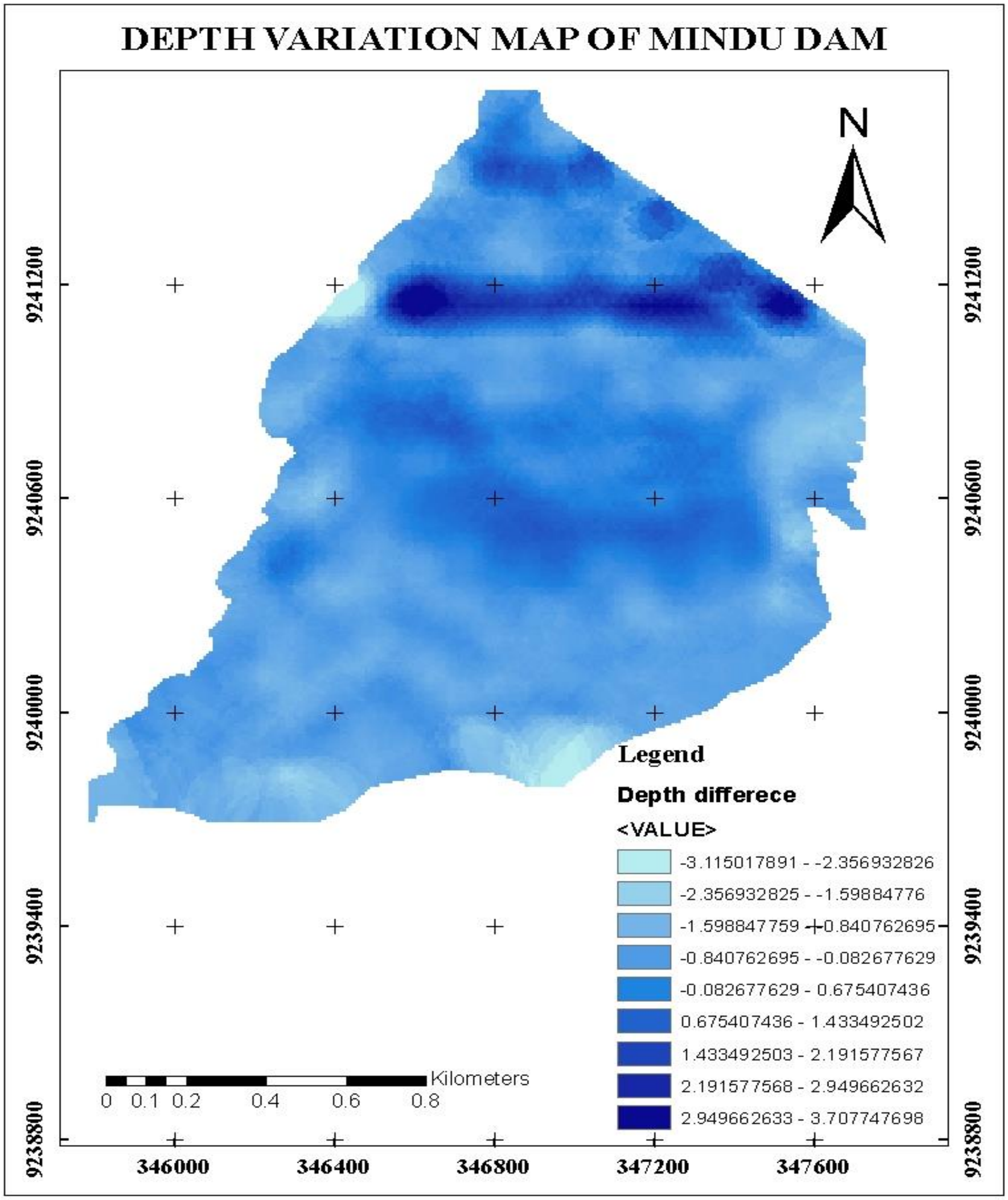

Figure 4.3 Depth variation map of Mindu reservoir.

CHAPTER FIVE

CONCLUSION AND RECOMMANDATIONS

5.1 CONCLUSION

The main objective of this study was to assess the accuracy of satellite derived bathymetry using sounding data of Mindu dam. The depth information was derived from sentinel 2 image and then assessed using the sounding data to obtain the depth variation between the two data sets. Bathymetry maps of the two data sets were generated and presented in chapter four by Figure 4.1 and 4.2. The depth variations were then plotted to visualize how the depth varies at different positions presented by Figure 4.3 and then analyzed statistically and obtained a mean value of 0.26, standard deviation of 0.947 and root mean square 0.982 presented in Table 4.13.

From the standards provided by EOMAP and the results obtained in this study 55.27% of the derived depths are within the accepted uncertainty between 0 to 0.5m, 31.74% of the depth variation fall between 0.5m to 1m, and the remaining 12.99% of the derived depths are not within the acceptable uncertainty as the depth variation is above 1m. The maximum and minimum error of sounding techniques can vary depending on factors like the equipment quality, environmental condition and calibration of the equipment used. Generally, high-quality systems can have low errors with maximum errors often in the range of a few meters or less and these sources of error may have contributed to the depth variation

Again, the error of the derived depths of this study may be due to different factors such as the resolution of the image, the atmospheric and water conditions, and the processing technique used. Thus, it cannot be concluded that the technique did not perform well on dams but rather it can be concluded that the technique can be used to derive depth information to approximate water level of dams as 87.01% of the derived depths fall within the acceptable range of 0 to 1m.

Therefore, from the results obtained in this study considering the depth variation at different points, the technique can be used to derive depths over optically shallow waters. There are points that had approximately the same depths from both techniques and therefore proving its validity, but for the points that didn’t agree it cannot be concluded that the technique is not applicable unless all conditions for this technique were met.

5.2 RECOMMENDATION

Another researcher should use a different model/approach to derive the bathymetry information and compare the results obtained from the two different models and assess the performance of these models of this technique on different water bodies.

A different and more accurate satellite mission that provide images at higher resolutions such as Quick Bird with ground level pixel size of approximately 2.4 * 2.8m. And IKONOS with 1m to 5m spatial resolution should also be used by another researcher to assess the performance of this technique on different shallow water sources including dams.

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