ARDHI UNIVERSITY

VERTICAL ACCURACY ASSESSMENT OF FABDEM_V$_{1-0}$, NASADEM, COPERNICUS 30, AW3D30Ev3.2 AND TanDEM-X-3'' PUBLIC GLOBAL DEMs IN TANZANIA USING TGGCPs

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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 Bachelor 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 "**Vertical Accuracy Assessment of FABDEM_V1-0, NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3'' Public Global DEMs in Tanzania Using TGGCPs**" in partial fulfillment of the requirements for the award of degree of Bachelor of Science in Geomatics at Ardhi University.

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Ms. REGINA V PETER

(Supervisor)

Date ……………………

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I, ULEMA, JAIROS K 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 dissertation to my beloved family; my parents; Kedmon Ulema and Angelina Mwaluko (Rest in Peace), my siblings; Benadeta Ulema, Salome Ulema, Florida Ulema and Upendo Ulema whose unwavering support and encouragement have been the foundation of my academic journey. I am forever grateful for your love.

ABSTRACT

For many different purposes, digital elevation models (DEMs) are a common source of elevation data at the national level. Thus, having the DEM with the highest level of accuracy is crucial for a variety of applications. The following public GDEMs were used in this study: FABDEM_V_{1-0}, NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3" out of which FABDEM_V_{1-0} has not been validated in Tanzania. FABDEM_V_{1-0}, NASADEM, COPERNICUS 30 and AW3D30Ev3.2 have a horizontal spatial resolution of 1" and TanDEM-X-3" has a horizontal spatial resolution of 3", these GDEMs are referenced to WGS84 as horizontal datum and EGM08, EGM96, WGS84 geoid models as vertical datum. The recently released GDEM which is FABDEM_V_{1-0} together with recently vertically validated NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3" are assessed for the best GDEM in Tanzania.

This study evaluates vertical accuracy of five GDEMs across Tanzania and assesses their vertical accuracy using GPS Ground Control Points (GGCPs) located across nine selected different land covers. The GGCPs' height measurements are originally ellipsoidal, so they were converted to orthometric heights using the EGM08 geoid model. To maintain consistency, the GDEMs' orthometric heights, based on the EGM96 model, were also converted to EGM08 geoid model orthometric height.

To evaluate the accuracy of the GDEMs, this study uses statistical measures such as Mean, Standard Deviation (SD), and Root Mean Square (RMS) of height differences between the GDEMs and the GGCPs. The assessment is based on the least value of SD and RMS. The study compared FABDEM_V_{1-0} with NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3" to determine their level of agreement or disagreement at the common grid intersections.

Countrywide performance, the pair of FABDEM_V_{1-0} vs NASADEM was found to be the best, while the pair of FABDEM_V_{1-0} vs COPERNICUS 30 performed better in many terrain land covers. On the other hand, the pair of " FABDEM_V1-0 vs TanDEM-X-3" showed higher disagreement at common grid intersections in countrywide.

For the vertical assessment of GDEM using GGCPs, the results indicated that FABDEM_V_{1-0} was much closer to GPS controls countrywide and in many samples of terrains than NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3". Overall, the statistics indicated that FABDEM_V_{1-0} is the best GDEM in Tanzania.

Keywords: GDEM, GGCPs, Terrain, Land cover and Vertical Accuracy Assessment.

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ACRONYMS AND ABBREVIATIONS

AOI	Area of Interest
ADEOS	Advanced Earth Observing Satellite
ALOS	Advanced Land Observing Satellite
ASPRS	American Society of Photogrammetry and Remote Sensing
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
DLGs	Digital line graphs
EGM96	Earth Geoidal Model of 1996
EGM08	Earth Geoidal Model of 2008
GDEMs	Global Digital Elevation Models
GGCPs	GPS Ground Control Points
GLAS	Geoscience Laser Altimeter System
GNSS	Global Navigation Satellite System
GPS	Geographical Positioning System
ICESat	Ice, Cloud, and Land Elevation Satellite
InSAR	Interferometric Synthetic Aperture Radar
JAXA	Japan Aerospace Exploration Agency
JdeF	Jonathan de Ferranti
JERS-1	Japanese Earth Resources Satellite-1
LIDAR	Light Detection and Ranging
METI	Ministry of Economy, Trade and Industry
MLHHSD	Ministry of Lands Housing and Human Settlement Development

NASA	National Aeronautics and Space Administrations
NGA	National Geospatial-Intelligence Agency
NUM	Number of Scenes
PRISM	Portable Remote Imaging Spectrometer
QAI	Quality Assurance Information
SAR	Synthetic Aperture Radar
SMD	Surveys and Mapping Division
SNAPU	Statistical-cost Network-flow Algorithm for Phase Unwrapping
SRTM	Shuttle Radar Topography Mission
TRF	Tanzania Reference Frame
SGST	School of Geospatial Science and Technology
RMS	Root Mean Square
MIN	Minimum
MAX	Maximum
DED	Digital Elevation Data

CHAPTER ONE

INTRODUCTION

The development of Digital Elevation Models (DEMs) has a rich history spanning several decades, closely aligned with the progress in remote sensing, geospatial technologies, and computing capabilities. In the early stages, creating elevation models required manual measurements using conventional surveying techniques. Surveyors would physically measure the height and position of specific points on the Earth's surface to reconstruct its topography. While conventional surveying methods were initially employed, they presented several challenges, firstly, they were highly time-consuming, as surveyors had to meticulously measure and record data point by point. This process required significant human effort and could only cover a limited area within a considerable time frame. As a result, the coverage achieved by these traditional methods was often insufficient for large-scale mapping or comprehensive analysis of terrain (Li et al., 2017).

Furthermore, conventional surveying techniques were prone to human errors, which could introduce inaccuracies in the derived elevation data. The precision of the measurements relied heavily on the skills and expertise of the surveyors involved. Additionally, certain terrains or inaccessible areas posed challenges for traditional surveying, such as rugged mountainous regions or dense forests, where reaching specific points for measurement was arduous or even impossible (Li et al., 2017).

Conventional surveying techniques had limitations in terms of time consumption and limited coverage, prompting the exploration of alternative methods for obtaining elevation data. This led to advancements in remote sensing technologies like radar and LiDAR. As a result, Digital Elevation Data (DED) became more readily available, providing a digital representation of the Earth's landscape and its characteristics (Ravibabu et al., 2008). Elevation can be stored digitally in various ways, including gridded models, triangular irregular networks, and contours. DED has become a major source of data in various sectors with wide-ranging uses (Croneborg et al., 2015).

It is usual practice to validate any DED before usage in order to identify any errors and, consequently, their potential effect when utilized for various applications. This helps assess the vertical accuracy of any DED. A DED is validated by comparing it to a different, more accurate data source that used an independent data collecting method (Lakshmi et al., 2018). Due to their extensive coverage, high resolution, and uniform data quality, most DED nowadays are generated from spaceborne remote sensing techniques (Bates et al., 2019).

Because they are a discrete global grid that has been mosaicked to cover the whole earth's surface, these DED are known as Global Digital elevation models (GDEMs). Some GDEMs are freely available to users, for example FABDEM, ALOS, NASADEM, COPERNICUS and MERIT while others are commercially distributed for example TanDEM-X, all available online from developers' official websites. The majority of developing countries hardly ever manage to construct their own accurate national digital elevation databases. The primary factors are, among others, the expense of the equipment that enable quick and thorough coverage. Users of DED in Tanzania, the study's area of interest (AOI), have been looking for a public GDEM that best suits their nation for a variety of purposes. As a result, the community of scientists has been interested in validating GDEMs as they become available to determine their applicability for various applications in Tanzania. There is a list of the public GDEMs that have already been validated and evaluated over the years.

i. Validation of COPERNICUS DEM GLO 30 AND 90, AW3D30 V3.2, and NASADEM Using TGGCP. Validation of the GDEMs using TGGCPs countrywide and in selected land covers performance of the GDEMs countrywide using TGGCPs at 95% confidence level shows that NASADEM to be closer to the control point than the other GDEMs (Mbura, 2022).
ii. Validation of ALOS-1"-v3.1 and NASADEM using Tanzania GPS Ground Control Points and their comparison to ASTER-1"-v3, SRTM-1"-v3 and ALOS-1"-v2.2 the results showed that NASADEM is much closer to GPS controls countrywide as well as in many terrains compared to ASTER-1"-v3, SRTM-1"-v3, ALOS-1"-v3.1 and ALOS-1"-v2.2. (Mavunde, 2021).
iii. Validation of TANDEM-X-0.4" In Areas available in Tanzania and It's Comparison to other GDEMS. TanDEM-X-0.4" is more superior to all GDEMs with RMS of 0.78m, followed by TanDEM-X-3" and ALOSv2.2-1" with RMS of 2.71m and 2.87m respectively (Minja, 2020).
iv. Comparison and Vertical Performance Assessment of SRTM-1"-v3, ALOS-1"-v2, MERIT-3" and TanDEM-X-3" Public Global DEMs in Tanzania Using GPS Ground Controls. In countrywide validation using GGCPs, TanDEM-X-3" shows better performance over SRTM-1"-v3, ALOS-1"-v2 and MERIT-3" (Mapunda, 2019).
v. Assessment of vertical performance of MERIT-3" GDEM in Tanzania using GPS ground control points and its comparison with SRTM-3"CGIAR-CSI v4.1 and

ALOS-1"-v2 was carried out. The results showed that, the fitting of SRTM-3"CGIAR-CSI v4.1 to MERIT-3" GDEM is inferior compared to the fitting of ALOS-1"-v2 to MERIT-3" GDEM country wide (Mng'ong'o, 2018)

vi. Vertical Assessment of Public Global Digital Elevation Models Including ″1SRTM Generally, and in Eight Sample Land Covers and Terrains of Tanzania. 1" SRTM was superior to all GDEMs validated until 2016 (Ulotu, 2017).

Since there is newly released DEM which has not been validated, FABDEM_V_{1-0} therefore, in this research, its assessment for vertical performance has been carried out to assess its performance relative to the NASADEM, AW3D30v3.2, COPERNICUS 30 and TanDEM-X-3" GDEMs, also to the GGCPs countrywide and in 12 representative land covers sample found in Tanzania for the determination of the GDEM with the best vertical accuracy in Tanzania.

1.1 Statement of Research Problem

Since most developing nations have inadequate digital geospatial data, they depend on public GDEMs for a variety of purposes. Tanzania is currently looking for the best GDEM to rely on; prior studies on the assessment of public GDEMs revealed poor results in places like forest covers and high terrains/mountains. This research is evaluating the vertical performance of the recently released GDEMs, namely FABDEM_V_{1-0}, NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3" by using Tanzania GGCPs. This is done because of the importance of digital elevation data provided by public GDEMs in various fields and the continuous release of public GDEMs, which generally are expected to perform better.

1.2 Objectives of the Research

1.2.1 Main objective

The main aim of this research is to determine the best public GDEM in Tanzania for the use in various applications by assessing FABDEM_V_{1-0} using GGCPs in Tanzania mainland. The assessment includes various land covers and a general comparison to other GDEMs which are NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3"

1.2.2 Specific objectives

i. In order to have a uniform reference datum, all heights are converted from the various vertical datums used by the GDEMs to orthometric heights using EGM08. Ellipsoidal heights from the GGCPs are also converted to orthometric heights using the EGM08

ii. Comparison of the GDEMs both countrywide and selected landcovers

1.3 Hypothesis

FABDEM_V_{1-0} exhibits superior vertical accuracy compared to NASADEM, COPERNICUS 30, AW3D30Ev3.2, and TanDEM-X-3".

1.4 Significance of the research

The accuracy of the chosen GDEMs in various places needs to be assessed in order to improve the next generation of global DEMs. Users may be sure which GDEM best meets their needs by comparing them based on the application's nature, the terrain's characteristics, and the land cover. GDEMs and their derivatives, such as slope, aspect, and moisture index, have a wide range of uses in a variety of fields.

Here are a few applications for GDEMs:

i. Commercial forestry in deriving enhanced Canopy Height Models (CHM)
ii. Orthophoto rectifications
iii. Developing flood hazard models
iv. Geological applications in the fields of geomorphology, geophysics and geology
v. Infrastructure planning, mapping and assessment
vi. Disaster risk management
vii. Water resource management and hydrological modelling
viii. Gravity smoothing and prediction

1.5 Beneficiaries of the Research

In the fields of geographic information systems (GIS), remote sensing, and earth and environmental sciences, GDEMs are often applied. The beneficiaries include a wide range of professions, including Cartographers, Geodesists, Geomaticians, Engineers, hazard mitigation groups, military, natural resource managers, conservation organizations, and many more.

1.6 Scope of the study

The area of interest covers Tanzania mainland (1°N 12°S, 29°E to 41’E) and the research will deal mainly with the areas where the GGCPs are available. *Figure 1.1* map of Tanzania showing the available coverage of GGCPs.

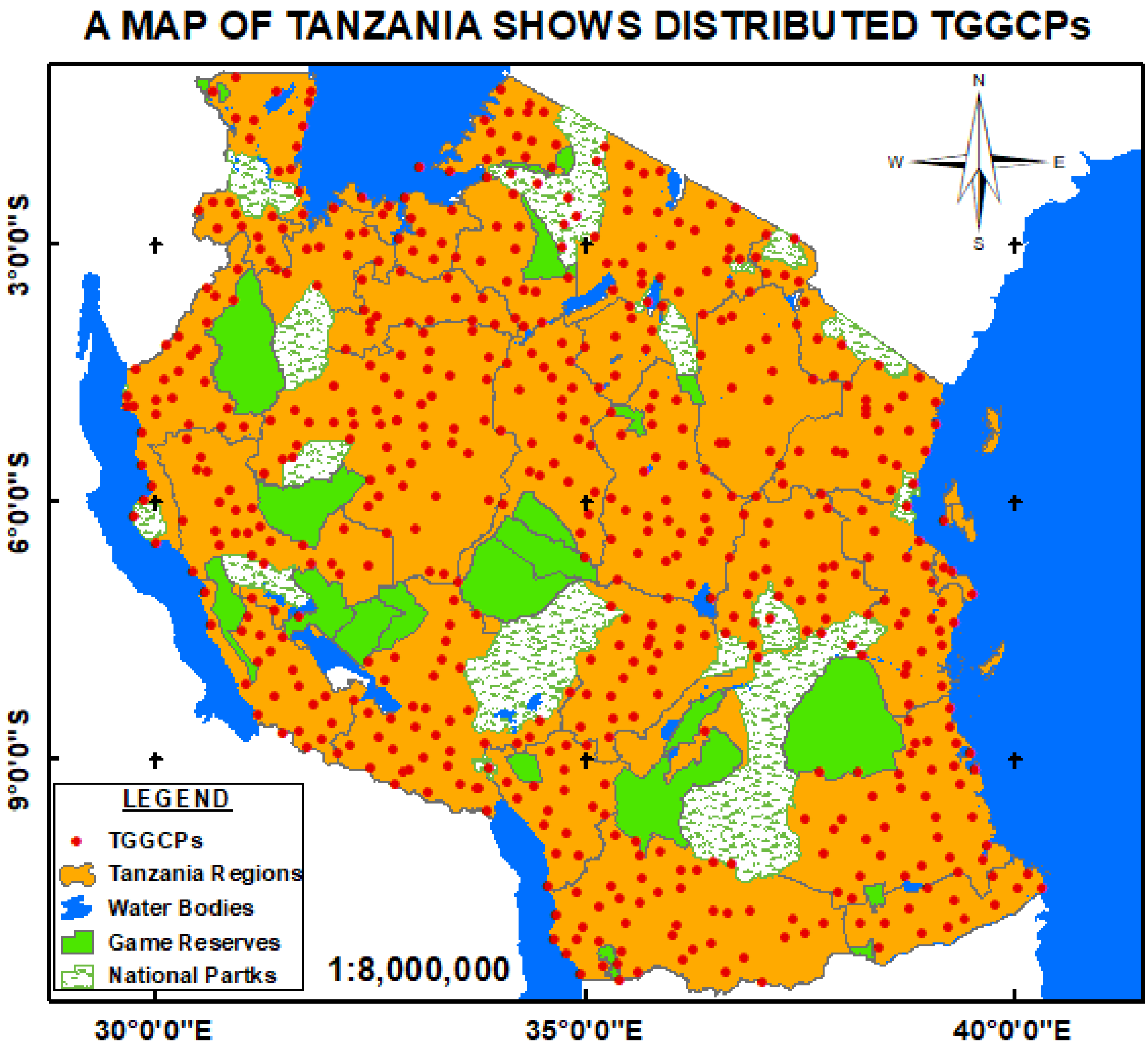

Figure 1.1: A map of Tanzania showing the available coverage of GGCPs

1.7 Structure and organization of the Research

This research consists of five chapters as follows;

a) Chapter one: Introduction

The first chapter provides an overview of the research by presenting the study's background, objectives, hypothesis, scope, significance, and the individuals or groups who will benefit from the research. It serves as a guide for readers to gain a clear understanding of the research topic and the expected outcomes.

b) Chapter two: Literature review

In this chapter, a comprehensive analysis is provided on the GDEMs (Global Digital Elevation Models) utilized in this study, along with a review of previous work done by other authors in terms of validation, comparisons, methods employed, and theoretical foundations related to the topic.

c) Chapter three: Methodology

This chapter systematically presents the methods and procedures followed during data collection and processing. It also describes the specific datasets used and the software employed for data management and processing.

d) Chapter four: Results and Analysis

The fourth chapter showcases the results obtained from the data processing discussed in chapter three, accompanied by a detailed analysis and discussion of these findings.

e) Chapter five: Conclusion and Recommendation

In this concluding chapter, a succinct summary is provided of the accomplishments achieved through the study. Additionally, recommendations are presented to enhance the obtained results.

CHAPTER TWO

LITERATURE REVIEW

GDEMs are a necessary element in the modern era of remote sensing and Geographic Information Systems (GIS). They provide a broad reflection of the earth's physical surface and aid in understanding the nature of the terrain (Burrough, 1986). Data modeling, data management, quality, and application development are crucial factors to take into account while studying GDEMs (Lakshmi et al., 2018). The height difference between the modeled height and the real height on land is known as vertical accuracy (Luebke, 2019). Additionally, it provides a description of both random and systematic errors in elevation data. Both measured to a higher accurate reference, the systematic error is calculated by a statistical bias and the random error by the deviation of the height difference (Wessel et al., 2018). Vertical absolute and relative height accuracy can be used to evaluate a GDEM's accuracy (Rizzoli et al., 2017). Absolute height accuracy is the uncertainty in a point's height with respect to a known vertical datum that results from uncorrected, gradually developing systematic errors (Wessel, TanDEM-X Ground Segment DEM Products Specification Document, 2016). The variance between two height estimations brought on by random mistakes is known as relative vertical height accuracy (Wessel, TanDEM-X Ground Segment DEM Products Specification Document, 2016). Within certain data sets, relative accuracy quantifies point-to-point vertical accuracy and defines the accuracy of local height variations (Luebke, 2019). Therefore, evaluating a GDEM's correctness is crucial since its use in different applications affects the results of that task. A review of the descriptions of the GDEMs use in the research, their applications, and the typical procedure used in GDEM validation is presented.

DED encompasses different types of models, such as Digital Elevation Models (DEM), Digital Surface Models (DSM), and Digital Terrain Models (DTM), depending on the data collection methods employed on the Earth's surface. The formation of DED can be localized or global, and the resolution varies based on the specific requirements, available technology, and devices used. Primary sources utilized to create DED include topographical maps, photogrammetric methods, GPS measurements, and stereo satellite photos (Lakshmi et al., 2018).

A digital elevation model (DEM) is a type of raster grid that represents the elevation of the Earth's terrain without vegetation or human-made structures. It provides information about the height of the land surface, with each pixel in the digital image corresponding to a specific elevation value. Figure 2- 1 illustrates the concept (Croneborg et al., 2015).

On the other hand, a digital surface model (DSM) is an elevation model that includes not only the bare soil of the Earth's surface but also natural features like trees and plants, as well as constructed objects such as power lines, towers, and buildings. The term "surface" in a DSM typically refers to the topmost surface that reflects radar signals. It encompasses all visible objects within the scene.

In contrast, a digital terrain model (DTM) represents the three-dimensional depiction of the land surface, including linear features such as rivers, ridges, and break lines. In terms of bare-earth topography, a DTM is similar to a DEM (Singh, 2013). To better understand the differences between DSM and DTM, *Figure 2.1 and Figure 2.2* provide illustrations that demonstrate variations in data collection and the presentation of raster images.

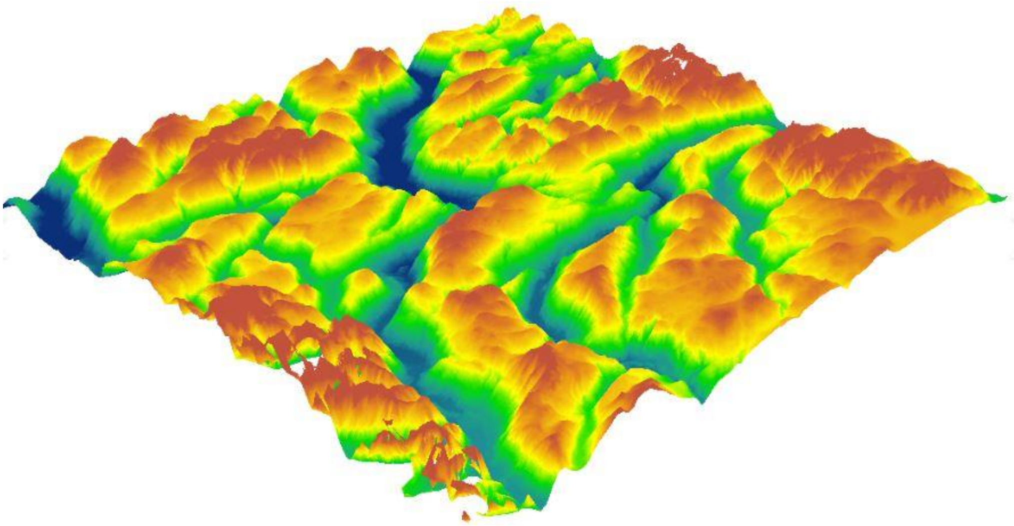

Figure 2.1: A bare earth DEM captured on land

According to Figure 2.1 above obtained from (https://surveyinggroup.com/dsm-dem-dtm-elevation-models-in-gis/). Red denotes high ground, green denotes low ground, and yellow denotes gently sloping terrain on land; blue denotes the water's surface.

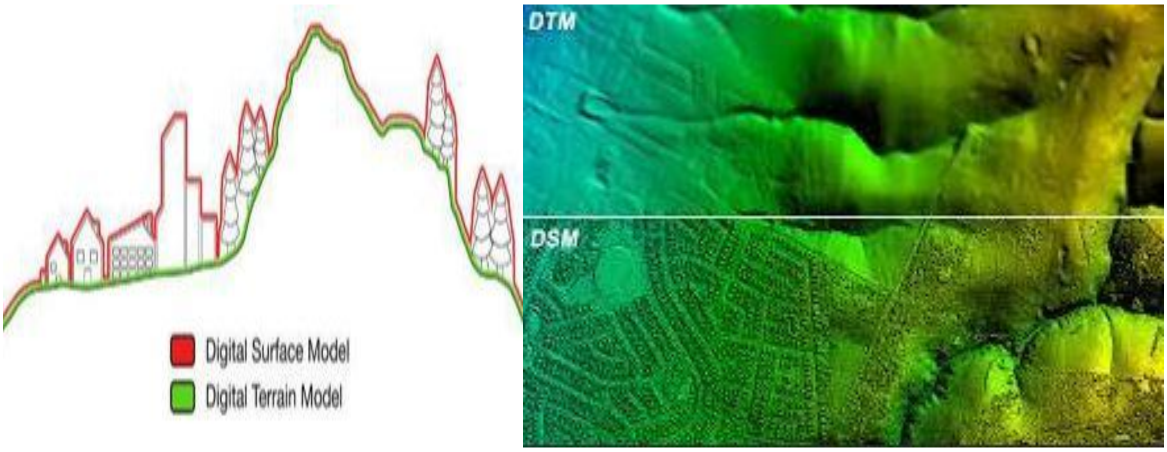

Figure 2.2: Data capture during DSM and DTM creation

(Source: www.geoimage.com.au)

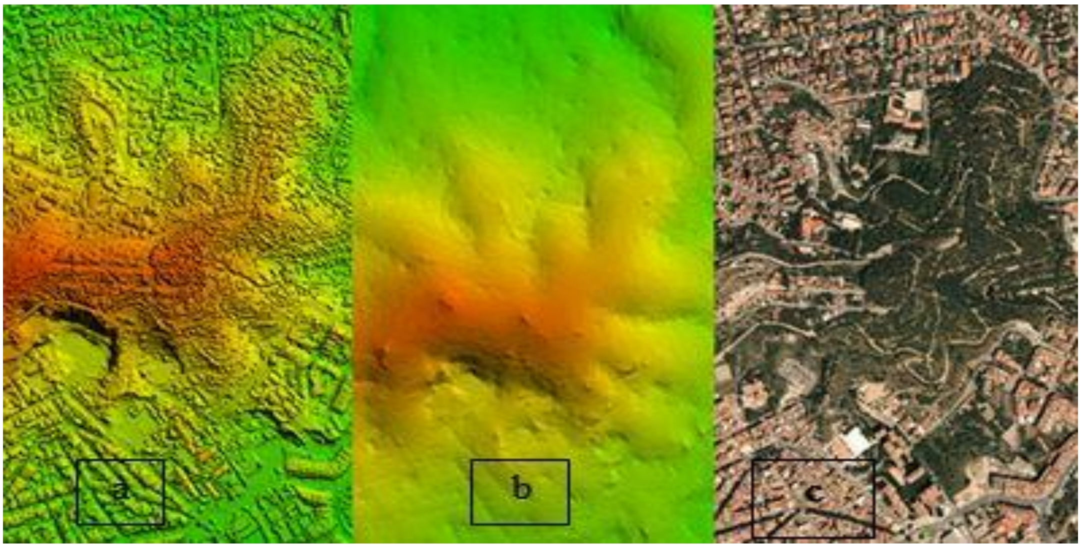

Figure 2.3: Difference between a DSM (a) and DTM (b) from real ground data (c)

(Source: www.spatialsource.com.au)

DED (Digital Elevation Data) has diverse applications, including soil mapping, disaster risk reduction, ecological modeling, geomorphology change detection, orthophoto rectification, contour mapping, engineering planning, navigation, urban studies, and glacier observations. It provides various variables like gradient, aspect, curvature, flow direction, moisture index, and irradiance (Ravibabu et al., 2008). Before using DED, factors to consider include project area, surface type, model type, source, resolution, accuracy, datum, and units. Understanding the data quality is crucial as different sources have restrictions and variations in data collection (Schumann et al., 2018). Mistakes in modeled elevation data can impact investigation results (Wechsler et al., 2006). DED's accuracy in both horizontal and vertical planes determine its quality. The horizontal location of a pixel with respect to a reference datum is unknown, which is known as the horizontal accuracy. Vertical accuracy, according to (Wechsler et al., 2006), is the degree of error in a pixel's height relative to a reference height. The fundamental quality metric for DED (Croneborg et al., 2015) is accuracy represented as vertical error, which is described in *Table 1- 1.*

Table 1.1: Accuracy of DEMs expressed as vertical error

Vertical error (m)	Characteristics
<0.5	Very high
0.5-1	High
1-5	Medium
5-10	Low
>10	Very low

2.1 Description of GDEMs used in the Research

In this research the GDEMs used are FABDEM_V_{1-0}, NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3". The research focuses on validation of FABDEM_V_{1-0} and other GDEMs are used for comparison purposes as they have been previously used in Tanzania in studies done by (Ulotu, 2017); (Marwa, 2017); (Mng'ong'o, 2018); (Mapunda, 2019); (Minja, 2020); (Mavunde, 2021); (Mbura, 2022).

2.1.1 FABDEM_V_{1-0}

FABDEM (Forest And Buildings removed Copernicus DEM) dataset, which is a version of the Copernicus GLO 30 Digital Elevation Model (DEM), eliminates inaccuracies caused by buildings and trees. The data is available globally with a 1 arc second grid spacing, which translates to approximately 30 meters at the equator. FABDEM is licensed under a Creative Commons "CC BY-NC-SA 4.0" license, which prohibits commercial use and requires redistribution under the same license if the data is modified or used to create derivative works.

The data is provided in Geotiff format and is divided into 1x1 degree tiles, which are further organized into 10x10 degree zipped folders. The files are labeled based on the southwest corner of the tile, such as N51E005_ FABDEM_V_{1-0}.tif indicating an area between 51-52 degrees N and 5-6 degrees E.

The zipped folders for the FABDEM dataset are named according to their southwest and northeast corners. For instance, N10E010-N20E020_ FABDEM_V_{1-0}.zip represents an area from 10-20 degrees N and 10-20 degrees E. A corrupt file, Tile N00E011_ FABDEM_V_{1-0}.tif, has been replaced and the Geotiff tags have been updated to reflect this change. The Coordinate Reference System used by FABDEM is WGS84 (EPSG 4326) for horizontal and EGM2008 (EPSG 3855) for vertical. Note that the pixel spacing of FABDEM is different from that of COPERNICUS DEM GLO 30, as FABDEM has been resampled to a uniform latitudinal and longitudinal grid spacing above 50N and below 50S. On the other hand, Copernicus DEM GLO30 pixel's longitudinal spacing varies as a function of latitude above 50N and below 50S.

2.1.2 NASADEM

The National Aeronautics and Space Administration Digital Elevation Model (NASADEM) is a global DSM that was derived from telemetry data collected during the Shuttle Radar Topography Mission (SRTM). NASA and the National Geospatial-Intelligence Agency (NGA) collaborated on the SRTM, which was also supported by the German and Italian space agencies. SRTM's primary objective was to produce a near-global DEM of the Earth using radar interferometry. During its STS-99 mission, which launched on February 11, 2000, and lasted 11 days, the Space Shuttle Endeavour carried the SRTM payload. NASADEM has a spatial resolution of 1 arc sec (30 m) and uses Orthometric EGM96 as its vertical datum and WGS84 as its horizontal datum. It covers all land between 60° N and 56° S latitude and is distributed in 1 degree latitude by 1 degree longitude tiles. This represents approximately 80% of the Earth's total landmass, and it is an improvement over the DEM and related products generated from SRTM data. NASADEM employs multiple radar images to create interferograms with 2D phase arrays that provide more precise elevation data. The latest unwrapping techniques and auxiliary data that were not available during the initial processing of SRTM are used to fill in gaps in the data (Hensley et al., 2001)

2.1.3 COPERNICUS DEM

Copernicus DEM is a Digital Surface Model (DSM) that depicts the surface of the Earth, including structures, infrastructure, and vegetation. There are three distinct versions of the Copernicus DEM available, referred to as EEA-10, GLO-30, and GLO-90. The European Space Agency (ESA) and Airbus produced Copernicus DEM instances with varying resolution (10 m, 30 m, 90 m), geographic extent (European and global), varying format (INSPIRE, DGED, DTED), and varying access rights (within the GLO-30 coverage the access to few areas is restricted to some users' categories). This DEM's vertical datum is Orthometric EGM 2008, and its horizontal datum is WGS 84. The WorldDEM data provides the foundation for the Copernicus DEM. The German State, represented by the German Aerospace Centre (DLR), and Airbus Defence and Space have formed a Public-Private Partnership to support the TanDEM-X Mission, which is the basis for the WorldDEM providing. The mission's main objective was to create a global, consistent, and highly accurate Digital Surface Model (DSM) using Synthetic Aperture Radar (SAR) interferometry. When operating as a single-pass SAR interferometer (InSAR), TerraSAR-X and TanDEM-X used the bi-static InSAR StripMap mode. To create the DEM product, at least two full data coverages of the Earth's surface were obtained. Data collection began in December 2010 and was finished in January 2015 (Blaszczyk et al., 2019).

2.1.4 ALOS World 3D (AW3D30E v3.2)

The ALOS Global Digital Surface Model (AW3D30) is a global dataset generated from images collected using the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) aboard the Advanced Land Observing Satellite (ALOS) from 2006 to 2011. As described by the Japan Aerospace Exploration Agency: The Japan Aerospace Exploration Agency (JAXA) releases the global digital surface model (DSM) dataset with a horizontal resolution of approx. 30-meter free of charge. The dataset has been compiled with images acquired by the Advanced Land Observing Satellite "DAICHI" (ALOS). The dataset is published based on the DSM dataset (5-meter mesh version) of the "World 3D Topographic Data", which is the most precise global-scale elevation data at this time, and its elevation precision is also at a world-leading level as a 30-meter mesh version. This dataset is expected to be useful for scientific research, education, as well as the private service sector that uses geospatial information. This version of the ALOS World 3D dataset is provided in a WGS84 ellipsoidal vertical datum and WGS84 for horizontal datum, this dataset was converted from the orthometric version using the EGM96 geoid model available (Caglar et al., 2018).

2.1.5 TanDEM -X- 3"

TanDEM -X stands for Digital Elevation Measurement, a TerraSAR-X add-on. It is made up of two X-band SAR-equipped satellites called TerraSAR-X and TanDEM-X. TanDEM-X was created by a public-private cooperation between the German Aerospace Center (DLR), Airbus Defence and Space GmbH, and German Research Center of Geosciences (GFZ). The creation of a worldwide, reliable, high-resolution DEM with extraordinary global accuracy is the mission's main goal. All land surfaces were obtained at least twice during data collection and up to seven or eight times for difficult terrain. The TanDEM -X DEM, which contains the final global DEM of the Earth's landmasses, is the primary output of the TanDEM -X mission. Data acquisition was completed in January 2015 and production of the TanDEM-X global DEM was completed in September 2016 with a coverage of 150 million sq.km. The elevations of the TanDEM-X global DEM are specified in relation to the X-band interferometric SAR returns' reflecting surface. Therefore, a Digital Surface Model (DSM) is what the TanDEM-X DEM products primarily represent. TanDEM-X mission's final products were made available to researchers in 2016 for experimental study. As of March 2018, TanDEM-X data could be accessed by the public user population. There are varieties of products variants for TanDEM-X; these are TanDEM-X-DEM, TanDEM-X Intermediate DEM and DEMs on special user request. The TanDEM-X DEM is provided in pixel spacing of 0.4 arc-second, larger pixel spacing of 1 arc-second, and 3 arc- seconds are available. The latter have an improved relative vertical accuracy at the expense of detail. The horizontal and vertical datum used for TanDEM-X global DEM is WGS84-G1150 in its new realization, the heights of TanDEM-X are ellipsoidal heights. All information layers (gridded data) are given in Geographic coordinate system. TanDEM-X-3" is accessible without quota limitations and free of charge for scientific use. On the other hand, the 12m and 30m TanDEM-X DEMs can be ordered by scientific users via a proposal submission and after a successful evaluation, data is provided with restriction. For an area greater than 100,000 sq.km data is provided with a service fee charged based on the price list (refer to *Figure 5*) given by TanDEM-X Science Coordination team (*https://tandemxscience.dlr.de).* For further review on TanDEM-X read TanDEM-X Ground Segment DEM Products Specification Document (Rizzoli et al., 2017).

2.2 Application of GDEMs

The practical and analytical uses of Global Digital Elevation Models (GDEMs) in calculating ground height and height above ground are diverse. Depending on the data acquisition, a GDEM can either be derived from a Digital Elevation Model (DEM) or a Digital Surface Model (DSM). Below is a list of applications for DEMs and DSMs, as discussed by (Balasubramanian, 2017).

2.2.1 Applications of DEMs

i. Water resource management

DEMs play a crucial role in WRM by providing terrain shape information, which influences water flow. This includes hydrological and bathymetric modeling, flow channel characterization, water catchment mapping, wetland mapping, water supply and sanitation, and floodplain management.

ii. Geological applications

DEMs find applications in geology, geomorphology, and geophysics. They are used for landform and geo-hazard mapping, subsidence or fault mapping based on shaded relief maps. High-resolution and accurate DEMs are required for monitoring seismic fault zones and assessing damages caused by earthquakes and volcanic events.

iii. Coastal monitoring

In coastal areas, DEMs are used to monitor and assess the impacts of climate change. This includes monitoring sea level rise, mapping coastal inundation, and studying seafloor morphology.

iv. Infrastructures

DEMs are employed in planning, mapping, and assessing various engineering infrastructures. For example, in road infrastructure planning and construction, DEMs help optimize construction vehicle routes and ensure a safer working environment.

v. Agricultural sector

DEMs are utilized in the agricultural sector for informing planting and irrigation strategies. They help avoid waterlogged or water-stressed crops in different terrains. Additionally, DEMs assist in developing contour-farming strategies to reduce soil erosion and crop nutrient loss along slope directions.

2.2.2 Application of a DSM

i. Aviation

DSMs are used during the construction or maintenance of runways to assess encroachment and identify any obstructions along the runway approach zone.

ii. Telecommunication

DSMs are employed in 3D modeling for designing transmission lines and managing vegetation along the line.

iii. Urban planning

DEMs, DSMs, and their derivatives find wide application in urban environmental planning and infrastructure assessment. They help assess the impact of proposed buildings on residents' view sheds, identify suitable construction sites, and evaluate drainage structures and patterns.

iv. Commercial forestry

DEMs and DSMs contribute to deriving Canopy Height Models (CHM), which aid in assessing tree biomass, classifying strand structure, planning harvest schedules, road planning, and mapping in commercial forestry.

These applications illustrate the varied utilization of GDEMs in different sectors. The above examples provide clarity on how GDEMs are employed in various domains.

2.3 Methods of Validating GDEMs

Validation refers to the process of verifying and establishing the correctness and accuracy of something. In the context of public Global Digital Elevation Models (GDEMs), validation is being carried out to assess the vertical accuracy, which refers to the potential difference in height between the predicted and actual measurements of the land. Elevation data is generated using various technologies such as LiDAR, photogrammetry, and radar, each offering different levels of precision. Multiple versions of public DEM datasets are available, and the most accurate one is sought after. Different methods for evaluating DEMs are employed worldwide to identify the DEM with the highest level of precision. The following approaches are used to determine the vertical accuracy of the DEM:

2.3.1 Vertical Accuracy Assessment Using Ground Control Points

The method involves evaluating the elevations of a Digital Elevation Model (DEM) by comparing them to Ground Control Points (GGCPs). This process includes several steps: first, identifying the vertical reference system of both the DEMs and GGCPs to ensure a consistent vertical datum for conversion purposes. The geometric heights of the GGCPs are transformed into Orthometric heights by subtracting the geoid height of the GGCPs points (Augustino, 2020).

The discrepancy between the elevation of a GGCP and its corresponding DEM value is used to assess the vertical accuracy of the DEM. Since the GGCPs may not precisely align with the exact location of a DEM point, bilinear interpolation is employed to estimate the associated DEM elevation for each control point position. Positive differences indicate that the interpolated data is accurate, with the DEM elevation being lower than that of the GGCP. Conversely, negative differences indicate areas where the DEM height exceeds the GGCP elevation. After estimating the errors, statistical measures such as maximum and minimum values, mean, standard deviation, and root mean square are computed to provide insights into the correctness of the DEM in relation to the GGCPs. This approach is preferred due to the permanent nature and high precision of ground control points, which enhance the spatial accuracy of the data. However, it should be noted that this method is not recommended in densely forested regions or areas with rugged/mountainous terrain where obtaining GGCPs can be challenging (Ulotu, 2017)

Since GPS elevation data are usually referenced to WGS 84 ellipsoid, to convert them to a height system given by the GDEM a geoid undulation is subtracted from any given GPS elevation data. A Geoid is and equipotential surface of the earth's gravity field that closely approximates the earth in least square sense. The U.S. National Geospatial-Intelligence Agency (NGA) EGM Development Team publicly releases, official Earth Gravitational Models. These models are used to compute Geoid undulation values (N) required for conversion between Orthometric heights and ellipsoidal heights using equation 2.1 and *Figure 2.4* shows the relationship between heights.

$$h = H + N \qquad (2.1)$$

Where, H is Orthometric heights, h is ellipsoidal heights and N is Geoid undulation.

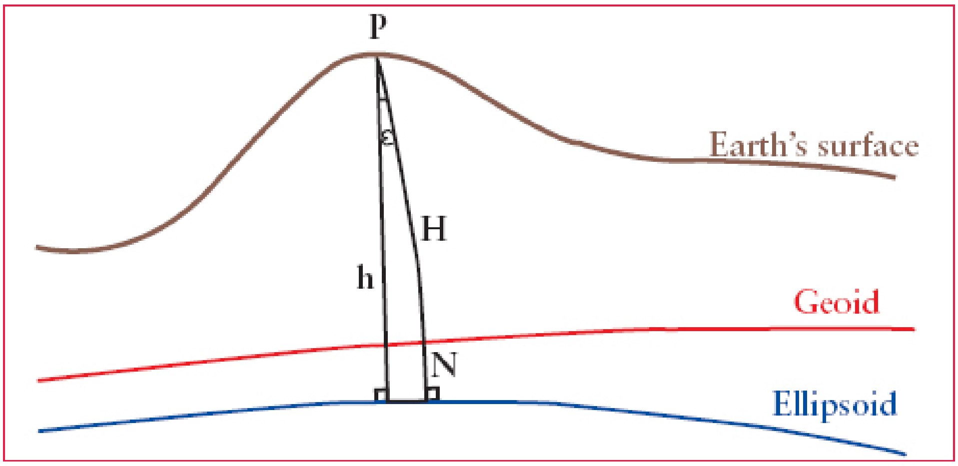

Figure 2.4: Relationship between Geoid, Ellipsoid, and Orthometric heights

2.3.2 Vertical Accuracy Assessment Using ICESATs/GLAS

This approach is implemented in regions of the world, particularly at extreme north and south latitudes, where the availability of ground control points is limited due to challenging environmental conditions. In such areas, the accuracy of Global Digital Elevation Models (GDEMs) can be compromised, which can have an impact on user applications. To tackle this issue, Innovative Imaging and Research Corporation (I2R) has developed an automated method that utilizes NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) and its Geoscience Laser Altimetry System (GLAS) to assess the accuracy of GDEMs. ICESat measures various parameters, including cloud and aerosol heights, ice sheet mass balance, land topography, and vegetation characteristics. The data product is referenced to the Japan Topex ellipsoid (Pagnutti et al., 2009). For further details on the operation of ICESat and GLAS, as well as accuracy reports, a study by (Carajabal et al., 2005) can be reviewed.

To validate a GDEM, an algorithm has been developed using MATLAB software. This algorithm reads the ICESat GLAS data files to extract latitude, longitude, elevation, geoid, and peak amplitude voltage. It also reads the elevation data of the GDEMs, applies scaling factors to convert the data to appropriate units, and performs a validity check on the ICESat GLAS surface altimetry data using the GDEMs' elevation data. The algorithm evaluates the differences in elevation between the two datasets. In essence, the algorithm takes a specific GDEM as input, compares its elevation values with the reference data from ICESat GLAS, and conducts a statistical analysis of the elevation differences, including average delta, standard deviation (STD), and root mean square error (RMSE), to determine the accuracy of the given DEM. Additionally, the software automatically generates histograms of elevation differences by comparing the ICESat GLAS laser shot data to interpolated GDEM elevation values (Pagnutti et al., 2009). This method has been employed by (Rizzoli et al., 2017) to validate the TanDEM-X dataset (Takaku et al., 2016) for the 'AW3D' Global DSM generated from ALOS Prism and by (METI/ERSDAC et al., 2009) for ASTER GDEM.

2.3.3 Vertical Accuracy Assessment Using Topographic maps

Topographic maps, which depict elevation using contour lines and spot heights, are readily available. These maps are created through ground survey techniques using tools like total stations or GPS receivers to collect elevation data. They also incorporate data from aerial photographs and other sources. The elevation measurements used to generate topographic maps can be either randomly distributed or structured in a pattern with equal intervals along transects. To create Digital Elevation Models (DEMs), the contour lines or spot heights are interpolated to form a regular matrix of elevation values (Ravibabu et al., 2008)

A report by (Elkhrarchy, 2016) describes how a 1:10000 topographic map sheet, covering a portion of the study area, was utilized as a reference to analyze SRTM and ASTER elevation data. The map sheet is first digitized and saved as a JPEG file, and then it is georeferenced using ArcMap software. The spot elevations from the map sheet serve as reference points and are saved in a separate layer. These elevations are transformed to match the vertical datum of the GDEMs. Subsequently, the elevations from the map sheet are compared to the SRTM and ASTER GDEMs using a GIS tool called "extract values to point" to estimate the absolute accuracy of the GDEMs. A statistical analysis of the height differences is then conducted, revealing that the vertical accuracy of the SRTM and ASTER data is approximately ±6.87m and ±7.97m, respectively.

However, this method does have some challenges. When extracting elevation data from cartographic contour lines, there is a risk of vertical errors if the wrong elevation value is assigned to a contour line. Additionally, the process of digitization can be time-consuming and laborious (Elkhrarchy, 2016).

2.3.4 Vertical Accuracy Assessment of GDEMs Using Another DEM

To assess the agreement or disagreement between two Global Digital Elevation Models (GDEMs), the differences in elevation at common grid intersections are calculated. Positive differences indicate locations where the reference GDEM had higher elevations than the corresponding GDEM, while negative differences occur at locations where the reference GDEM had lower elevations. Before computing the differences, the elevations of the GDEMs need to be converted to a consistent vertical reference frame. Subsequently, a statistical analysis of the height differences is performed. ASTER GDEMv3 was evaluated by comparing it to other 1-arc-second (30-meter) DEMs that cover the entire Conterminous United States (CONUS), namely the National Elevation Dataset (NED) and SRTM dataset, using pixel-to-pixel differencing. Additionally, TanDEM-X-0.4" & 3" was compared to other global DEMs, with TanDEM-X-0.4" & 3" showing favorable performance (Grohhmann, 2018)

2.4 Methods of analyzing the GDEMs accuracy

After validation, a number of techniques are used to assess the accuracy of a GDEM, including statistical analysis of height differences between a GDEM and reference data and visual comparisons of different derivatives from a GDEM and reference data (Nikolakopoulos et al., 2010).

2.4.1 Visual comparison

When analyzing GDEMs in their raster format, one may not be able to fully understand the landscape since DED reflect the topography of the bare soil and above-ground features. For a simple visual explanation, elevation profiles depicting the landscape or other characteristics in the region are created. A path's difficulty or the viability of setting up a trail along a certain route may be determined using profiles, which display the change in elevation surface along a line (Alganci et al., 2018).

Drawing profiles across a river channel may be used to determine the width and depth of the river. This approach allows for the generation of various elevation profiles from the real topographical data and comparison with the appropriate spot on the GDEM tile (Nikolakopoulos et al., 2010). Lines are formed in different directions from two sets of photos, such as a Google Earth image and GDEM raster images, and then the profiles are made using appropriate software, such as ArcMap (Alganci et al., 2018).

2.4.2 Statistical analysis

The accuracy of GDEM is evaluated using a mathematical method in this manner. It entails measuring the variations in height between GDEMs and reference data sets in terms of Mean Error (ME) and Root Mean Square (RMS) (Elkhrarchy, 2016). A data set's accuracy increases with decreasing RMSE. The ME (see Equation 2.1) indicates whether a series of measurements undervalues (negative ME) or overvalues (positive ME) the real value, and it represents the bias of the surface. The RMSE (see Equation 2.2) collects the variations in elevation values between the DEM and the reference data set into a single indicator of predictive power. It is a single quantity characterizing the error surface (Elkhrarchy, 2016)

$$\mathrm{ME} = \frac{1}{n}\sum_{i=0}^{n} \Delta H^{GGCPs,DEM} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.2$$

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta H^{GGCPs,DEM})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.3$$

Whereby ME =Mean Error, RMS=Root mean square, n=total number of values, ΔH=Elevation difference, GGCPs=GPS Ground Control Points, DEM=Digital Elevation Model

2.5 Method selected for this Research

This study focuses on FABDEM_V1-0's vertical accuracy assessment in a few chosen regions of Tanzania, although other GDEMs are also included for comparison. The approach chosen to evaluate the general vertical accuracy of GDEMs is based on the use of ground control points. The analysis measures the height difference between GDEMs and GGCPs using statistics like Mean, Standard Deviation, and Root Mean Square. The following factors led to the selection of this method. First the GPS ground control are considered a superior data to the GDEMs as they were observed on the actual ground. In addition, they are widely distributed in Tanzania to cover various land covers and the data is easily accessible for the selected area of study from MLHHSD. Second in order to determine how much the data sets agree or disagree with one another over the AOI, the FABDEM_V1-0 GDEM is compared to other GDEMs. This is due to the fact that previous GDEMs were openly accessible prior to FABDEM_V1-0, were widely assessed, and were used for a variety of purposes in Tanzania, making it crucial to compare these data sets. Third, a statistical analysis is performed using the Mean, Range, Standard Deviation, and Root Mean Square of the height differences between the GDEMs and GGCPs.

For unification of vertical datum, EGM2008 is selected as the reference datum despite the fact that most GDEMs used in this study are referenced to different EGMs. The main reason being, EGM2008 reflects actual gravity data than other EGMs yielding more accurate height information when used in conversion (Pavlis et al., 2012). For instance, EGM96 was developed by synthesizing orbital tracking from numerous satellite missions, whereas EGM2008 was developed from surface gravity data using GRACE mission which provided the first truly global gravity field map (Roman et al., 2010). Furthermore, a study conducted by (Abbak, 2014) examined the impact of EGM96 on the accuracy of Digital Elevation Models (DEMs) generated from SRTM data.

CHAPTER THREE

METHODOLOGY

This research focus on the assessment of the vertical performance of GDEMs using GGCPs. Therefore, this section focuses on the methods, procedures and data collections which carried out in this research.

3.1 Assessment of the GDEMs

To achieve the research objective, four steps were undertaken. Firstly, it was necessary to establish a common reference system by unifying the datum across all the datasets used. Secondly, the elevation differences between all the Global Digital Elevation Models (GDEMs) and Ground Control Points (GGCPs) were calculated. Thirdly, a comparison was made between five GDEMs: FABDEM_V$_{1-0}$, NASADEM, COPERNICUS 30, AW3D30Ev3.2, and TanDEM-X-3". This involved computing the height differences at the common grid intersections of these datasets, with FABDEM_V1-0 resampled to 3 arc-sec and the elevation values of the other GDEMs extracted at 3 arc-sec resolution. Lastly, statistically evaluating the elevation differences within the defined Area of Interest (AOI) and for specific land cover types.

3.1.1 Unification of vertical datum

Conversion of all elevations from AW3D30Ev3.2, TanDEM-X-3" as well as GGCPs are ellipsoidal height, so they are converted to Orthometric height using EGM2008 Geoid model using equations (3.1), (3.2) and (3.3). NASADEM give Orthometric heights (H) based on EGM96 model, this GDEM is converted to ellipsoid height using EGM96 geoid model then to Orthometric heights based on EGM2008 using equation (3.4) and (3.5).

a) Conversion of GGCPs, AW3D30Ev3.2 and TanDEM-X-3" to EGM08 Orthometric Height

In order to have the same format as height of GDEMs, the Tanzania GPS Ground Control Points are converted from ellipsoidal height to EGM08 orthometric height using the GNSS leveling equation.

$$\mathrm{H}_{\mathrm{EGM08}}^{\mathrm{GGCPs}} = \mathrm{h}_{\mathrm{GGCPs}} - \mathrm{N}_{\mathrm{EGM08}} \quad \ldots\ldots 3.1$$

Whereby; $\mathrm{N}_{\mathrm{EGM08}}$ is Geoidal height/geoidal undulation of EGM08

$\mathrm{h}_{\mathrm{GGCPs}}$ is Ellipsoidal height of GGCP

$\mathrm{H}_{\mathrm{EGM08}}^{\mathrm{GGCPs}}$ is Orthometric height of GGCP

$$\mathrm{H}_{\mathrm{EGM08}}^{\mathrm{AW3D30E\_V3.2}} = \mathrm{h}_{\mathrm{AW3D30E\_V3.2}} - \mathrm{N}_{\mathrm{EGM08}} \quad \ldots\ldots 3.2$$

Whereby,

$H_{EGM08}^{AW3D30E\_V3.2}$ is Orthometric height of AW3D30E_V3.2 of EGM08

$h_{AW3D30E\_V3.2}$ is Ellipsoidal height of AW3D30E_V3.2

N_{EGM08} is Geoidal height/geoidal undulation of EGM08

$$H_{EGM08}^{TanDEM-X-3''} = h_{TanDEM-X-3''} - N_{EGM08} \ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

Whereby;

$H_{EGM08}^{TanDEM-X-3''}$ is Orthometric height of $\mathrm{TanDEM-X-3''}$of EGM08

$h_{TanDEM-X-3''}$ is Ellipsoidal height of $\mathrm{TanDEM-X-3''}$

N_{EGM08} is Geoidal height/geoidal undulation of EGM08

b) Conversion of GDEMs Orthometric Height to EGM08 Orthometric Height

The vertical datum NASADEM is EGM96 Orthometric height so the conversion is needed to have a uniform vertical datum with the GGCP, so the vertical datum will be converted to EGM08 Orthometric height by using the following equations,

$$h_{NASADEM} = H_{EGM96}^{NASADEM} + N_{EGM96} \ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

$$H_{EGM08}^{NASADEM} = h_{NASADEM} - N_{EGM08} \ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

Whereby; $h_{NASADEM}$ is Ellipsoid height of NASADEM

$H_{EGM08}^{NASADEM}$ is Orthometric height of NASADEM of EGM08

$H_{EGM96}^{NASADEM}$ is Orthometric height of NASADEM of EGM96

N_{EGM96} is Geoidal height/geoidal undulation of EGM96

N_{EGM08} is Geoidal height/geoidal undulation of EGM08

3.1.2 Height differences between GGCPs and GDEMs

Computation of height differences between GDEMs and GGCPs over the AOI uses equation (3.6). To extract elevation from GDEMs of the corresponding control point. In Golden surfer software navigate the following path; start the app>Grids>Residuals>Input grid-file (DEM grided file)>XYZ Data (GGCPs but with Z=0). *Consider the Figure 3.1* for illustration.

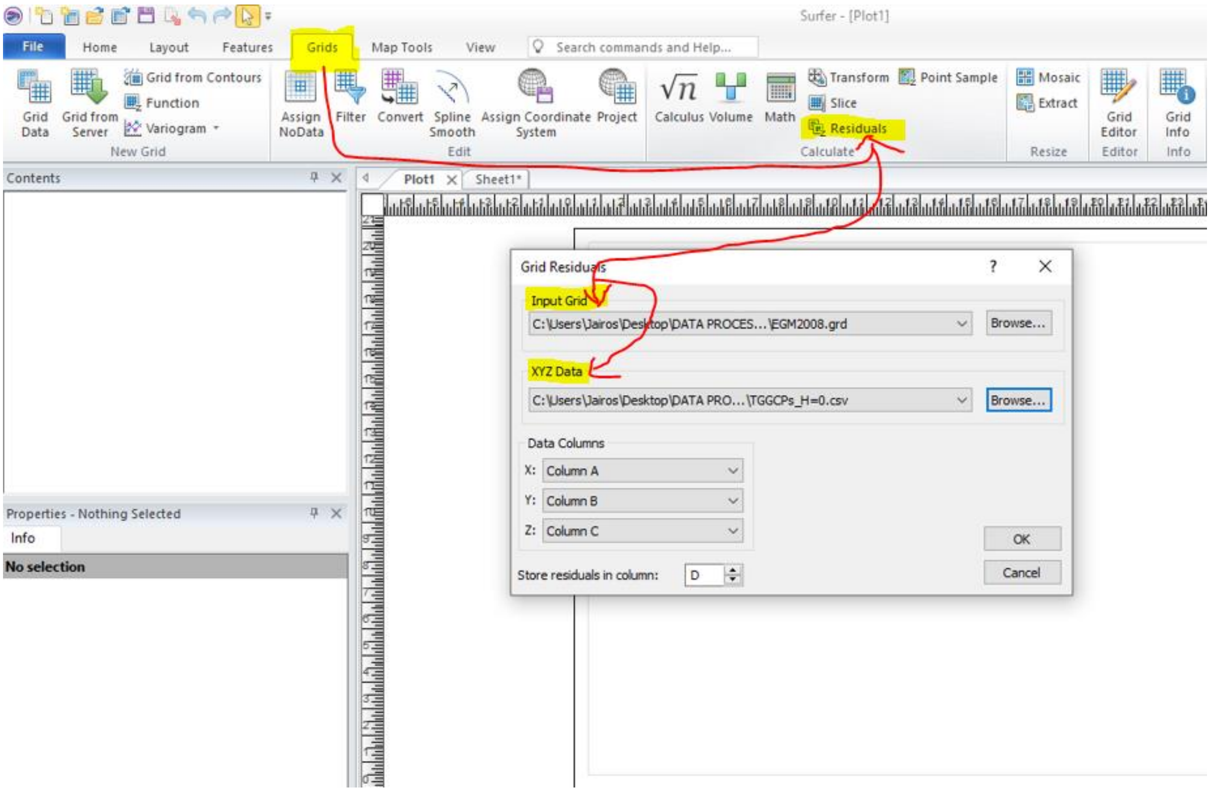

Figure 3.1: Using the Surfer grid-residual tool to obtain height in the GDEMs/EGMs

$$\Delta H^{GGCPs,GDEMi} = H^{GGCPs}_{EGM08} - H^{GDEMi}_{EGM08} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.6$$

Whereby;

$\Delta H^{GGCPs,GDEMi}$ is the elevation difference between GGCP and the respective GDEM

H^{GGCPs}_{EGM08} is the Orthometric height of GGCPs based on EGM2008 geoid model

H^{GDEMi}_{EGM08} is the Orthometric height of respective GDEM based on EGM2008 geoid model

3.1.3 General Comparison of the GDEMs at Common Grid Intersections Over the AOI

The differences in height between the GDEMs at their common grid intersection over the AOI are computed using Golden_Software_Surfer_20.1.195 grid-math tool. Two GDEMs grids are subtracted from one another and the result is a grid of elevation differences between the GDEMs, *see Figure 3- 2*. To use the grid math tool all GDEMs are supposed to have common grid characteristics (spatial resolution and size), navigate the following path; Grids>Math>Add Grids (input the GDEMs for math operation) >A-B>Output Grid.

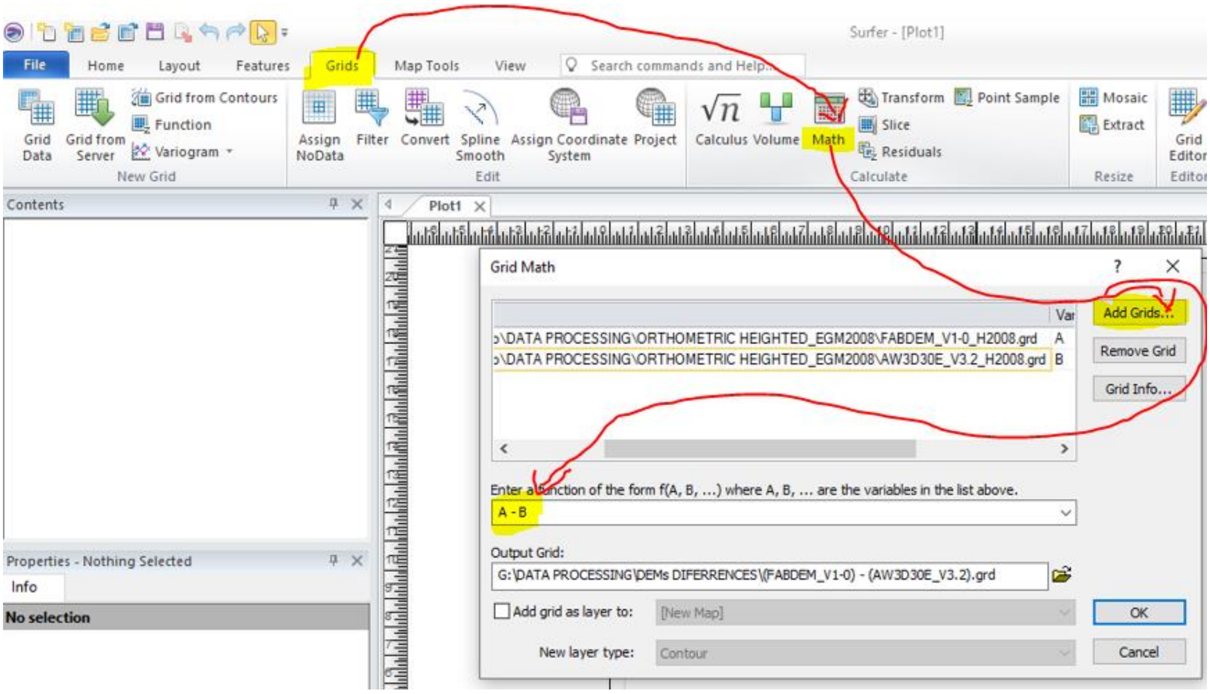

Figure 3.2: Using the Surfer grid-math tool to obtain height differences of GDEMs/EGMs

Because of this, FABDEM_$V_{1\text{-}0}$, NASADEM, AW3D30Ev3.2, and COPERNICUS 30 were resampled to 3 arc-second using Global_Mapper_Pro_23.0_Build_091421 to match TanDEM-X-3", as seen in Figure 3-3, through the following path; File> Export>Export Grid Elevation Format> (Choose Geotiff) > Geotiff Options (Click here to calculate spacing in other unit) >arc-second (X=3, Y=3) >Export Bounds (lat/long-define the area of interest). Equation (3.7) describes the mathematical formula used to determine the elevation difference between FABDEM_$V_{1\text{-}0}$ and other GDEMs.

$$\Delta H^{GDEM1,GDEM2} = H^{GDEM1} - H^{GDEM2} \qquad \ldots\ldots\ldots 3.7$$

Whereby;

$\Delta H^{GDEM1,GDEM2}$ is the Orthometric height difference between two GDEMs

H^{GDEM1} and H^{GDEM2} are the Orthometric height for the GDEMs

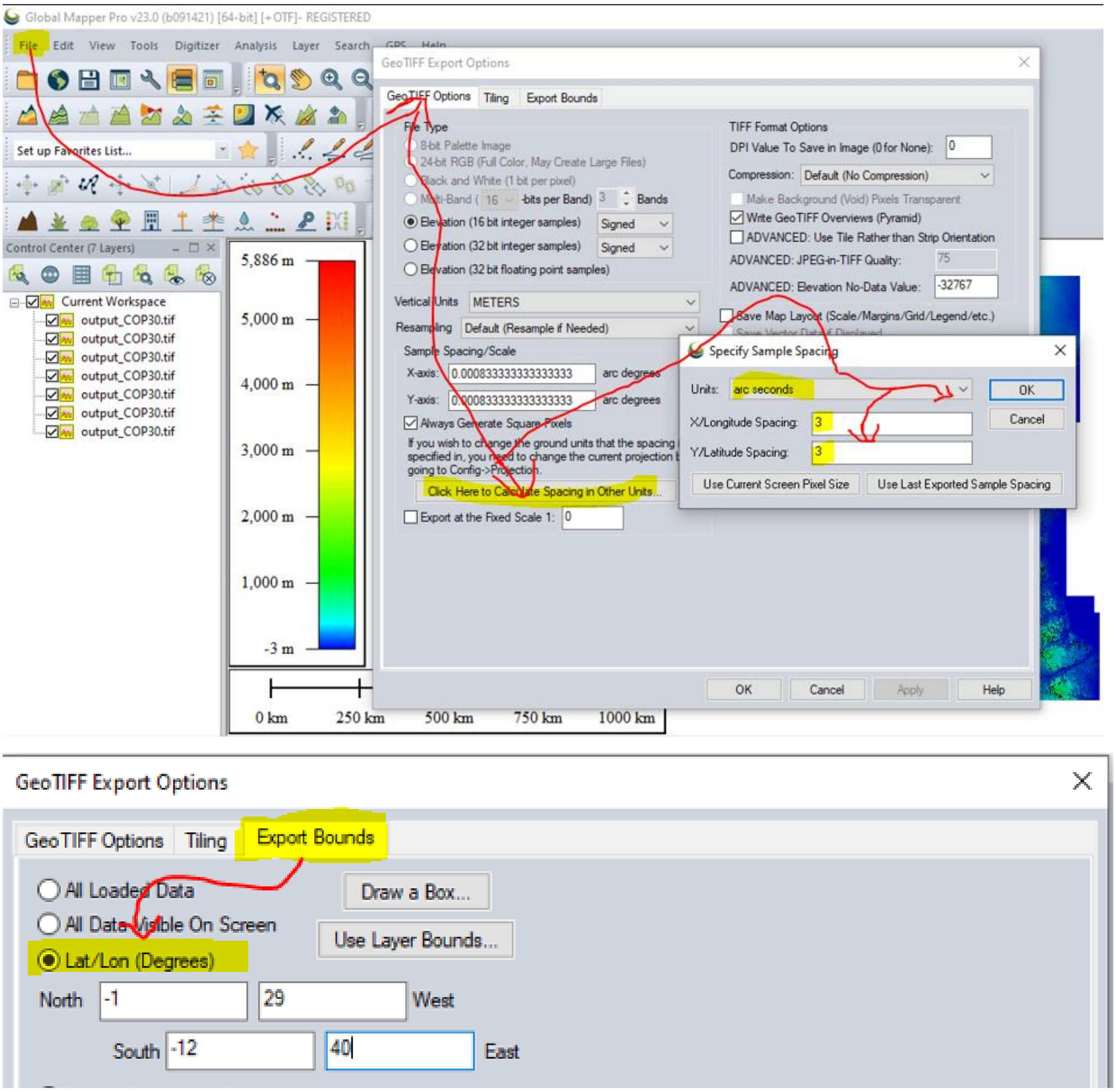

Figure 3.3: Using the Global mapper software to Resample GDEMs/EGMs to 3-arc seconds

3.1.4 Statistical assessment of height differences between GDEMs and GGCPs in the AOI and selected land covers

The statistical assessment in this study is used to determine the vertical accuracy of the FABDEM_V$_{1\text{-}0}$. The vertical accuracy of the GDEMs is obtained by statistical analysis of height differences between GDEMs and GGCPs as well as between individuals GDEMs. The statistical parameters are the Mean (ME), Standard Deviation (SD), and Root Mean Square (RMS), which are determined by the mathematical relationship shown by equations (3.8), (3.9), and (3.10). A GDEM can be considered superior if it has a lower RMSE with high vertical accuracy.

$$\text{ME}=\frac{1}{n}\sum_{i=1}^{n}\Delta H^{GGCPs,GDEM} \ldots\ldots 3.8$$

Whereby;

ME is mean

$\Delta H^{GGCPs,GDEM}$ is Orthometric height differences between GGCPs and respective GDEM

n is number of GGCPs

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta H^{GGCPs,GDEM})^2} \ldots\ldots 3.9$$

Whereby;

RMS is Root Mean Square

$\Delta H^{GGCPs,GDEM}$ is Orthometric height differences between GGCPs and respective GDEM

n is number of GGCPs

$$\text{SD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\Delta H^{GGCPs,GDEM} - ME)^2} \ldots\ldots 3.10$$

Whereby;

SD is Standard Deviation

n number of GGCPs

ME is Mean

$\Delta H^{GGCPs,GDEM}$ is Orthometric height differences between GGCPs and respective GDEM

3.1.5 Statistical assessment of height differences between GDEMs in the AOI and selected land covers

Same procedures applied to the statistical assessment of height differences between GDEMs in the AOI and selected land covers, where orthometric height differences between GDEMs obtained in equation (3.7) used in the following mathematical relationship

$$\text{ME}=\frac{1}{n}\sum_{i=1}^{n}\Delta H^{GDEM1,GDEM2} \ldots\ldots 3.11$$

Whereby;

ME is mean

$\Delta H^{GDEM1,GDEM2}$ is Orthometric height differences between GDEMs

n is number of values of a particular difference

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta H^{GDEM1,GDEM2})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.12$$

Whereby;

RMS is Root Mean Square

$\Delta H^{GDEM1,GDEM2}$ is Orthometric height differences between GDEMs

n is number of values of a particular difference

$$\text{SD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\Delta H^{GDEM1,GDEM2} - ME)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.13$$

Whereby;

SD is Standard Deviation

n number of values of a particular difference

ME is Mean

$\Delta H^{GDEM1,GDEM2}$ is Orthometric height differences between GDEMs

3.2 Reliefs Selected

There are twelve selected regions in nine terrains and land covers for this research. The selection is referred to previous studies on the assessment of GDEMs in Tanzania by (Minja,2020), (Agustino,2020), (Mavunde,2021) and (Mbura,2022). These reliefs are;

a) Dodoma features a flat and sparsely vegetated terrain, shown in Figure 4, with boundaries ranging from latitudes 5.3°S to 6.92°S and longitudes 35.6°E to 37.4°E.

b) Kilimanjaro and Arusha regions exhibit mountainous and forested terrains. The selected area spans latitudes 2.36°S to 4.4°S and longitudes 36.3°E to 38.42°E.

c) The lake zone comprises Mwanza, Kagera, and Geita regions, situated between latitudes 1.03°S to 3.46°S and longitudes 30.51°E to 35.16°E.

d) Lindi region showcases a flat and forested coastal terrain, occupying latitudes 8.39°S to 10°S and longitudes 37.60ºE to 39.72ºE.

e) Mbeya region is characterized by highlands and forested terrain, spanning latitudes 7.14°S to 9.61°S and longitudes 32.28ºE to 34.84°E.

f) Morogoro features a slightly mountainous and forested terrain, with boundaries ranging from latitudes 5.90°S to 8.67ºS and longitudes 36.43°E to 38.17ºE.

g) Mtwara exhibits a coastal terrain that is predominantly flat with some forested areas. It extends between latitudes 10.33ºS to 11.20°S and longitudes 38.24°E to 40.35ºE.

h) Tabora region consists of a flat and slightly plain terrain, located within latitudes 4°S to 6.8°S and longitudes 31.82°E to 33.90°E.

i) Tanga region showcases a forested and slightly flat terrain, occupying latitudes 4.41°S to 5.86°S and longitudes 37.29°E to 39.11°E.

3.3 Data requirement, description and management

GGCPs data are obtained from the Tanzanian Ministry of Lands, Housing, and Human Settlement Development (MLHHSD). The data consist a list of coordinates (latitude, longitude) and elevation (h) information which consist of CORS, Zero, first and second order stations distributed throughout the country.

Table 3.1: Sources of data

DATA	FORMAT	SOURCE(Website)
GGCPs	Latitude, Longitude and Elevation	Ministry of Lands Housing and Human Settlement Development (MLHHSD) through the surveys and mapping division (SMD).
FABDEM_V_{1-0}	GeoTIFF	https://data.bris.ac.uk/data/dataset/25wfy0f9ukoge2gs7a5mqpq2j7
NASADEM	GeoTIFF	https://opentopography.org/
COPERNICUS 30	GeoTIFF	https://opentopography.org/
AW3D30Ev3.2	GeoTIFF	https://opentopography.org/
TanDEM-X-3"	GeoTIFF	https://download.geoservice.dlr.de/TDM90/#download
EGM 08	GeoTIFF	https://www.usna.edu/Users/oceano/pguth/md_help/html/egm96.htm
EGM 96	GeoTIFF	https://www.usna.edu/Users/oceano/pguth/md_help/html/egm96.htm

Table 3.2: Summary of GDEMs used in this research

S/N	Name	Date	Owner	Resolution	Datum	
					Vt	Hz
1	FABDEM_V_{1-0}	17 December, 2021	Laurence Hawker, Jeffrey Neal-University of Bristol	30m	EGM08	WGS84
2	NASADEM	11 February, 2020	NASA	30m	Orthometric EGM96	WGS84
3	AW3D30Ev3.2	24 May, 2021	JAXA-Japan	30m	WGS84(EGM96 GEOID)	WGS84
4	COPERNICUS 30	January 2019	ESA, DLR, ADS	30m	OrthometricEGM08	WGS84
5	TanDEM-X-3"	March 2018	DLR-German	90m	WGS84	WGS84

3.2.1 Data Management

In order to save disk space and make the download procedure easier, GDEMs data are downloaded as zipped files (compressed files). One must extract files from the received compressed data in order to access specific raster data. The majority of DEM (raster data) tiles are in the TIFF image file format.

TanDEM-X-3" data set is a little bit unique in comparison to other global DEMs, because each tile download includes a comprehensive list of 7 auxiliary files, including a height error map (HEM), a water indication mask (WAM), a coverage map (COV), a consistency mask (COM), a layover and showdown mask (LSM), and 2 amplitude mosaic layers. *See Figure 3.4.* To access a GDEM raster data open the DEM folder *see Figure 3.5.*

Name	Size	Packed	Type	Modified	CRC32
..			Local Disk		
TDM1_DEM__30...	5,774,867	4,762,572	TIF File	9/23/2017 6:07 AM	E28FA045
TDM1_DEM__30...	5,774,867	4,811,749	TIF File	7/13/2017 3:54 PM	3F564EED
TDM1_DEM__30...	5,774,867	3,858,406	TIF File	7/13/2017 3:55 PM	E3D7ADAA
TDM1_DEM__30...	5,774,867	1,580,837	TIF File	7/13/2017 3:51 PM	B17CFF99
TDM1_DEM__30...	5,774,867	4,738,583	TIF File	7/13/2017 4:00 PM	3E3AF768
TDM1_DEM__30...	5,774,867	4,863,517	TIF File	7/13/2017 3:50 PM	F5B1CA4F
TDM1_DEM__30...	5,774,867	4,849,589	TIF File	7/13/2017 3:50 PM	04B5BD42
TDM1_DEM__30...	5,774,867	4,785,283	TIF File	7/13/2017 3:51 PM	21F84EBA
TDM1_DEM__30...	5,774,867	5,044,256	TIF File	7/12/2017 5:29 PM	6817E260
TDM1_DEM__30...	5,774,867	5,075,256	TIF File	7/12/2017 5:28 PM	C30ACCE3
TDM1_DEM__30...	5,774,867	4,798,458	TIF File	9/23/2017 5:53 AM	803FA6D7
TDM1_DEM__30...	5,774,867	4,761,414	TIF File	7/13/2017 3:59 PM	8ECA3AA5
TDM1_DEM__30...	5,774,867	4,141,044	TIF File	7/12/2017 5:28 PM	BF760AC4
TDM1_DEM__30...	5,774,867	3,131,623	TIF File	7/12/2017 5:31 PM	14419629
TDM1_DEM__30...	5,774,867	3,711,942	TIF File	7/12/2017 5:30 PM	95EB0EEA

Figure 3.4: Auxiliary files for TanDEM-X-3" after extraction from zipped format

Name	Size	Packed	Type	Modified	CRC32
..			Local Disk		
AUXFILES			File folder	9/22/2017 8:44 PM	
DEM			File folder	9/22/2017 8:44 PM	
PREVIEW			File folder	9/22/2017 8:44 PM	
demProduct.xsd	56,501	5,526	XSD File	9/22/2017 7:57 PM	405C3CCC
generalHeader.x...	6,429	1,823	XSD File	9/22/2017 7:57 PM	886D3A22
TDM1_DEM__30...	139,535	14,752	XML Document	9/22/2017 7:57 PM	4B5C4FDB
types_inc.xsd	4,208	957	XSD File	9/22/2017 7:57 PM	D08C3122

Figure 3.5: To access DEM raster data

To extract elevations from GDEM raster data, various steps have to be followed. The tiles have to be first mosaiced in order to create a single grid that covers the AOI because they are downloaded as individual single tiles. Second, using software like Golden Software Surfer 20.1.195 and Global Mapper Pro 23.0 Build 091421, one can manage DEM data by extracting elevation, mosaic, and converting to different formats like DAT file (a generic data file tool) that enables one to view latitude(X), longitude(Y), and elevation(z) from a DEM (.tiff) data easily for comparison. The sections that follow explain how to obtain grid information from a GDEM and how to access GDEM data. Additionally, procedures are provided for extracting elevations and saving raster data in (.DAT format). The demonstration below is made of using Golden Software Surfer 20.1.195 and Global Mapper Pro 23.0 Build 091421 software.

i. Opening and merging of GDEM (.TIFF) files

- Global Mapper Pro 23.0 Build 091421: File > Open data File > select required tiles > view contents for raster data.
- To Mosaic several tiles to get one tiff, Global Mapper Pro 23.0 Build 091421: File> Export>Export Grid Elevation Format> (Choose Geotiff) > Geotiff Options >Export Bounds (lat/long-define the area of interest)> Ok.

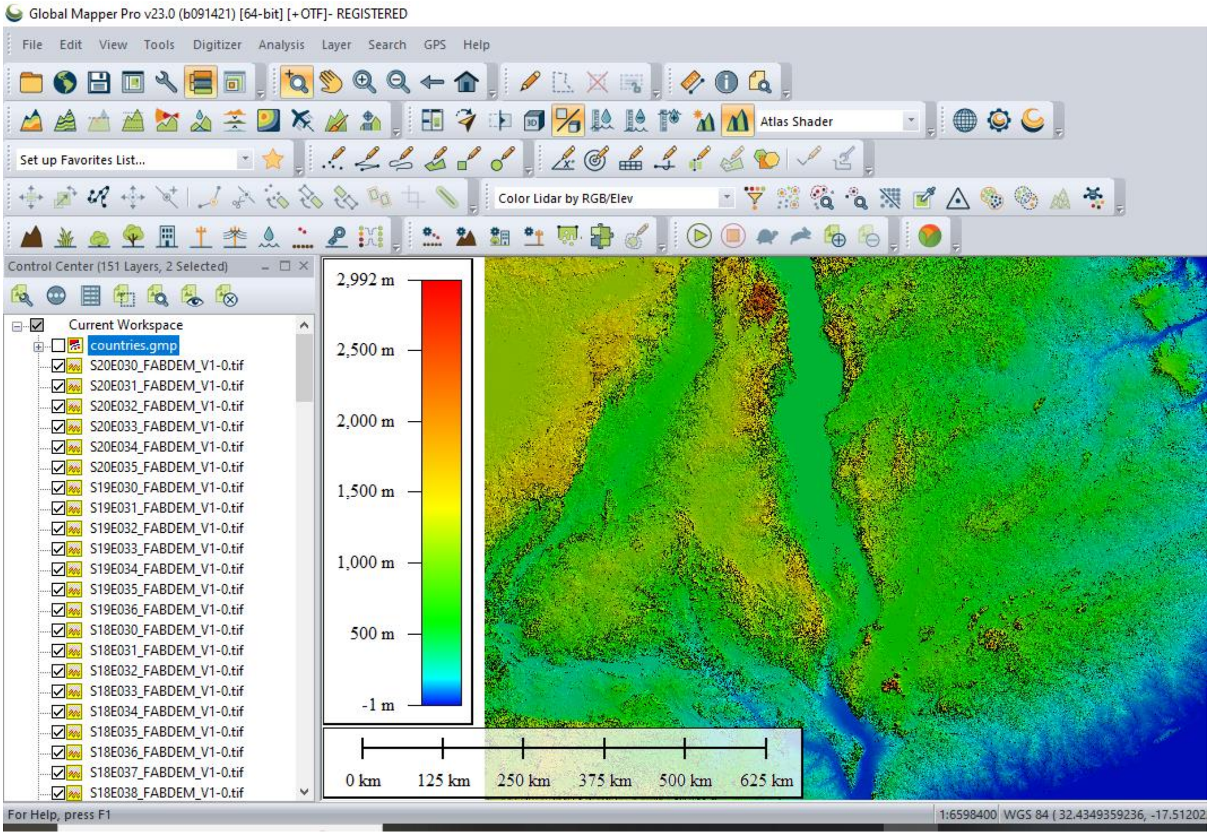

Figure 3.6: FABDEM_V1-0 tiles as viewed in Global Mapper Pro 23.0 Build 091421 software

ii. To extract elevation from a GDEM(h/H) or EGM (N)

In order to extract elevation for a specific data point (in this instance, the GGCPs), where X and Y stand for longitude and latitude and Z for elevation, we have to use a GDEM grid. Setting the Z column to 0 and saving it separately from the original data in.csv format. In the next step, the Surfer grid residual tool is used to extract the elevation of the GGCPs from the GDEM using the X (latitude) and Y (longitude) data from the GGCPs. *Refer to Figure 3.1.*

3.4 Software's used to manage and process data

Below is a list of all the software programs needed to manage data, extract data, and do computations; Global Mapper Pro 23.0 Build 09142, Golden Software Surfer 20.1.195, QGIS-OSGeo4W-3.4.6-2-Setup-x86_64, ArcGIS 10.8, Microsoft Office 2016(Microsoft Excel and Microsoft Word).

- **Global Mapper Pro 23.0 Build 09142**

i. To convert the GDEMs' format from GeoTIFF to grid format and to an XYZ Grid for elevation extraction.
ii. It used to merge separate GDEM tiles that were downloaded into a single tile covering the AOI.
iii. It has been used to resample GDEMs to 3 arc-second.
iv. To compute height differences between the GDEMs.

- **Golden Software Surfer 20.1.195**

i. To extract elevation data (height) from geoid models and GDEMs that are being used to compare GDEMs and GGCPs.
ii. Calculation of the Mean, SD, Variance, Number of Values, Maximum Value, and Minimum Value.
iii. To compute height differences between the GDEMs.

- **ArcGIS 10.8**

To prepare map presented.

- **QGIS-OSGeo4W-3.4.6-2-Setup-x86_64**

To select the features by polygon especially in the process of selecting the GGCPs on the specific land covers (regions).

- **Microsoft Office 2016(Microsoft Excel and Microsoft Word)**

i. To calculate Root Mean Square from obtained height differences.
ii. To organize and prepare results in tables,
iii. To write the research report.

CHAPTER FOUR

RESULTS, ANALYSIS AND DISCUSSION

This chapter provides an in-depth analysis of the outcomes stemming from a comprehensive comparison between GDEMs and the subsequent assessment of their performance utilizing GGCPs. The results have been presented over the AOI and the selected land covers. The results are all discussed, and the accuracy is measured using the Root Mean Square (RMS), with the lower the RMS value, the higher the vertical accuracy.

4.1 Results

4.1.1 Statistics of comparison between GDEMs countrywide

The statistics were obtained using the equations (3.7, 3.11, 3.12 and 3.13) and the mathematical relationships described in chapter 3 of the book. The results are shown in *Table 4.1*.

Table 4.1: Statistics of height differences between GDEMs at common grid intersection countrywide

HEIGHT DIFFERENCES	MIN (m)	MAX (m)	MEAN (m)	SD (m)	RMS (m)
($FABDEM\_V_{1-0}$) - (NASADEM)	-483	397	-0.805	3.118	3.220
($FABDEM\_V_{1-0}$) - (AW3D30E_V3.2)	-611	618	-1.938	3.809	4.273
($FABDEM\_V_{1-0}$) - (Copernicus 30)	-118	118	-1.339	3.784	4.014
($FABDEM\_V_{1-0}$) - (TanDEM-X-3")	-2045	1754	3.120	30.763	30.922

4.1.2 Statistics of height differences between the GDEMs in the selected land covers

The land covers and terrains assessed are assigned with letters K1, K2, K3, K4, K5, K6, K7, K8 and K9 for simplification of tabular presentation of the results

Table 4.2: Symbols representing the selected land covers

Symbol	Land Cover	Regions
K1	Flat and bare terrain	Dodoma
K2	Mountainous and forested terrain	Kilimanjaro and Arusha
K3	Lake zone areas (Victoria)	Mwanza, Kagera, Geita and Mara
K4	Flat and forested coastal terrain	Lindi
K5	Highlands and forested terrain	Mbeya
K6	Slightly mountainous and forested terrain	Morogoro
K7	Barely flat and forested coastal terrain	Mtwara

K8	Flat and plain terrain	Tabora
K9	Forested and fairly flat terrain	Tanga

Table 4.3: Statistics of height differences between FABDEM_V1-0 and NASADEM in the representative land covers in Tanzania at their common grid intersections

REGIONS	NO.	SUM(m)	MIN(m)	MAX(m)	MEAN (m)	SD (m)	RMS(m)
K1	4203145	-3389311	-111	70	-0.806	4.176	4.253
K2	6232705	-5126326	-439	189	-0.822	3.868	3.779
K3	16279777	-558945	-272	98	-0.034	2.365	2.365
K4	6843505	-10260478	-93	67	-1.499	2.597	2.121
K5	9111445	-9133355	-233	181	-1.002	3.066	2.897
K6	6945925	-9781964	-180	230	-1.408	3.832	4.908
K7	2208085	-1773116	-80	41	-0.803	2.695	2.573
K8	10658160	-17354906.253	-135.413	63.94	-1.628	2.140	1.389
K9	3832918	-5805363.456	-461.179	156.15	-1.515	3.669	3.341

Table 4.4: Statistics of height differences between FABDEM_V1-0 and AW3D30E_V3.2 in the representative land covers in Tanzania at their common grid intersections

REGIONS	NO.	SUM(m)	MIN(m)	MAX(m)	MEAN (m)	SD (m)	RMS(m)
K1	4207252	-5997321.500	-83.5	58.25	-1.425	3.141	3.449
K2	6232705	18802279	-526	1475	3.017	6.975	6.289
K3	16279777	-25609568	-183	90	-1.573	2.404	1.818
K4	6843505	-41736305	-168	84	-6.099	6.465	2.146
K5	9111445	-16524616	-404	160	-1.814	3.839	3.384
K6	6945925	-26733780	-240	223	-3.849	5.085	3.324
K7	2208085	-4997728	-149	84	-2.263	2.931	1.862
K8	10658160	-27376370.561	-75.177	43.237	-2.569	2.201	1.325
K9	3832918	-16477347.535	-1129.051	158.949	-4.299	7.508	6.156

Table 4.5: Statistics of height differences between FABDEM_V1-0 and COPERNICUS 30 in the representative land covers in Tanzania at their common grid intersections

REGIONS	NO.	SUM(m)	MIN(m)	MAX(m)	MEAN (m)	SD (m)	RMS(m)
K1	4203145	-3389311	-111	70	-0.806	4.176	2.854
K2	6232705	-4802209	-60	51	-0.770	2.011	1.858
K3	16271581	-6165869	-61	81	-0.379	2.400	2.369
K4	6766593	-15590691	-89	54	-2.304	2.853	1.683
K5	8970860	-14374749	-96	118	-1.602	3.958	3.620
K6	6945925	-15535493	-131	99	-2.237	5.394	4.908
K7	2208085	-3488880	-54	54	-1.580	2.502	1.939
K8	10658160	-19959285.346	-33.903	18.64	-1.873	1.951	0.549
K9	3832918	-5051693.026	-81.226	54.447	-1.318	3.500	3.242

Table 4.6: Statistics of height differences between FABDEM_V1-0 and TanDEM-X-3" in the representative land covers in Tanzania at their common grid intersections

REGIONS	NO.	SUM(m)	MIN(m)	MAX(m)	MEAN (m)	SD (m)	RMS(m)
K1	4203144	13457366	-78	170	3.202	5.066	5.992
K2	6232705	13675953	-465	1482	2.194	6.304	5.910
K3	13661145	27966202.327	-724	1054	2.047	16.159	16.029
K4	6770540	-605940.762	-1194	132	-0.089	17.901	17.901
K5	8453549	23806294.165	-1391	1263	2.816	20.480	20.285
K6	6945925	21162812	-172	429	3.047	6.348	5.570
K7	2208085	1578526	-49	124	0.715	2.812	2.719
K8	10658160	-1822690.359	-49.23	38.053	-0.171	1.864	1.856
K9	3763011	9852133.120	-224.642	270.248	2.618	5.304	4.613

4.1.3 Statistical assessment of height differences between GDEMs and GGCPs Countrywide

The mathematical relationships illustrated by equations (3.6, 3.8, 3.9, and 3.10) in Chapter 3 were used to get at these results.

Table 4.7: Statistics of height differences between GGCPs and GDEMs countrywide

HEIGHT DIFFERENCES	NO.	SUM(m)	MIN(m)	MAX(m)	MEAN (m)	SD (m)	RMS(m)
H (GGCPs- FABDEM_V_{1-0})	590	-79.634	-6.563	41.773	-0.135	2.954	2.957
H (GGCPs-NASADEM)	590	-392.952	-7.794	36.011	-0.666	3.116	3.186
H (GGCPs vs AW3D30E_V3.2)	590	-1632.439	-15.110	31.816	-2.767	3.283	4.294
H (GGCPs-COPERNICUS 30)	590	-714.342	-12.804	35.975	-1.211	3.055	3.286
H (GGCPs- TanDEM-X-3")	586	426.714	-8.387	39.208	0.728	2.984	3.072

4.1.4 Statistical assessment of height differences between GDEMs and GGCPs in the AOI and selected land covers

These are the results of the statistical assessment of height differences between GDEMs and GGCPs in the AOI and selected land covers, in which the same mathematical relation applied to compute results for statistical assessment of height differences between GDEMs and GGCPs countrywide.

Table 4.8: Statistics of height differences between GGCPs and FABDEM_V_{1-0} in the representative sample land covers in Tanzania

REGIONS	NO.	SUM(m)	MIN(m)	MAX(m)	MEAN (m)	SD (m)	RMS(m)
K1	29	6.035	-1.643	3.036	0.208	1.105	1.124
K2	39	19.271	-4.197	9.966	0.494	2.281	2.333
K3	64	-105.529	-4.587	23.390	-1.649	3.488	3.858
K4	35	-74.582	-5.397	0.624	-2.131	1.306	2.499
K5	39	32.131	-3.199	6.202	0.824	1.804	1.983
K6	27	-8.589	-5.034	2.502	-0.318	1.814	1.842
K7	11	-21.559	-4.167	5.391	-1.960	2.719	3.352
K8	48	-16.456	-6.563	4.396	-0.343	1.905	1.935
K9	23	5.491	-6.116	6.550	0.239	2.315	2.327

4.2 Discussion of the Results

This study aims to evaluate the vertical accuracy of FABDEM_V_{1-0} GDEM (Global Digital Elevation Model). The statistical measures employed in this assessment are the SD and Root Mean Square (RMS). The RMS is utilized for comparing one GDEM to another and determining which one is superior. A smaller SD and RMS indicate higher accuracy within the dataset.

4.2.1 General performance of GDEMs countrywide

Results from Table 4.1, show the overall fit between GDEMs countrywide. From The table, (FABDEM_V_{1-0} -NASADEM) is more superior to all differences between the GDEMs with RMS of 3.220m, followed by (FABDEM_V_{1-0} - COPERNICUS 30) and with RMS of 4.014m, meanwhile the (FABDEM_V_{1-0} - TanDEM-X-3") shows higher disagreement at their common grid intersections with RMS of 30.922.

Table 4.9 displays the performance levels of height differences among GDEMs across various land covers. The height difference values of 1 represent the highest performance, while values of 2 indicate good performance. Normal performance is denoted by values ranging from 3 to 5, while poor performance is represented by a value of 6. Lastly, the worst performance is indicated by a value ranging from 7 to infinity.

Table 4.9: Performance level of height difference between GDEMs in twelve land covers based on value of mean, SD and RMS

HEIGHT DIFFERENCES	K1	K2	K3	K4	K5	K6	K7	K8	K9
(FABDEM_V_{1-0}) - (NASADEM)	4	4	2	2	3	5	3	1	3
(FABDEM_V_{1-0}) - (AW3D30E_V3.2)	3	6	2	2	3	3	2	1	6
(FABDEM_V_{1-0}) - (COPERNICUS 30)	3	2	2	2	4	5	2	1	3
(FABDEM_V_{1-0}) - (TanDEM-X-3")	6	6	16	17	20	6	3	2	5

According to Table 4.9, (FABDEM_V_{1-0}) - (COPERNICUS 30) had greater agreement in most land cover than all other differences of GDEMs, whereas (FABDEM_V_{1-0}) - (TanDEM-X-3") had significant disagreement in most land cover.

4.2.2 Statistical assessment of height differences between GDEMs and GGCPs Countrywide

According to Table 4.7, in terms of mean and RMS with the values -0.135m, 2.957m respectively. FABDEM_V$_{1\text{-}0}$ is closer to the control point than other GDEMs, and was followed by TanDEM-X-90, NASASEM Copernicus 30 where by AW3D30E_V3.2 exhibits the worst performance than other GDEMs.

4.2.3 Statistical assessment of height differences between GDEMs and GGCPs in the selected land covers

Generally, results from the differences between GGCPs and GDEMs, FABDEM_V$_{1\text{-}0}$ shows better performance in most selected land covers compared to other GDEMs. On the other hand, AW3D30E_V3.2 performs poor in most of selected land covers when compared to other GDEMs.

The reason behind for FABDEM_V$_{1\text{-}0}$ to perform better than the other GDEMs used in this study in both countrywide and many landcovers is that; FABDEM (Forest and Building removed DEM) created by modifying the COPERNICUS DEM by removing the forests and buildings where influenced good results for FABDEM_V$_{1\text{-}0}$ since elevations obtained above the terrain surface of the earth where GGCPs are monumented.

CHAPTER FIVE
CONCLUSION AND RECOMENDATION

5.1 CONCLUSION

The main goal of the vertical accuracy assessment of GDEMs was to determine the reliability and suitability of these publicly available DEMs for various applications by assessing FABDEM_V_{1-0} using GGCPs and its comparison to other GDEMs in Tanzania mainland. The assessment included various land covers and a general comparison to other GDEMs which are NASADEM, COPERNICUS 30, AW3D30Ev3.2 and TanDEM-X-3".

The statistical results obtained in this study show that FABDEM_V_{1-0} is superior to all other GDEMs, including NASADEM, COPERNICUS 30, AW3D30Ev3.2, and TanDEM-X-3, both in countrywide and in the selected land covers. The overall fit (RMS) of FABDEM_V_{1-0} to GGCPs is 2.957 meters, followed by TanDEM-X-3", NASADEM, COPERNICUS 30, and AW3D30E_V3.2 with 3.072m, 3.186m, 3.286 m, and 4.294m, respectively.

When evaluating the performance of GDEMs in various land covers, it has been observed that FABDEM_V_{1-0} and TanDEM-X-3 exhibit superior performance in numerous terrains compared to other GDEMs. This conclusion is based on their lower RMS values across multiple terrains. On the other hand, AW3D30Ev3.2 displays a significantly larger range of RMS values, ranging from 2.976m to 7.522m, indicating the poorest performance among the GDEMs in various terrains.

When GDEMs' height differences are assessed, the FABDEM_V_{1-0} vs COPERNICUS 30 pair agrees more closely with low values of mean, SD, and RMS as for fitting GDEMs.

5.2 RECOMENDATION

To ensure the identification and evaluation of the most suitable GDEM for Tanzania across all land covers in the future, it is advised to conduct further research. The research should focus on assessing the performance of FABDEM_V_{1-0} against recently released GDEMs, such as the updated version of FABDEM which is FABDEM_V_{1-2}. Furthermore, it is recommended to compare FABDEM_V_{1-2} with other publicly available GDEMs in various land covers. By undertaking these investigations, it would be possible to choose the best GDEM for Tanzania under various land cover situations.

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