INVESTIGATION OF DEBRIS FLOW IN THE MUDA RIVER BASIN KEDAH, USING REMOTE SENSING, HYDROLOGY, GIS, AND GEOELECTRICAL METHODS

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by

ABUBAKAR SIRAJO

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF SYMBOLS

-	Negative
%	Percentage
ρ_a	Apparent resistivity
+	Positive
>	Greater than
^{0}	Degree
C	Current electrodes
c	Free space
f_0	Initial infiltration rate
f_c	Final infiltration rate
f_P	Infiltration capacity at any time t
k	Horton's decay constant
km	Kilometre
km^2	Kilometer Square
m	meter
m^3	Meter cube
MHz	millihertz
mm	millimeter
N	Number of pixels
P	Potential electrodes
t	Time
V	Potential
W_i	Weight for factors
y	Manual gain
ε_r	Dielectric constant

Ω.m	Ohm-meter
σ	Conductivity
I	current
R	Resistance
k	Geometric factor
r	Distance between the current electrodes
v	voltage

LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
DEM	Digital Elevation Model
DN	Digital Number
DTM	Digital Terrain Model
EM	Electro Magnetic
ERT	Electrical Resistivity Tomography
ERTS	Earth Resources Technology Satellite
ETM	Enhanced Thematic Mapper
FM	Formation
GIS	Geographic Information System
GPR	Ground Penetration Radar
GPS	Global Positioning System
IP	Induced Polarization
IR	Infrared
IS	Infiltration Station
KC	Kappa Coefficient
KS	Kappa Statistics
LST	Land Surface Temperatures
LULC	Land Use Land Cover
MD	Minimum Distance
MRB	Muda River Basin
MSS	Multispectral Scanner System
NASA	National Aeronautics and Space Administration
NDMI	Normalized Different Moisture Index

NDVI	Normalized Difference Vegetation Index
NE	North-East
NGA	National Geospatial-Intelligence Agency
NIR	Near-Infrared
NNE	North-North-East
OA	Overall Accuracy
OLI	Operational Land Imager
RBV	Return Beam Vidicon
SAM	Spectral Angle Mapper
SLC	Scan Line Corrector
SRTM	The Shuttle Radar Topography Mission
SSW	South-South-West
SVM	Support Vector Machine
SW	South-West
SWIR	Short Wavelength Infrared
TIRS	Thermal Infrared Sensor
TM	Thematic Mapper
USGS	United States Geological Survey
WO	Weighted Overlay
WOA	Weighted Overlay Analysis
Worldclim	World Climatology

LIST OF APPENDICES

PENYIASATAN ALIRAN PUING DI LEMBANGAN SUNGAI MUDA KEDAH, MENGGUNAKAN KAEDAH-KAEDAH PENDERIAAN JAUH, HIDROLOGI, GIS, DAN GEOELEKTRIK

ABSTRAK

Kajian ini menyelidiki kejadian aliran puing pada 4 Julai 2022 di Kampung Iboi, Lembangan Sungai Muda (MRB), Kedah, yang mengakibatkan kerugian kewangan dianggarkan sebanyak RYM25.91 juta serta meragut tiga nyawa. Dengan menggunakan pendekatan multidisiplin yang merangkumi penderiaan jauh, hidrologi, Sistem Maklumat Geografi (GIS), dan teknik geokejuruteraan, kajian ini mengenal pasti faktor permukaan dan bawah permukaan yang menyumbang kepada kejadian aliran puing serta memetakan kawasan berisiko tinggi, dengan penekanan terhadap langkah pencegahan. Model Ketinggian Digital (DEM) dan imej satelit Landsat 8 serta Landsat 5 (resolusi 30 meter) telah digunakan, Kedua-dua imej satelit dari 2011 dan 2022 dianalisis untuk membandingkan perubahan dalam penggunaan tanah dan litupan tanah, bersama data pemendakan daripada WorldClim2.0 dan bacaan hujan tempatan. Ciri bawah permukaan dianalisis melalui data kajian keberintangan dan ujian penyusupan. Analisis perubahan liputan tanah menggunakan kaedah Minimum Distance dan Spectral Angle Mapper menunjukkan penurunan litupan vegetasi masing-masing sebanyak 16.58% dan 13.43%, sementara kawasan pertanian meningkat sebanyak 15.32% dan 7.54%. Analisis Indeks Vegetasi Terubah Normal (NDVI) menunjukkan penurunan indeks vegetasi daripada 1 pada tahun 2011 kepada 0.8 pada tahun 2022. Ketepatan klasifikasi bagi kedua-dua kaedah mencapai 80%, dengan statistik kappa sebanyak 0.8. Parameter penyebab seperti kecerunan, jumlah hujan, panjang aliran, ketinggian, ketumpatan saliran, aspek cerun, Guna Tanah dan Litupan Tanah (LULC), NDVI, erosiviti hujan, ketumpatan lineamen, dan geologi

digunakan untuk membangunkan peta komposit bahaya aliran puing dan kerentanan tanah runtuh melalui analisis penimbang berwajaran berasaskan GIS. Kira-kira 40% daripada MRB dikategorikan dalam zon bahaya tinggi dan sangat tinggi, 25% dalam zon sederhana, manakala 35% dalam zon bahaya rendah dan sangat rendah. Kerentanan tanah runtuh pula diklasifikasikan kepada sangat rendah (20%), rendah (20%), sederhana (22%), tinggi (20%), dan sangat tinggi (18%), dengan Kampung Iboi dikenal pasti sebagai kawasan yang sangat terdedah. Ekstraksi lineamen menunjukkan ketumpatan tinggi struktur geologi di kawasan berisiko. Kajian keelektrikan kerintangan mengenal pasti zon tepu (0Ωm–100Ωm), tanah sisa (100Ωm–1300Ωm), bongkah granit (1300Ωm–3500Ωm), dan retakan. Analisis penyusupan di sepanjang profil ini menunjukkan kadar penyusupan yang rendah, sejajar dengan kehadiran zon tepu. Aktiviti pembalakan di Kampung Iboi didapati mengurangkan daya pengukuhan akar serta mempercepatkan pereputan bahan organik dan luluhawa, yang memberi kesan terhadap proses hidraulik, kestabilan tanah, dan ketepuan. Kawasan cerun melebihi 20° dengan masa ketepuan pantas sekitar 24 minit dikenal pasti sebagai paling mudah terjejas oleh aliran puing.

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ABSTRACT

This study investigates the July 4, 2022, debris flow event in Kampung Iboi, Muda River Basin (MRB), Kedah, which caused an estimated RYM25.91 million in financial losses and claimed three lives. Employing a multidisciplinary approach of remote sensing, hydrology, Geographic Information System (GIS), and geoelectrical techniques, the study identifies surface and subsurface factors contributing to debris flow and delineates hazard-prone areas, with an emphasis on preventive measures. A Digital Elevation Model (DEM) and satellite imagery from Landsat 8 and Landsat 5, both with a 30-meter resolution, were utilized. The two satellite images from 2011 and 2022 were analyzed to compare changes in land use and land cover, alongside precipitation data from Worldclim2.0 and rainfall measurements. Subsurface features were analyzed using resistivity data and infiltration tests. Change detection via Minimum Distance and Spectral Angle Mapper methods revealed a vegetation cover decline of 16.58% and 13.43%, respectively, while agricultural land increased by 15.32% and 7.54%. Normalized Difference Vegetation Index (NDVI) analysis indicated a vegetation decrease from 1 in 2011 to 0.8 in 2022. Classification accuracies of 80% and kappa statistics of 0.8 were achieved for both methods. Causative parameters such as slope, precipitation, flow length, elevation, drainage density, aspect, Land Use Land Cover (LULC), NDVI, rainfall erosivity, lineament density, and geology were used to develop composite debris flow hazard and landslide susceptibility maps through GIS-based weighted overlay analysis. Approximately

40% of MRB falls within high and very high hazard zones, 25% in moderate zones, and 35% in low and very low zones. Landslide susceptibility was categorized as very low (20%), low (20%), moderate (22%), high (20%), and very high (18%), with Kampung Iboi being particularly vulnerable. Lineament extraction highlighted a high density of geological structures in hazard-prone zones. Resistivity surveys identified saturation zones (0Ωm–100Ωm), residual soil (100Ωm–1300Ωm), granitic boulders (1300Ωm–3500Ωm), and fractures. Infiltration analysis along these profiles indicated low infiltration rates, aligning with saturation zones. Logging activities in Kampung Iboi were found to reduce root reinforcement and accelerate organic matter decomposition and weathering, impacting hydraulic processes, soil stability, and saturation. Slopes greater than 20° with rapid saturation times of 24 minutes were particularly susceptible to debris flow which is associated with weathering and organic matter decomposition at deforested areas.

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Debris flow is defined by different researchers as the massive movement of sediments, water mixture, rocks, trees, and other heavy materials usually from mountainous areas to downstream (Han et al., 2020a; Liang et al., 2012). Gravity influences one type of sediment motion on a slope, while fluid dynamic forces propel the other. Heavy rainfall, deforestation, and conversion of vegetation cover to agricultural activities are identified among the factors responsible for debris flow in Malaysia (Shah et al., 2017). As observed in Kampung Iboi, Baling, within the Muda River Basin (MRB), Kedah, during the incident on July 4, 2022, debris flows are typically triggered by intense rainfall and landslides originating from mountainous regions. These events often lead to subsequent cascading geological hazards (Han et al., 2020b). The disaster was claimed to have caused three fatalities and some property damage worth not less than RM25.91 million (5.4 Million USD) (Mizwan et al., 2023). The phenomenon of debris flow is typically caused by continuous geological process known as cascading geological disaster (Ahmad et al., 2023). Typically, the process of debris flows begins with slope erosion, creates a water path, and then leads to the formation of small rivers on slopes with a lower gradient, rainwater that has accumulated and flowed quickly downstream can hasten erosion when the water circulation is diminished, large boulders are deposited (Wu et al., 2019).The Cascading geological disasters in the Kampung Iboi MRB begin from the landslide and develop a debris flow, debris flood, and mud flood which is related to the previous logging and agricultural activities in the area according to Ahmad et al. (2023). The chain of propagation of the cascading disaster is presented in Figure 1.1.

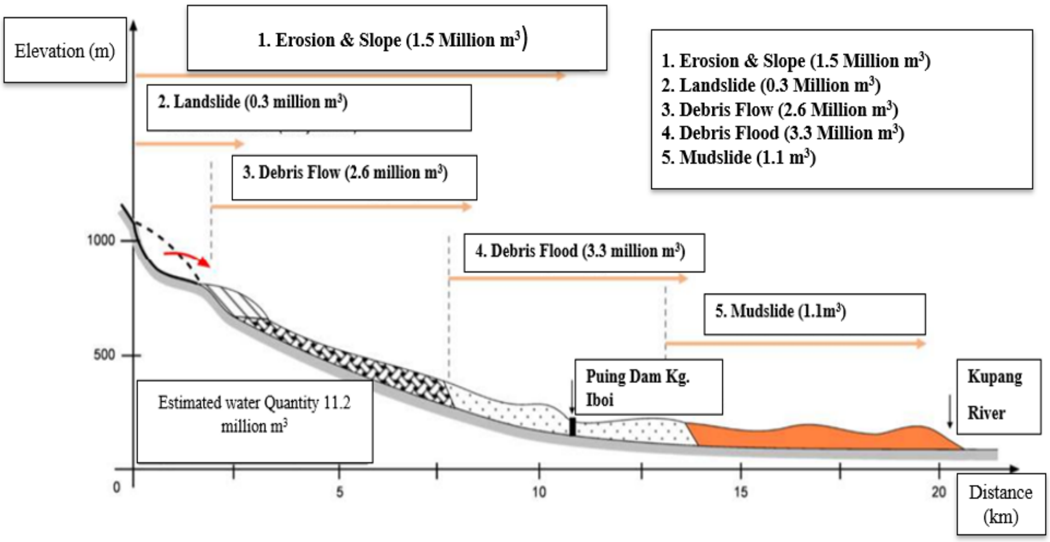

Figure 1.1 Cascading geological disaster process. Each process leads to the other, the first event usually starts from slope erosion followed by a landslide, debris flow, debris flood, and mudslide.

[Modified after Ahmad et al. (2023); Norsham; (2022)]

Debris flow is usually caused by cascading geological disasters globally (Han et al., 2021; Huggins et al., 2020; Nguyen et al., 2013; Shi et al., 2015; Wei et al., 2018). In Malaysia, cascading geological disasters, as opposed to a single, continuous geological activity, are typically responsible for the occurrence of debris flow Ahmad et al. (2023), it frequently occurs from upstream to downstream in the MRB (Wu et al., 2019). Debris flow as a natural disaster is very difficult to avoid. However, early forecasting and awareness may help in minimizing its impact and occurrence as it becomes a major challenge in Malaysia (Ahmad et al., 2023). This is possible after identifying the susceptible areas (Nguyen et al., 2013). Areas that are affected by the previous debris flow in Malaysia and their potential causes are summarized in Table 1.1

Table 1.1 Disaster category and process causing debris flow incidents in Malaysia

S/N	Month/year	Location	Types of disaster	Causes
1	August 2011	Kampung Orang Asli Sungai Ruil, Cameron Highland, Pahang	Debris flow, mud flood	Heavy Rainfall
2	October 2013	Bertam Valley, Cameron Highland, Pahang	Debris flow	Heavy Rainfall
3	November 2014	KM 28, Jalan Tamparuli, Ranau, Sabah	Debris flow	Heavy Rainfall
4	May 2015	KM 38.80, Jalan Penampang Tambunan Dongongan, Sabah	Debris flow	Heavy Rainfall
5	June 2015	Channel of Fraser's Hill, Pahang	Debris flow	Heavy Rainfall
6	June 2015	Channelized Mesilau river, Kundasang, Sabah	Debris flow	Earthquake & rainfall
7	August 2015	Channelized Kedamaian and Panataran river, Kota Belud, Sabah	Debris flow	Earthquake & rainfall
8	August 2021	Gunung Jerai, Kedah	Debris flow, debris flood, and mud flood	Heavy rainfall
9	February 2022	Kenyir Dam, Terengganu	Debris flow	Heavy Rainfall
10	July 2022	Kampung Iboi Kedah	Debris flow, debris flood, and mud flood	Heavy Rainfall

Sources Ahmad et al. (2023); Rosli et al. (2021).

The catchment area of the MRB, as shown in Figure 1.2, encompasses more than 45% of the state of Kedah (Adeeko et al., 2020). The MRB flows from the east channeling through Kampung Iboi, Baling, Sik, and Sungai Petani districts down to lowerland until the Strait of Malacca in the west, the basin has a length of 180km with a catchment area of 4210km^2 Zakariah et al. (2021), the annual rainfall analysis in the region varies from 2000mm/year to 3000mm/year (Van et al., 2018).

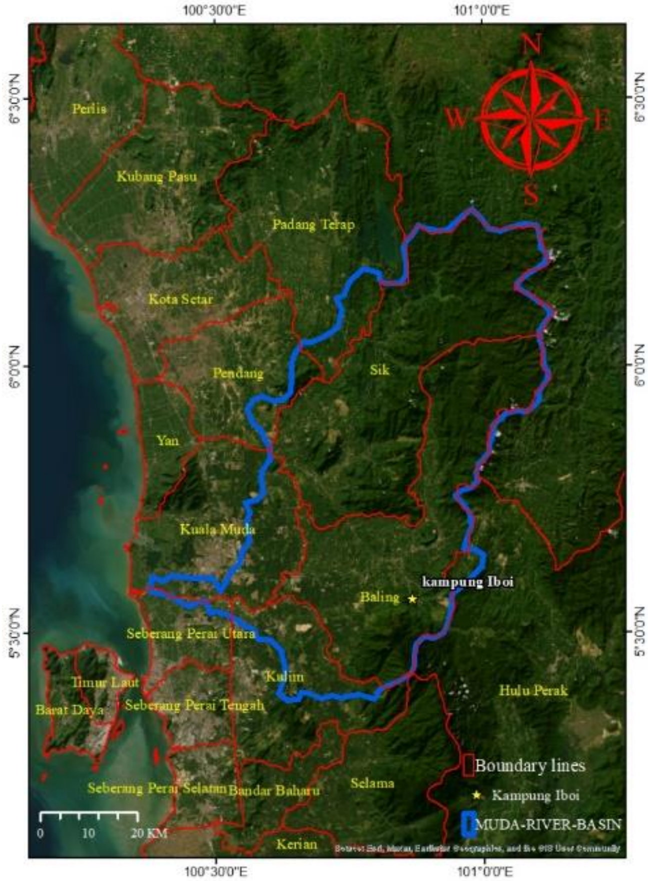

Figure 1.2 The Muda River Basin (MRB) area is depicted in blue, while the Kampung Iboi area is indicated by a star symbol. Additionally, the district and state boundary lines are delineated in red

Remote sensing is applied in this study for details about the surface using satellite data (Landsat 5 and Landsat 8) for 11 years time intervals from 2011 to 2022 to develop a composite map of land use land cover changes that will help to understand the land use in the area and monitor the changes in vegetation cover from 2011 to 2022. Using two different satellite images from different sensors, such as Landsat 5 and Landsat 8, for land use/land cover (LULC) change detection can provide valuable insights due to several key factors related to the different capabilities of each satellite and sensor. These differences are particularly useful when analyzing changes over time. Landsat 5 was launched in 1984 and operated until 2013, while Landsat 8 was launched in 2013 and is still operational. By using images from both satellites, you can cover a longer time period, which is critical for detecting land use and land cover changes over decades.Two supervised classification algorithms Minimum Distance (MD) and Spectral Angle Mapper (SAM) were employed in this research because they are accurate in detecting temporal changes. Their accuracy for change detection analysis was proved by many researchers (Arnab et al., 2022; Feyissa & Gebremariam, 2018; Geeraert et al., 2019; Malede et al., 2023; Minta et al., 2018; Samie et al., 2019). The selection of classification techniques and their algorithm in this research is based on their accuracy, the details for classification algorithms and their accuracy can be found in (Abburu & Golla, 2015; Arnab et al. 2022c; Madariya et al., 2022). Generally supervised classification techniques are more accurate in detecting the LULC according to Linda et al. (2023). To detect and analyze the vegetation cover of the MRB using the reflective bands of the two-satellite data, the Normalized Difference Vegetation Index (NDVI) was employed. The NDVI is a popular method for detecting vegetation changes and is employed to produce the normalized band ratio to highlight the presence or absence of vegetation cover (Zaidi et al., 2017). Additionally, the generated NDVI images could be utilized to determine the pattern of changes that took place between 2011 and 2022; this was because the NDVI differencing technique showed the best ability to detect changes in vegetation. The analysis of debris flow hazard, and landslide susceptibility zones in the MRB in this study was done by understanding the process of debris flow, the qualitative approach to identifying debris flow hazards uses information about the topography, hydrology, geological settings, and geomorphology of the MRB as well as information on vegetation coverage and LULC of the study area. In this research weighted overly analysis in GIS was used to develop a debris flow hazard map, and landslide susceptibility map using Different triggering parameters including slope, precipitation, elevation, drainage density, aspect, (refers to the compass direction in a slope faces) LULC, NDVI, rainfall erosivity factor, flow length, flow direction, flow accumulation, distance from lineaments and geology. All resistivity surveys and infiltration analyses are conducted in areas susceptible to landslides and prone to debris flow hazards in Kampung Iboi. To analyze the factors contributing to debris flow and landslides in Kampung Iboi, a region known for its susceptibility to such events and recently affected by a landslide and debris flow on July 4, 2022, was selected. The implementation of 2D-resistivity and infiltration analysis presents a comprehensive subsurface and shallow subsurface approach. This methodology facilitates the assessment of the regional subsurface geological structure as well as the morphology of the underlying formations in Kampung Iboi. The outcomes of these investigations have facilitated the development of a subsurface geological model in Kampung Iboi, thereby enhancing our understanding of the factors that trigger debris flow and landslides.

2-D Resistivity for subsurface investigation is a non-destructive imaging technique that injects the current into the ground for subsurface investigation and is good for detecting subsurface triggering factors (saturation zones, granitic bodies, fault, residual soils, and alluvium deposit) of debris and landslides, numerous geophysical methods have been developed and are still widely used for details about the subsurface such as ground penetrating radar, electrical resistivity imaging, induce polarisation, and electrical resistivity tomography (Ducut et al., 2022a). By obtaining measurements on the ground surface, a resistivity survey aims to ascertain the subsurface resistivity distribution. Several geological factors, including mineral and fluid composition, porosity, and degree of rock water saturation, have a significant influence on the resistivity of the ground. Therefore, it becomes feasible to precisely evaluate the actual resistivity of the sub-surface (Nordiana et al., 2018).

By employing hydrological analysis techniques, hydrological parameters including drainage density, stream order, flow direction, flow accumulation, precipitation intensity, rainfall erosivity factor, and rainfall intensity were analyzed to know the hydrological impact of the cascading geological disaster in the MRB. Infiltration test was also employed across 31 stations in the Kampung Iboi at different locations prone to debris flow hazard and susceptible to landslides, as one of the famous hydrological methods that can help to determine the rate of water infiltration into the subsurface for possible prediction and analysis of debris flow occurrence. Infiltration analysis helps to investigate the effect of different variables on infiltration rate that can contribute to debris flow, which includes soil texture and structure, environmental factors at the soil surface, soil moisture content, saturation zones, the type of vegetation cover, LULC, agriculture, and anthropogenic activities on the surface of the earth.

This study examines the debris flow process and its possible causes in the MRB, which is prone to cascading geological disasters that have a detrimental impact on both human lives and the economy. The investigation utilizes remote sensing, hydrology, Geographical Information Systems (GIS), and 2D-resistivity methods. The research also analyzes the debris flow process, identifies triggering factors, and creates composite maps for assessing the debris flow hazard. Similarly, areas susceptible to landslides in the basin were also identified using landslide susceptibility analysis.

1.2 Problem Statement

The most recent debris flow events (Gunung Jerai, Yan, Kedah- 18 August 2021, Bentong, Pahang, Hulu Langat, Selangor, and Negeri Sembilan- 18 December 2021, Hulu Terengganu- 27 February 2022, and Kampung Iboi, Baling, Kedah-4 July

2022) (Jaapar et al. (2023), reveals that knowledge and research of debris flow in Malaysia is still in its early stage possibly due to lack up proper awareness about devastation attached to the disaster. An incorrect and incomplete database of events may result from failing to recognize the necessary terminology and procedures for investigating cascading geological disasters (Jaapar et al., 2023a). Previous works on debris flow in Malaysia focused more on physical site analysis, historical records with soil laboratory test analysis, and some studies also focused on rainfall patterns and intensity (Abdullah et al., 2014; Kasim et al., 2016, 2021; Mizwan et al., 2023a). However, their research lacks the required geophysical investigation such as 2D resistivity, and hydrological analysis such as infiltration analysis to map out the precursor of debris flow. Furthermore, physical site visits are limited to only affected areas but cannot predict future occurrence sites and determine the prone zones. Only recently, due to the Kampung Iboi event in 2022, the Malaysian government has put more focus on understanding and mitigating this disaster (Norsham, 2022). Due to the lack of debris flow studies in this area, this work tries to fill in the gap by investigating the debris flow of Kampung Iboi using remote sensing, 2D-resistivity, infiltration analysis, and GIS. composite maps for landslide susceptibility and debris flow hazard in the MRB for cascading geological disaster analysis for possible mitigation majors were also developed in this research.

The cascading geological disaster in Kampung Iboi MRB on 4th July 2022 began with landslides, which then evolved into debris flow, debris flood, and mud flood. Generally, previous logging and agricultural activities contribute to triggering debris flow and flooding in Kedah State (Ahmad et al., 2023; Jaafar et al., 2020; Norsham, 2022; Qahlani, 2023). In the previous debris flow in Kampung Iboi, the sediments and debris materials were transported along the Sungai Kupang River. After the water content has increased the debris flow turns into a debris flood, when the debris and sand are stranded the debris flow turns into mudflow. The process of erosion occurred before and during the event. The MRB has been significantly impacted by frequent human activity that undermined environmental principles for national progress, cutting trees and the forest canopy can lead to increased erosion at logged sites and an increase in sediment discharge (Ghani et al., 2010). Forest conversion to other land use such as agriculture, and infrastructure development in Kedah is about 9% of the total area between 1988 and 2017, which is equivalent to 33,391ha (Mohd et al., 2020). Deforestation and logging activities for cultivation and other human wants were the major land use in the basin previously (Mohd et al., 2020; Norsham, 2022; Ramasamy, 2017). However, no detailed studies have been conducted specifically in the Kampung Iboi MRB using combined supervised classification algorithms (MD, SAM, and NDVI) to detect the LULC change particularly related to deforestation that led to soil erosion and exposure, for debris flow and other cascading geological disasters until 2022.

Most of the geophysical studies using resistivity such as Ghazali et al. (2013); Nordiana et al. (2018b); Olabode et al. (2020); Safani et al. (2023); and Zikiri et al. (2020) for subsurface investigation related to slope failure and mass movement focuses on the saturation zones and granitic boulders as the subsurface triggering factors in different locations. Based on the reviewed literature, details geophysical investigation of the Kampung Iboi MRB debris flow was not conducted. However, in this research saturation zones, granitic boulders, residual soils, the thickness of alluvium and debris deposits, and fractures are detected using 2D-resistivity techniques as subsurface triggering factors which is related to surface exposure to soil erosion due to previous logging and weathering activities by frequent heavy rainfall.

Shakir et al. (2018) used some different hydrological parameters such as rainfall, suspended solid, stream flow, and water level to assess the flood risk in the basin. This research employs infiltration analysis, drainage density, stream order, precipitation, rainfall data, rainfall erosivity factor, flow direction, flow accumulation, and flow length as the hydrological parameters to investigate the debris flow in the MRB, hence the new idea helps in mapping a new debris flow hazard and landslide susceptibility zones.

A detailed understanding of the debris flow process and its potential causes required standard information from both the surface and the subsurface which is lacking in the previous research, particularly in Kedah and the MRB. However, this is the first study that provides new insight into the cascading geological disaster investigation to understand the debris flow process and its potential causes for debris flow hazard analysis, and landslide susceptibility from a holistic way covering the surface (remote sensing and GIS) and subsurface (2D-resistivity, and Hydrology) in the MRB.

1.3 Research Objectives

The objectives of this research are:

i. To monitor the Land Use Land Cover Changes (LULC) of the Muda River Basin using remote sensing.

ii. To image the subsurface for geological structure identification for debris flow using the 2D-resistivity technique.

iii. To assess the effect of water infiltration rate and the influence of hydrological parameters on the debris flow in the MRB using hydrological techniques.

iv. To develop a debris flow hazard map and landslide susceptibility using GIS for the analysis of debris flow disasters for future urban and rural planning.

1.4 Novelty and Significance of the Research

This research is unique for its comprehensive examination of the debris flow process in the MRB, encompassing initiation, runoff, and deposition. The analysis of initiation revealed both surface and subsurface factors at play. The runoff process was investigated by assessing soil infiltration capacity and slope gradient. Additionally, the study identified areas where debris was deposited, determined deposition thickness, and identified river channels used for debris transportation. Notably, this study employed different approaches, utilizing remote sensing, 2D-resistivity, hydrology, and GIS techniques to investigate the debris flow process and potential causes. Similarly, debris flow hazard and landslide susceptibility mapping analysis were developed in this research. The research validated detailed triggering factors related to vegetation conversion and logging that render susceptible areas prone to soil erosion and cascading geological disasters (Mohd et al., 2020; Norsham, 2022). Subsurface conditioning factors, for triggering debris flow and landslides including saturation zones, granitic boulders, residual soils, and fractures Liu et al. (2011) were detected for the first time in the MRB by this study. The analysis of debris flow hazard and landslide susceptibility highlighted areas particularly susceptible to these events. Granite undergoes a variety of physical, chemical, and biological weathering processes that gradually weaken areas, making them prone to mass movement (Chigira et al., 1977). Similarly, slopes exceeding 20^0 exhibited a high likelihood of debris flow initiation Risiko et al. (2015) with a rapid infiltration saturation time of 24 minutes.

The combined result provides new insight and more details about the cascading geological disaster process and its contributing factors in the MRB. Also, it highlights the areas prone to debris flow hazards that can be used by the authorities concerned for urban and rural planning to minimize future occurrences.

Investigation of the debris flow in the MRB is very important not only for saving life purpose but also for preventing the main source of surface water supply (Muda River), for both Kedah and Penang State, from being contaminated with mud and other sediments triggered by debris flow events. Muda River Basin supplies around 80% of fresh water to Penang and supplies about 96% and 50% to Kedah and Perlis respectively (Ramasamy, 2017). The Penang state is undergoing major population expansion, further urbanization, and quick land developments that will eventually raise the need for water supply, which depends on the Muda River. Penang's manufacturing industries contribute significantly to the state's water demand (Ramasamy, 2017).

1.5 Scope of the study

In this study surface and subsurface triggering factors as well as the debris flow process in the MRB were investigated. The lowlands of Kampung Iboi and a few downstream settlements experienced mudslides and flooding due to the debris flow phenomenon that followed the landslides. Several public impressions have been shaped by the cause of this disaster, including logging operations, forest plantations, and upstream bursting ponds.The cause of the incident is a rare geological phenomenon, that is the flow of debris, similar to what happened in Sungai Lubok Panjang, Jerai; Sungai Lui, Hulu Langat; and Telemung River, Bentong (Norsham, 2022). But in the case of the Kampung Iboi tragedy, the destructive power of the flood

20 disaster is the debris. Kampung Iboi is in a tropical climate region, locally influenced by sever rainfall. Analysis by Malaysia Meteorological Agency on rainfall at every station in the district Kampung Iboi (Baling), Sik, and Kulim showed heavy rain from 4.00 pm until 6.00 pm on July 4, 2022 (Ahmad et al., 2023). The phenomenon of alluvium and debris deposition in Kampung Iboi produce a source of debris in the river's grooves. Furthermore, the flow of debris and alluvium deposits was enhanced by the high active erosion along Sungai Kupang, the flow of debris is a networked geological process that was followed by debris, flooding of debris, and mudslides. In the incident of 4 July 2022 over 2,589,021m3 of debris flowed and deposited (Mizwan et al., 2023a). As the quantity of water increased, the flow phenomenon turned into a flood of debris containing 3,275,467m3. The flow of debris has been widening the river between 10 to 100 times and exposing the bedrock of the river. As the number of waters increased, the flow of debris changed and became a flood of debris and flowed for about 5.1km. This study investigated this terrible catastrophe from a variety of angles (e.g. monitoring the vegetation cover and land use land cover changes, geomorphology of the area, geological settings, hydrological influence such as infiltration analysis and subsurface triggering factors). Composite maps for cascading geological disasters connected to debris flow and landslide susceptibility were developed using GIS. The surface contributing factors for the cascading network geological disaster were investigated using MD, SAM, and NDVI change detection classification algorithms. Granitic boulders, saturation zones, residual soil, alluvium, debris deposit thickness, and fractures were detected as the subsurface contributing factors using 2D-resistivity. Hydrological parameters such as drainage density, stream order, flow direction, flow accumulation, precipitation intensity, and rainfall intensity were all developed to understand the hydrological

influence of the cascading geological disaster in the MRB using hydrological analysis tools. Similarly, infiltration analysis as one of the famous hydrological techniques was conducted in the field across different locations prone to debris flow hazard, and landslide susceptibility for more details about the infiltration rate and its influence on debris flow. Kampung Iboi in the MRB was focused as a study case for all subsurface investigation (2D-resistivity and Infiltration analysis) due to the recent occurrence of debris flow on the 4th July, 2024 in the area and limited time, and exposure to high debris flow hazard and landslides susceptibility.

1.6 Thesis Layout

This thesis is divided into five (5) different chapters: introduction, literature review, methodology, results and discussion, and conclusion.

Chapter 1 contains details about the general introduction and background. It outlines the problem statements, research questions, objectives, novelty, significance of the research, and research scope. Chapter 2 discusses the literature review on remote sensing for change detection analysis using MD, SAM, and NDVI. 2-D resistivity literature review related to saturation zones detection granitic boulders, fractures, and residual soils for debris flow, landslide, and other related mass movement were also reviewed. Literature review on hydrological analysis and infiltration was reviewed according to the research objectives. GIS application for debris flow hazard mapping and landslide susceptibility was all reviewed in the Chapter 2 section. Chapter 3 discusses the data acquisition process and processing based on the aforementioned objectives. Chapter 4 focuses on the results and discussions. Chapter 5 is for conclusion and recommendation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Debris flow and landslide basic concepts as well as basic theories related to the techniques used in investigating the debris flow were discussed in this chapter. Previous studies related to Remote sensing, 2-D resistivity, GIS, and hydrological techniques (Infiltration) for the debris flow process and their potential causes were also discussed, similarly, studies related to debris flow hazard mapping and landslides susceptibility analysis were also reviewed according to the research objectives.

2.2 Debris Flow

Debris flow is a type of geological disaster that occurs when a mass of loose, wet, and saturated debris such as soil, rocks, and vegetation flows rapidly down a slope, often triggered by heavy rainfall or landslide (Han et al., 2020a; Liang et al., 2012). Debris flows pose a significant threat to human lives and safety by impacting infrastructure, residences, and natural environments (Liang et al., 2012). Consequently, there has been a growing interest in recent years in investigating and comprehending debris flows with the aim of devising effective strategies to mitigate their adverse effects (Wang et al., 2022). Notably, scholars and researchers have made notable advancements in debris flow research, benefiting from technological and knowledge-related progressions that have led to an enhanced understanding of the mechanisms and triggers underlying debris flows. Moreover, researchers have delved into the characteristics and behavior of debris flows, encompassing sediment composition and fluid-solid interactions (Li et al., 2021). These investigations have significantly contributed to the development of engineering measures and strategies for assessing hazards and managing risks (Wang et al., 2022). On the whole, the existing body of literature concerning debris flows highlights the devastating power of such events, the factors that induce them, the risks they pose to human life and infrastructure, and the methodologies and strategies for mitigating their impact (Imaizumi et al., 2021).

2.2.1 Classifications of Debris Flow

Depending on the topography and geology of the areas, debris flow can be classified into hillslope debris flow and channelized debris flow (Figure 2.1). Hillslope Debris flow makes a new flow path down the slope, while channelized debris flow, flows along the path created by rivers, gullies, and valleys (Imaizumi et al., 2021) .

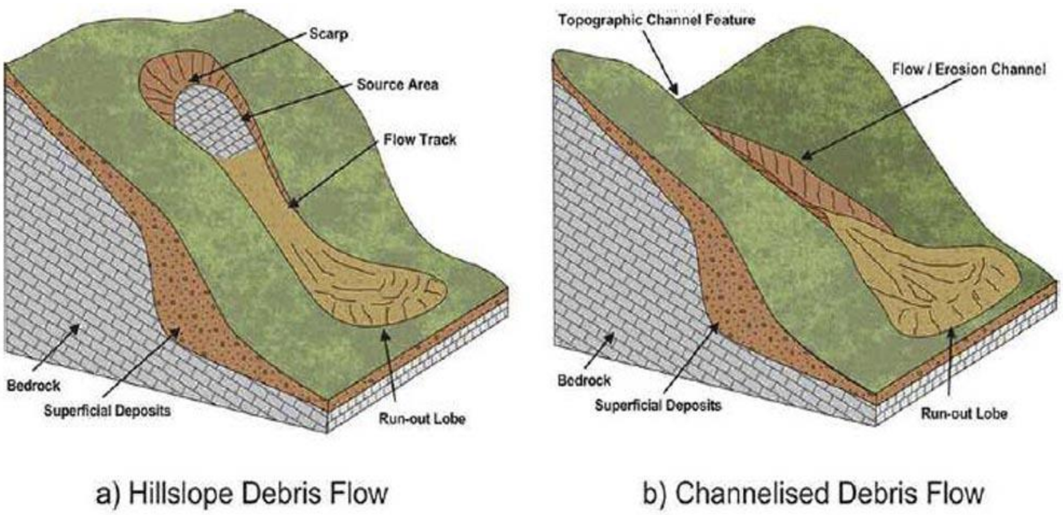

Figure 2.1 (a) Hillslope Debris flow and (b) Channelised Debris Flow. [(Imaizumi et al., 2021)]

2.2.1(a) Three Main Types of Debris Flow

Debris flow can be classified according to the nature of its physical appearance such as aggregations of stones, turbulent muddy, and viscous as discussed below

2.2.1(a)(i) A Stony-type debris flow

A stony-type debris flow is a specific type of debris flow characterized by the presence of coarse materials like stones, boulders, and gravel in the moving mass (Takahashi, 2014). Unlike finer sediments such as sand and silt, these flows contain a higher proportion of larger particles. Stony-type debris flows have a major impact on the shaping of mountainous and hilly landscapes, as their occurrence is influenced by steep slopes and abundant coarse sediments. Understanding the mechanics of these flows is crucial for assessing natural hazards and implementing measures to reduce risks in vulnerable areas (Takahashi, 2014).

2.2.1(a)(ii) Turbulent muddy debris flow

A turbulent-muddy-type debris flow is a distinct classification of debris flow characterized by its composition of fine-grained substances, including mud, silt, and clay, in conjunction with water. This particular composition engenders dynamic and fluidic flow behavior. These debris flows predominantly consist of fine-grained materials, namely mud, silt, and clay, and are frequently intermingled with water, resulting in a fluidic consistency (Takahashi, 2014).

2.2.1(a)(iii) Viscous Debris Flow

Viscous debris flow is a form of mass movement distinguished by its elevated viscosity. This attribute denotes a dense and adhesive composition resulting from a significant concentration of minute particles suspended in water. Viscous debris flows primarily consist of fine-grained substances such as clay, silt, and mud, often intermixed with water. These diminutive particles contribute to the development of a dense, paste-like consistency. In contrast to more fluid debris flows, viscous debris flows exhibit slower movement due to their heightened viscosity. Nonetheless, they are capable of traversing substantial distances downhill, albeit at reduced velocities when compared to turbulent or muddy debris flows. Intense precipitation, rapid snowmelt, or seismic events can act as triggers for viscous debris flows by destabilizing slopes and mobilizing loose, fine-grained sediments. The presence of water is a critical factor in maintaining the desired viscosity of the flow (Takahashi, 2014).

2.2.2 Triggering Factors of Debris Flow

Debris flow is usually caused by landslides from mountainous areas, it usually occurs as a cascading geological disaster (Han et al., 2020b). In Malaysia, the phenomenon of debris flow is typically not caused by a single, continuous geological process but rather by a process known as cascading geological processes (Ahmad et al., 2023). The process of debris flow typically commences with slope erosion, which generates a water channel, subsequently resulting in the development of minor rivers on slopes featuring a reduced gradient. Rainwater that has gathered and rapidly streamed downstream can expedite erosion. Once the water circulation subsides, substantial boulders are deposited (Wu et al., 2019). Deforestation and logging activities, along with persistent rainfall, have been identified as primary catalysts for environmental transformations and geological hazards in several Malaysian states (Shith et al., 2021). Furthermore, interference with hill slope regions has been recognized as a contributing factor to debris flow occurrences in Malaysia (Shah et al., 2017).

2.2.3 Concept of Landslide

The term "landslide" refers to the movement of a large amount of rock, debris, and sediments downslope. Conversely, a landslide is a form of mass wasting event that occurs when a slope's resisting force is exceeded, causing soil and rock to flow outward or downward while being directly affected by gravity (Reichenbach et al., 2018). As a geological hazard, landslides are brought on by a variety of elements, including volcanic eruptions and frequent rainfall. This usually starts when a hillside becomes too flimsy to bear the weight on it. It is considered to be one of the most perilous natural hazards that can be brought on by both anthropogenic activities like logging and natural forces like rainfall (Guzzetti et al., 1999).

2.2.4 Concept of Susceptibility mapping, and Hazard zonation

A method used to divide a slope into zones according to the degree of actual or anticipated landslide susceptibility and hazard is called hazard zonation, or susceptibility to debris flows and landslides (Lee & Talib, 2005). To quickly evaluate the stability of a slope over a wide area, landslide susceptibility and hazard zonation are crucial. Landslide susceptibility refers to the probability of slope failures in particular regions stemming from geological and environmental factors (Lee & Talib, 2005). A landslide susceptibility map can predict or give crucial information about the location of potential future landslides. On the other hand, a hazard map can predict the areas and timing of landslides and debris flows in the future (Wubalem, 2020). In landslide susceptibility mapping and debris flow hazard analysis, the selection of the causative parameters is one of the crucial steps. However, there are no clear guidelines for determining which factors are most important (Wubalem, 2020). The elements that cause landslides in the research region are chosen based on a review of the literature, local interviews, data availability, and environmental conditions in the area. The parameters usually used are slope, aspect, elevation, precipitation, rainfall data, drainage density, stream order, LULC, NDVI, Distance from the river, geology, and rainfall erosivity factor. etc.

2.2.5 Stratigraphy and General Geological Settings of the Muda River Basing Kedah

Based on geological contexts, MRB is divided into six formations: Triassic (Jerai Granit), Cambrian (Jerai formation), Ordovician (Mahang formation), Silurian Devonian (Sungai Fatani formation), Permian-Triassic (Semmogal formation) and Quaternary (Quaternary Sediment). A stratigraphic chart provides a summary of them (Figure 2.2). However, close to 70% of the study area is made up of granite from the Bintang Range in the southeast and the Main Range in the center. The Mahang formation is mostly found southwest of the study area and is composed of arenite and silicate facies, argillitic facies, and limestone facies. The formation is comparable to the Sungai Petani and Baling formations, which are isolated from the granite body. The Semanggol formation is composed of chert, rhythmic, and conglomerate facies. The primary fault in Kedah is the Bok Bak Fault Zone, which extends from southeast Kelantan to central Perak and Bukit Perak in Kedah and ends there (Zakariah et al., 2021). The geological map of the MRB and DEM presenting the basin in 3D-view is presented in (Figure 2.3 and Figure 2.4 respectively).

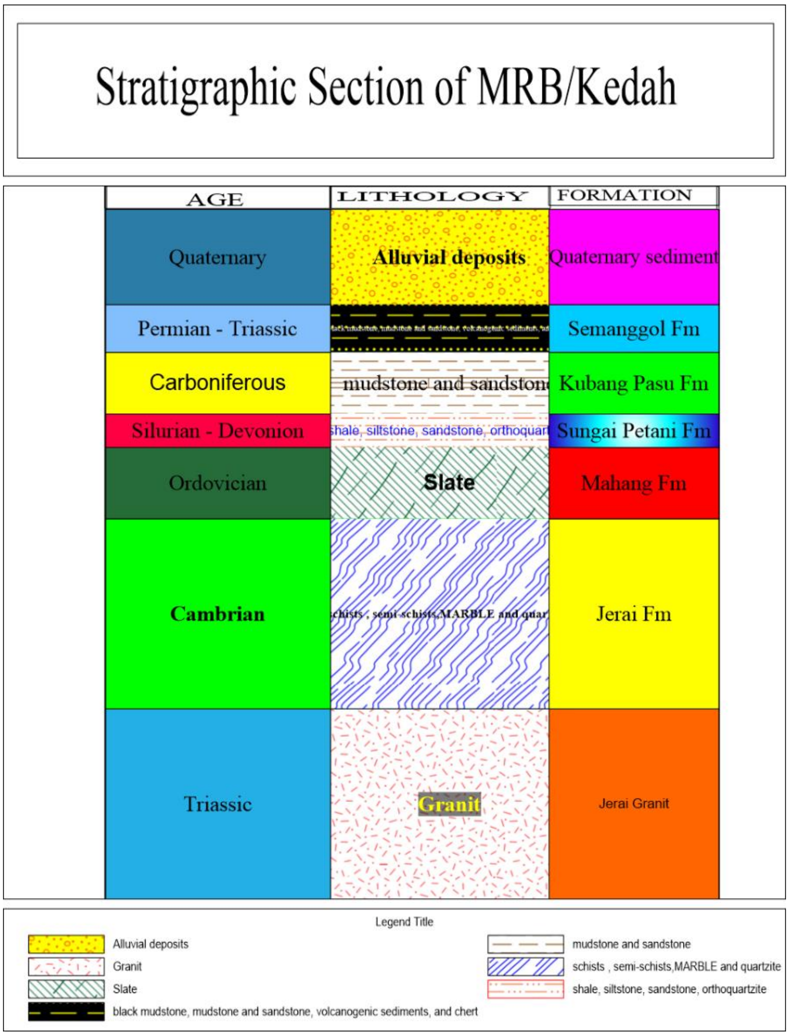

Figure 2.2 Stratigraphic Section of MRB.

[Modified from (Zakariah et al., 2021)]

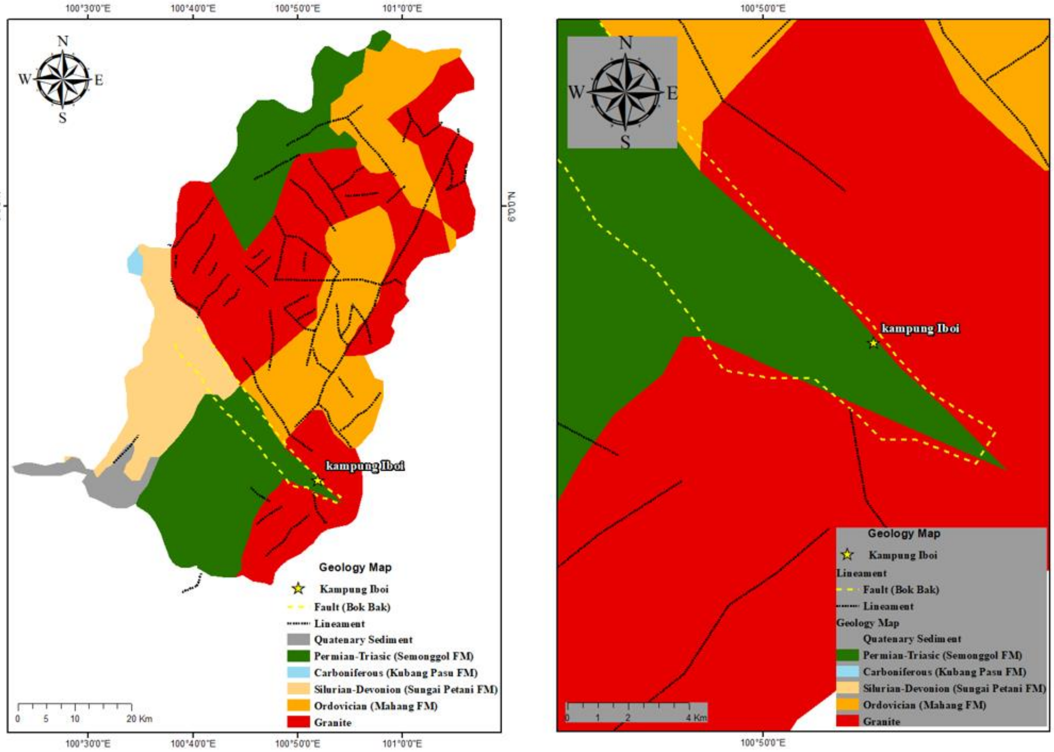

Figure 2.3 Geological map of MRB, with Kampung zoomed at right side. [Modified from (Zakariah et al., 2021)]

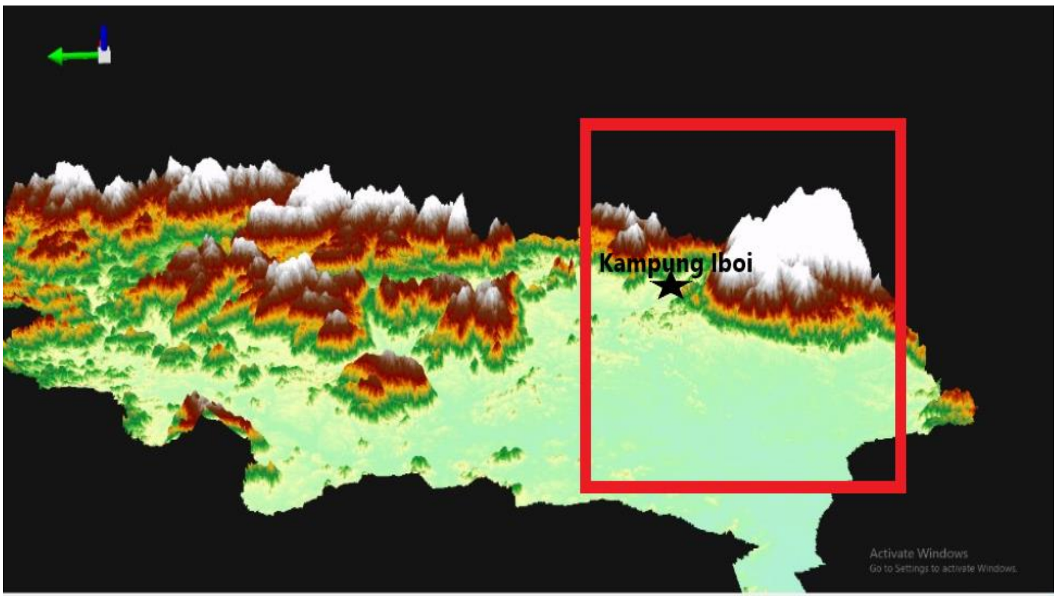

Figure 2.4 DEM presenting the MRB in 3D-view

2.3 Remote Sensing Theory

The growing availability of satellite data has fueled the rise in interest in remote sensing research. Remote sensing is extensively used in a variety of environmental monitoring activities, as well as in the analysis and detection of environmental issues (Amici et al., 2017). One key application is the identification of changes within images taken at different points in time, which can be applicable to a broad range of contexts. Change detection techniques are employed in situations such as land use and cover changes, deforestation, urbanization, water bodies, and natural disasters. Remote sensing technology has emerged as the foremost and indispensable source of data for monitoring and analyzing temporal changes (Amici et al., 2017). Advancements in remote sensing imaging systems and the increased availability of high-resolution satellite imagery have simplified the processing of images for remote sensing applications. This has made it easier for researchers, as they no longer have to rely on field surveys. The utilization of remote sensing has also facilitated easy access to data and analysis, making it an effective tool for detecting environmental changes. Real-time satellite data is widely employed in various applications that rely on remote sensing. In the context of urban development and vegetation cover changes, understanding how individuals interact with nature and utilizing this understanding for decision-making is crucial. The specific application for which change detection is used determines the method for discriminating different types of changes (Kleynhans et al., 2015).

2.3.1 Supervised Change Detection and Classification

To carry out supervised classification, it is imperative to acquire training samples encompassing each class to be classified within the image (Kleynhans et al., 2015). As denoted by its name, supervised categorization necessitates human intervention. To gather the spectral signature value, a human operator must meticulously choose a contiguous set of pixels from an image that accurately describes the region of interest. This undertaking is time-consuming owing to the prerequisite knowledge it entails. Subsequently, the collected training samples are stored as signature files, which are subsequently employed for image classification. The efficacy of supervised classifications is contingent upon the caliber of the training locations (Madariya et al., 2022b). Supervised classification techniques consist of the following algorithms.

2.3.1(a) Minimum Distance (MD)

Minimum Distance (MD), classification approach is used in multi-feature space to divide unknown image data into groups that have the shortest distances between them. A minimum distance is equivalent to a maximum similarity when using distance as an index of similarity (Umrikar, 2012).

2.3.1(b) Spectral Angle Mapper (SAM)

The spectral pattern matching between spectral clusters and reference categories is tested by the spectral angle mapper (SAM) technique, which compares the spectral similarity between endmembers and picture pixels. With the use of angular distances, the degree of spectral similarity between two spectra can also be calculated. SAM is not sensitive to the size of the training data set, the variance of the data, or the