GEOGRAPHIC INFORMATION SYSTEM BASED THREE-DIMENSIONAL SOIL WATER DYNAMIC MODEL FOR LANDSLIDE MODELLING

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by

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LIST OF SYMBOLS

R_{WA}	Antecedent Working Rainfall
α_t	Deduction Coefficient
η	Porosity
K_{sat}	Saturated hydraulic conductivity
$\Delta\theta$	Soil moisture content
ψ	Wetting front
$f(t)$	Infiltration
$F(t)$	Cumulative infiltration
K_n	Hydraulic conductivity
u	Pore water pressure
γ'	Saturated soil unit weight
h	Thickness
G	Gravity
G_s	Soil gravity
e	Void ratio
c	Cohesion
c'	Effective cohesion
θ_r	Residual moisture content
θ_e	Effective porosity
τ	Driving force
C	Percentage of clay
S	Percentage of sand
S_{normal}	Resisting force normal

LIST OF ABBREVIATIONS

AHP	Analytic hierarchy process
CT	Rainfall threshold
DEM	Digital Elevation Model
DL	Danger level
FOS	Factor of Safety
GIS	Geographic Information System
GSSHA	Gridded Surface/Sub-surface Hydrologic Analysis
IEOF	Infiltration Excess Overland Flow
L	Layer
LOS	Levels of Simplification
MaCGDI	Malaysian Center for Geospatial Data Infrastructure
NADMA	National Disaster Management Agency
OSHA	Occupational Safety and Health Administration
P	Point
SEOF	Saturated Excess Overland Flow
SPC	Slope Physical Characteristic
SWD	Soil Water Dynamic
USGS	United States Geological Survey
2D	Two-Dimensional
3D	Three-Dimensional

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SISTEM MAKLUMAT GEOGRAFI BERDASARKAN MODEL DINAMIK AIR TANIH TIGA-DIMENSI BAGI PERMODELAN TANAH RUNTUH

ABSTRAK

Model geospatial tiga dimensi (3D) semasa mengabaikan kepentingan perubahan dinamik dan lebih fokus kepada pemodelan statik. Dengan menekankan ciri dinamik geospatial 3D tanah runtuh yang tercetus oleh pergerakan air tanih, kajian ini bertujuan untuk membangunkan Model Dinamik Air Tanih Tiga-Dimensi (3D SWD FLOW) untuk mewakili pergerakan yang berkesan dan mengurangkan implikasi bahaya tanah runtuh menggunakan pendekatan novel Tahap Bahaya (DL). Oleh kerana spektrum tanah runtuh yang sangat luas, tiada pendekatan tunggal untuk memetakan tanah runtuh, serta menilai bahaya yang berkaitan dengannya; Oleh itu, kajian ini telah mengatasi cabaran ini dengan mewujudkan rasional saintifik untuk aplikasi optimum peta tanah runtuh dan model ramalan 3D. Ciri-ciri fizikal cerun tidak mencukupi untuk mewakili kerentanan tanah runtuh (Timur-Barat Gerik Jeli, 41.68%; Jalan Tun Sardon, 23.52%). Kedua-dua lokasi mencapai kedudukan yang sangat baik menggunakan kaedah ketumpatan titik bersepadu (97.43% dan 47.05%) dan ambang hujan (P_3 =6.075-0.309P_{15}) menunjukkan kawasan kajian terdedah kepada tanah runtuh. Berdasarkan empat lokasi pemantauan cerun (P1 hingga P4), P3 merekodkan penyusupan paling banyak dengan 99.134 cm. Cerun adalah tidak stabil, seperti yang ditunjukkan oleh Faktor Keselamatan untuk P2 (0.6517), P3 (0.8580), dan P4 (0.4113). Cerun di bahagian bawah (kecuali P1) diklasifikasikan sebagai sangat berisiko tinggi melalui teknik novel DL yang menunjukkan nilai kurang daripada 0.25. Penyelidikan ini secara signifikan menyumbang kepada ramalan kestabilan cerun dan visualisasi fenomena semula jadi dalam 3D, yang membantu untuk memantau cerun di Malaysia.

GEOGRAPHIC INFORMATION SYSTEM BASED THREE-DIMENSIONAL SOIL WATER DYNAMIC MODEL FOR LANDSLIDE MODELLING

ABSTRACT

The current three-dimensional (3D) geospatial model neglects the importance of dynamic changes and focuses more on static modelling. By emphasizing the dynamism of 3D geospatial landslides triggered by soil water movement, this study aims to develop a three-dimensional Soil Water Dynamic Flow (3D SWD FLOW) model to represent an effectual movement and mitigate the severe implications of landslide hazards using a novel Danger Level (DL) approach. Due to the tremendous breadth of the spectrum of landslides, there is no sole approach for mapping landslides and assessing the hazards associated with them; hence, this study has overcome these challenges by establishing the scientific rationale for the optimal application of landslide maps and 3D prediction models. The slope's physical characteristics are insufficient to represent landslide susceptibility (East-West Gerik Jeli, 41.68%; Jalan Tun Sardon, 23.52%). Both locations achieved excellent positioning with integrated point density (97.43% and 47.05%) and the rainfall threshold (P3 = 6.075-0.309 P15) indicates that the study area is vulnerable to landslides. Based on the four main locations for slope monitoring (P1 to P4), P3 recorded the most intense infiltration with 99.134 cm. The slope was unstable, as indicated by the Factor of Safety for P2 (0.6517), P3 (0.8580), and P4 (0.4113). The lower slope (except P1) was classified as very high-risk through the novel DL technique, resulting in a value of less than 0.25. This study significantly contributes to predicting slope stability and visualizing the natural phenomena in 3D, which aids in slope monitoring in Malaysia.

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The Three-Dimensional Geographic Information System (3D GIS) is a system that manipulates, manages, presents, and analyzes information integrated with 3D phenomena (Rahman et al., 2001). This study emphasizes a dynamic 3D geospatial data model to represent the 3D phenomena of landslide hazards by building a 3D model and visualizing the process that represents the actual phenomena that occur on the surface of the earth. The process that is happening beneath the earth is unnoticeable and this situation indicates the need for 3D modelling since 2D is not adequate to support the structure model. This 3D model can, therefore, visualize situations beyond the limits of human sight. The model will demonstrate the process, along with the actual value of natural environments and ultimately help monitor the slope and evaluate its stability through mathematical computations.

There are various types of data models used for representing 3D data in 3D GIS. These include point clouds, 3D Triangular Irregular Networks, voxels, octrees, and BREP (Domenech and Clément, 2014). Doa et al. (2017) highlighted 3D data models that include the Tetrahedral network (Tan et al., 2002), Object-Oriented Model (Shi et al., 2003; Rahman, 2005), Solid Object Management System (Zlatanova, 2002), CityGML model (Groger et al., 2007), EUDM model (Nguyen-Gia et al., 2011), and improved CityGML model (Biljecki et al., 2016).

In landslide studies, 3D GIS helps reform the critical slip surface by using the integration technique of Monte-Carlo simulation and a GIS-based 3D limit equilibrium model (Jia et al., 2012). Research also revolves around the use of Unmanned Aerial Vehicle (UAV) that provides a 3D spatial analysis of landslide volume piles (Usman et al., 2018). UAV is often utilized in 3D landslide reconstructions by evaluating spatiotemporal changes with Digital Elevation Model (DEM) and Digital Surface Model (DSM) (Bilaşco et al., 2019). Most recent studies utilize commercial software such as Scoops3D (Zhang and Wang, 2019) and RS2 (Ersoy et al., 2020) for landslide assessment and analysis. Nonetheless, the use of available 3D software requires all predefined data that are sometimes not obtained in a study, and the results or simulations also do not meet the criteria set in research.

The 3D GIS data model is essential owing to the high level of detail that the 3D objects can obtain as they can get a certain smooth level that can convince the viewers that they are watching real objects (Dao et al., 2017). However, instead of focusing more on the level of detail and realistic representation, this study addresses the dynamic movement of the natural environmental process of 3D GIS. The movement of an object in various orders takes place in the form of 3 Dimensional (3D). The 3D modelling that focuses on environmental studies is gaining more attention, especially concerning floods, water quality, and air pollution. Studies involving natural processes of nature (movement of air and fluid) are more challenging. Air and fluid form an indeterminate spatial extent that is difficult to sense and have no specific boundaries. As such, applying 2D methods to 3D phenomena restrict scientists in several aspects. The independent use of the current 3D GIS data model and landslide data analysis cannot satisfy the 3D modelling of landslides triggered by soil water infiltration because this data model requires dynamic movement and various mathematical computations.

More research is required to develop a new model for a better landslide hazard analysis (Chan, 1998). Correspondingly, the essential landslide triggering criteria emphasized in the current study are rainfall, soil water infiltration, Factor of Safety (FOS), and soil classification (Figure 1.1). Rainfall threshold and FOS are generally used to determine the strength of the slope. This study also includes soil classification and soil water infiltration by considering its importance in landslide-induced factors. Combining all triggering factors producing Danger Level (DL), a novel approach introduced for slope stability.

As further research is needed to overcome the limitations in current landslide analysis and prediction, the development of the 3D SWD FLOW model provides a dynamic simulation of rainfall, landslides, and soil water infiltration. The study also presents a novel Danger Level (DL) approach for determining slope stability based on the level of slope resilience derived from the combined values of all triggering factors.

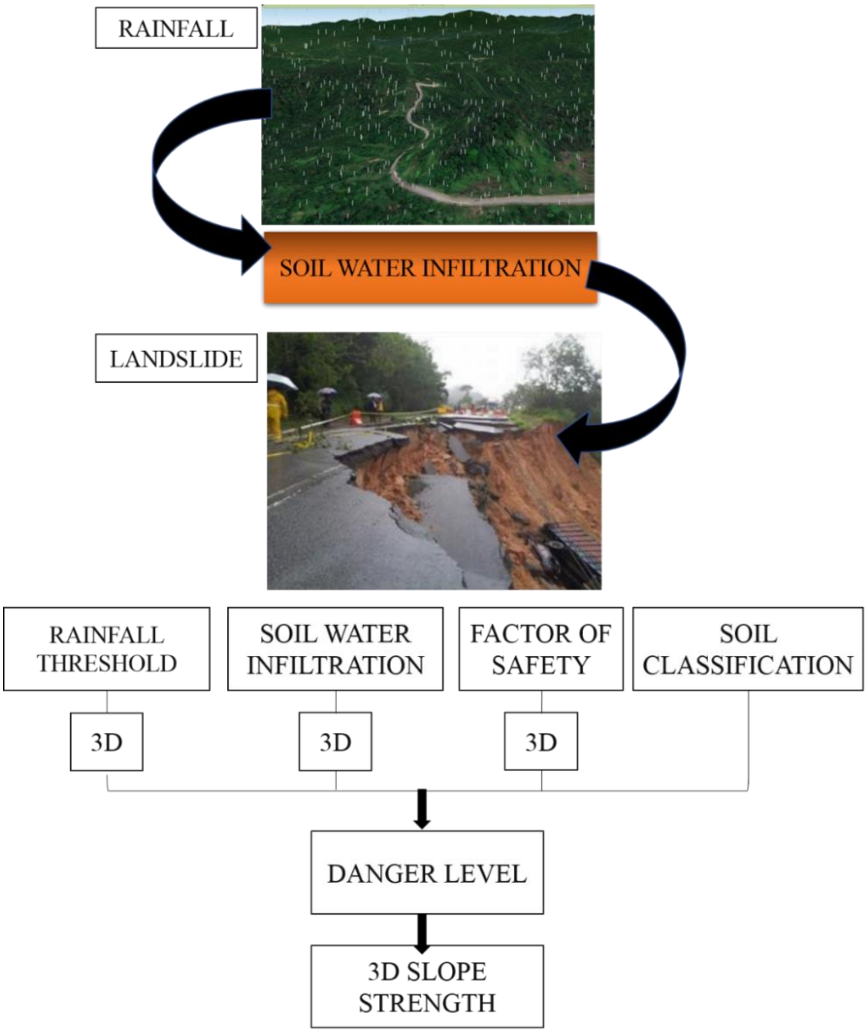


Figure 1.1 Important research criteria

1.2 Problem Statement

Spatial GIS in landslide studies has started to gain much attention in recent years. GIS practitioners among geologists and environmentalists have limited information of integrating the landslide process with a geospatial concept. This study offers a greater understanding among geologists, hydrologists, and environmentalists regarding spatial data analysis and susceptibility landslide mapping. From a geologist and environmentalist point of view, landslide hazard assessment is better with engineering geomorphological and geological input (Parry, 2016) and it provides a classification of geologic terms (Aafaf et al., 2020). The challenge faced by environmental scientists in building a robust and reliable model using environmental data is due to the diversity of environmental data from multiple sources (Binh et al., 2019). GIS can provide a platform for better data management and analysis; however, an understanding of these fields is required to avoid misinterpretation and bias in conducting research. Since most of the landslide information obtained was mainly based on field monitoring at accessible locations, there is a chance that many more landslides might occur in remote and inaccessible areas (Batar & Watanabe, 2021). Thus, a landslide susceptibility map can help identify the relative chance of future landslides merely based on a locale's inherent features or areas. It is also essential to consider future rainfall patterns while producing landslide susceptibility maps (Ahmed, 2015) that could assist the local governments in landslide hazard mitigation, land use planning, and landscape protection (Batar and Watanabe, 2021). Landslides have devastating consequences for human life and the broader economic system of many countries throughout the world (Nefeslioglu et al., 2008). Landslide susceptibility maps provide risk managers with timely, reliable information concerning landslide occurrences. As a result, accurate susceptibility mapping can serve as critical information for a wide range of users in the corporate and public sectors, government agencies, and the scientific community on a local and international scale (Fell, 2018).

Malaysia is encircled by the Pacific Ring of Fire, seismic zones, and active volcanoes. Even though Malaysia is geographically located outside the ring and is in a stable region, the location is relatively near and whatever happens along the ring will be felt throughout the country. According to Shuib (2015), it is no longer certain that Malaysia is free of earthquakes. Malaysia is generally spared severe natural disasters such as earthquakes, volcanic eruptions, and typhoons, but the country often faces floods, landslides, and severe haze. Major landslides, even though non-fatal, can result in severe disruptions to the transportation network and adversely affect the public. Although various landslide risk reduction strategies have been implemented, the number of deaths associated with landslides increases with each disaster occurrence. There is a conspicuous void in comprehending and integrating the science of landslide occurrences, risk perceptions, disaster preparedness, and responses (Alam, 2020). Thus, bridging the knowledge gap requires specific scientific and technical challenges in hazard and risk assessment as well as emergency response, which must be addressed.

3D geospatial models in landslide studies are gaining less attention than other environment-related studies due to the complex integration of geotechnical and hydrological processes (Sorbino and Nicotera, 2013). The current model mostly separates the material failure from propagation due to the complexity of integrating the dynamic process with a computational framework (Wang et al., 2019). Landslide studies need to consider theories and opinions in geology (slope material, soil strength) and environmental science (atmospheric condition based on Antecedent Working Rainfall). Thus, the current study deals with engineering and mathematical equations (FOS, Extended Multilayer Green and Ampt method, wetting front soil suction head, Corey method, and random walk) to create the 3D geospatial data model using Java. The complexity of 3D landslides motivates the researcher to utilize the existing commercial software with developer function. A complex model for three-dimensional geospatial movement typically involves several analyses combined to meet the necessary outcome. Although we often need to use different software to obtain the outcome, somehow, the outcome is not the result that we expected. Thus, most of the current studies have applied hybrid approaches such as finite-element groundwater and limit equilibrium stability analysis adopted in Geo-Slope 2000. Standard methods of analysis have specific features that may limit their effectiveness in a various ways. Due to the lack of seepage forces in Limit Equilibrium Method (LEM), the FOS can be overestimated by up to 30%. (Pyke, 2017). Finite Element Method (FEM), on the other hand, has limitations in a number of situations, such as dynamic analysis of a boundless domain, crack propagation, and stress concentration problems (John, 2003). As for 3D slope stability analysis using DEM, it necessitates rather complex algorithms aimed at iteratively predicting landslides, which are tedious and yields results that do not reflect their potentialities (Palazzolo et al., 2021). The limitations of the current 3D data model of landslide analysis cannot satisfy the requirement in 3D landslide modelling. The issues described provide an opportunity to develop a 3D SWD FLOW. A knowledge gap exists as to what extent can the 3D geospatial landslide model integrate the natural environmental process with multiple important triggering factors and visualize it in a dynamic 3D model. Hence, an attempt to model 3D fluid and landslides with an indeterminate spatial extent is required to establish a more comprehensive nature representation model.

Landslide monitoring usually analyzes rainfall that links the landslide-prone areas with high rainfall intensity. It is well-recognized that extreme precipitation intensities rise with the global mean surface temperature (Shahid, 2011; Kharin et al., 2013; Fischer and Knutti, 2016; Myhre et al., 2019). The hydrological cycle is expected to accelerate with global warming, resulting in more extreme precipitation events (Tabari, 2020). Warmer oceans increase the amount of water that evaporates into the air. When more moisture-laden air moves over land or converges into a storm system, it can produce more intense precipitation (Wuebbles et al., 2017). According to Myhre et al. (2019), if current trends continue, the most extreme precipitation events currently recorded will approximately double in frequency with each additional degree of global warming. As global warming becomes more severe, landslide research must emphasize rainfall patterns. While rainfall is recognized as the significant triggering factor of landslides (Sobie, 2020; Huang et al., 2020), the focus should be emphasized on the process in the soil before landslide hazards occur (Hong et al., 2006; Beyabanaki et al., 2013) because the lag time between rainfall and landslides is necessary (Evans et al., 2007). Soil moisture and infiltration processes provide a clear understanding of how water decreases slope strength, thereby resulting in a landslide (Abraham et al., 2020). Recent studies have agreed that the inclusion of soil moisture and complex infiltration patterns of hydrologic information can improve landslide forecasting quality (Marino et al., 2020; Wicki et al., 2020). Even though FOS is generally used to measure slope stability, FOS cannot be applied in all slope types, for instance, the rock-type slope. The rock-type slope is stable without external forces, although the value of FOS mentions otherwise. Thus, in the current study, the selected main triggering factors were combined to develop a Danger level (DL) approach for better slope stability determination. DL integrates four main factors to determine slope stability: soil water infiltration, rainfall, FOS, and soil classification.

1.3 Research Questions

The research questions are addressed as follows:

a) What environmental, hydrological, and geological factors influence the patterns of spatial landslide inventory to produce a better landslide susceptibility map?
b) Why are 3D geospatial landslides required in managing landslide triggers with an actual dynamic representation of 3D phenomena?
c) How can the rainfall, soil water infiltration, FOS, and soil characteristics integration be performed to measure the 3D slope strength?

1.4 Research Aim

The study aims to develop a Three-Dimensional Soil Water Dynamic Flow (3D SWD FLOW) data model that emphasizes the natural dynamic movement of 3D phenomena. The model describes the actual process of 3D phenomena by visualizing the phase of precipitation infiltrating into a deeper layer of sub-surface soil that decreases slope strength and leads to landslides. Various spatial landslide inventories were produced to classify landslide patterns based on historical data to construct various landslide susceptibility maps. The limitation in spatial landslide analysis and mapping allows for improvement via a 3D data model design. Danger level (DL) was introduced as a novel approach for slope risk determination.

1.5 Research Objectives

The three main objectives specified in this study are as follows:

a) To analyze the impact of various environmental inputs on the accuracy of spatial landslide susceptibility.
b) To develop a Three-Dimensional Soil Water Dynamic Flow (3D SWD FLOW) that produces 3D dynamic models for rainfall, infiltration of soil water, and landslides.
c) To visualize 3D slope strength using the Danger Level (DL) approach based on risk classification.

1.6 Research Scope

This study aims to develop a three-dimensional SWD FLOW data model that incorporates the primary landslide triggering parameters that are frequently employed in landslide assessments. The study began with a spatial analysis of landslides that integrate several inventories to ascertain the trend of landslides and establish a risk of potential landslide occurrences based on susceptibility maps. Comprehensive landslide analysis is essential for integrating environmental and geological aspects through 3D SWD FLOW, which generates a 3D model for rainfall threshold, soil water infiltration, and landslides. Finally, soil classification is associated with rainfall, FOS, and soil water infiltration to develop a Danger Level (DL) that categorizes the potential of landslide occurrences at any point on the slope.

Nonetheless, several limitations were encountered in this study:

a) The 3D model of soil water infiltration is based on gravitational force only. The effect of soil water movement due to capillary force and ground water level were not included in this study.

b) A spatial investigation, inventory, and mapping were done using historical landslide information for Peninsular Malaysia, Jalan Tun Sardon, and East-West Gerik Jeli Highway. However, the 3D model is based on one slope only. The 3D SWD FLOW model could be applied in another location if it meets all of the required data.

c) The 3D model does not include a user interface.

d) The study did not involve Infiltration Excess Overland Flow (IEOF), Saturated Excess Overland Flow (SEOF), and other streamflow generating processes.

e) The coding was written in open-source software and did not involve any commercial 3D software.

1.7 Research Contributions

The 3D geospatial data model is often associated with a costly and lengthy procurement process that offers a 3D model platform for a GIS application. The real-world object, movement, and process can be represented in 3D with the proliferation of 3D software. The development of the 3D geospatial model is more oriented to a static structure and terrain that enhances the Level of Simplification Levels (LOS) to provide a realistic 3D representation.

This study has developed a new 3D SWD FLOW data model that emphasizes the dynamic movement of natural phenomena. The study began by conducting multiple spatial inventories to produce various landslide susceptibility maps. The limitation in the landslide spatial analysis shows the requirement of a higher dimension, and the natural soil water infiltration into the soil is beyond the reach of human sight. Thus, a 3D geospatial data model is the best way to represent this process. The natural phenomena integrated with this 3D data model constitutes the process of rainfall that initiates the soil water infiltration and triggers landslides. All of these natural processes move dynamically in the real world and the slope should not be disturbed or altered for research purposes. Therefore, this study visualized the natural process of the real world in 3D dynamic representation for better data interpretation and manipulation based on the changes in slope data. The 3D SWD FLOW data model was designed to analyze slope data based on rainfall, soil water infiltration with different layers of soils, and FOS value that indicates slope strength. Besides, this study aims to utilize open-source software to develop 3D data model instruction to prove that the 3D data model can also be cost-effective. The complexity of 3D landslides lies in dynamism integration with computational instruction (Wang et al., 2019). Although the 3D SWD FLOW data model does not highlight LOS, this study is one of the first to attempt to model a dynamic natural landslide process with software that is not explicitly created for 3D models.

Rainfall and soil water infiltration are discussed comprehensively in this study; however, it is still important to evaluate slope strength with the incorporation of rainfall, soil water infiltration, FOS, and soil classification. The new approach of Danger Level (DL) applied to the concept of slope stability improvises existing techniques without modifying the universally understood form. This study aligns with the national policy of the National Slope Master Plan 2009-2023 that highlights the action plan and strategy to decrease landslide risks. According to the Landslide Disaster Management Handbook, the catastrophic effect of landslides in Malaysia causing this disaster is categorized as a relative frequency disaster.

The findings of this study would benefit the Public Works Department, which is responsible for monitoring and enhancing slope safety in Malaysia for better slope management. The findings are also beneficial to the National Disaster Management Agency (NADMA), which coordinates disaster risk reduction initiatives. The spatial map and information can help enrich the data in the Malaysian Centre for Geospatial Data Infrastructure (MaCGDI), while the susceptibility map provides the analysis of suitability that is useful for the Federal Department of Town and Country Planning and the Department of Environment.

Likewise, this study is beneficial for 3D GIS specialists in utilizing the 3D SWD FLOW data model and adding more dynamic types with better slope texture representation. Besides, this study can further diversify the types of data required by geologists and environmentalists for a better slope analysis. Hydrologists can also apply this data model and emphasize the soil water movement aspect for a more realistic visualization of soil water.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the issues of geographic data management for landslides, three-dimensional surface topography changes, and landslide triggering variables involving the slope's physical features and environments will all be covered.

Geospatial data management for landslides requires a reference to the current method of mapping sub-surface soil and the spatial representation of multidimensional data, as described in Section 2.2. The first objective requires the analysis of geographical inventory and the landslide mapping of historical spatial data. This subject is commonly associated with geological and mining activities that involve the exploration of sub-surface terrains. The map displays the soil region as a sequence of identical types, from the surface to the deeper ground, as spatial mapping emphasizes spatial location. As landslide analysis involves data hidden beneath topography, a higher dimension, specifically 3D, is required for sub-surface analysis.

3D modelling of soil water infiltration involves identifying current hydrological and soil deformation models, as described in Sections 2.3 and 2.4. Slope deformation is due to environmental and geological elements that constantly refer to the landslide triggering factors. The reference to these three primary landslide triggers is vital to design the 3D SWD FLOW model to achieve the second research objective. The major landslide triggering factors include sub-surface soil water infiltration, the atmospheric effect of rainfall, slope characteristics, and soil conditions as defined in Section 2.6. Further research is needed since these factors have been studied separately, although linked to one another. This section is important to develop a new approach of 3D slope strength that contributes to achieving the third research objective.

2.2 Landslide Susceptibility Map (LSM)

A landslide susceptibility map (LSM) indicates locations that are prone to landslides on a scale of low to high. The susceptibility map encompasses the locations of landslides and the elements that contribute to their occurrences such as slope, soil type, and the running water in a region. The parameters chosen are decided by the data available and the direction of research. Different studies have applied different types of analysis, for example, fuzzy logic (Roy and Saha, 2019), evidential belief functions (EBF) (Anis et al., 2019; Subrata and Sujit, 2020; Beheshti et al., 2021), and weight of evidence (WoE) (Batar and Watanabe, 2021).

Susceptibility has been widely applied in the geographical realm with the explicit goal of developing a landslide susceptibility map (LSM). Developing a landslide susceptibility map (LSM) that employs relevant methodology and identifying the appropriate conditioning variables are among the most frequently applied strategies for mitigating landslide impacts (Nohani et al., 2019). Numerous research, including Mersha and Meten’s (2020) and Radha and Milap’s (2012), has integrated bivariate statistical methods and Geographic Information Systems (GIS). The models of landslide susceptibility identify the geological, geomorphological, and other physical factors that influence landslide susceptibility. Landslide vulnerability models can also be quantitative or qualitative. Quantitative susceptibility modelling employs bivariate, multivariate, and machine learning statistical techniques.

Machine learning approaches are used to evaluate non-linear relationships involving events and variables. Scientific discoveries in remote sensing technology, Geographical Information Systems (GIS), and computational capabilities have been achieved throughout the last two decades. Additionally, statistics-based approaches for landslide susceptibility modelling have been found to effectively reduce costs while increasing efficiency. As a result, high-resolution maps of unprecedented access locations can now be created.

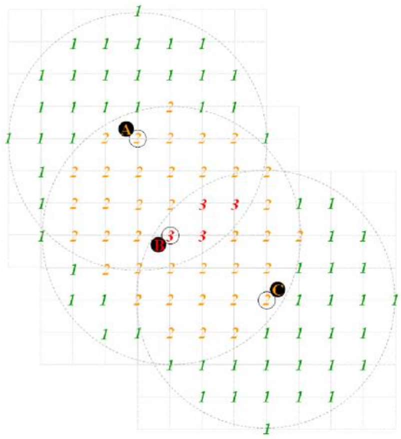
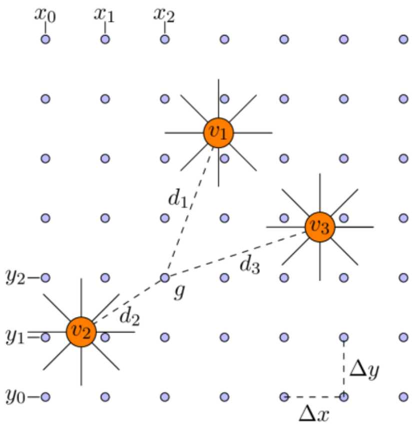
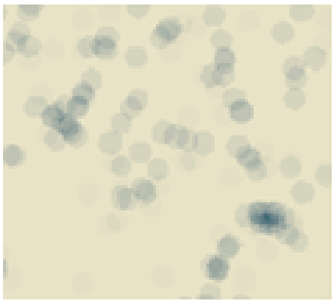
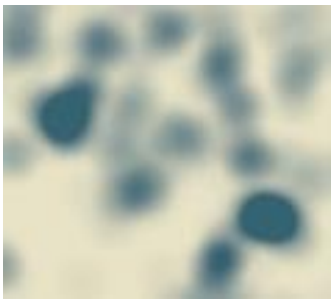
The parameters used in every research are different from one another. The most used parameters to produce LSM include curvature, slope, aspect, elevation, lithology, elevation, distance from fault, slope angle (Nohani et al., 2019; He et al., 2019; Wubalem and Meten, 2020), normalized difference vegetation index (NDVI) (Zulhaidi et al., 2010; Tseng et al., 2015; Pradhan et al., 2019), distance from the river (Raja et al., 2017; Roy and Saha, 2019; Mersha and Meten, 2020), distance from the road (Seyedeh et al., 2011; Shahabi and Hashim, 2015; Pasang and Kubíček, 2020; Shuai and Zhou, 2021), land use (Shafri et al., 2010; Oliveira et al., 2017; Wubalem, 2021; Irjesh et al., 2021), stratum rock property, vegetation coverage index, and terrain humidity index (Bin et al., 2021). Overall, different parameters used in different studies influence the probability of a successful research outcome.

The high success rate for determining landslide susceptibility indicates that the map is accurate and acceptable. For instance, research has indicated that the landslide susceptibility map results in a success rate of greater than 80% (Al-Thuwaynee et al., 2012), 82.41% (Zhang et al., 2016), 84.83% (Wubalem, 2021), 88.9% (Wubalem and Meten, 2020), and up to a 90.10% successful rate (Silalahi and Pamela, 2019). Besides, according to recent research, most landslide susceptibility evaluations obtain excellent validation scores based on an examination of 50 peer-reviewed papers (Fleuchaus et al., 2021). As a result of these findings, the current study adopts a similar methodology but with a greater emphasis on additional analyses.

This study employed curvature, slope, aspect, hillslope, raster, elevation, soil type, lithology, and rainfall. The additional parameters include the outcome from the point and kernel density. The significant differences between the two analyses are shown in Table 2.1.

Table 2.1 Comparisons between Kernel and Point Density

	Point Density	**Kernel Density**
Definition	Point features in a cell's neighborhood are used to estimate the area in magnitude-per-unit.	Fit a smooth tapered surface to each point or polyline and calculate a magnitude-per-unit area.
Density Calculation	The density is calculated only for points within the neighborhood.	Density is calculated only for points or segments of lines inside the neighborhood.
Density raster result	Larger radius values result in a more generalized density raster.	The density raster is smoother and more generalized when the search radius is set to a larger value.

Example	 Example of point density analysis in Evangelista and Beskow (2019).	 Example of kernel density analysis in Connor et al. (2019).
Result		
Previous study	Hydrologically sensitive areas (Thomas et al., 2017), traffic accidents (Netek et al., 2018), and the development of the smart city (Ali Haidery et al., 2020).	Emergency response (Krisp and Špatenková, 2010), criminal hot spot (Kalinic and Krisp, 2018), and bioenergy plant distribution (Laasasenaho et al., 2019).

A raster that evaluates the number of points in each cell's region is known as point density. The shape and size of the neighborhood are essential in this analysis. The final phase reclassifies the results into bands for further analysis.

The kernel density revolves around each point to form a bivariate kernel function. At each point along the curve, the height can be expressed as raster values, with the greatest value in the center and descending values outwards. Once the kernels for each point have been constructed, the raster values are calculated. This signifies that the shape and bandwidth of the kernel are critical. In this context, using too little bandwidth will result in an extremely smooth map, while the use of too much bandwidth will result in a spikey map.

The most notable distinction between the two methods is that the effects of a single point in the point density analysis are consistent across the search radius. In contrast, in the kernel density analysis, the effect of a single point reduces as one moves away from the point. There are significant differences between the point density output and the kernel density output when computing the population density around every output cell (Silverman, 1986).

2.3 Geospatial Data Handling for Sub-surface soil

This study emphasizes the landslides triggered by soil water infiltration into the sub-surface soil layers, which infiltrates according to the type of soil at each soil layer because a different soil type gives a different infiltration rate and saturated hydraulic conductivity. A comprehensive literature review on the topic is required; hence, this section describes the methods used in sub-surface soil mapping and its spatial representation in multi-dimensional.

2.3.1 Current Visualization Technique for Sub-surface Soil

The sub-surface soil consists of layers with different types of soil. The thickness of the soil is required to identify slope strength. However, the measurement of slope thickness is different from one soil to another. For a surface covered by rock fragments with 80%, the depth is measured from the rock's surface.

In some areas, the depth variations are rather complex that they usually cause inadequate topography of the boundary. Nonetheless, irregularities of the boundary of the horizon and layers are common. The distance between the upper and lower boundary is known as the thickness of the horizon and the thickness varies based on the pedon.

Meanwhile, the surface and sub-surface soil water dynamics strongly influence plant growth and chemical behavior. Thus, knowledge of the spatial distribution of soil hydraulic properties and the sub-surface soil layering structures is critical for understanding the classical quantification of sub-surface water movement. However, the typical approach has several disadvantages in assessing the spatial nature of soil hydraulic characteristics because it samples only the sub-surface friction, which makes the evaluation challenging. As such, a flat or a no-slope area is a better place for infiltration because it does not catalyze the water movement, thus giving the water time to penetrate. In contrast, a steep slope forces the water across rapidly on the slope surface (Fallis, 2013). According to Brito et al. (2006), vegetation land use, sandy soil, and no-slope are among the areas with high infiltration, while poor infiltration is represented by the areas with clay soil, impervious land use, and slope greater than 25%.

Ground Penetrating Radar (GPR) and automated surface elevation maps are a hybrid technology used to determine the first continuous clay lens's surface topography to determine spatially directed converging water flow routes. The remote sensing method helps identify the nitrogen status of crops and leaves using an aerial imagery system (SVI), with research focusing on the effects of sophisticated soil water over numerous growing seasons (Gish et al., 2002). In fact, non-destructive testing of structures and soils using GPR has matured to the point where most flaws or initial issues have been reduced (Lucas and Panjota, 2018). Apart from GPR, GIS has also been extensively utilized in the analysis of water infiltration.

The application of the Geographic Information System (GIS) enables the identification of potential water infiltration areas where the variables regulating permeability are ranked and classified according to their influence in the ArcGIS environment (Fallis, 2013). Nonetheless, the use of ArcGIS requires various layers of the map before the analysis can be done, and the layers include soil layer, land use, digital elevation model, and elevation data. Studies have found that the area with high infiltration is residential, whereas the area with low infiltration is industrial. Recent studies have also utilized GIS to find the connection between infiltration and groundwater pollution (Gallagher, 2019), to identify runoff potential (Vikas and Tallavajhala, 2020), and to determine cumulative soil infiltration (Kang et al., 2020). In addition, the derivation of a map in GIS can show a predictor result (Graeme, 1994; Jean and Roberto, 2020). Weight assignment can also be done by determining statistical criteria and spatial relationships such as high-density landslide maps and susceptibility analysis maps.

Based on landslide studies, the failure mechanism is mainly caused by the loss of the matric suction of soil due to high seasonal rainfall. Huat et al. (2006) determined slope angle and ground cover's influence on water infiltration and soil matric suction. Evidently, the infiltration depends on the surface cover where the infiltration is lower in the covered surface than the bare surface. Water infiltration also decreases if the slope steepness increases, and it is higher in the toe compared to the top of the slope. Hence, the higher the rain intensity, the higher the soil infiltration rate and this leads to lower FOS.

Infiltration has been known as part of hydrological and environmental studies. The present study applies several theories across various fields of study to determine the best way to integrate soil water infiltration with landslides. The water movement in different types of soil is one of the parameters emphasized in this study. Since the spatial mapping for infiltration only focuses on suitability analysis and prediction, developing multilayer soil in higher dimensions is, thus, required. As different soil also has different soil water movement patterns based on the infiltration value, representation of this process in 3D is likewise necessary.

The currently available studies have represented soils as a whole. Thus, a 3D SWD FLOW data model was designed to represent the process of soil infiltration by enabling the mathematical computation of various soil data and visualizing the data in 3D. Section 3.4 elaborates on the 3D SWD FLOW data model in detail.

2.3.2 Spatial Representation of Multi-dimensional Soil Data

The 3D word is usually misused in most available software that only displays the 2.5 Dimension (2.5D). The ArcGIS software can store TIN, terrain dataset, raster, and LAS dataset as 2.5D functional surfaces. 2D GIS data can display x and y information, while 3D GIS data can store x, y, and z values. Z-values in ArcScene can represent height and other information such as fatality rate and chemical levels. ArcScene only displays 2.5D data because it can only show one z-value for every x and y data. However, the 3D can store more than one z-value for every x and y location. The 3D city model is widely used in ArcScene because it can support 3D multipatch building where the floor, roof, and the foundation can have different z-values for the same 2D coordinate, and it is known as a thematic-geometric data structure (Döllner & Buchholz, 2005; Döllner, et al., 2006). ArcScene is usually used to render a city model (Günay, 2019) and the elevation point (Li et al., 2019). This type of 3D model is called a solid model surface. Another example of a solid model surface is highway building and the surface of the earth. This solid model is commonly used in computer-aided design (CAD) engineering.

The 3D volumetric in ESRI ArcScene becomes 3D when a 3D object is integrated with the 3D universe and surface analysis in GIS. Meanwhile, 2.5D models are widely used in extruded surface and DEM (Kessler et al., 2009; Gorte and Lesparre, 2012). There is also Multi 2.5D that represents multidimensional (Peningga,2008). Likewise, the unfamiliar 2.7D used by Moenickes et al. (2002) and 2.8D also exist, as mentioned by Groger and Plumer (2011). These dimensions are used before reaching 3D, which is exclusively used for solids, voxel, and tetrahedrons in geometric primitives (Zamyadi et al., 2013).

The 3D image analysis software is used for the 3D reconstructions of pore space to measure morphological changes in the soil structure and connected pore networks under boundary conditions. Peth et al. (2010) addressed the potential of these quantitative data to enhance deformation approaches in soils. The soil structure and associated porous space geometries are highly complicated; hence, the technology of 3D image analysis enables the sophisticated pore space to be quantified as per the hydraulic and mechanical stress changes. Soils are non-rigid structures that change pore space geometries locally. Further developments in imaging methods and 3D soil structure dynamics analysis with physical transport function measurements require a more comprehensive understanding of the soil ecosystem interactions.

ArcMap plays an essential role in mapping, classifying, storing, and analyzing data for research that involves environmental aspects. ArcMap is not only recognized by those in the GIS field but also those in geology, forestry, chemistry, safety, health, and many other fields. Since the present study highlights the soil and water infiltration in 3D, the study area can only be displayed in 2.5D in ArcGIS. However, ArcGIS is crucial for analysis and mapping; thus, another method with different software and approach is needed to produce the expected results.

2.4 The Existing Soil Water Flow Modelling

This section reviews rainfall and soil water infiltration, especially in high elevation areas. This section also explains the current soil water infiltration model with an emphasis on the different physical, empirical, and semi-empirical classifications.