Landslide flow path modelling
A Case Study on Aranayaka Landslide

A dissertation submitted for the Degree of Master of Computer Science

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Declaration

The thesis is my original work and has not been submitted previously for a degree at this or any other university/institute.

To the best of my knowledge it does not contain any material published or written by another person, except as acknowledged in the text.

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This is to certify that this thesis is based on the work of

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under my supervision. The thesis has been prepared according to the format stipulated and is of acceptable standard.

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Abstract

Recent population growth and developments taking place close to landslides prone hilly areas increase their vulnerability. Climate change impacts further raise the potential of landslide hazard. Therefore, to prevent loss of lives and damage to property, proper observation and analysis of unstable slope behavior is crucial.

Landslide flow path forecasting is important for determining a landslide flow route and it is an essential element in hazard mapping. However, due to the complex nature of the phenomenon and the uncertainties of associated parameters flow path prediction is a challenging task.

In this work, the major landslide incident at Aranayaka area in Kegalle district is taken as the case study to model the flow path. At the location, potential source areas were identified on the basis of the Digital Elevation Model. Spreading area assessment was based on two flow directional algorithms namely D8 and Multiple Direction Flow Algorithm. Using this prototype model, a user can interactively get landslide specific statistics such as the maximum width of the slide, runout distance, and slip surface area. Results obtained by the model were compared with the actual Aranayaka landslide data set the landslide hazard map of the area.

Landslide flow paths generated from the implemented tool using D8 algorithm shows more than 65% agreement and Multiple Direction Flow Algorithm shows more than 69% agreement with the actual flow paths and other related statistics. Also, the generated flow path directions and predicted possible landslide initiation points fit inside the actual landslide boundary with good agreement.

Acknowledgment

First and foremost, I wish to express my deepest gratitude and appreciation to Dr. Prasad Wimalarathne, my supervisor, University of Colombo, School Of Computing, for his excellent guidance, care, patience, and providing me with an outstanding atmosphere for doing research from the initial to the final level.

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I convey my special thanks to all the staff members in National Building Research Organisation for their guidance and invaluable encouragement during the project.

Last but not least, I extend my sincere thanks also to my family. I am thankful for my Mother for her love and kindness to whom, I dedicate this work. It is a pleasure to express my gratitude wholeheartedly to my father and my loving brother and sister for their inseparable support and care in the successful completion this research and for supporting me throughout the toughest years of my academic life, and also to my husband for his encouragement and guidance throughout my university life. This project will not be possible without his encouragement that kept me going in the hardest times.

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List of Abbreviations

3D FDS-3D Formal Data Structure

3D TIN-3D Triangular Irregular Network

3D-NS-Three-Dimensional Navier-Stokes

3DOOM- 3D Object-Oriented Model

ASCII- American Standard Code for Information Interchange

DAN-Dynamic ANalysis

DEM-Digital Elevation Model

DSM-Digital Surface Modelling

DTM-Digital Terrain Model

DTM-Digital Terrain Modelling

GIS-Geographic Information Systems

GPS-Global Positioning System

IDW-Inverse Distant Weighted

JICA-Japan International Cooperation Agency

LiDAR-Light Detection and Ranging

MDF-Multiple Direction Flow Algorithm

NBRO -National Building Research Organisation

OO 3D- Object-Oriented 3D Topological

RAM-Random Access Memory

SDF- Single Direction Flow Algorithm

UAV -Unmanned Ariel Vehicles

Chapter 1. Introduction

1.1 Background

A landslide is a wide range of ground movements which happens when a slope changes from a stable to an unstable condition [1]. As per the fact sheet published in 2004 by U.S. Department of the Interior, landslides occur due to geological, morphological causes or human activities. Some of the natural and human factors are weak or sensitive materials, weathered materials, underground erosion, vegetation removal, excavation of slope, mining, and artificial vibration [2].

There are many categories of landslides. These are Rock Slides, Earth Flows, Debris Slides, Debris Flows and Rock Falls [3]. Debris Flows and Rock Falls occur in Sri Lanka, but most of the time we refer to all the slides as landslides. Rainfall is the triggering factor of most landslides in Sri Lanka. At times of heavy rainfall, water penetrates through the top soil on the ground into the deep soil layers beneath, consequently filling in empty pores in the soil. When the water in pores reaches to saturation, it brings to bear a pressure internally called ‘pore water pressure' and most of the time this causes a landslide.

Landslides were not a well-known incident in Sri Lanka until recent years. However now, occurrences of landslides have become more frequent and lately, Sri Lanka faced more than 38 landslides within the year 2017 due to heavy rains in fifteen districts. In the previous years also we experienced major landslides in Koslanda, Meeriyabadda, Niyadagala, Aranayaka etc.

1.2 Motivation

There are lots of lives buried under landslides in 2017 as the victims did not have a proper idea where to evacuate when a debris flow was approaching. Some people unknowingly ran into the landslide flow path and lost their valuable lives. If there were suitable awareness about the susceptible landslides and their predicted flow paths, many lives would have been saved as victims know where to evacuate when they notice the environment signals of a landslide. People who are living in the 12 districts which have been identified as areas prone to landslide hazard are well aware of the environment changes and prior identification signs of landslides. However, the absence of paying attention to the environment during rains and lack of knowledge where to evacuate during a slide, have caused the loss of many valuable human lives.

Landslide flow path prediction is very important for determining the flow route and the depositional area, which are essential elements for producing landslide hazard maps, early warnings, evacuation and landslide mitigation. It is a key component in risk assessment and design of remedial measures against rapid landslides.

Therefore, the development of an indicative susceptible map of the flow path and run out spreading is important in the identification of hazardous zones and in decision making to minimize the socio-economic impacts during a landslide disaster.

1.3 Problem Statement

National Building Research Organisation (NBRO) is the only government institution dealing with investigations, risk analysis, hazard mapping, ground movement & rainfall monitoring, early warning for evacuation, and awareness related to landslides in Sri Lanka over the past few decades. By gathering useful information in fieldwork, analyzing them, and assessing the associated landslide risk, NBRO prepares Landslide Hazard Zonation Maps covering all the areas prone to landslide hazard in 12 districts in the country.

NBRO has different divisions which are directly involved in landslide work. Geotechnical Engineering division does the subsurface studies and soil investigations; Human Settlements Planning and Training Division does geospatial mapping and digital surface modeling; and Landslide Research & Risk Management Division does the identification of landslide-prone areas, early warning, & mitigation.

Lack of integration of data produced by different divisions may not result in the prediction of landslide flow path and other statistics such as debris-flow volume, and runout distance of the landslide. Also, lack of a user-friendly graphical user interface (GUI) which combines related data together and produces valuable outputs may also have discouraged interested users who favor a visual approach. Moreover, the analysis involves processing of very large DEMs and processing certain computations repeatedly large number of times are common and requires efficient computational techniques. Therefore, there should be a method which grabs the useful data from relevant divisions and produce valuable information which could be used in the awareness, early warning, evacuation, and mitigation.

1.4 Aims and Objectives

At present, rainfall threshold is the main factor for issuing of landslide early warning in Sri Lanka. Together with the warning, if integration of possible landslide runout flow paths can be predicted, then it will be a major advantage as it helps to understand the behavior of landslides to design adequate protection measures and to assess the required evacuation time for the population. The important point of runout modeling is to predict accurate dynamics and the potential area that might be affected by a slide.

When dispensing early warning it is impossible to visit each and every site before issuing of warning. Even without site specific information, if there is a method that can be used get an idea of the landslide-prone area, then according to the rainfall the flow path of that area can be predicted and evacuation paths can be decided. Instructing people accordingly will reduce the possible damages to lives during the landslide. Also, this work can be used as a tool to get an idea about the elevation and possible flow paths of a site prior to visiting.

Main Objectives of this project can be summarized as below,

- Develop a tool that integrates landslide related data produced by different divisions at NBRO to predict landslide flow path for Aranayaka Landside.
- Allow users to analyze the debris flow path generated from D8 SDF algorithm and MDF algorithm with actual landslide flow path.
- Generate landslide statistics such as Area of Main Landslide Body, Landslide crown, Maximum Width, Length of the main body and Flow length of Aranayaka Landslide.
- Without site specific data, predict possible landslide initiation points, flow path at Aranayaka Area.

1.5 The scope of the Project

This research mainly focuses on the tragic landslide at Aranayake as a case study. It happened on 17th May 2016 at around 4.30-5.00 in the evening, completely burying parts of three villages, namely Siripura, Elangapitiya, and Pallebage [4].

The study area Aranayaka is located in the eastern part of Kegalle district, with the elevation ranges from 250m to 1800m above Mean Sea Level with mountainous topography. Predominant rock types of the area are Charnokitic gneisses and Garnet biotite gneisses [5]. This landslide prone area commonly experiences heavy rains during the monsoon periods and the landslides recorded within these areas are higher in this period. Sloping terrain conditions and the favorable morphology incorporated with the intense rainfall caused the most triggered and fatal slides of Aranayaka landslide in those study areas.

In this study, the key aim is to identify the flow path of Aranayaka landslide and inactively predict statistics of that landslide such as debris-flows volume and runout distance.

1.6 Structure of the Dissertation

The report is organized as follows.

Chapter 2:

This chapter presents the literature review of the research including related works in the field of landslides. Researches conducted using different models to predict flow paths and their accuracies are evaluated in this chapter.

Chapter 3:

In chapter 3, in depth analysis of the Aranayaka landslide is discussed as these data are used for evaluation of the developed algorithms.

Chapter 4:

This chapter discusses the methodology carried out for implementation. Also, Basic theories adopted by this research are discussed and justified.

Chapter 5:

This chapter discusses the methodology used in the evaluation procedure of the final developed tool.

Chapter 6:

This chapter lists out the final achievements and generated statistical results throughout the entire research project.

Chapter 7:

This chapter is the final chapter of the document and it includes the conclusion and proposed possible future enhancements.

Chapter 2. Literature Review

2.1 Introduction

This chapter presents the survey of the literature that was carried out in order to gather information and knowledge for conducting this research, and duly documented in this dissertation. To make the survey a success, a number of different knowledge sources including field related books, published research papers were referred.

As described in the previous chapter the term “landslide” is a process of downward movement of a slope. Slope forming can be materials such as rock, soil, artificial fill, or a combination of any of those. The movement of the material can be falling, toppling, sliding, spreading, or flowing. Figure 2.1 shows a classification of types of landslides.

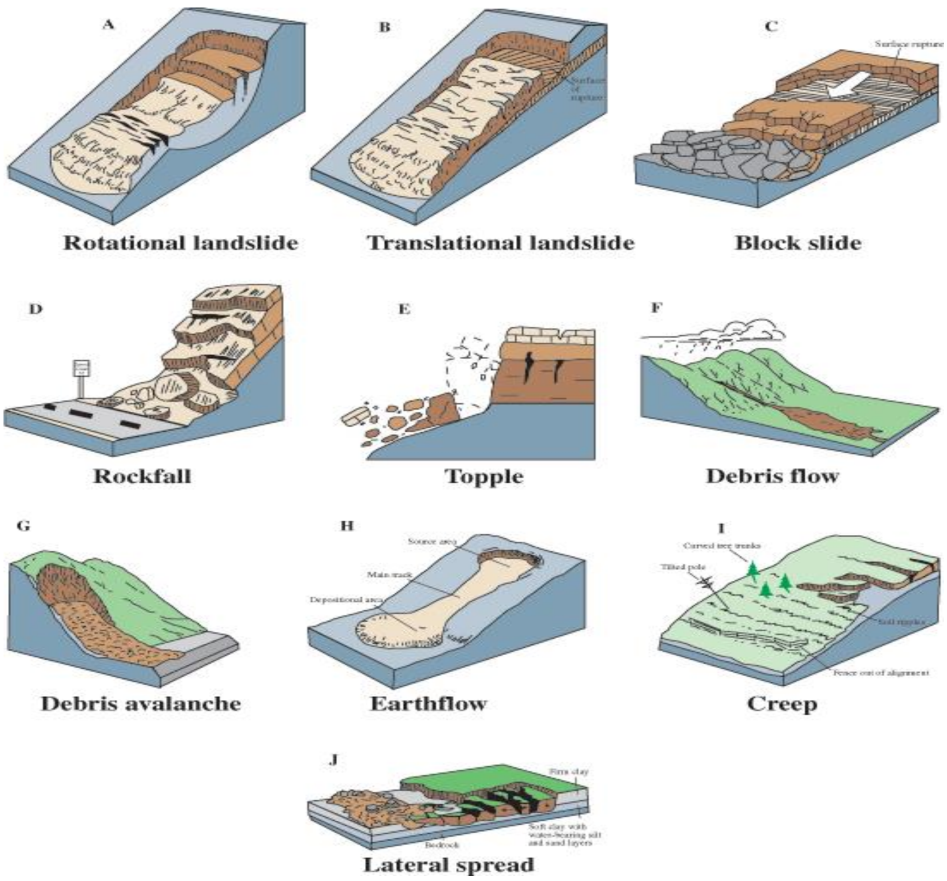

Figure 2.1: Types of Landslides [2]

Landslide specific terminologies are used throughout this report. Figure 2.2 shows the main glossary used in the context of a landslide.

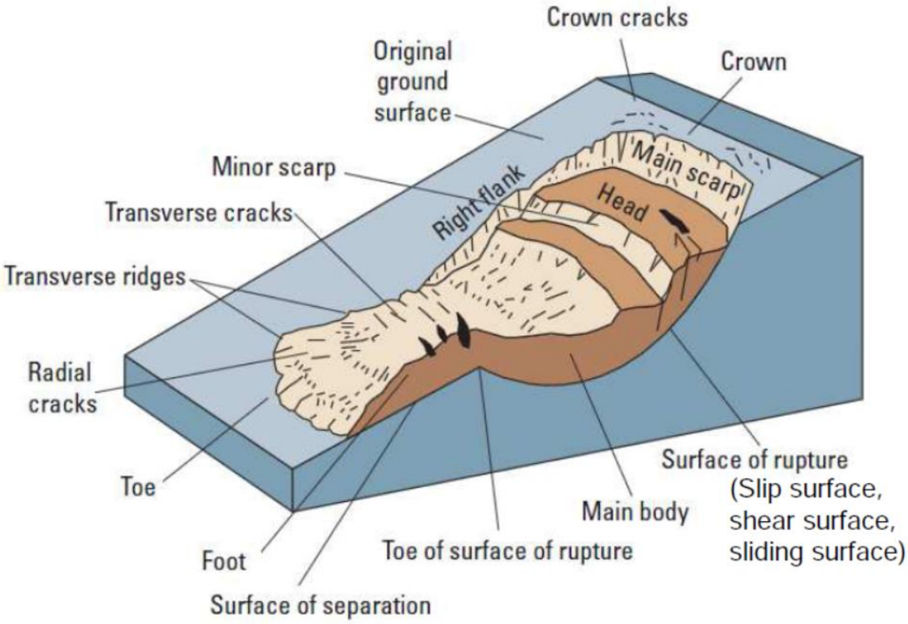

Figure 2.2: Landslide Glossary [2]

Landslides are among the natural geohazards which result in the loss of life and damage to the natural and built environment and cause huge social and economic problems worldwide. There are lot of researches carried out globally to predict, mitigate and manage these types of disasters and do better decision-making. Following are some attempts done by people around the world to predict landslide initiation points, flow path and run out distance.

2.2 Literature Review

In 2000 Gorsevski et al. came up with a hazard prediction mechanism which used Digital Elevation Model (DEM) with the geographic information system (GIS) [5]. In this approach, classification of stable and unstable landslide-prone areas was done using decimation analysis which is a multivariate rule building technique and to in the judgment, the normal distribution is used. If data do not fit with the normal distribution, K nearest neighbor classification is used with k set to 5. Prior knowledge based on experience and heuristic knowledge is used to minimize the error as the prediction can make misclassification.

DEM is also used in a testing model for the timing and location of shallow landslide initiation by Casadei et al., which was developed in 2003. This paper demonstrates how to integrate dynamic and spatially distributed shallow subsurface runoff model with infinite slope model to predict the spatial distribution of shallow land sliding [6]. The model used here couples the infinite slope stability equation with a dynamic hydrological model. It represents an attempt to model the hydrological response of hill slopes with a minimum set of parameters, using widely available data.

In the paper “Combining Spatial Models for Shallow Landslides and Debris-Flows Prediction” done by Gomes et al. a map has been constructed which contained landslides initiation points, debris-flows volume and runout distance of mass movements in Quitite and Papagaio in Rio de Janeiro city, Brazil [7]. In this study, the landslide model (SHALSTAB) was integrated with the debris-flow simulation model (FLO-2D) to get more vulnerable mass movements and compare the result with the landslide and debris-flow event of February 1996. To get the best fit model back analysis method is used for some parameters. However, obtained data from back-analysis should be carefully evaluated as the model does not consider the natural changes of the rheological parameters during the event and results are very sensitive to the wide variability of rheological parameters and the set of best-fit parameters may diverge from reality [7].

Calibration of numerical models for debris flows in Yosemite Valley, California, USA is a numerical comparison of actual runout distances with numerical simulations by P. Bertoloand G. F. Wieczorek [8]. For this comparison 6, pre-known landslides in Yosemite Valley were used. This study also used the two-dimensional FLO-2D model with the one dimensional DAN (Dynamic ANalysis) model to predict and compare the runout distance in the study area. In this paper also the back analysis for the debris flow has been performed on selected sites using a trial and error method. They have applied the Digital Terrain Model (DTM) of the sites, as the used DAN and FLO-2D models highly depend on the topology of the landslide. A combination of DAN and FLO-2D can predict the debris-flow behavior in other areas with geology, morphology, and climate similar to Yosemite Valley [8].

Dynamic simulations of landslide runout carried out by Tesfahunegn Abera Gebreslassie for his master's research using DAN3D and BING models [9]. Finneidfjord quick-clay landslide has taken as the case study to stimulate the above models.DAN3D and BING models require terrain models of the path and the mass at the release area, shear strength and the dynamic viscosity as inputs and calculate the runout distance and the flow velocity. This study shows that the runout distance is higher using DAN3D than BING model, however, DAN3D uses ten times execution time than BING model.

In 2006, P. Tarolli and D. G. Tarboton presented an approach to determine susceptible origination points for landslides using a terrain stability model. In this, high-resolution terrain data derived from airborne laser altimetry (LIDAR) survey were used [10]. Mapped landslide runout zone was compared with available stability map and the evaluation. It was done using different terrain stability models and it showed that the relative density from a most likely landslide initiation point approach is useful for the effectiveness of a terrain stability map in this study area (the Northeastern Region of Italy) [10]. Also using this study they identified that DTM with the scale of 10 m width is ideal as DTM larger than 10 m results in loss of resolution and degrades the results in complex landslides occurred in this region.

A model called TSUNAMI3D was developed by Gyeong-Bo Kim to predict sub-aerial landslides which caused tsunamis. This model used laboratory experimented with tsunamis for validation. The ultimate goal of this research was to obtain better tsunami calculation tools for real-world application of 3-D models for landslide tsunamis. For this approach, two three-dimensional Navier-Stokes (3D-NS) models and FLOW-3D models were used [11]. Those models used soil rheology on complex domain geometry to simulate waves generated by deformable subaerial landslides as subaerial landslides phenomenon are complex to model.

In 2016, a paper presented by Formetta et al. came up with a methodology to systemically calibrate, verify, and compare different models and select the models whose behavior is the most reliable for a particular case study. This approach integrates hydrological model package, (NewAge-JGrass) and other components, such as uDig open-source geographic information system, physically based landslide susceptibility model, parameter calibration algorithm and a model for pixel-by-pixel comparison of modeled and actual landslide [12]. The procedure was applied in a test case on the Salerno–Reggio Calabria highway landslide with effective performance. This integrated method would be useful for landslide early warning systems and for decision makers who deal with risk management assessments.

GIS is a widely researched method for landslides. The paper by F.C. Dai and C.F. Lee also used GIS in their study. To describe the physical characteristics of landslides and the statistical relations, existing digital maps and aerial photographs of Lantau Island in Hong Kong were used with GIS. When predicting slope instability with a logistic multiple regression model, parameters such as slope gradient, lithology, elevation, slope aspect, and land-use were used [13]. This model predicts landslide occurrence with Logistic multiple regression with an accuracy of 85%.

Landslide runout analysis — current practice and challenges by Scott McDougall presents a good review of tools and methods that have been developed, challenges faced by researchers, challenges solved by researchers, simulation of debris flows and potential future works [14].

Quinn et al. came up with a concept of TOPMODEL which is a mathematically simple model which relies on the preprocessing of digital terrain data. It has been tested with Booro-Borotou catchment and the model follows flow assumptions and the derivation of ln(a/tan **a)** distribution from the DTM data, where ln is the Napierian logarithm, a is the upslope area per unit contour length, and tan a is the slope gradient [15]. This TOPMODEL is used by Venkatesh et al. with two approaches namely, Single Direction Flow Algorithm (SDF) and Multiple Direction Flow Algorithm (MDF). These algorithms applied to Malaprabha catchment. However, when analyzing the effect of these approaches on the simulation, the results show that the SDF and MDF have a slight effect on the efficiency of the model and also on the model parameters, though, choice of these approaches does not have any effect on the simulation of flows [16].

In 2009 Guang-ju et al. discussed two flow directional models, the agree method and the shortest path method. These two were tested on the Xitiaoxi Catchment and the results indicate that both methods can be successfully applied to discharge simulation [17]. Both approaches use a DEM and a stream vector as inputs and obtain a good agreement between observed and modeled drainage structures.

In 1997, a new procedure for representation of flow directions and calculation of upslope areas using rectangular grid digital elevation model was presented by David G. Tarboton [18]. The procedure is based on representing flow direction as a single angle taken as the steepest downwards slope on the eight triangular facets centered at each grid point. The upslope area is then calculated by proportioning flow between two downslope pixels according to how close this flow direction is to the direct angle to the downslope pixel [18]. Different other flow directional methods are also discussed in the work and results from these different methods differ on the choice of methods; however, the new method offered a simple effective approach for consideration.

In National Road N7, Argentina numerous catchments are prone to debris flows. Therefore, a study was carried out by Valérie Baumann in 2007 [19]. For the estimation of the debris flow spread, GIS-based model (Flow-R) has been used with basic probabilistic and energy calculations. The results are realistic and it will be useful for detailed studies.

The study carried out by Petter Pilesjö et al. compares different methods for the estimation of drainage directions and flow accumulations from gridded DEMs. Different shapes of DEMs and different flow accumulation in hydrological models were analyzed in their work [20]. Also John P. WILSON et al. have done a review of flow routing algorithms such as D8, Rho8, FD8, DEMON etc… However, authors concluded that this work requires a greater investment in fieldwork and data modelling in a variety of landscape settings for actual comparison of flow routing algorithms [21].

In Sri Lanka, there is very limited literature available on the analysis of landslides by integrating different models. Therefore, this research would fill that gap to some extent by integrating and developing models for landslides in Sri Lankan Context.

2.3 Chapter Summary

Literature of currently available tools and methods to conduct landslide runout analysis and modeling for certain types of landslides around the world are discussed throughout this chapter. Application of already available run out generation tools such as Flow-R, DAN3D are discussed and different run out modeling algorithms such as D8, Rho8, FD8, MDF are analyzed.

Chapter 3. Analysis of Aranayaka Landslide

3.1 Background of Aranayaka Landslide

In this chapter, a detailed analysis is carried out to identify the background of the selected landslide. Siripura, Elagapitiya landslide is large scale debris and mudflow occurred in Elagapitiya, Aranayake in Kegalle District (7° 9'15.48"N, 80°25'50.29"E). Approximate length of the landslide is about 2.26 km. Landslide flowed through the Samasara Kanda at Elagapitiya disappearing houses of three villages with many of its inhabitants without a trace.

During the four days from 14.05.2016 to 17.05.2016, this region experienced a cumulative rainfall of about 435 mm, as per the data from automated rain gauges of NBRO. With the continuation of rainfall, a sudden landslide occurred on 17th May 2016 at around 4.30-5.00 in the evening.

This landslide had taken place on a slope inclined towards the north-east direction. When its geomorphological formation is considered, the affected area is having a sharp slope. The slides occurred on the upper and middle of the slope, where the slope is nearly vertical at two places. At the intermediate area of the slope and just below the escarpment, there are two major valleys oriented towards north and north-west.

Subsurface consists of heavily jointed rocks. Therefore, this area has had a high potential for a landslide. There had been many houses and the entire area had been cultivated with minor export crops (cloves, coffee, pepper etc.) and fruits.

3.2 Analysis of Aranayaka Landslide

According to the 1:10,000 scale landslide risk zonation map created by NBRO for the Aranayaka Divisional Secretariat, landslide initiation zone falls on to the high hazard area of the risk zonation map.

The width of the crown of the landslide is about 345 -350 m and the widest part of the landslide is approximately 600 m. The region covered with the debris at the toe of the landslide could be split into two regions: the left side is about 75-125 m wide while the right-side is about 350-450 m wide.

Deep-rooted vegetation is essential for guaranteeing the stability of soil slopes. Vegetation like forest cover allows water to infiltrate the soil slowly, and deep root systems protect the slope by strengthening loose overburdens by anchoring into the hard layer. The root system of tea plants is not capable of providing such protection. It was observed that the area where this landslide has been triggered is mostly covered by the tea plantation, which may have been a contributing factor to the landslide.

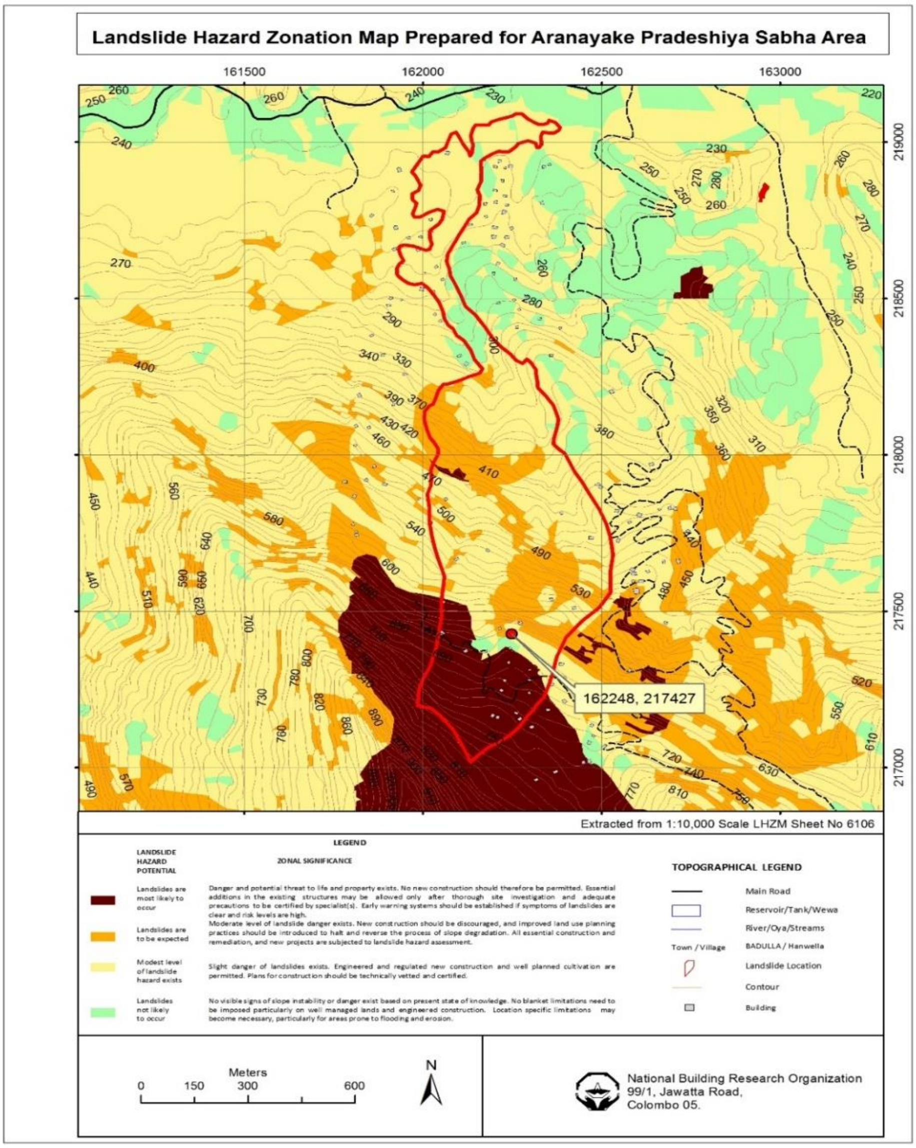

Figure 3.1:1:10,000 scale landslide risk zonation map for the Aranayaka Divisional Secretariat (Source: NBRO)

Several major factors contributed to this disastrous event. Some of them are improper land use methods in the tea cultivation which caused high pore water pressures, thin soil layer and rock underneath, and the heavy rainfall.

The debris flow that started at the steep escarpment at the upper level had moved down to the flat terrain. The debris flow had then moved down the second steep escarpment destroying the houses in the lower level. The speed of the debris flow would have increased several times more when it moved downwards along the escarp slope found at the intermediate region of the slope. Figure 3.1 shows the actual flow path area mapped in 1:10,000 contour line map.

The mass of collapse flew down from 2 directions, and it is assumed that it joined into one stream and ran down as a debris flow. Most of the debris seemed to be deposited near the end point of the valley. Two directions can be clearly seen from the generated drone image map after the landslide as shown in Figure 3.2.

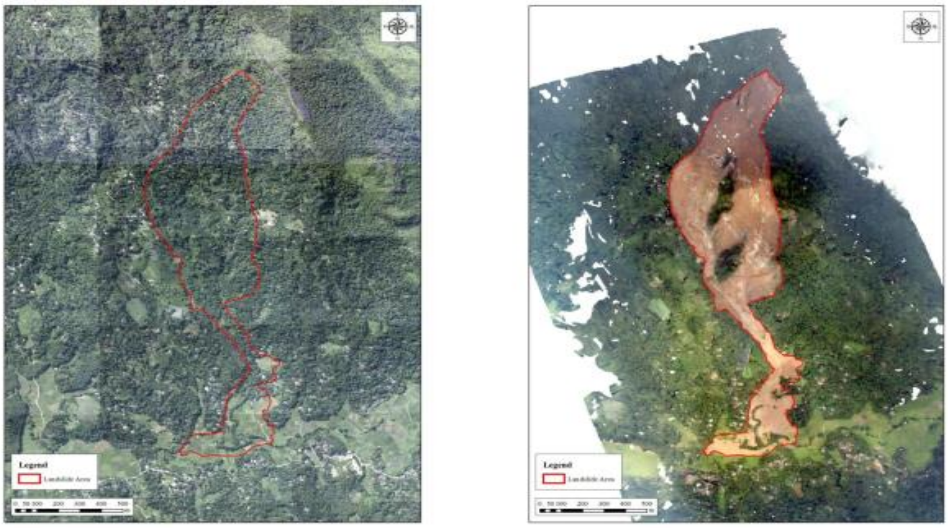

Figure 3.2: Aranayaka Landslide before and after [4]

3.3 Chapter Summary

A depth background analysis, courses for the selected Aranayaka landslide and available statistics are discussed and Landslide statistics presented over this chapter is used to evaluate the tool developed in this project.

Chapter 4. Design and Implementation

Development of the model is done using MATLAB R2017 which is a multi-paradigm numerical computing environment developed by MathWorks [22]. It is used for analyzing data, developing algorithms and creating models. Matlab was chosen since it provides a flexible environment for mathematical and technical computing. It is based on a high-level programming language and as such, the functions provided here are easy to modify and open for amendments.

MATLAB image processing toolbox is used for the analysis of Digital Elevation Models (DEMs). The developed tool follows an object-oriented programming (OOP) approach to building flow directions and stream networks.
Following methodology is carried out,

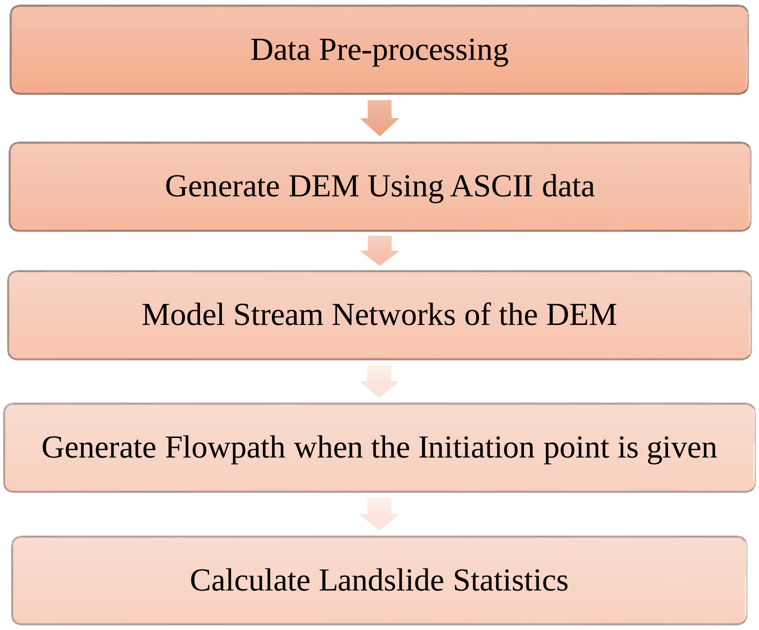

Figure 4.1: Methodology

Step 1: Data Pre-processing

Contour data formatted as shape file was obtained from Survey department of Sri Lanka and converted to ASCII format which is a convenient format to MATLAB. The conversion is done by using inbuilt functions of ArcGIS software.

ArcGIS is a type of GIS which can be used for capturing, storing, checking, and displaying data related to positions on Earth's surface. GIS can use any information that includes location. The location can be expressed in many different ways, such as latitude and longitude, address, or ZIP code [23].

Step 2: Generate DEM Using ASCII data

DEMs are widely used in various types of hydrological modelling. By proper use of a relevant DEM, it would be theoretically possible to estimate critical parameters in hydrological processes of surface water, such as flow direction and flow accumulation. These models could then be combined with other data sets, like rainfall data and infiltration capacity, for practical use.

A 10m resolution couture data was used to obtain DEM of Aranayaka Landslide area. DEM file is created as a grid object which contains a numerical matrix and information on georeferencing. Grid object is associated with datasets such as flow accumulation grids, gradient grids etc. Created DEM has a projected coordinate system (e.g. UTM WGS84) and that elevation and horizontal coordinates are in meter units.

The geographic location of each DEM cell is determined by a coordinate system which assigns a projected location in the xy-plane to each element in the DEM matrix. Thus, the 2D-Euclidean distance d between two cells with the linear index i and j is calculated with X and Y being matrices with the same size as Z where each element refers to the x- and y-coordinate respectively. Euclidian distance defined as squared distances between two vectors in multidimensional space is the sum of squared differences in their coordinates as shown in *Equation 4.1.*

$$dij = \sqrt{(xi - xj)^2 + (yi - yj)^2} \qquad \text{---------} \textit{ Equation 4.1}$$

2D-Euclidean Distance [24]

Step 3: Model Stream Networks of the DEM

An instance of stream object encapsulates the information on geometry and connectivity of a stream network based on the flow direction of a digital elevation model. A flow routing algorithm determines the way in which the outflow from a given cell will be distributed to one or more neighboring downslope cells. The choice of flow routing algorithm is important as it affects the calculation of the upslope contributing area, the prediction of flow accumulation.

Flow directions are classified into single-neighbor and multiple-neighbor flow algorithms. Single-neighbor algorithms pass the flow from each cell to its lowest neighboring cell which is water flows along the steepest gradient. Multiple-neighbor algorithms comprise a number of different approaches to model the flow, which is particularly important for simulating water distribution on hill slopes. The MDF algorithm partitions and transfers discharge in each cell in multiple directions to all downward neighbor cells and thus allows for divergence and convergence of flow [15, 25].

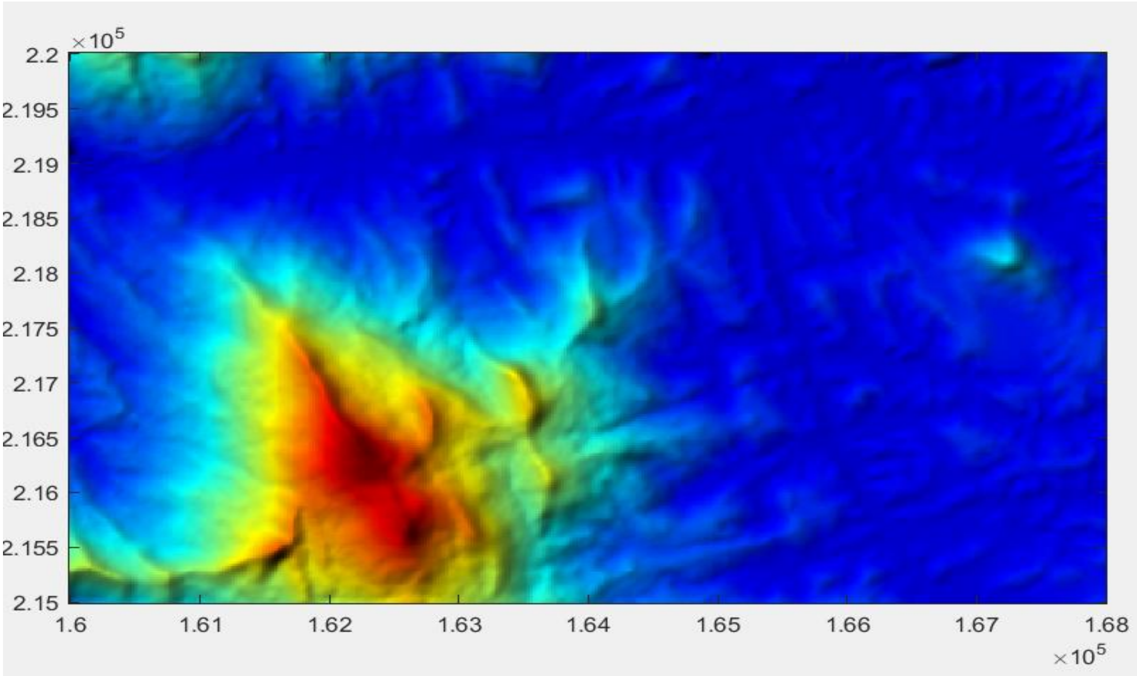

Figure 4.2: Example of generated DEM

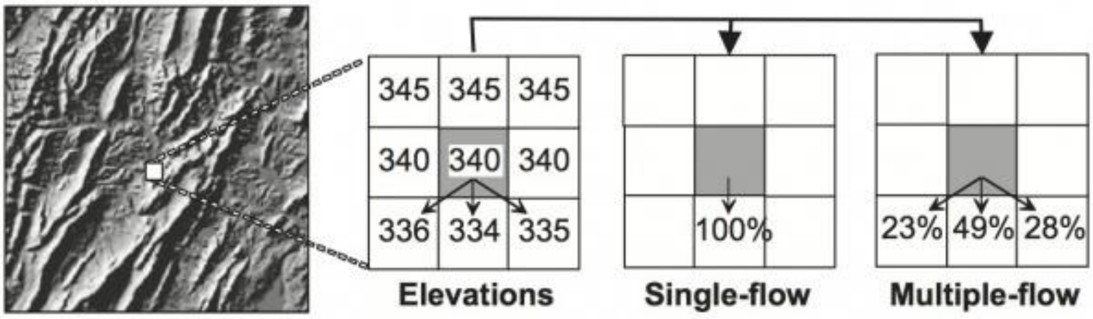

Figure 4.3: Flow accumulation by single flow direction, and multiple flow directions [26]

To use SDF or MDF it is important to calculate the gradient of the location. Finding the maximum gradient requires the calculation of all slopes between all neighboring cells. The slope Sij between two neighboring cells i and j is calculated by Equation 4.1 where dij is the distance between the cells i and j as calculated in Equation 4.1. Applied to all cells and their respective neighbor cells the results are transferred to a matrix S with i as row indices and j as column indices of the slope values.

$$Sij = \frac{Zi-Zj}{dij} \qquad \text{-------}\textit{Equation 4.2}$$

Gradient [27]

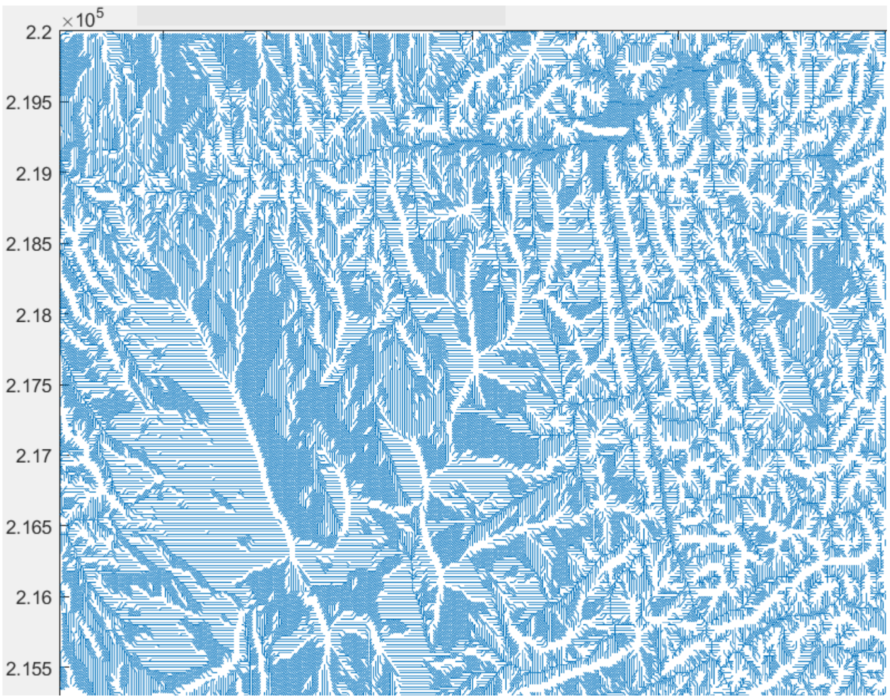

Figure 4.4: Example of generated Streams

Step 4: Generate Flow path when the Initiation point is given

To create a flow path, a flow direction object has to be created which can be used to calculate terrain attributes such as flow accumulation, drainage basin outlining, flow path extraction, etc. Flow direction can be calculated from the original digital elevation model and it contains a topological ordering of the DEM nodes.

The debris flow runout algorithms, control the direction of the flow from one cell to its eight neighbors. To serve the purpose, few SDF and MDF algorithms were used.
The D8 (deterministic eight-node) single-flow-direction algorithm is one of the basic and well-known algorithms which directs flow from each grid cell to one of eight nearest neighbors based on the gradient of the slope. To calculate the primary flow, the direction the slope (*Si*) to each neighbor has to be calculated and set the direction for which *Si* is the greatest [21].

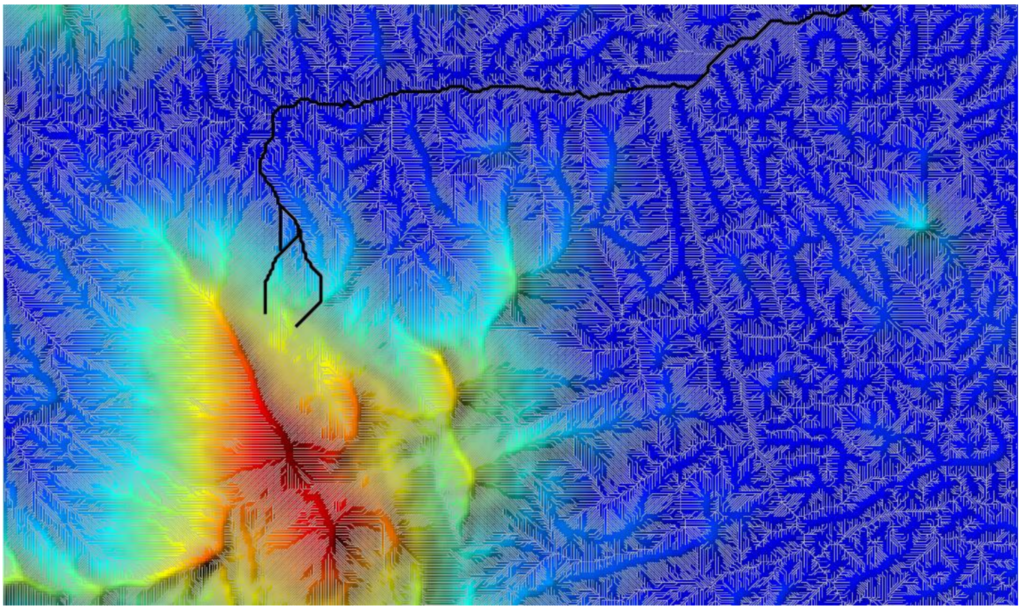

Figure 4.5: Example of generated flow path-SDF

However, SDF produces unrealistic, over-concentrated flow in topographic lows while divergent or braided flows are not represented [28]. To overcome the weaknesses of SDF, a MDF was developed. The MDF algorithm partitions and transfers discharge in each cell in multiple directions to all downward neighbor cells and thus allows for divergence and convergence of flow [15].

The FD8 is the first MDF algorithm and it directs water to every adjacent downslope cell on a slope weighted basis. The slope gradients, slope lengths, and two weights are used to direct the flow from the center cell to each downslope cell in a 3 x 3 moving window. Each cell receives a fraction of the discharge from each upslope cell, and therefore, the upslope contributing area of the receiving cell is typically composed of partial contributions from many different cells [21]. In this study SDF algorithm (D8) and one MDF algorithm is developed and tested.

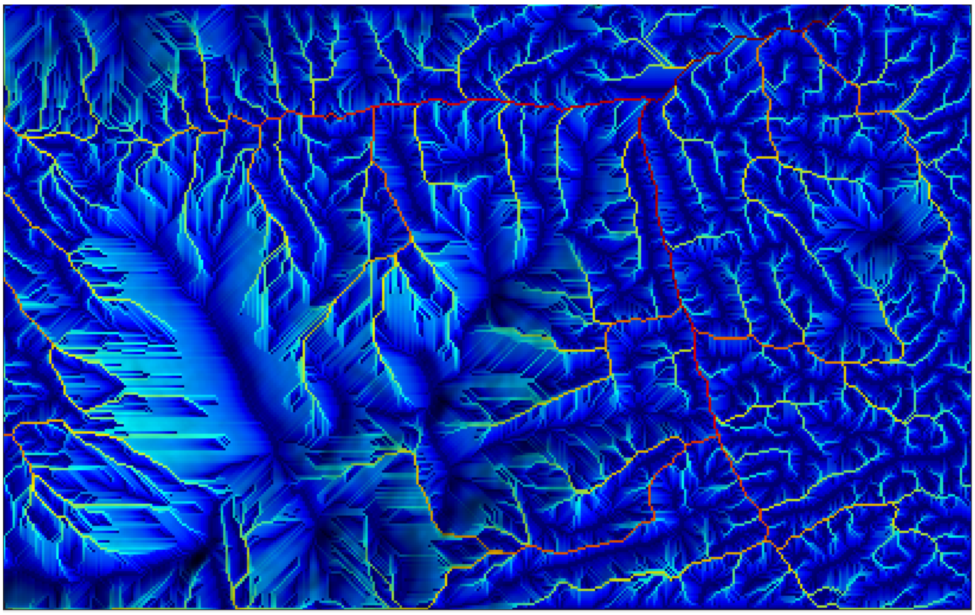

Figure 4.6: Example of generated flow path-MDF

Step 5: Calculate the Landslide Statistics

Finally, statistics of the landslide such as landslide area, runout distance can be generated. To calculate the above statistics main user input is the initiation points of the landslide. Statistics are produced using flow paths generated from different flow routing algorithms. These statistics can be verified with actual Aranayaka landslide data taken from NBRO.

To calculate statistics multiple points are selected from the generated main body of the landslide. As shown in figure 11 and 12, B and C are the initiation points and A is selected as the toe of the main body. The Euclidian distance between points of the flow paths B-A and C-A are calculated and from that total main body area (area covered by A, B, C points), crown width (Euclidian distance between B-C), maximum width is derived. All these statistics are calculated for both SDF and MDF flow paths.

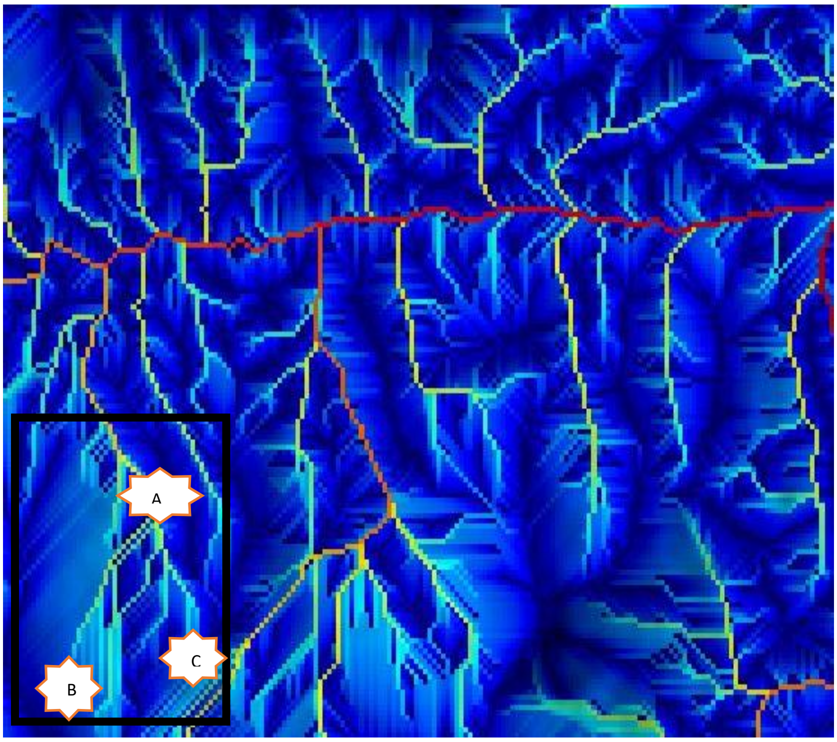

Figure 4.7: Selected points from the main body of the landslide (MDF)

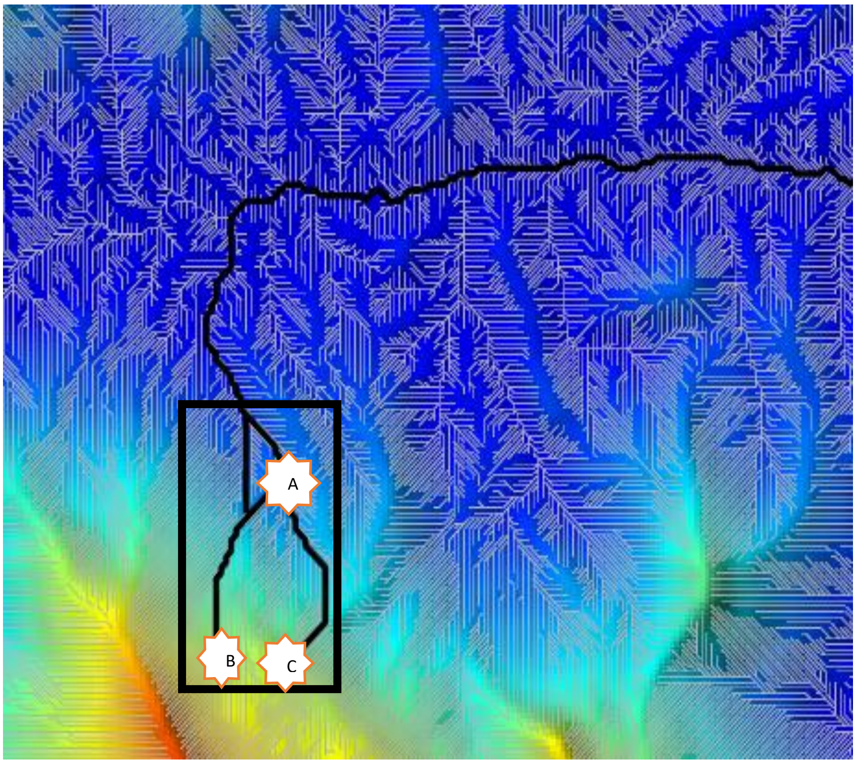

Figure 4.8: Selected points from the main body of the landslide (SDF)

Maximum runout distance is another important statistic that can be generated from the SDF and MDF models. When the flow path initiation points are given the linear indices starting at initial points based on flow directions derived from the stream networks in the area. For B and C, the starting points length of the flow path Vs elevation graphs is generated for both SDF and MDF models. Both models produced almost similar graphs as shown in figure 13 and 14.

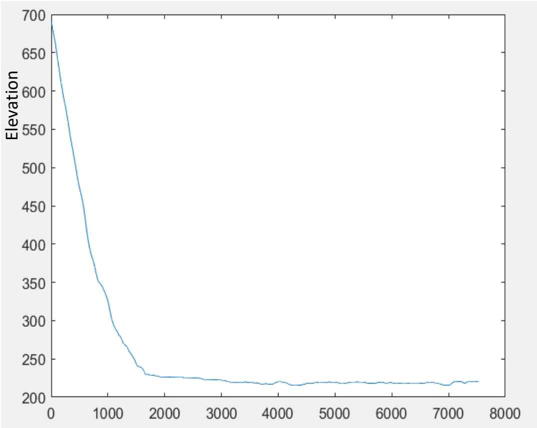

Figure 4.9: Elevation Vs Distance for point B

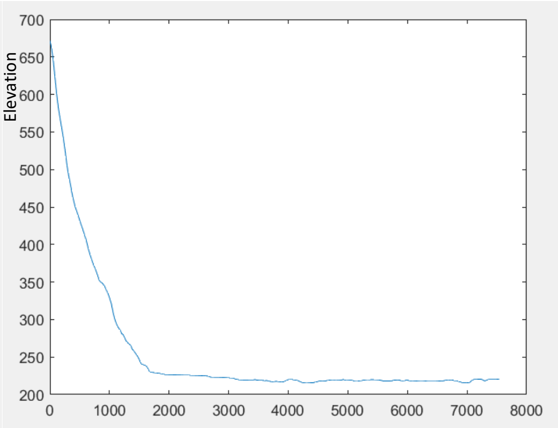

Figure 4.10: Elevation Vs Distance for point C

As per the calculations the maximum runout distance is around 7.5 Km for both models. However, as per the generated graphs, it is observed the elevation is more or less the same or the slope does not have rapid changes after 1.75Km. Therefore adjustments have to be made to calculate runout distance.

4.1 Chapter Summary

Contour data in shape files format obtained from Survey department of Sri Lanka are the main inputs to the generated model. With the use of DEM created with the ASCII formatted data of the Aranayaka area, all stream networks are generated based on the elevation. These generated streams are used to identify and visualize flow paths by setting the initiation point or channel head of the flow direction manually. Then landslide statistics are calculated for both D8 and MDF algorithms. The models have been geo-referenced appropriately, so the actual boundary can be laid on top of the produced models by examining longitude and latitude. Statistics and flow paths generated in this are taken for evaluation in the next phase.

Chapter 5. Evaluation

5.1 Evaluation Criteria

The developed model can be evaluated using the pre and post available data of the landslide. In Aranayaka post landslide data such as drone images after the disaster and actual flow path and other related statistics such as length of the landslide, and flow volume are taken as the baseline for the evaluation criteria. Therefore, the accuracy of the generated information from this research can be tested with available post data for compatibility and for deviations.

After creating all the available streams of the landslide area, the flow path is predicted with the given landslide initiation point. Afterward, the actual boundary created with ARC GIS can be placed on top of the generated model to check for closeness.

5.2 Evaluation Approach

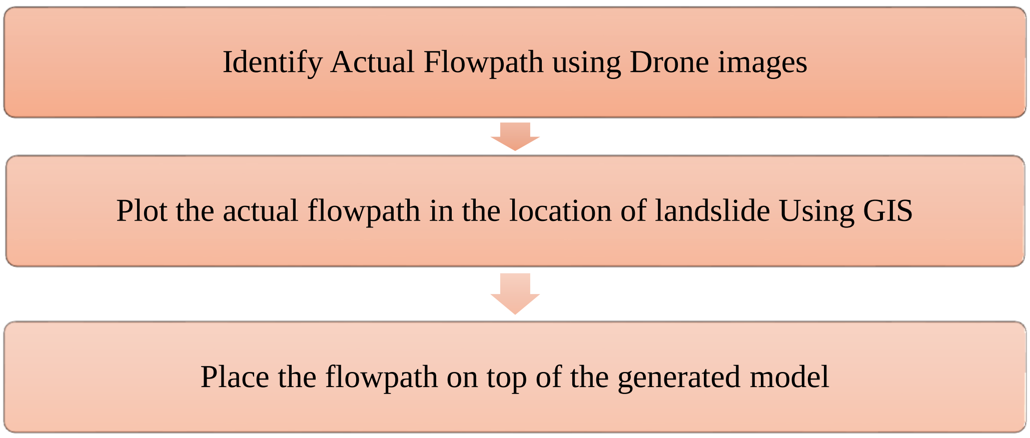

Figure 4.1: Evaluation Methodology

Step 1: Identify the Actual Flow path using Drone images

Unmanned Aerial Vehicles (UAV) is a useful technology to capture aerial images with Global Positioning System (GPS). Using drones for mapping is a fast, lost cost, safe and accurate method. Then image processing techniques can be used to combine the images and develop orthophoto from many individual photographs. Additionally, generating contours, Digital Surface Modelling (DSM), and Digital Terrain Modelling (DTM) can be developed through this image processing software. After gathering this information, it is easy to calculate the number of damaged buildings, vegetation loss, soil loss and soil accumulation. Also, it helps to estimate any challenges and further actions that should be taken by visualizing the 3D image of the landslide.

The following shows the activities that were carried out in the field assessment. The drone was flown over from the mid-point of the landslide and captured geotag aerial photographs.

DJI Panthom III drone was used to collect this information and both autopilot and manual flying was carried out. "DGI Pro" and "Drone deploy" software was used to control the drone and Google Earth was taken as the base map. The flying path was manually set and continuous photos were taken during the mission. The drone captured multiple photos of each distinct feature, from multiple angles. Sufficient image overlap should be identified for better map detail and for efficient processing. In this case, 55%-65% image overlaps were preserved throughout the task. Altogether 577 images were taken to cover the entire landslide area. The mapping accuracy is dependent on different factors such as drone condition, camera quality, weather condition of the area, flying heights, GPS accuracy, etc…Autopilot mode was used to minimize the handling error while capturing the images.

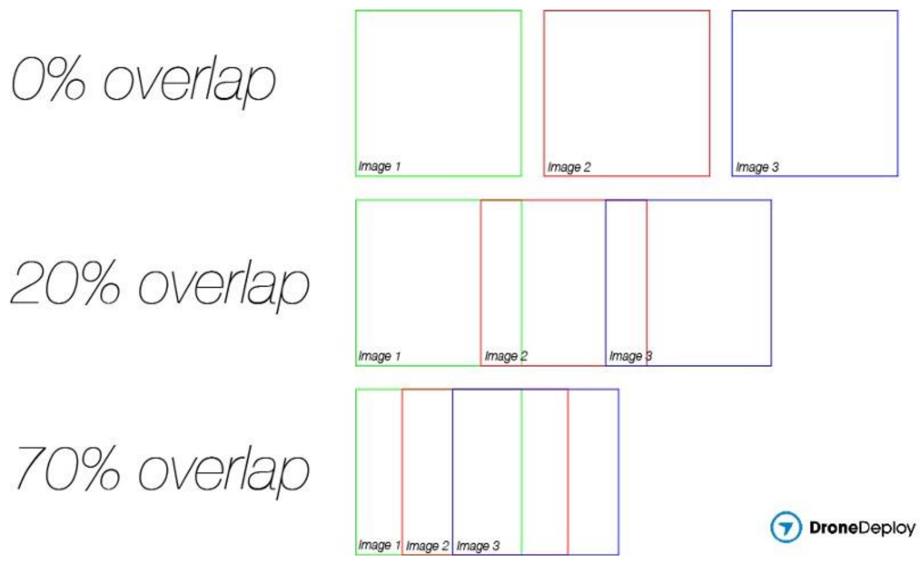

Figure 5.2: Drone Image Overlap [29]

Generation of 3D model and Digital Elevation Model (DEM) was done using Agisoft photo scanner software. It is image processing software which automatically builds professional quality textured 3D models from a robust alignment of still images. The contours were generated primarily from newly generated DEM (after landslide) and previous contours were obtained from secondary sources.

Figure 5.3: DEM Created using Drone Images

Step 2: Plot the actual flow path in the location of landslide Using GIS

The goal is to verify the flow path of the Aranayaka Landslide generated by the model. For this purpose landslide flow path generated by drone images are plotted in the Aranayaka map by georeferencing. ArcGIS is used for the mapping. It is a geographic information system (GIS) for capturing, storing, checking, and displaying data related to positions on Earth's surface. By relating seemingly unrelated data, GIS can help individuals and organizations to understand better spatial patterns and relationships. Locations can be expressed in many different ways, such as latitude and longitude, address, or ZIP code.

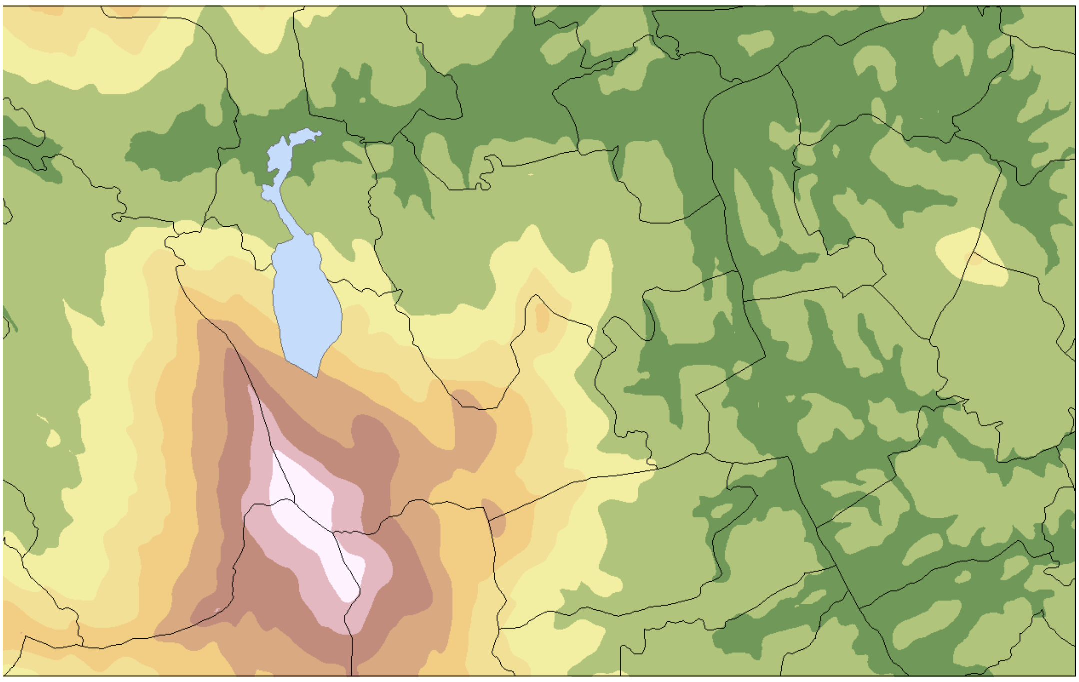

Figure 5.4: Actual Landslide Flow path Mapped in DEM

To map the landslide flow path, contour data of the studied area was taken from Sri Lanka Survey Department (SLSD) which is the national surveying & mapping organization.

For evaluation of the carried out work, Aranayaka landslide data were taken from National Building Research Organisation (NBRO) which is designated as the national focal point for landslide risk management in Sri Lanka. Using the data obtained from NBRO, actual boundary of the Aranayaka landslide area is generated on top of the contour map. The produced boundary is used to evaluate the model generated from MATLAB.

Step 3: Place the flow path on top of the generated model

Actual landslide flow path mapped from ARC GIS in the previous step is placed on top of the generated model by geo-referencing. For geo-referencing in MATLAB M_Map v1.4 toolbox is used. M_Map is a set of mapping tools written for Matlab and it includes routines to project data using spherical and ellipsoidal earth-models [30].

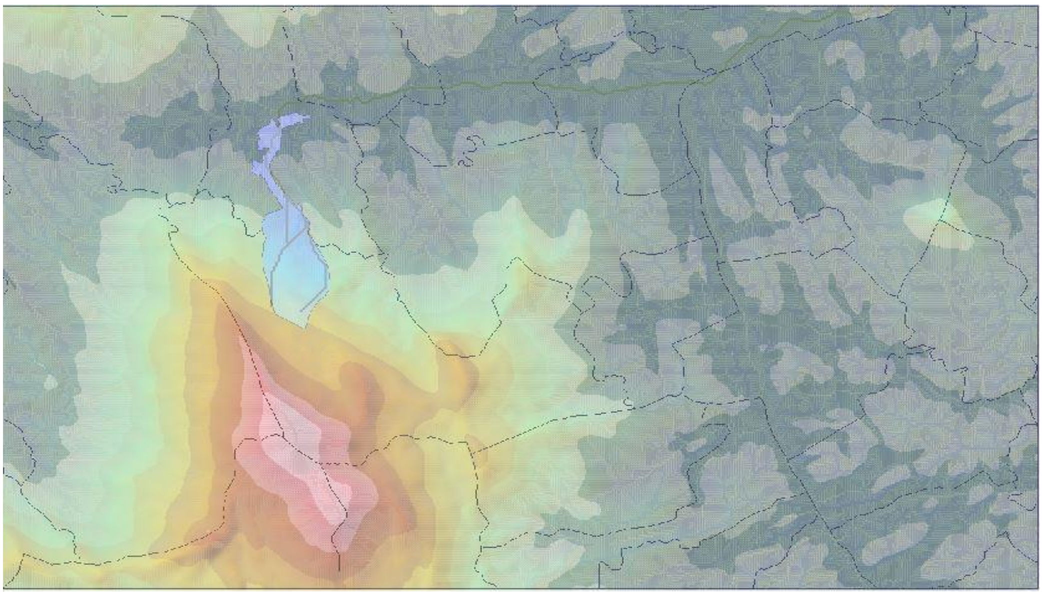

Figure 5.55: Actual Landslide Flow path Placed on the flow path generated from SDF

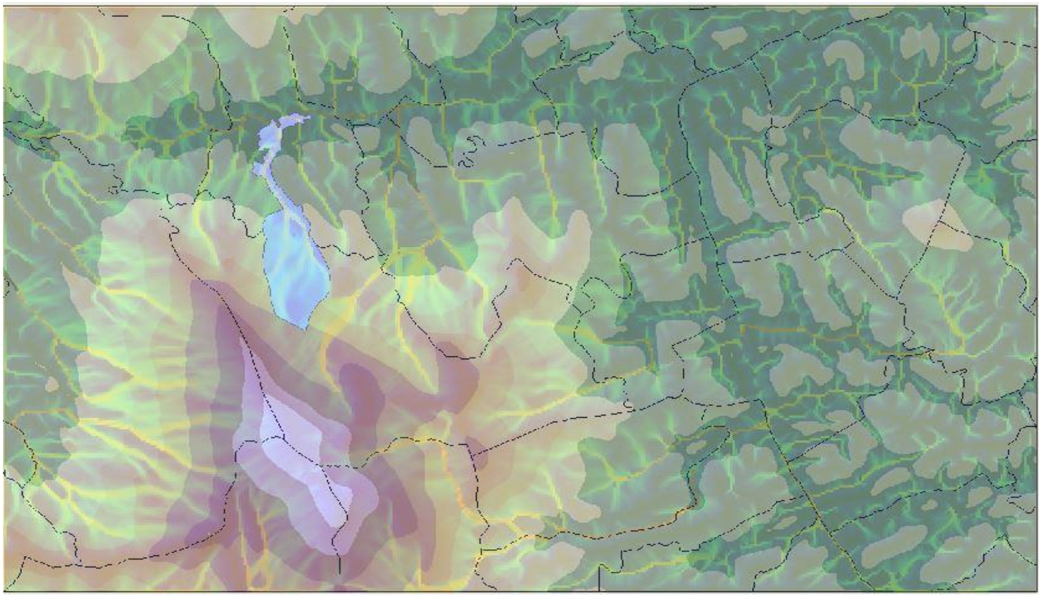

Figure 5.6: Actual Landslide Flow path Placed on the flow path generated from MDF

5.3 Chapter Summary

This chapter illustrates the methodology carried out to evaluate the developed tool with the actual landslide flow path and statistics. DJI Panthom III type UAV is used to take photographs of the Aranayayaka landslide area. These photos are then processed with Agisoft image processing software in a high end workstation and the shape of the actual flow path is obtained. This created flow path boundary is then placed on the correct position of the Aranayaka Divisional secretariat area by mapping longitude and latitude. The output generated from the above processes is taken as the reference for evaluation. Flow paths produced from the implemented tool then placed on the corresponding longitude and latitude on the actual flow path boundary.

Aranayaka landslide actual data are taken from NBRO and a comparison of the results produced from the project and actual data is done in the next Result and Conclusion chapter.

Chapter 6. Results

Based on the result of different simulations, it is observed that both SDF and MDF flow paths fit inside the actual landslide boundary when the initiation points are given and flow directions are also in the acceptable direction of the actual landslide.

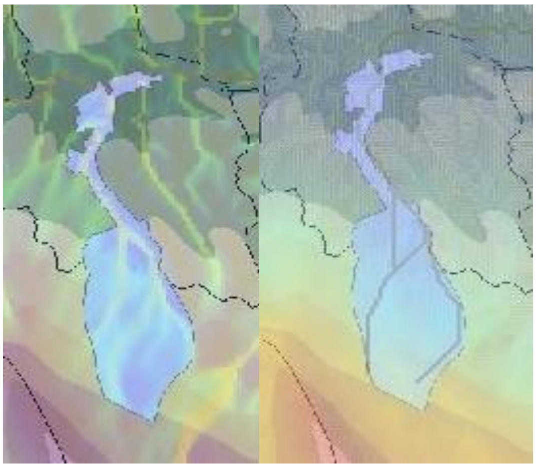

Figure 6: SDF and MDF flow paths with the actual boundary.

Actual landslide statistics are obtained from NBRO as per their detailed analysis and investigation carried at the actual landslide site area. These actual statistics and statistics generated from SDF and MDF are shown in the following table.

	Actual	**SDF**	**MDF**
Area of Main Landslide Body	0.56 Km^2	0.366 Km^2	0.388 Km^2
Landslide crown (C-D)	345.45 m	329.8m	325.57m
Maximum Width (E-F)	600.07m	486.6m	619.9m
Length of the main body	1.26 Km	792.5m	1.18Km
Flow length	2.268 Km	1.75 Km *	1.75 Km*

Table 6.1: Generated statistics from SDF and MDF with actual statistics.

*After Adjustments

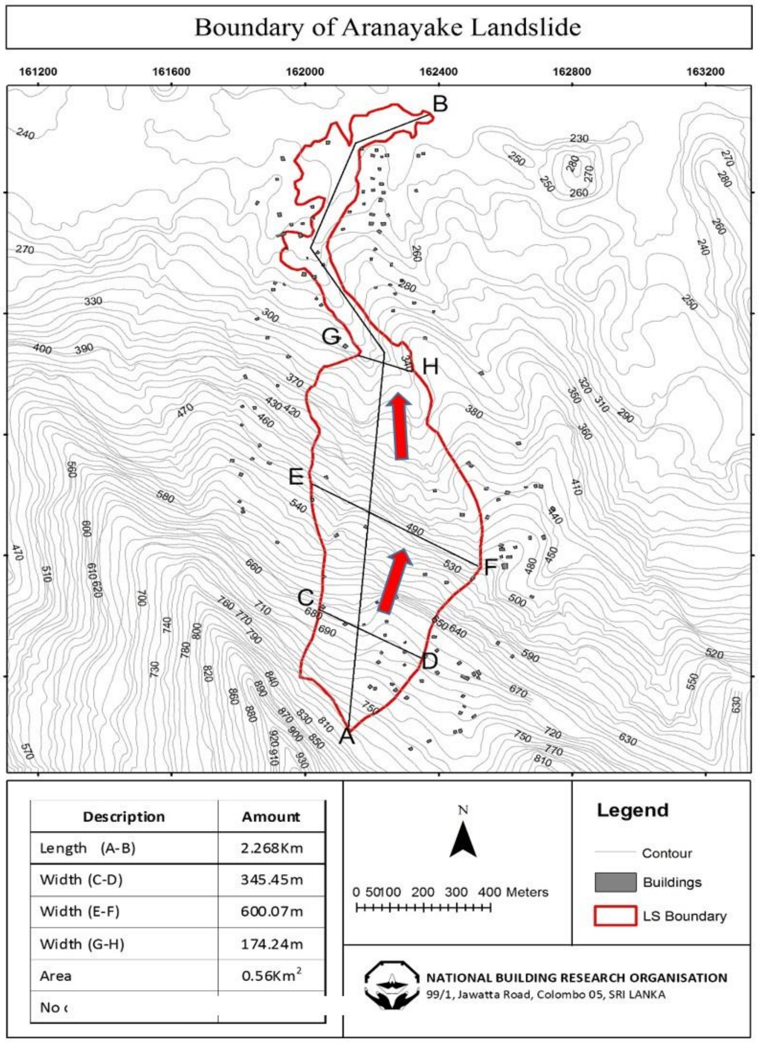

Figure 7: Aranayaka Landslide Statistics. (Source NBRO)

	SDF Deviation (%)	MDF Deviation (%)
Area of Main Landslide Body	34.6	30.7
Landslide crown (C-D)	4.5	5.7
Maximum Width (E-F)	18.9	3.3
Length of the main body	34.1	6.3
Flow length	22.8	22.8

Table 6.2: Percentage of deviation from the actual statistic.

Among the generated statistics maximum width, length of the main body and flow length are really important indicators to identify the spreading area. Therefore people of the predicted perimeter can be alarmed to evacuate as the area is identified as high risk and landslide prone. Also, safe evacuation paths can be determined by examining the predicted flow path of the landslide so the lives of people will not be damaged during the evacuation process.

MDF algorithm produced the length of the main body of Aranayaka Landslide as 1.18Km which is very close to the length of the main body of 1.26 Km, Also MDF calculated the Maximum width of the landslide deviates only 3.3% from the actual Aranayaka data. However, both D8 and MDF algorithms generate a flow length of 1.75 Km which has 22.8% of deviation from actual flow length.

Chapter 7. Conclusion

The landslide flow paths and statistics predicted by the implemented tool show good agreement with the actual landslide data collected for the selected case study. However, MDF algorithm produced more fitting flow paths and relevant statistics for the selected landslide.

Variation of the generated flow paths and other statistics would have caused due to unavailability of site specific data such as soil condition, soil type, spreading velocity, the volume of the slip surface, gravity and other forces.

Even not knowing any of the site specific data this tool can be used and predict results with more than 65% accuracy with couture data of the landslide-prone area as the only input. When compare the implemented tool with the other flow path based tools such as FLOW-R, RAMMS, and DAN3D, all of these tools require site specific data which will be difficult to collect from all landslide-prone stiles prior to a landslide.

7.1 Future Work

This study has been mainly based on Aranayaka Landslide area. With additional work, this model can be expanded to fit with most of the Sri Lankan landslide context. Also other than used SDF and MDF algorithms, there are many more flow routing algorithms available. These algorithms also can be implemented and integrated with this model to compare the results for higher accuracy.

When calculating runout distance and spreading of the landslide, geotechnical information about the landslide is important. Therefore, the implemented tool can be extended by integrating site specific geology related knowledge and checking for results produced with site specific data and without site specific data, and test for accuracy of predictions.

References

[1] na, "Landslides 101," [Online]. Available: https://landslides.usgs.gov/learn/ls101.php. [Accessed 20 01 2017].

[2] U.S. Department of the Interior, "Landslide Types and Processes," July 2004. [Online]. Available: https://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html. [Accessed 20 July 2017].

[3] "Department of conservation," 2016. [Online]. Available: http://www.conservation.ca.gov/cgs/geologic_hazards/landslides/Pages/LandslideTypes.aspx. [Accessed 20 July 2017].

[4] *22nd May 2016, Aerial Survey report on inundation damages and sediment disasters,* 2016.

[5] Peter V. Gorsevski, Paul Gessler and Randy B. Foltz, "Spatial Prediction of Landslide Hazard Using Discriminant Analysis and GIS," in *GIS in the Rockies 2000 Conference and Workshop Applications for the 21st Century*, Denver, Colorado. , 2000.

[6] M. Casadei, W. E. Dietrich and N. L. Miller, "Testing A Model For Predicting The Timing And Location Of Shallow Landslide Initiation In Soil-Mantled Landscapes," *Earth Surface Processes and Landforms,* vol. 28, p. 925–950, 2003.

[7] Roberto Arnaldo Trancoso Gomes, Renato Fontes, Osmar Abílio de Carvalho Júnior, Nelson Ferreira and Eurípedes Vargas do Amaral, "Combining Spatial Models for Shallow Landslides and Debris-Flows Prediction," *Remote Sensing*, no. 5, pp. 2219-2237, 2013.

[8] P. Bertolo and G. F. Wieczorek, "Calibration of numerical models for small debris flow in Yosemite Valley, California, USA," *Documentation and monitoring of landslides and debris flows for mathematical modelling and design of mitigation measures,* 13 December 2005.

[9] T. A. Gebreslassie, "Dynamic simulations of landslide runout in cohesive Soils," Oslo, 2015.

[10] P. Tarolli and D. G. Tarboton, "A new method for determination of most likely landslide initiation points and the evaluation of digital terrain model scale in terrain stability mapping," *Hydrology and Earth System Sciences,* no. 10, p. 663–677, 2006.

[11] G.-B. Kim, "Numerical Simulation Of Three-Dimensional Tsunami Generation By Subaerial Landslides," 2013.

[12] Giuseppe Formetta, Giovanna Capparelli, and Pasqua, "Evaluating performance of simplified physically based models for shallow landslide susceptibility," *Hydrol. Earth System,* no. 20, p. 4585–4603, 2016.

[13] F. Dai and C. Lee, "Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong," 2001.

[14] S. McDougall, "Landslide runout analysis — current practice and challenges," *Canadian Geotechnical Colloquium,* vol. 57, pp. 605-620, 2017.

[15] P. Quinn, K. Beven, P. Chevallier And O. Planchon, "The Prediction Of Hillslope Flow Paths For Distributed Hydrological Modelling Using Digital Terrain Models," *Hydrological Processes,* Vol. Vol. 5, Pp. 59-79, 1991.

[16] V. B., "Comparison of Single and Multiple Flow Direction Algorithm for Computing Topographic Parameters in Topmodel," 2000.

[17] J.-f. G. P. T. K. T. Guang-ju ZHAO, "Comparison of two different methods for determining flow direction in catchment hydrological modeling," *Water Science and Engineering,* vol. 2, no. 4, pp. 1-15, 2009.

[18] D. G. Tarboton, "A New Method For The Determination Of Flow Directions And Upslope Areas In Grid Digital Elevation Models," *Water Resources Research,* Vol. 33, No. 2, P. 33, 309-319.

[19] V. Baumann, "Debris flow susceptibility mapping at a regional scale along the National Road N7, Argentina," in *CGS Geotechnical Conference*, Argentina, 2011.

[20] Q. Z. Petter Pilesjö, "Theoretical Estimation Of Flow Accumulation From A Grid-Based Digital Elevation Model," In *Proceedings Of Gis Am/Fm Asia'97 And Geoinformatics'97 Conference*, Taipei, 1997.

[21] G. A. D. Y. a. C. S. L. John P. WILSON, "Water in the Landscape: A Review of Contemporary Flow Routing Algorithms," pp. 213-236.

[22] "MathWorks," The MathWorks, Inc., [Online]. Available: https://in.mathworks.com/. [Accessed 1 10 2017].

[23] "What is GIS?," Esri, [Online]. Available: http://www.esri.com/what-is-gis. [Accessed 12 11 2017].

[24] P. Barrett, "Paul Barrett," Wikimedia Foundation, Inc, [Online]. Available: http://www.pbarrett.net/techpapers/euclid.pdf. [Accessed 05 01 2018].

[25] S. S. Gruber, Land-surface parameters and objects in hydrology., Elsevier, 2009.

[26] "Landscape Evolution Modeling with CHILD," Community Surface Dynamics Modeling System, [Online]. Available: http://csdms.colorado.edu/wiki/Labs_Landscape_Evolution_Modeling_With_Child_Part_2. [Accessed 13 01 2018].

[27] M. Cooper, "Depth Recovery through Linear Algebra," in *Line Drawing Interpretation*, Springer Science & Business Media., p. 118.

[28] A. P. Nicholas, "Cellular modelling in fluvial geomorphology," in *Earth Surface Processes and Landforms*, 2005, p. 645–649.

[29] "Making Successful Maps," DroneDeploy, [Online]. Available: https://support.dronedeploy.com/v1.0/docs/making-successful-maps. [Accessed 15 10 2017].

[30] "M_Map:A mapping package for Matlab," rich@eos.ubc.ca, [Online]. Available: https://www.eoas.ubc.ca/~rich/map.html. [Accessed 15 01 2018].

[31] P. Dulanjalee, "Landslide Flow Path Assessment for Susceptibility Mapping at a Regional Scale," in *'Investing in Disaster Risk Reduction for Resilience''- NBRO holds 8th Annual Symposium*, Colombo, 2017.

[32] L. K. a. D. M. E. Boyagoda, " Subsurface Geotechnical Characterization," in *International Symposium, NBRO*, Colombo, Sri Lanka, 2016.

[33] E. E. Duncan and A. A. Rahman, "An Amalgamation Of 3d Spatial Data Model For Surface And Subsurface Spatial Objects.," in *Knowing To Manage The Territory, Protect The Environment, Evaluate The Cultural Heritage*, Rome, Italy, 2012.