B. TECH. PROJECT REPORT

ON

Geospatial Numerical Model for Simulating Debris Flow

By:

PEDDHOLLA SAI KUMAR REDDY

DISCIPLINE OF COMPUTER SCIENCE AND ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December, 2019

Geospatial Numerical Model for Simulating Debris Flow

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degree of Bachelor of Technology

in the

Discipline of Computer Science and Engineering

Submitted by:
PEDDHOLLA SAI KUMAR REDDY (160001043)

Guided by:
Dr. SURYA PRAKASH
Associate Professor, Discipline of Computer Science and Engineering, IIT Indore
Dr. NEELIMA SATYAM
Associate Professor, Discipline of Civil Engineering, IIT Indore

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December, 2019

Declaration of Authorship

I hereby declare that the project entitled **"Geospatial Numerical Model for Simulating Debris Flow"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in the Discipline of Computer Science and Engineering and completed under the supervision of **Dr. SURYA PRAKASH**, Associate Professor, Discipline of Computer Science and Engineering, IIT Indore and **Dr. NEELIMA SATYAM**, Associate Professor, Discipline of Civil Engineering, IIT Indore is an authentic work.

Furthermore, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature:

____

Date:

____

Certificate

This is to certify that the thesis entitled "**Geospatial Numerical model for Simulating Debris Flow**" and submitted by Peddholla Sai Kumar Reddy, Roll No. 160001043, in partial fulfillment of the requirements for CE 493 B.Tech Project embodies the work done by him under my supervision. It is certified that the declaration made by the student is correct to the best of our knowledge.

Supervisor
Dr. SURYA PRAKASH
Associate Professor,
Indian Institute of Technology Indore
Date:

Supervisor
Dr. NEELIMA SATYAM
Associate Professor,
Indian Institute of Technology Indore
Date:

Abstract

The report presents a Simulation tool for dynamics of Debris flow on complicated regions, using mathematical integrations of equations with depth averaging. The equations were solved by assuming shallow water depth. The main part of the simulation tool was implemented using Programming language Python. The model provides visualization of flow by series of text files heat maps, and an interface which is user-friendly. The model includes effect of entrainment on the debris flow. The report consists the details of the governing equations. The model was used in analyzing two case studies of debris flow one in Manathavady and the other in Vythiri region, Kerala. Existing data of the debris flow volume is used for back analysis of the events in addition to it compare the values of the conservative variables used. The results obtained using the tool were compared with the RAMMS result which were satisfactory.

In the quest for further study, I extend this work by creating a GUI for analyzing the effects of soil parameters on the debris flow. By back analyzing the already occurred debris flow, one could estimate soil properties of the region. Hence the Debris flow simulation model can be used as a viable option for further study on disaster management.

Acknowledgements

I would like to thank our B.Tech Project supervisors Dr.Surya Praksh and Dr.Neelima Satyam for their guidance and constant support in structuring the project and their valuable feedback throughout the course of this project. Their overseeing the project meant there was allot that we learnt while working on it. We thank them for their time and efforts.

I am really grateful to the Institute for the opportunity to be exposed to systemic research, especially, Dr.Neelima Satyam's lab for providing the necessary hardware utilities to complete the project. I extend my special thanks to Ms. Minu Treesa Abraham, JRF, Discipline of Civil Engineering, IIT Indore, for the constant support and help during the course of this research.

Lastly, we offer our sincere thanks to everyone who helped us to complete this project, whose name we might have forgotten to mention.

Contents

List of Tables

List of Figures

List of Abbreviations

DEM	**Digital Elevation Map**
GIS	**Geographic Information System**
EPC	**Earth Pressure Coefficient**
LGR	**Landslide Growth Rate**
PED	**Potential Erosion Depth**
IFA	**Internal Friction Angle**
CSS	**Critical Shear Stress**

Chapter 1

Introduction

Debris flow are the flows that are driven the earth's gravity on the material which is a highly saturated, the components of the mixture include debris loose sand and mud across a steep valley. Some flow properties such as turbulence and viscosity are observed in debris flow. Generally, the mud flow contains more water compared to debris flow, which makes it more easily flow able. Due to this larger content of water, the flow poses plastic behavior [1]. Debris flow originate from a area where the mass is fluidized. A huge amount of water is added to the mass which in turn makes the material fluidized. Erosion and sediment transfer are common in hilly areas, these occur mainly due to debris flow. A huge population is being affected due to these frequent debris flows, this constitutes to be a major factor. These debris flow have high velocity, due to which they possess high threat to human life and property compared to others. They have the capacity to propagate even under mild slope areas (below 5 degrees).

Going beyond theoretical study, the by developing numerical model of debris flow has significant applications in design of mitigation measures and hazard evaluation. The model can also be used for quantitative analysis of debris flow characteristics such as velocity of the flow, height of the flow, the force executed on the obstacles. Construction of different simulations can be done by changing the governing parameters such as rheology, soil parameters. This allows us to understand the susceptibility of the given area under different circumstances. This information can be used if the viability of the parameters is known for controlling the flow.

Entrainment is an uprooting of one substance by another substance. Bed entrainment causes deflection in the rheology of the flowing mass and the topography of the surface. The effect of change on surface topography results in landslide. So the effect caused by entrainment on the flowing surface and the flowing mass may lead to further landslides. Entrainment property needs to be studied of the flow along with the flow behavior. According to the previous studies regarding entrainment, explain that it is a complex phenomenon. The process of entrainment consists of shearing, plowing and thrusting of flow materials and the mass between flowing mass and the entrainment mass.

The effects of entrainment while flow of mass: 1. it increases the volume the flowing mass; 2. physical properties of the flowing mass changes; 3. surface will be changed. In many landslides it has been observed that the entrainment effect is huge. In some cases, it has been observed that the volume at the start of flow is negligible compared to the final volume after the flow.

This article describes the development and use of the simulation model, which could simulate the flow over complex surfaces, which is implemented in python. The model is based on solving hyperbolic partial differential equations using finite difference formulas. It uses depth average integration methods and also assumes shallow water depth. In this model, the flow is assumed to be of one phase and the flow behavior is determined by rheology properties. In this numerical model several flow laws can be implemented.

The usage of this simulation tool is to provide a general interface in which one can analyze various concepts which can be tested. The model is developed so that it can be flexible to work, using various settings of different parameters, this characteristic makes the model more adaptable for researchers to analyze various types of simulations to variety of situations. Various flow types can be compared by implementing different rheological properties of the flow. The model was developed in Python which includes several packages in python which are used for the simulation purpose.

In the next chapter, we describe the hyperbolic partial differential equations of the present model, the different laws of flow which were considered, the numerical methods used to solve the equations and the specifications required for the parameters required to run the model. We also discuss a case study by showing the procedure of running the model and also discuss the results.

Chapter 2

Literature Review

This chapter discusses about the previously used methods a previously studies literature which have been used for the analysis of debris flow. These literatures include a numerical model called Massmov2D which is implemented in GIS platform, analysis of entrainment on debris flow, different rheological study of the flow of mass. This chapter describes the highs of Massmov2D and its methods of implementation which can be used and also its drawbacks which need to be improved. For further detailed study please refer to [1,2,3].

2.1 Governing Equations

The equations were based on classical Savage Hutter theory, it assumes that the flow to be of single-phase homogeneous material [1]. The flow dynamics equations were modeled considering the flow to be a 2D continuous medium. To solve the equations depth integrated approximations were used. This approach has been considered as a classical approach for modeling debris flow. The depth integrated approximation is based on a classical assumption that assumes the length of horizontal bed of the flowing mass is considered to be very much larger than the thickness of the flowing mass. This assumption is known as shallow water assumption. By assuming this condition, we can assume the horizontal velocity of the flowing mass to be negligible.

By these assumptions the flow can be analyzed using 2D integrations, by this we avoid complex 3D integrations. The equations which govern the debris flow are calibrated in 2D space using x and y coordinates. The governing equations proposed are shown below:

$$\frac{\partial h}{\partial t} + c_x \frac{\partial (hu)}{\partial x} + c_y \frac{\partial (hv)}{\partial y} = 0 \text{...} \quad 1$$

$$\frac{\partial u}{\partial t} + c_y u \frac{\partial u}{\partial x} + c_x v \frac{\partial u}{\partial y} = -c_x g (S_x + k \frac{\partial (c_x h)}{\partial x} + S_f q_x \text{...... ..} \quad 2$$

$$\frac{\partial v}{\partial t} + c_y v \frac{\partial v}{\partial x} + c_x u \frac{\partial v}{\partial y} = -c_y g \left(S_y + k \frac{\partial (c_y h)}{\partial x} + S_f q_y \right) \text{......} \quad 3$$

cosines of the flowing mass. The equation (2) corresponds momentum balance equation the above equation (1) corresponds to mass balance equation where h is the thickness of the flow, the thickness is considered normal to the bed. The variables u and v correspond to velocities along x and y direction along the bed. The coefficients c_x and c_y correspond to the direction where g corresponds to acceleration due to gravity. The second term as well as the third term in the equation correspond to convective acceleration i.e. the acceleration produced due to change in spatial position. The right hand side of equation (2) corresponds to different accelerations due to time. The first term corresponds to acceleration to gravity, the second term corresponds to the acceleration to pressure differences and the term which includes S_f corresponds to the resisting force to the flow.

In the momentum balance equation, the term k corresponds to earth pressure coefficient. The earth pressure coefficient corresponds to the ratio of tangential stress to normal stress. The value of earth pressure coefficient for perfect fluids is 1, but the value varies a lot for plastic materials. The values of EPC ranges diversely for different types of materials. The values will be based on active and passive states of the material. The values of EPC depend on the IFA, δ.

$$k_a = \frac{1-Sin(\delta)}{1+Sin(\delta)} \dots\dots\dots\dots 4$$

$$k_p = \frac{1-Sin(\delta)}{1+Sin(\delta)} \dots\dots\dots\dots 5$$

The k_a corresponds to active state to regions where flows expand and the term k_p corresponds to regions where flows compress.

$$c_x \frac{\partial(uh)}{\partial x} + c_y \frac{\partial(vh)}{\partial y} \geq 0 \dots\dots\dots\dots 6$$

$$c_x \frac{\partial(uh)}{\partial x} + c_y \frac{\partial(vh)}{\partial y} < 0 \dots\dots\dots\dots 7$$

The equation (6) is the condition for flow expansion and equation (7) is the condition for flow compression. The terms in momentum balance equation q_x and q_y are shown below

$$q_x = \frac{-u}{\sqrt{u^2+v^2}} \text{.........8}$$

$$q_y = \frac{-u}{\sqrt{u^2+v^2}} \text{........9}$$

2.2 Flow Laws

The flow resisting gradient S_f in the momentum balance equation corresponds to shear stress. this term is responsible for the energy dissipation while flowing of the mass. This resisting gradient variable corresponds to the rheological properties of the mass which is flowing. In many materials, they simply do not follow a linear equation. The relation is shown in figure 2.1. To calculate the yield stress, we consider a parameter i.e. N (yield stress) and μ is considered to be a hard parameter. The relation between flow resisting gradient and yield stress is as shown below

$$S_f = \mu N + \frac{\rho g u^2}{\xi} \text{.................10}$$

A threshold value of yield stress determines the relation between stress and strain. Below the threshold the relation is linear as the values go beyond thresholds the relation is exponential.

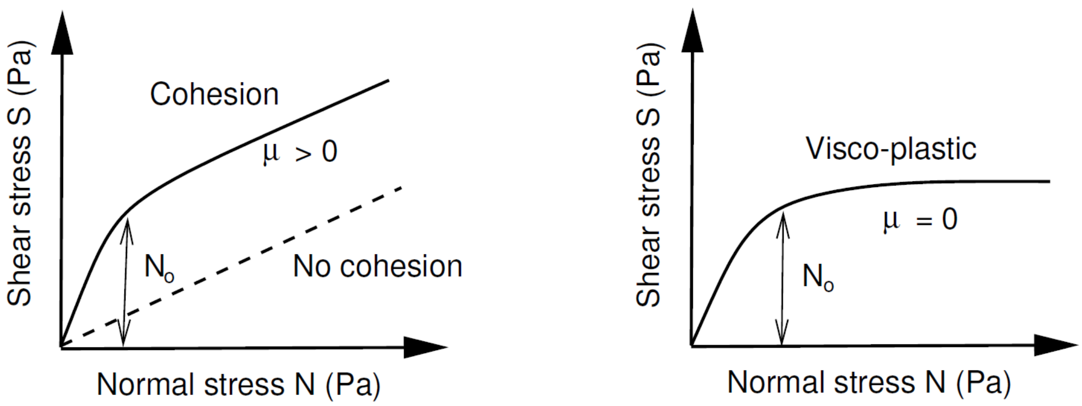


Figure 1:Relation between shear stress vs normal stress. Determines the behavior of debris flow. [Source: Ramms manua].

The relation between shear rate, yield stress and shear stress which is resisting is shown below

$$\tau(z) = \tau_c + \mu\left(\frac{\partial v^{\beta}}{\partial z}\right) \text{.....................11}$$

In the equation (11) left hand side corresponds to the resisting shear stress, μ corresponds to the parameter for viscosity, τ_c corresponds to the yield stress. The above relation is based on

Bingham rheology. This type of rheology is used for particles where a small amount is sufficient for lubrication of the flowing mass. The more general model than Bingham rheology is Coulomb viscous rheology which considers additional friction component. this component depends on the normal stress. The relation for Coulomb viscous is shown below

$$\tau(z) = \tau_c + \mu(\frac{\partial v^{\beta}}{\partial z}) + (\sigma - u)tan\varphi \text{..........................}12$$

In coulomb viscous it also considers internal fluid pressure and the basal friction angle. The property which is considered is internal fluid pressure, this property is mixed with the normal stress which leads to dissipation of energy during the flow of the mass. This property makes the model more robust when this rheology is considered. Hence while using in real cases the ration of u/σ is considered constant. this leads to dissipating energy only due to friction where φ is considered as internal friction angle. These are all the three rheologies implemented incorporated in the model to make the model more robust. In models which include depth integration, the stress distribution is considered to be in the direction of normal to the flow. By including all these factors, the final equation of resisting shear stress is as shown below

$$S_f = tan(\varphi) + \frac{1}{\sigma}(1.5\tau_c + 3\frac{\mu u}{h}) \text{..........................}13$$

Hence, the parameters on which the rheological properties depend are based on different rheology some of them being (σ,μ,ρ,φ).

2.3 Entrainment

There are many models which determine the amount of volume uprooted while debris flow, but there are two main models they are Empirical model by McDougall and Hungr and physical based model studied by Fraccarallo and Capart [2]. We discuss the relations involved in both the methods. In the empirical method is simple and considered to be effective. In this method the entrainment rate is given by the product of growth of landslide thickness, the rate of growth and the velocity of the flowing mass. The equation representing the same is as shown below

$$E = E_r hv = -\frac{\partial Z}{\partial t} \text{....................................}14$$

In the equation (13) Z correspond to the amount of elevation of the flowing mass and E_r is a constant and this constant is independent of velocity and height of the flowing mass. this constant needs to be calibrated based on already data of debris flow. The initial value of LGR is estimated based on the volume of the eroded mass while debris flow and the amount of displacement of the debris flow. The equation of LGR is shown below:

$$V_f = \frac{ln(V_f/V_o)}{L} \text{..........................15}$$

In the above equation the term V_f and V_o correspond to volumes of the land after and before the process of entrainment and L is considered to be the estimated path of the flow.

The physical based approach is incorporated from Rankine approach [2]. This approach represents the conservation of momentum along the flow which is discontinuous. This type of method considers the properties such as densities, stress and velocities to be different at the point of intersection of the flowing mass and the land surface. It also considers point of contact of flowing mass and uprooted mass is discontinuous. The equation corresponding to this approach is shown below

$$E = \frac{\tau_s - \tau_e}{\rho_e v} = -\frac{\partial Z}{\partial t} \text{ ....16}$$

In the equation (15) τ_s corresponds to shear stress for the mass that is flowing and τ_e represents the resisting stress for mass which is being uprooted and the term ρ_e corresponds to bulk density of the uprooted mass.

The equation can be interpreted as shown in the figure. As the flowing mass flows on the static mass it exerts pressure corresponding to the shear stress, for the immovable mass to move the amount of pressure exerted should be more than the resisting shear deformation. When shear stress is greater than deformed stress the mass gains acceleration. For the moving ma possessing velocity v the amount of acceleration generated should be more such that the velocity of the immovable mass must be v within short span of time. When this happens the amount of mass uprooted will depend on Z.

According to momentum conservation the uprooted mass gains velocity based on the force which is directly proportional to difference of shear stress to deformed stress.

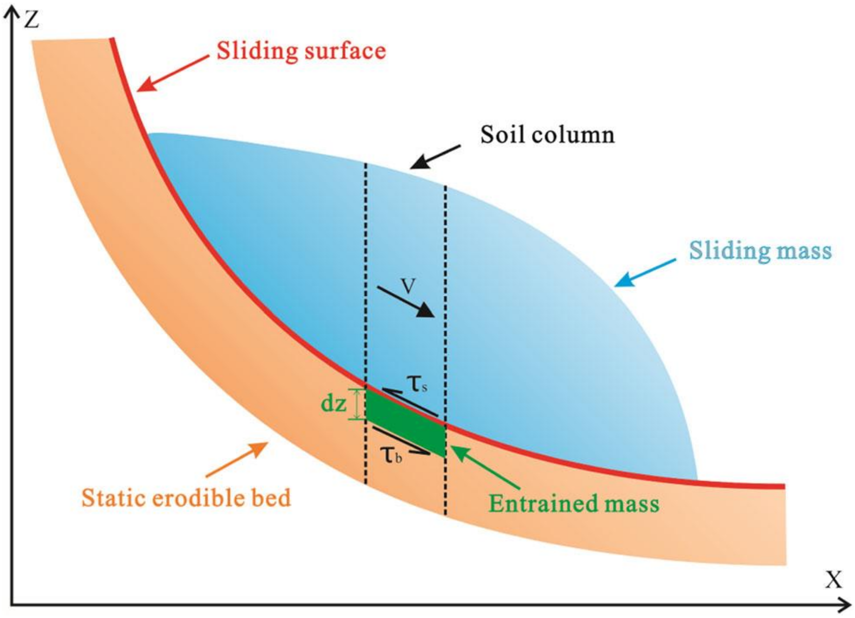


Figure 2: Diagram explaining bed entrainment model. [Source: [2]]

The empirical model is simple compared to the physical model, but the physical sense of the empirical model is low. So, it does not clearly explain the process of entrainment. Adding to this the empirical model does not consider the rheology of the flowing mass. In general studies it is known that the rheology change has a significant impact on the process of entrainment. So, in many ways the physical model is better compared to the empirical model. however, when the immovable mass is huge the shape of the surface has major role in the process of entrainment.

In the next chapter we will discuss about the best design to develop a robust model by incorporating the best methods based on the literature survey.

Chapter 3

Proposed Methodology

In this chapter we discuss the objectives of the problem and the final methodology that has been used to achieve the objectives.

3.1 Objectives

Previously lot of attempts were made to develop numerical models for simulating debris flow. Few attempts were made for simulating debris flow which are quite diverse from each other. One model considers only the digital elevation map, the outlet map of the region, the height of the region forms the surface while not considering different rheologies. Other studies were to understand the effects of different rheologies on the debris flow but a model for simulating debris flow is not created with the features involved. Some other studies were based on the effects of entrainment on moving mass and sliding surface. Hence, considering studies individually a robust model could not be developed to study the area effected by the debris flow. We then put all the related studies together, to develop a robust numerical model which can be used for diverse areas and related studies.
Contributions of the project are summarized below:

- To develop a new simulation tool which incorporates different types of rheologies and also produces results which can be analyses in GIS platform.
- To evaluation of applications of different rheological properties on diverse areas, the functionality and its accuracy.
- To perform parametric based studies, the back calculation of debris flow volume is performed by different parameters-based study.
- To analyse of the conservative variables which include flow height and flow velocity and their sensitivity towards different rheologies and entrainment properties.

- To conduct analysis for determining the parameters for a given area.

Here we explain in detail the design used to develop the simulation tool. We discuss about the numerical methods to solve the partial differential equations, the corresponding input files and parameters required to design the model.

3.2 Numerical Implementation

The numerical method to solve the hyperbolic partial differential equations (1) and (2) as mentioned in chapter 2.1 is a tough task. More importantly it is very difficult in the case of moving mass [6]. We incorporated a rather simple solution to solve the partial differential equations, additionally this method produced stable results a lot of accuracy.

In order to ease the understanding, the equations are modified and written in a more general form. This modified form of the hyperbolic partial differential equations is shown below

$$\frac{\partial}{\partial t}A + k_1\frac{\partial}{\partial x}B + k_2\frac{\partial}{\partial y}C + k_3(E+F) = 0 \text{............................} 17$$

where

$$A = \begin{pmatrix} h \\ u \\ v \end{pmatrix} \quad B = \begin{pmatrix} hu \\ u \\ v \end{pmatrix} \quad C = \begin{pmatrix} hv \\ u \\ v \end{pmatrix}$$

$$k_1 = \begin{pmatrix} c_x \\ c_x u \\ c_y v \end{pmatrix} k_2 = \begin{pmatrix} c_y \\ c_y v \\ c_x v \end{pmatrix} k_3 = \begin{pmatrix} 0 \\ c_x \\ c_y \end{pmatrix}$$

$$E = \begin{pmatrix} 0 \\ k\frac{\partial(gc_x h)}{\partial x} + gS_x \\ k\frac{\partial(gc_y h)}{\partial y} + gS_y \end{pmatrix} \quad F = \begin{pmatrix} 0 \\ q_x S_f \\ q_y S_f \end{pmatrix}$$

The governing partial differential equations are converted into the above form. The numerical method used to solve the above form of is Lax Wendorff's finite difference formulas. The complete area of study is considered to be a 2D mesh structure. The flow is considered a characteristic of two conservative variables, velocity of the flow and height of the flow. One of the assumptions by using lax Wendorff's equation is that a uniform cross section is considered for mesh i.e. $\Delta x = \Delta y$. This assumption does not to lead to any disadvantages because in generally used GIS software's the cell size is considered to be constant. The equation (18) is solved using finite central difference formula as shown below

$$A_{i,j}^{n+1} = A_{i,j}^{n} - 2\Delta t\left({k_1}_{i,j}^{n}\left(\frac{B_{i+1,j}^{n+1} - B_{i-1,j}^{n}}{2}\right) + {k_2}_{i,j}^{n}\left(\frac{C_{i+1,j}^{n+1} - C_{i-1,j}^{n}}{2}\right) + {k_3}_{i,j}^{n}\left(E_{i,j}^{n} + F_{i,j}^{n}\right)\right) \quad \ldots\ldots 18$$

In the above equation Δt is considered to be the time duration for each step, and the term E is calculated using central difference formula. The general problem while using this method is that the rise of dispersion effects that will cause unphysical movements. This problem will be more significant in case of large slopes. the solution to this problem is by performing a numerical method know as regularization on the variable which causes unphysical movements. The term in the right-hand side of the equation $A_{i,j}^{n}$ will not be stable, in order to stabilize this variable, we will use the below equation

$$NR\left(A_{i,j}^{n}\right) = (1 - CFL)A_{i,j}^{n} + CFL\left(\frac{A_{i-1,j}^{n} + A_{i+1,j}^{n} + A_{i,j-1}^{n} + A_{i,j+1}^{n}}{4}\right) \quad \ldots\ldots 19$$

The function NR in the above equation performs a weighted average to the complete area. The quantity of regularization is set based on the CFL value at corresponding points. So, in the model the CFL value is set based on the study on past occurred debris flows. Generally, the CFL value for flows occurring on these types of surfaces lie between 0.5 and 1.

This method has given very good results. For the numerical instability occurred based on the data, we can adjust the amount of regularization to be done based on the CFL value. In the case of boundary cells, we need to consider the mirror of the corresponding cell w.r.t the calculating cell. In this way we could also regularize the boundary cell values. Example for $A_{i-1,j}^{n}$ consider $A_{i+1,j}^{n}$; in the same way for $A_{i,j-1}^{n}$ consider $A_{i,j+1}^{n}$ and also vice versa.

There exists one more problem for first order solutions, that is the non-uniformity of considering the flow resisting gradient. This non uniformity generally occurs in the flows where there exists acceleration of the mass as well as deceleration of mass. This type of problem can be dealt using inter loops of the main time step duration. By dividing the *Δt* to further smaller steps we can reduce the non-uniformity of the flow resisting gradient. This type of method of solving the problem is same as Lax wendroffs method. For the maintenance of the flow the CFL value is monitored to be less than a particular value throughout the flow. CFL can be calculated based on the equation shown below.

$$CFL = u\sqrt{2}\frac{\Delta t}{s} \qquad \text{..............................20}$$

One of the assumptions which can be drawn from the finite difference formula is that the flow can be considered to be continuous and the flow can be deduced as smooth throughout the area.

Anyways this can be true in lot of, in some typical cases the surface topography can be considered to be horizontal continuous and there may also exist singular flows through channel, these points cannot be neglected. Such surfaces cannot be considered to be representing as a mesh considered as finite difference, central difference scheme cannot be used for these types of surfaces. Because to apply central difference scheme the surface needs to be continues. Whenever these types of surfaces are used, the flow automatically flows through the both directions of discontinuity.

The model is implemented using easy scripting language python with the usage of additional packages which makes the model more user friendly. Some functions such as calculating slope, some vector operations such as calculating divergence and gradient are implemented in python.

3.3 Entrainment

The erosion model considered to develop the simulation tool predicts the deepness of the eroded material caused due to uprooting of the debris flow. By using this approach, one could also calculate the amount of increase in the debris flow due to entrainment. By erosion of material we calculate the amount of elevation of the surface as the cause of uprooting of the material due to flow. Below we provide the method to calculate the amount of volume uprooted due to the flow of debris. More information on entrainment can be found in [6].

This model of entrainment is based on the study on the past debris flow. The previous study indicates that the amount of eroded mass or the depth of erosion is proportional to the strength of the flow i.e. the shear stress[6,7]. In some other studies it can be inferred that if the debris flow strength is very low then it cannot cause erosion. So in this model we consider a threshold value for the shear stress, which says that the process of entrainment occurs only if the value of shear stress is greater than the threshold value. The erosion model estimates the amount of erosion that can happen as a function of shear stress. The equation is as shown below

$$E_m = \begin{cases} 0 \; for \; \tau < \tau_c \\ \frac{dz}{d\tau}(\tau - \tau_c) for \; \tau \geq \tau_c \end{cases} \text{.............................21}$$

In the above equation E_m denotes the amount of depth of eroded material. This amount of volume eroded is proportional to PED and this controls the amount of height of erosion in the upward direction and as a linear function to the bed shear stress. The surface erosion rate for the corresponding area is calculated by inputting sensors inside the land. The value observed in the study is 0.025 m/s in downward direction. The bed in eroded until the erosion until the maximum erosion depth value is attained.

$$\frac{dz}{dt} = 0.025 \; for \; E_t \leq E_m \text{................................22}$$

In the above equation E_t is the erosion depth at t time.

If we know the values of the shear stress in all the cells, if for a particular cell the value exceeds after the process of erosion, then according to the value of the erosion depth is adjusted automatically and the amount of entrainment adds on until the value of E_m is reached. The height of the flow is not considered to change while the simulation is in the progress. This concept can be added for further development of the numerical model.

3.4 Input Ascii Files and Parameters

To run the model, it needs four input files which comprise the surface topography of the area, the outlet ascii file which shows the domain of the complete area, the release ascii file which indicates the initial height of the fluidized mass and the final vegetation ascii file which determines the amount of vegetation on the surface. The topography of surface is a primary input to simulation tool and this information is inputted as a Digital elevation map. The DEM not only defines boundary of the flow, this map determines the complete area which needs to be considered and also the mesh size. One restriction is that the flow is not allowed to go out of the DEM. The outlet map divides the complete area into two regions i) the region in which debris can flow ii) the region in which the debris cannot flow. And finally, the vegetation map which determines the PED value at a particular cell, this helps in robust calculation of the amount of entrainment.

These files can be created easily in ARC GIS platform. Along with these maps the model also requires the parameters of the soil properties and also the properties of the material that is flowing. These values must be known for each cell where the mass can flow (as discussed in the outlet map). The major factor that drives the flow of debris is the slope of the terrain. We use eight neighborhood values to calculate the value at a corresponding cell value. Example figure is shown below of how the values are interpreted to calculate the slope.

i-1, j-1	i-1,j	i-1,j+1
i, j-1	i,j	i,j+1
I+1, j	i+1,j	i+1,j+1

Figure 3: Eight neighborhood formulae for calculating slope

For calculating the slope at the cell x(i,j), we use eight neighborhood values, the formula is as shown below

$$\frac{dz}{dx} = \frac{\left((x_{i-1,j+1} + 2x_{i,j+1} + x_{i+1,j+1}) - (x_{i-1,j-1} + 2x_{i,j-1} + x_{i+1,j-1})\right)}{8*cellsize} \quad \text{............................22}$$

$$\frac{dz}{dy} = \frac{\left((x_{i+1,j-1} + 2x_{i+1,j} + x_{i+1,j+1}) - (x_{i-1,j-1} + 2x_{i-1,j} + x_{i-1,j+1})\right)}{8*cellsize} \quad \text{............................23}$$

$$\theta = tan^{-1}\sqrt{\frac{dz}{dx}^2 + \frac{dz}{dy}^2} \quad \text{..24}$$

In this way we calculate the slope at each particular cell based on above mentioned formula

3.5 Performance Evaluation Metrics

All experiments and results in the further chapters includes the explanation of using the simulation tool and demonstrating to run the simulation tool by considering a case study. The results obtained are explained in the further chapters.

Chapter 4

Graphical User Interface

The simulation tool is developed using tkinter package in python. The graphical user interface consists of two tabs. The first tab is known as Ascii files tab which asks the user to input the ascii files which include Digital elevation map, the domain of the area which needs to be considered, the release area and the surface map which defines the amount of vegetation. The second tab is Parameters which contains 12 types of parameters of soil. The instructions of using the graphical user interface are mentioned below.

4.1 Ascii Files Tab

In this tab, the user needs to input four ascii files the digital elevation map, the outlet map which shows the domain, the release area which corresponds to the point of initialization of debris flow and the surface map which determines the type of area of the complete area. It determines the amount of vegetation at each particular location. These maps need to be in a text format and can be added using an ADD button corresponding to each ascii file.

At the top left corner of the Ascii file frame, there is an INFO button, which on clicking displays the restrictions on the ascii files that need to be inserted. There exists a RUN SIMULATION button which is disabled initially and this is enabled only when all the required parameters are entered that includes the data in ascii tab as well as the parameter tab which consist of all the soil and entrainment properties required for the model.

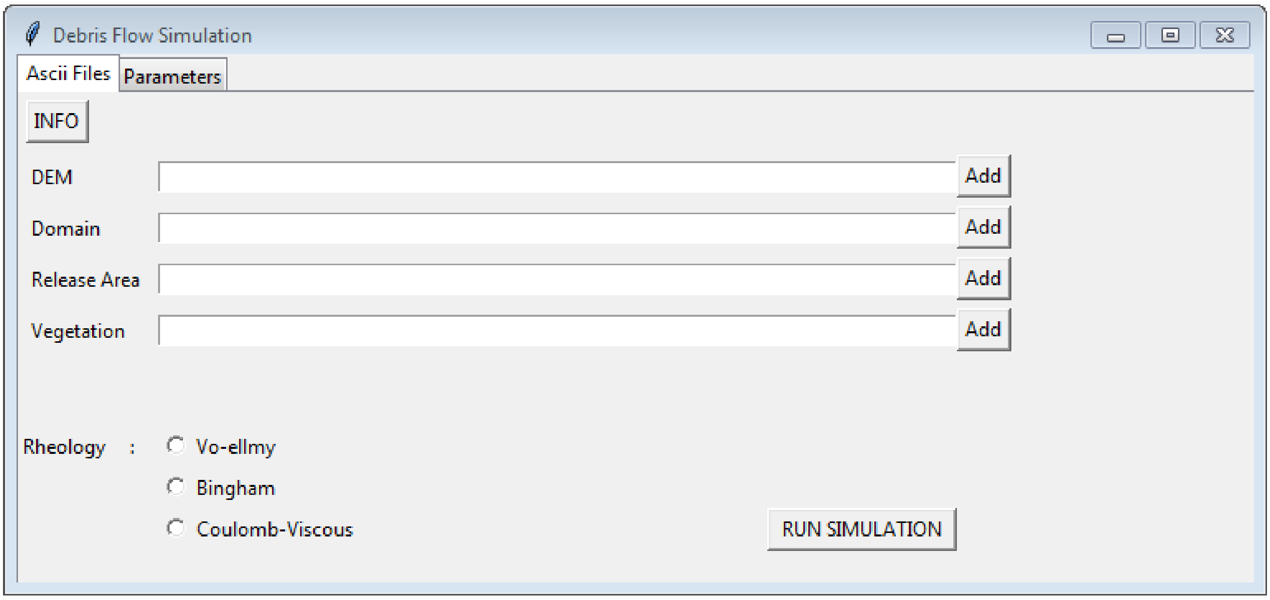


Figure 4: Debris flow simulation graphical user interface Ascii File tab.

One restriction in input ascii files is that, the maps should be such that they can be overlapped. The digital elevation map is considered to be the super set and all other maps should be inside the digital elevation map. All the files must be of text format. Based on the xllcorner and the yllcorner of each map, all the maps are aligned. and all are converted to the same size of the digital elevation map.

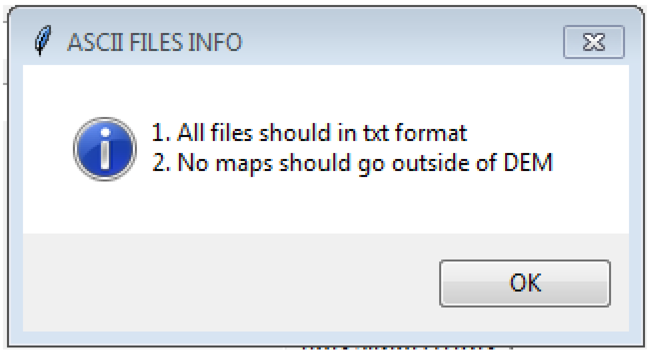


Figure 5: Ascii File INFO of the parameters.

As shown in the figure 4.1 the user should also specify the rheology of the flowing material. There are three different rheologies options from one user can choose.

4.2 Parameters Tab

This tab includes asks the user the input the properties of the flowing mass such as density of the material, the viscosity of the flow, the basal internal angle, the internal friction angle, the number of times steps the simulation must run, the degree of saturation. This tab also includes the properties of entrainment such the potential erosion depth, viscous turbulent friction, critical shear stress, maximum erosion depth. For making the model to be more user friendly, possible ranges of all parameters are also provided.

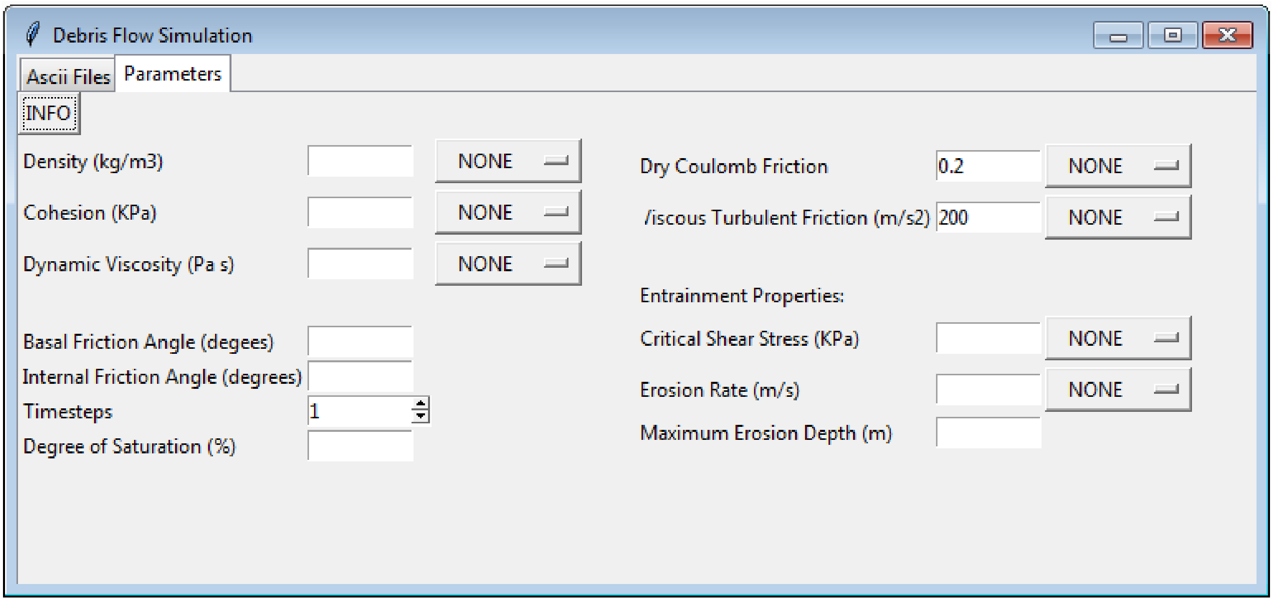


Figure 6: Debris flow simulation graphical user interface Parameter tab.

At the top left of the in the parameters tab, there is an INFO button which gives the information of the constraints on the parameters. There is also a drop-down menu which allows the user toto understand the possible ranges of values for each type of property..

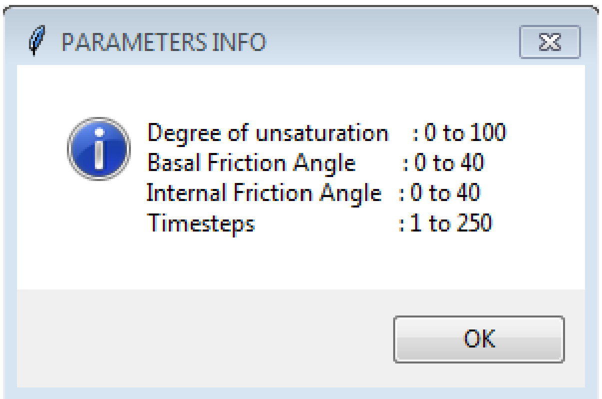


Figure 7: Ascii File INFO of the parameters

The following table denotes the required properties for the model, their SI units their constraints.

Table 1: Parameters and corresponding units

Parameter	**Unit**
Density	Kg/m3
Cohesion	KPa
Dynamic Viscosity	Pa s
Basal Friction Angle	Degrees
Internal Friction Angle	Degrees
Time steps	Constant
Degree of Saturation	%
Dry Coulomb Viscous	Constant
Viscous Turbulent Friction	m/s2
Critical Shear Stress	KPa
Erosion rate	m/s
Maximum Erosion Depth	m

Few of the parameters have a drop-down menu, which can be used in case of not knowing the value of the parameter. For different parameters the drop-down menu is categorized in different ways. Following table shows about the classification of the parameters.

Table 2: Parameters classes for approx. values

Parameter	**Class1**	**Class 2**	**Class3**
Density	Sand	Clay	Rock
Cohesion	Low	Medium	High
Dynamic Viscosity	Low	Medium	High
Dry Coulomb Friction	Low	Medium	High
Viscous Turbulent Friction	Low	Medium	High
Critical Shear stress	Low	Medium	High
Erosion rate	Loose	Normal	Dense

After inputting all the required parameters, the user has to press the RUN SIMULATION button. After pressing the button, the user has to choose the output folder where the results need to be stored. The output folder contains the times series of all the height, velocity and entrainment and also the heat maps of the conservative variables. In the next chapter we will discuss about the experiments conducted and the results.

Chapter 5

Experimental Evaluation

In this chapter, the tool is validated using the map details of two regions Manathavady and Vythiri. The results of the tool for the corresponding input are shown.

5.1 Datasets

In this chapter, the performance of the simulation tool is on two different regions which are manathavady region and Vythiri region. The ascii files of the regions are created using ARC GIS software and were used as input to the model for the results. The maps were created based on the previous occurred debris flows in manathavady and Vythiri regions.

5.2 Output Format

The output of the model contains four folders which include Entrainment, Height, Height heat maps, Velocity, Velocity heat maps, and the results also include two animation files of the height of the flowing mass and also the velocity of the flowing mass and an excel sheet which includes the maximum height and velocity values at each time step and the also the stability coefficient.

The following figure shows the output folder where all the files and folders are created after running the model.

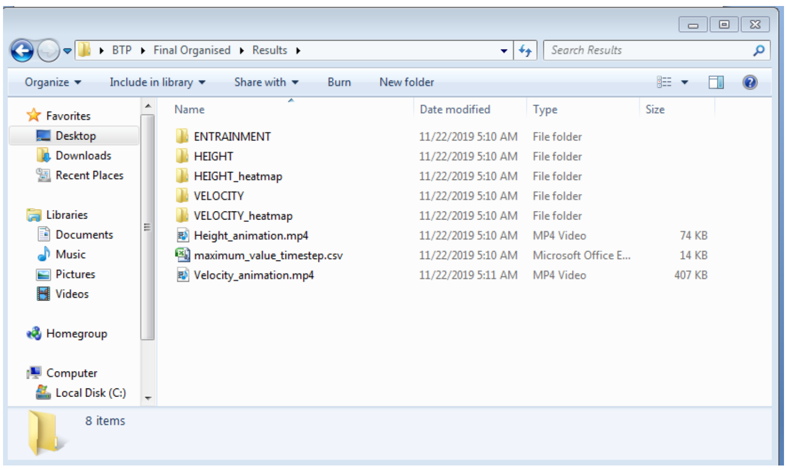


Figure 8:All files and folders after the model is executed

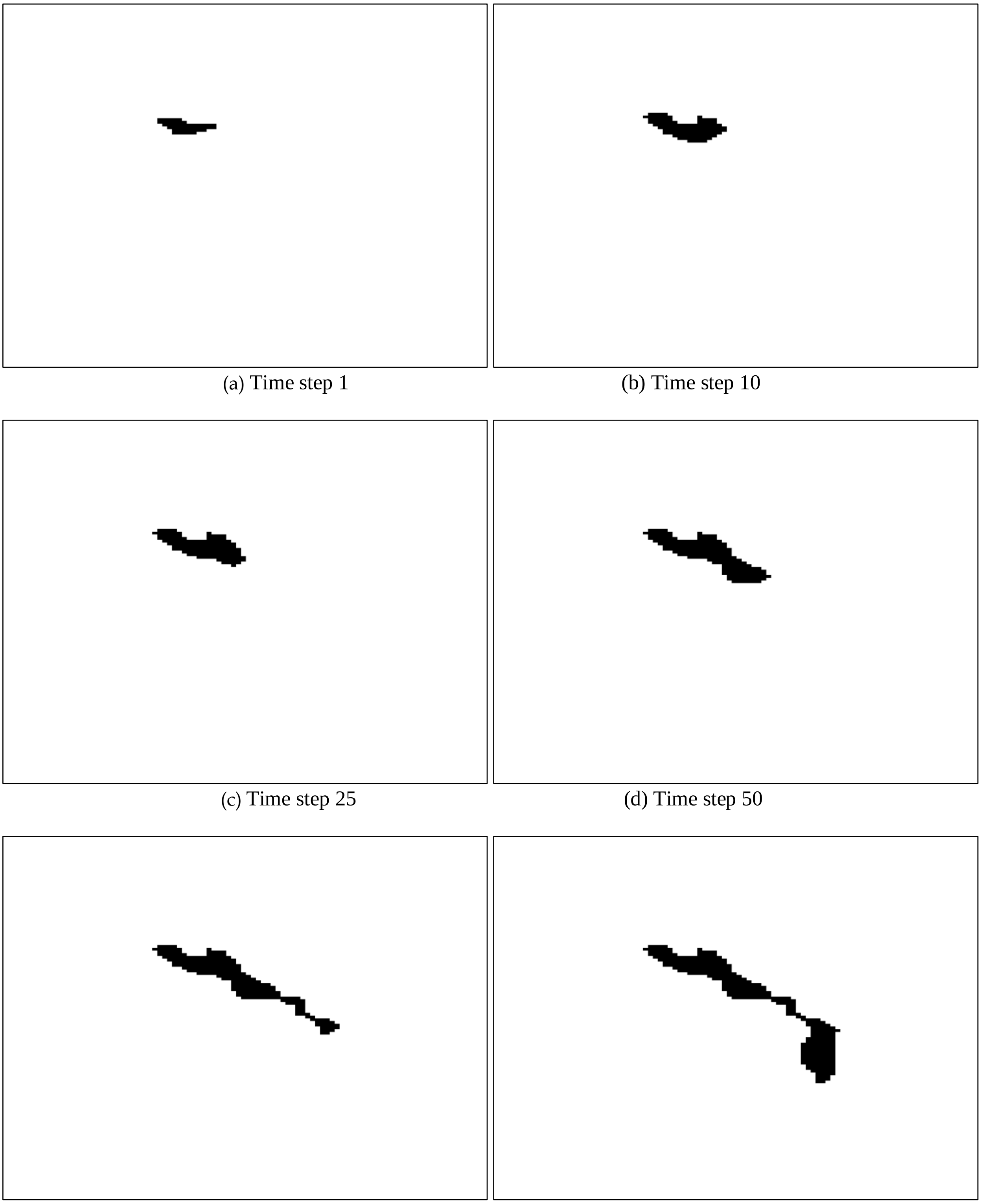
5.3 Manathavady Region

Manathavady is a region in Kerala which was affected by debris flow. The model was tested using the information of the debris flow occurred in this region. Based on the data the corresponding maps were created and the parameters were set. Given below is the list parameters and the values that were used to simulate the debris flow.

Table 3: Manathavady region parameter values

Parameter (Units)	**Value**
Density (kg/m3)	1500
Cohesion (K Pa)	0.06
Dynamic Viscosity (Pa s)	42
Basal Friction Angle (degrees)	13
Internal Friction Angle (degrees)	14
Time steps	150
Degree of Saturation (%)	100
Dry Coulomb Viscous	0.2
Viscous Turbulent Friction (m/s2)	220
Critical Shear Stress (K Pa)	1.1
Erosion rate (m/s)	0.025
Maximum Erosion Depth (m)	1

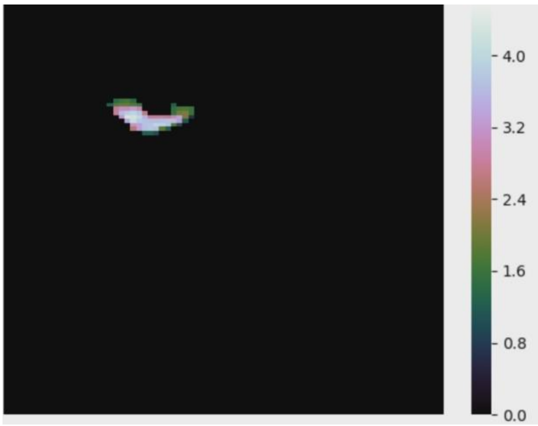
Heat maps of the flow:



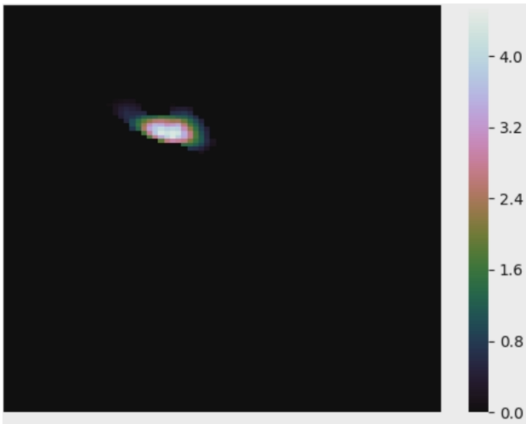
(a) Time step 1
(b) Time step 10
(c) Time step 25
(d) Time step 50
(e) Time step 100
(f) Time step 150

Figure 9: Domain of the flow

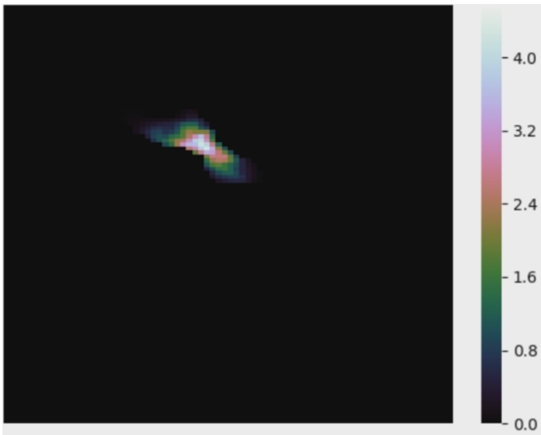
Height Animation Screenshots are shown below:



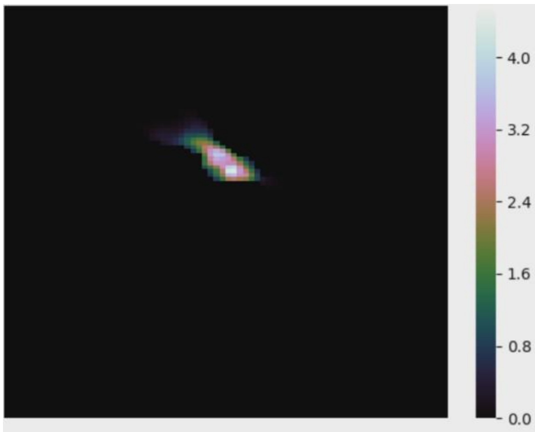
(a) Time step 1



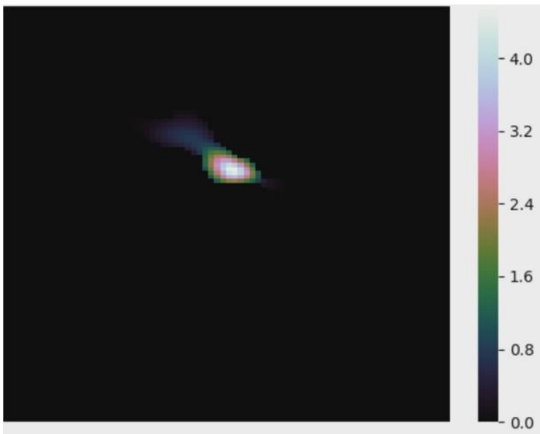
(b) Time step 10



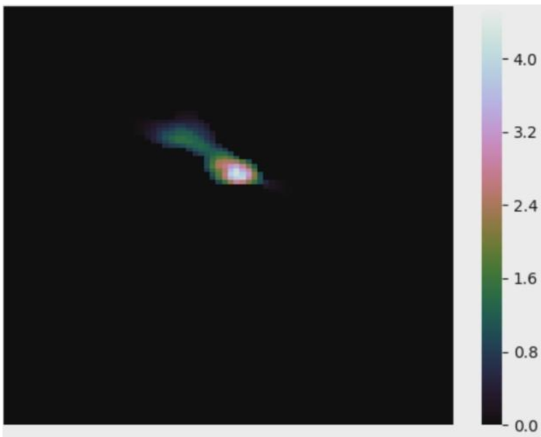
(c) Time step 25



(d) Time step 50



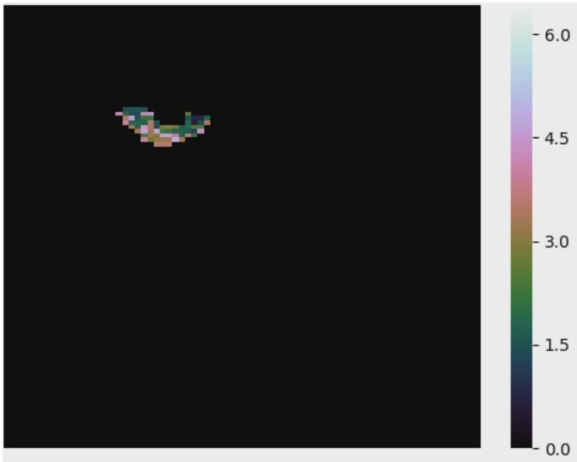
(e) Time step 100



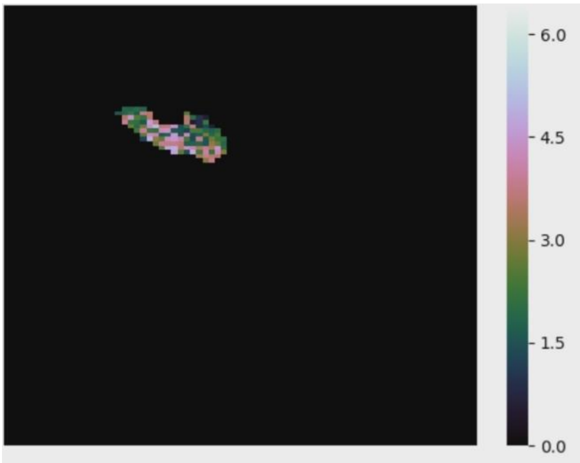
(f) Time step 150

Figure 10: Height Simulation of the flow

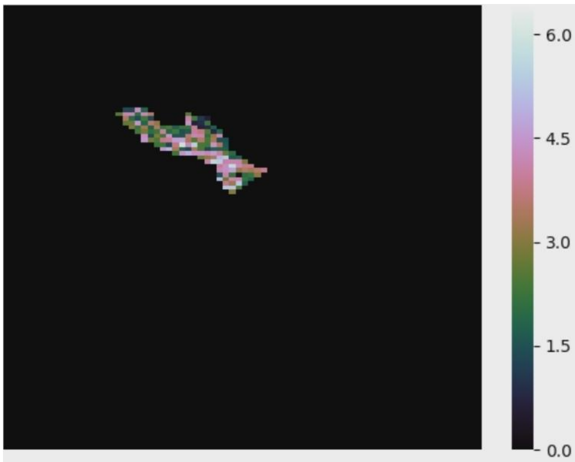
Velocity Animation Screenshots are shown below:



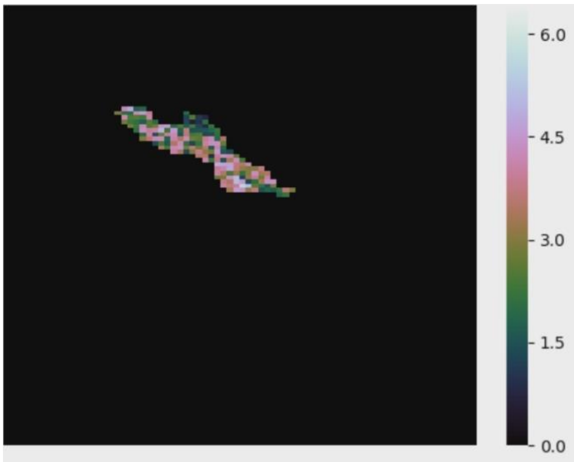
(a) Time step 1



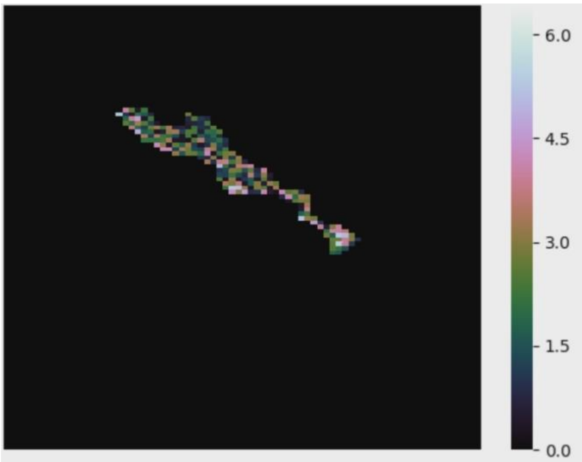
(b) Time step 10



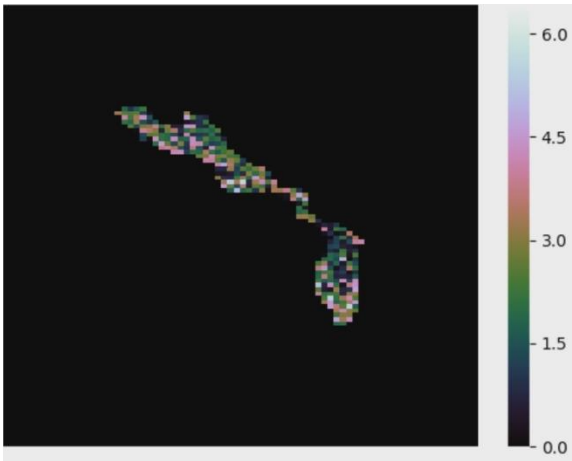
(c) Time step 25



(d) Time step 50



(e) Time step 100



(f) Time step 150

Figure 11: Velocity Simulation of the flow

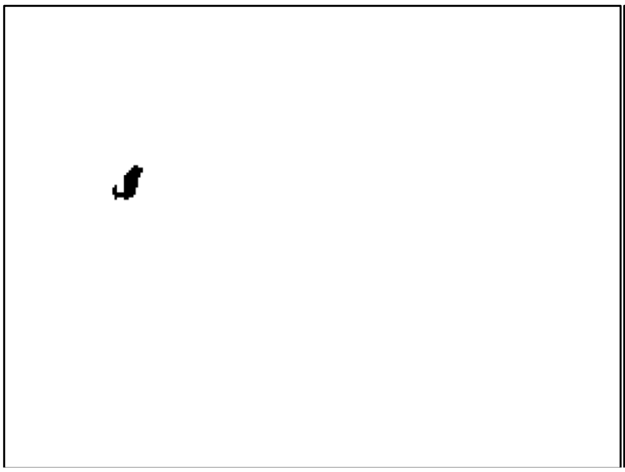
5.4 Vythiri Region

Vythiri is a region in Kerala which was affected by debris flow. The model was tested using the information of the debris flow occurred in this region. Based on the data the corresponding maps were created and the parameters were set. Given below is the list parameters and the values that were used to simulate the debris flow.

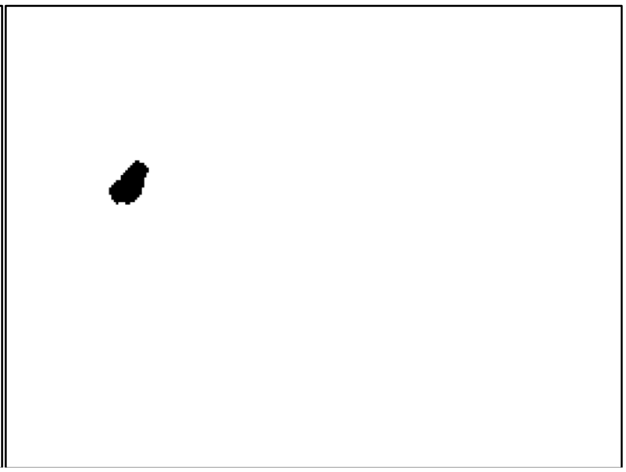
Table 4: Vythiri region parameter values

Parameter (Units)	**Value**
Density (kg/m3)	1900
Cohesion (K Pa)	0.082
Dynamic Viscosity (Pa s)	24
Basal Friction Angle (degrees)	10.2
Internal Friction Angle (degrees)	11
Time steps	150
Degree of Saturation (%)	100
Dry Coulomb Viscous	0.2
Viscous Turbulent Friction (m/s2)	250
Critical Shear Stress (K Pa)	1.3
Erosion rate (m/s)	0.03
Maximum Erosion Depth (m)	1

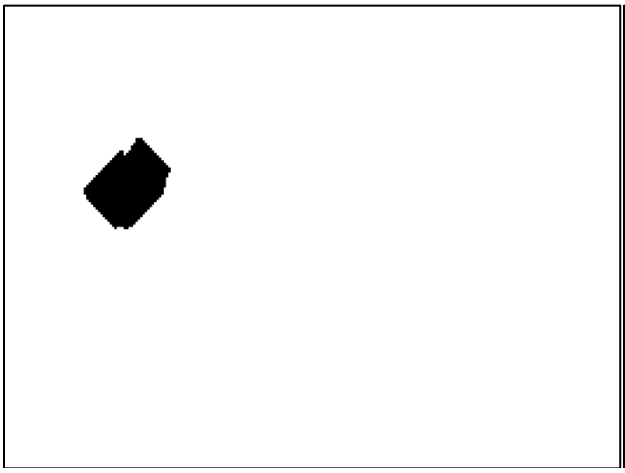
Heat maps of the flow:



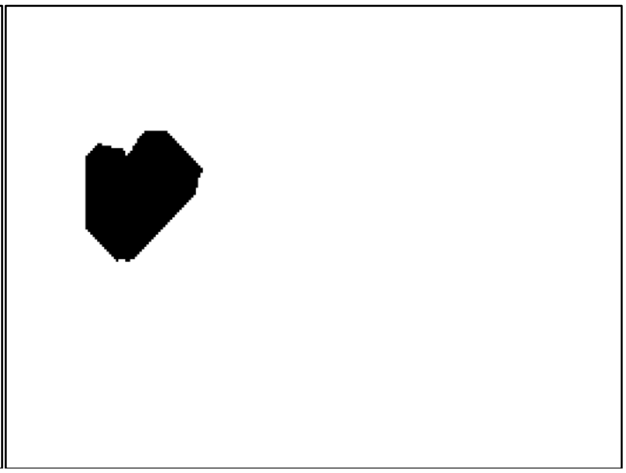
(a) Time step 1



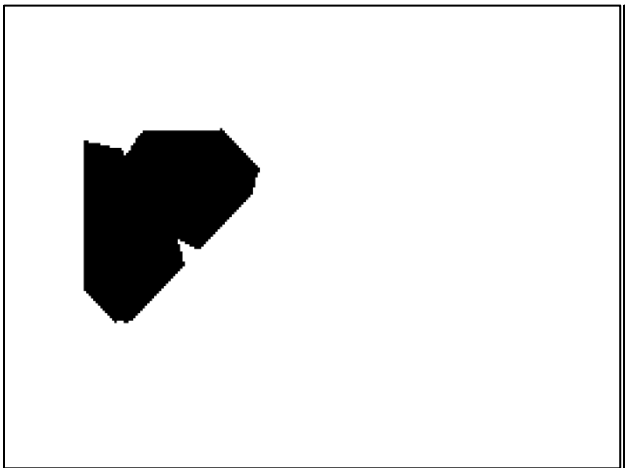
(b) Time step 10



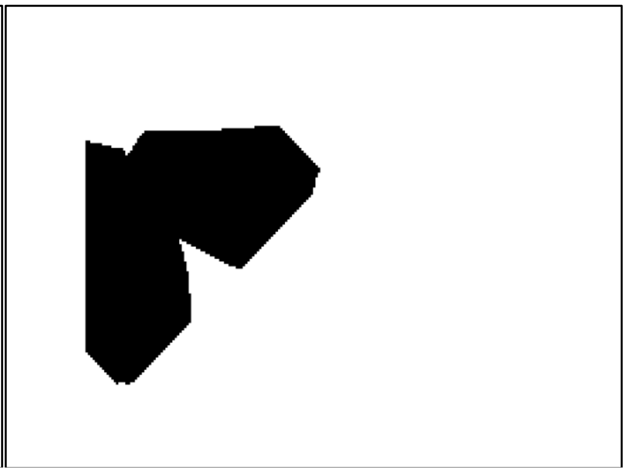
(c) Time step 25



(d) Time step 50



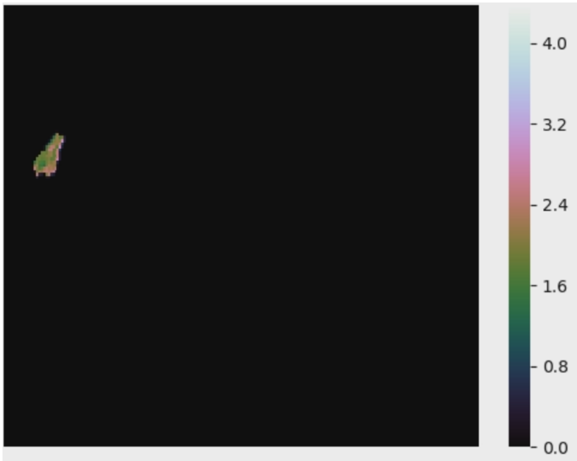
(e) Time step 100



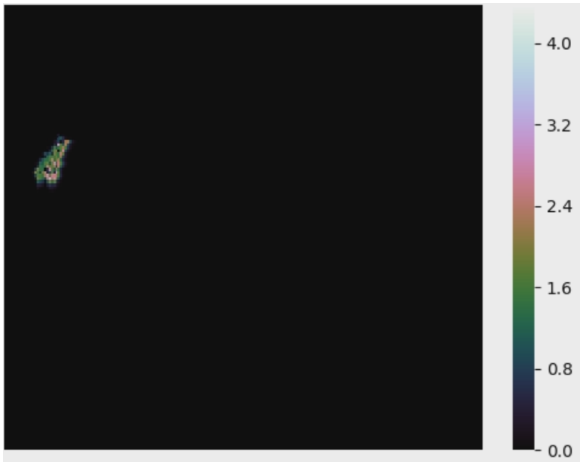
(f) Time step 150

Figure 12: Domain of the flow

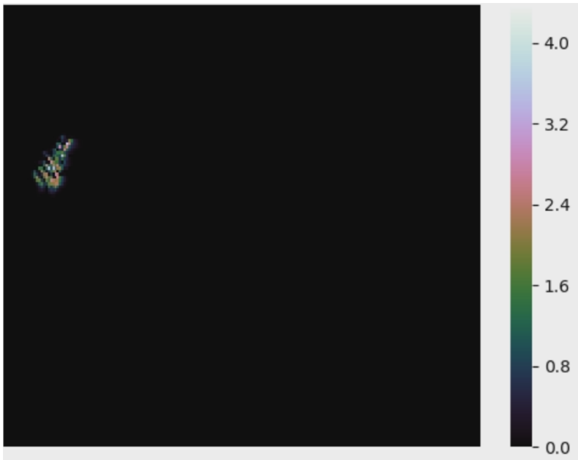
Height Animation Screenshots:



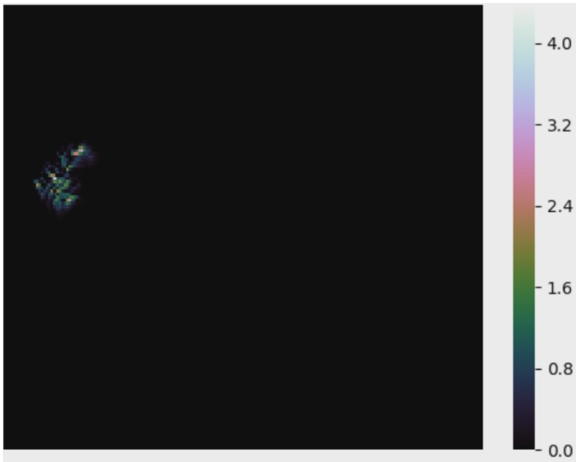
(a) Time step 1



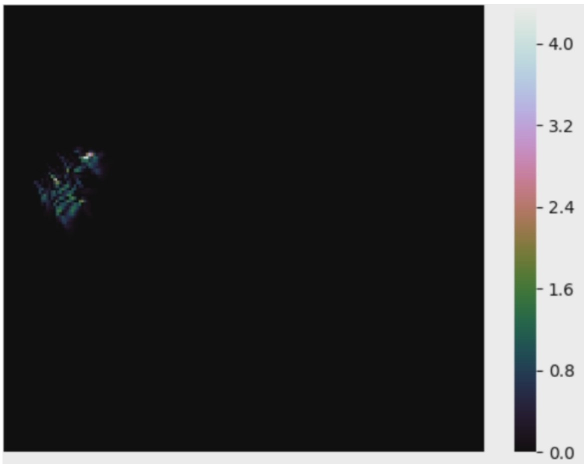
(b) Time step 10



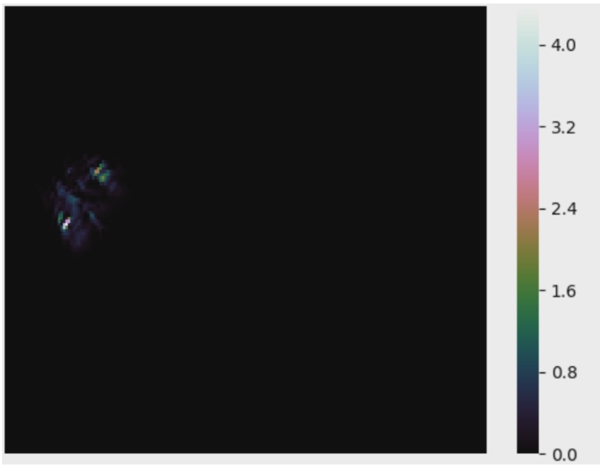
(c) Time step 25



(d) Time step 50



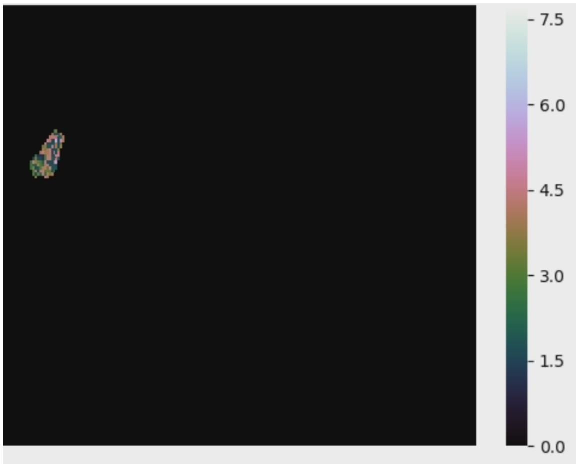
(e) Time step 100



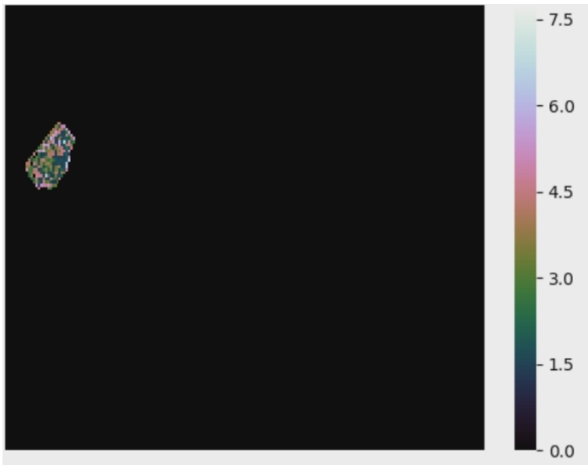
(f) Time step 150

Figure 13: Height Simulation of the flow

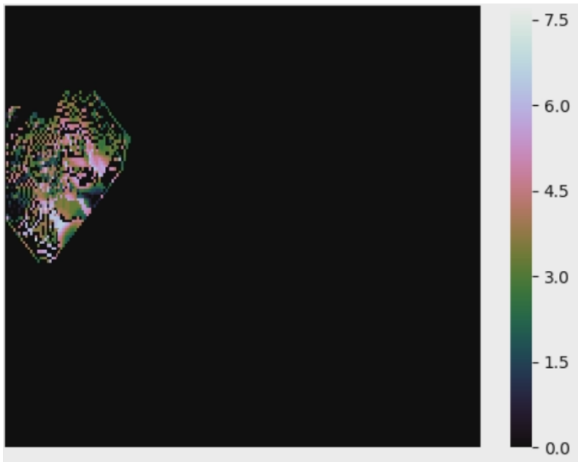
Velocity Animation Screenshots are shown below:



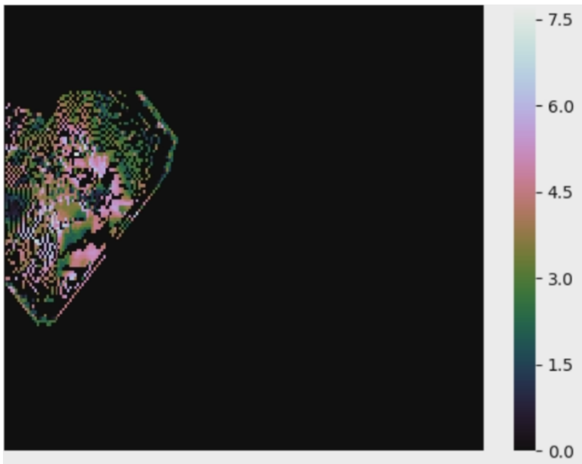
(a) Time step 1



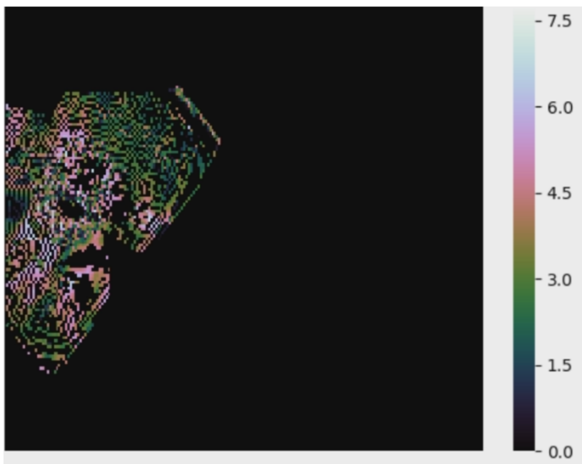
(b) Time step 10



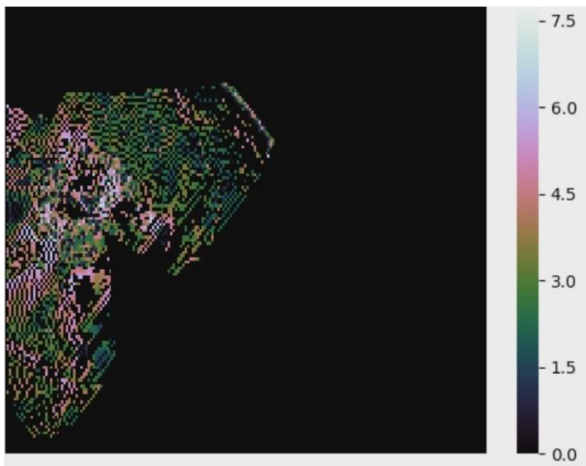
(c) Time step 25



(d) Time step 50



(e) Time step 100



(f) Time step 150

Figure 14: Velocity Simulation of the flow

Chapter 6

Conclusion & Future Work

The new robust numerical model for simulating debris flows along complex surfaces. This tool is developed to analyze the flow of large masses which would cause heavy loss to human life and property. Generally, it is hard to get the information of the flow which include direction and height of the flow as well as velocity. By developing a tool, one could easily study the flow of matter, indirectly this helps in disaster management and evaluating hazard as well. This also allows to evaluate flow properties such as velocity of the flow, height of the flow as well as impact force of the flow.

The simulation tool developed is by using flow equations which are generally used for continuous flow of fluids, the equations are solved in a 2D mesh using finite difference formulas. The tool also considers the diverse relations for the flow resisting gradient, this diversity makes the tool robust where the simulation can be performed for variety of materials of different characteristics. One of the drawbacks of this newly developed model is that it assumes the flowing mass to exhibit a single rheology behavior. This model can be further improved by considering the fact that the pressure due to pores in the material will vary along with the flow, this allows the model to be much more robust. This becomes the next challenge for further developers.

Comparing the present model with the older models, the current model incorporates all major effects which occur while debris flow. The core code of the model is developed in python, which makes the model to be more user friendly. by this property of the model a non-expert also can further study and analyze debris flows in different areas. Since python is a very easy scripting language to understand, one can easily understand the core code and develop it by adding new features. The model is basically built for conductive analysis of the parameters on which the debris flow depends and determine the corresponding parameters for the corresponding regions.

The input ascii files for a particular region can be generated by using Arc GIS platform, this allows easy study on new areas and their behavior in case of debris flow. In our study we used the tool to simulate the debris flow in Manathavady region. By analyzing the region and further back analyses based on the debris flow which has already occurred we could fix the parameters and run the simulation and found the final amount of the spread of the moving mass and the deposits of the uprooted mass. The results prove that the tool is able to predict the debris flow and can be used to simulate real events. Thus, ensuring that the tool can be used for mitigation purpose as well as evaluation of hazard.

References

[1] S. Beguería, T. W. J. Van Asch, J. P. Malet, and S. Gröndahl, "A GIS-based numerical model for simulating the kinematics of mud and debris flows over complex terrain," *Nat. Hazards Earth Syst. Sci.*, vol. 9, no. 6, pp. 1897–1909, 2009.

[2] W. Shen, T. Li, P. Li, M. Berti, Y. Shen, and J. Guo, "A two-layer numerical model for simulating the frontal plowing phenomenon of flow-like landslides," *Eng. Geol.*, vol. 259, no. June, p. 105168, 2019.

[3] S. P. Pudasaini, "A general two-phase debris flow model," *J. Geophys. Res. Earth Surf.*, vol. 117, no. 3, pp. 1–28, 2012.

[4] H. Y. Hussin, B. Quan Luna, C. J. Van Westen, M. Christen, J. P. Malet, and T. W. J. Van Asch, "Parameterization of a numerical 2-D debris flow model with entrainment: A case study of the Faucon catchment, Southern French Alps," *Nat. Hazards Earth Syst. Sci.*, vol. 12, no. 10, pp. 3075–3090, 2012.

[5] T. de Haas and T. van Woerkom, "Bed scour by debris flows: experimental investigation of effects of debris-flow composition," *Earth Surf. Process. Landforms*, vol. 41, no. 13, pp. 1951–1966, 2016.

[6] A. J. Horton, T. C. Hales, C. Ouyang, and X. Fan, "Identifying post-earthquake debris flow hazard using Massflow," *Eng. Geol.*, vol. 258, no. May, 2019.

[7] C. Berger, B. W. McArdell, and F. Schlunegger, "Direct measurement of channel erosion by debris flows, Illgraben, Switzerland," *J. Geophys. Res. Earth Surf.*, vol. 116, no. 1, pp. 1–18, 2011.

[8] S. McDougall and O. Hungr, "Dynamic modelling of entrainment in rapid landslides," *Can. Geotech. J.*, vol. 42, no. 5, pp. 1437–1448, 2005.

[9] S. L. Kuriakose, "Effect of Vegetation on Debris Flow Initiation," 2006.

[10] C. Berger, B. W. McArdell, B. Fritschi, and F. Schlunegger, "A novel method for measuring the timing of bed erosion during debris flows and floods," *Water Resour. Res.*, vol. 46, no. 2, pp. 1–7, 2010.

[11] Z. Han and G. Chen, "A method for estimating the bed-sediment entrainment in debris flow," *Japanese Geotech. Soc. Spec. Publ.*, vol. 2, no. 30, pp. 1089–1093, 2016.

[12] S. J. Birkinshaw, "Physically-based modelling of double-peak discharge responses at Slapton Wood catchment," *Hydrol. Process.*, vol. 22, no. 10, pp. 1419–1430, 2008.

[13] G. B. Crosta, S. Imposimato, and D. G. Roddeman, "Numerical modelling of large landslides stability and runout," *Nat. Hazards Earth Syst. Sci.*, vol. 3, no. 6, pp. 523–538, 2010.

[14] M. Ceccatelli, G. Gigli, L. Lombardi, M. Nocentini, and T. Salvatici, "Numerical modeling and characterization of a peculiar flow-like landslide," *Geoenvironmental Disasters*, vol. 4, no. 1, 2017.

[15] J. Aaron, S. McDougall, J. R. Moore, J. A. Coe, and O. Hungr, "The role of initial coherence and path materials in the dynamics of three rock avalanche case histories," *Geoenvironmental Disasters*, vol. 4, no. 1, 2017.

[16] G. B. Crosta, F. V. De Blasio, M. De Caro, G. Volpi, S. Imposimato, and D. Roddeman, "Modes of propagation and deposition of granular flows onto an erodible substrate: experimental, analytical, and numerical study," *Landslides*, vol. 14, no. 1, pp. 47–68, 2017.

[17] B. Salm, "Flow, flow transition and runout distances of flowing avalanches," *Ann. Glaciol.*, vol. 18, pp. 221–226, 1993.

[18] B. Choubin, M. Borji, A. Mosavi, F. Sajedi-Hosseini, V. P. Singh, and S. Shamshirband, "Snow avalanche hazard prediction using machine learning methods," *J. Hydrol.*, vol. 577, p. 123929, 2019.

[19] R. Manual, "RAMMS - rapid mass movements simulation, A numerical model for debris flows in research and practice, User Manual v1.7.0, Debris Flow, Manuscript update November 2017. WSL Institute for Snow and Avalanche Research SLF," pp. 1–116, 2017.