Utrecht University

Faculty of Geosciences

Numerical comparison between RAMMS debris flow simulations and actual events in the Illgraben catchment area, Switzerland

MSc thesis: Nils Roos (5716861)
Supervisors: Tjalling de Haas & Wiebe Nijland
Utrecht University, 2021
Faculty of Geosciences

Preface

This master thesis was written during a time we will probably all remember for the rest of our lives. I will probably remember it even more, as the time when I was writing my master thesis. Beside my interest in debris flows, and actually all processes that involve mountains, this project drew my attention because of the fieldwork it included. Unfortunately, because of the measures against the pandemic, fieldwork was cancelled. Nevertheless, I got to learn more and more about the area, and became increasingly knowledgeable about debris flows and modelling them. I have to admit, I did have a hard time motivating myself every now and then, but with the help of the people around me I think I succeeded in making a decent master thesis. First of all, I would like to thank my supervisor Tjalling de Haas. From all people, he helped me the most with bringing this thesis to a good end. Next, I would like to thank Amanda Aaberg, who spent quite some time explaining me the ins and outs of the GIS erosion and deposition analysis. Furthermore, I would like to thank my roommates, with which I spent quite some time with writing this thesis. Till the end they have given me the emotional support I needed. Finally, I also would like to thank my friends, for listening to my endless stories about debris flows in Illgraben.

Nils Roos

May 2021

Abstract

Debris flows can become hazardous in mountainous areas when growing to large volumes. The main mechanism causing a debris flow to reach a large volume is erosion. The RAMMS model has shown to be successful in simulating debris flow events realistically. However, this model still has shortcomings, of which erosion is the most important one. At the moment, erosion in RAMMS is poorly studied. In this research, actual measured debris flows were compared to simulated debris flow events in RAMMS to take a closer look at how the RAMMS model performs in terms of erosion. Two debris flow events, one very erosive and the other less erosive, were analysed with a quantitative GIS erosion and deposition analysis. This study shows that RAMMS is able to successfully simulate less erosive debris flows, but when a debris flow is very erosive, the simulated erosion is very different from the actual event. A reason for this could be that the erosive event had certain parameters without erosive properties, or that the many check dams along the channel prevented most erosion. Nevertheless, it shows that future research on how RAMMS performs in terms of erosion is crucial for successfully forecasting debris flows in the future, as erosive debris flows can be most hazardous when they grow to large volumes.

Table of contents

1. Introduction

A debris flow is a type of mass movement that occurs in mountainous areas with sufficient amounts of precipitation. A typical geological composition in combination with enough available water can trigger several hydrological mechanisms that can ultimately trigger a landslide (Godt & Coe, 2007). As a result, the material of this landslide can start to flow downhill as a mixture of mud and debris that forms a debris flow. Debris flows can form a natural hazard in mountainous areas. The main reason for a debris flow to become a hazard is that it can quickly grow to an enormous volume that can have a devastating effect. In the worst case, debris flows can become fatal with a recorded death toll of 77,779 from 1950 to 2011 (Dowling & Santi, 2014). With increasing frequency of extreme weather events caused by climate change, also the frequency and magnitude of debris flows as a natural hazard can increase, which could possibly lead to a higher death toll (Stoffel et al., 2014). In addition to the recorded death toll, Dowling & Santi, 2014 also found a relation between flow volume and casualties: a higher flow volume overall means higher death toll, although this relation is affected by population size).

There is already much knowledge about the behaviour of debris flows. For example, known indirect factors that affect debris flow behaviour are: soil moisture (Iverson et al., 2011), precipitation rates (Chien & Yuan, 2005) and the shape of the channel (Schurch et al., 2011). However, there is one factor that directly affects the volume of a debris flow: erosion. While a debris flow is eroding the channel, there can be uptake of material that becomes part of the debris flow, making it grow in size (Iverson et al., 2010; Frank et al., 2017). In other words: with more erosion, the debris flow can grow to a higher volume, which makes it a greater hazard. This is why it is crucial to have a better understanding of the erosion of debris flows.

Nowadays, more and more studies are being conducted on active debris flows and several models are constructed to make estimations of debris flow volumes and channel bed erosion directly. Nevertheless, most of these studies state the lack of information about the actual difference of the channel before and after and find it hard to accurately measure and predict channel erosion and deposition. Simulations by models provide a part of the solution by making it possible to look deeper into the mechanisms of debris flows and compare different debris flows. These simulations can also give an idea of the erosion and deposition quantities of the flow. The Rapid Mass Movement Simulation (RAMMS) model (Christen et al., 2010) is one of these debris flow models, shown to be successful at simulating debris flow events (e.g. Frank et al., 2017; Schraml et al, 2015; Simoni et al., 2012). On the other hand, also in this model there are many uncertainties in the results. For example, the model sometimes overestimates flow volumes (Cesca & d'Agostino, 2008), and Schraml et al. (2005) argue that a more reasonable range for input parameters is needed in order to make realistic simulations. Most importantly, most of the studies that investigated the performance of debris flows (Simoni & Mamoliti, 2012; Cesca & d'Agostino, 2008; Schraml et al., 2015; Gan & Zhang, 2019) tend to focus more on flow depth, instead of erosion. The latter is probably more important when looking at the flow volume and thus the hazardous aspect of debris flows.

In this research, the performance of the RAMMS model will be tested in combination with a GIS-based erosion and deposition analysis of two debris flows in the Illgraben channel in Swiss Alps. This channel is a well monitored debris flow channel with a high frequency of debris flows per year (McArdell et al., 2007, Uchida, 2020). These analyses are done to investigate the following research objectives:

1. Quantify patterns of actual erosion and deposition and in RAMMS in the Illgraben channel
2. Comparing different debris flows – testing whether RAMMS is able to successfully simulate erosion and how the different parameters affect erosion
3. Testing whether RAMMS performs better (i.e. more comparable to an actual event) when using a high-resolution DEM as input

this master thesis will start off with a literature review on what is known about debris flows and RAMMS nowadays, followed by information about the study area. These two chapters form the knowledge basis for investigating the research questions. Next, it will be explained how the research was conducted, from a GIS analysis that recognises erosion and deposition patterns, to explaining how to set up a simulation in RAMMS. Then, the results retrieved from RAMMS and the GIS analysis will be shown in several graphs, figures and maps, after which uncertainties of these results will be discussed and compared to what is known from literature. Finally, the founding's of all the chapters will be summarized in the conclusion.

2. Theoretical framework

In this chapter a literature overview of debris flows in general and more specifically of the RApid Mass Movements Simulation (RAMMS) model is given. This is an important part of this thesis because it provides a theoretical base from which becomes clear what literature gaps are still present for this field of research. Considering these literature gaps, the research questions of this thesis will follow, and it will become clear what this thesis could contribute to fill some of these gaps. First some basic physics of debris flows will be mentioned, after which the processes and dynamics of debris flows will be discussed. Following these subchapters, I will focus more on debris flow modelling and subsequently the RAMMS model. After each subchapter the knowledge gap of that part will be shortly highlighted, and these gaps will be summarized in the last subchapter including the research questions.

2.1 Physics of debris flows

2.1.1 Classification of debris flows

A debris flow is a type of mass movement that occurs in mountainous areas with sufficient amounts of precipitation. With a typical geological composition this rain can trigger several hydrological mechanisms that can ultimately trigger a landslide, and subsequently a debris flow when the landslide material starts flowing downhill (Godt & Coe, 2007). When looking at debris flows, three types of mass movement need to be distinguished. The first type is an avalanche, which mainly consists of solid particles rapidly moving downwards. The second type is a flood, mainly consisting of liquid particles moving downwards. The third type of mass movement, which is most poorly understood, is a debris flow, consisting of both solid and liquid particles (Iverson, 1997). For the classification of debris flows, also a distinction is made between three types (Takahasi & Das, 2014), as different debris flows can have very different compositions and behaviour. The three different types are classified as follows: Stony debris flow, turbulent-muddy flow, and the viscous debris flow (Uchida et al., 2020). Concluding from the names, the different types are classified mostly in terms of behaviour and composition. The stony debris flow is characterized by a high fraction of coarse sediment which can go up the size of boulders, with the largest rocks and boulders situated in the front of the flow, as can be seen in figure 2.1 (Takashi & Das, 2014; Egashira, 2011). The turbulent-muddy flow has a higher fraction of mud and is associated with volcanic activity, while the viscous type is characterized by multiple surges that follow after each other instead of one steady flow downstream (Takashi & Das, 2014). Now that the classification of different debris flows is explained, it can be further elaborated what physical processes happen when a debris flow occurs.

2.1.2 Initiation and mechanisms of a debris flow

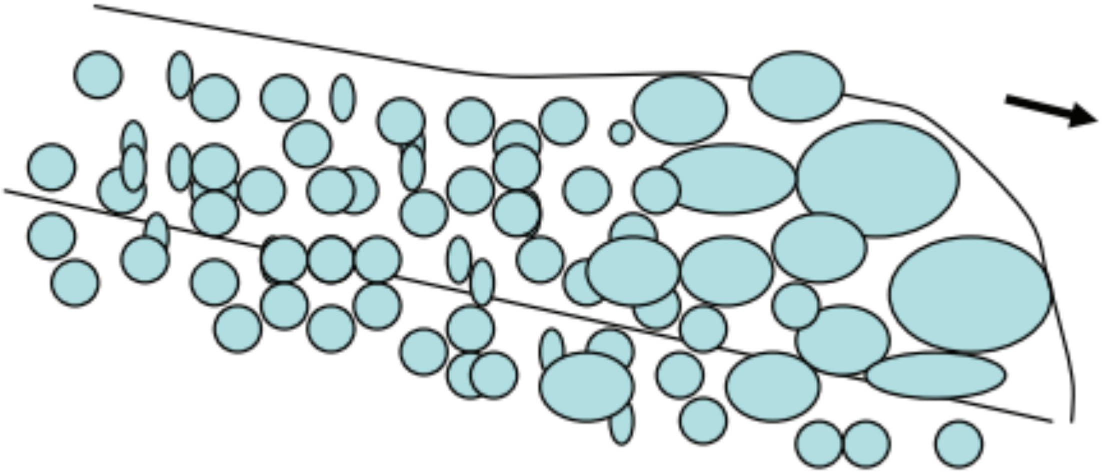


Figure 2.1: representation of distribution of the particles inside a debris flow (Egashira, 2011)

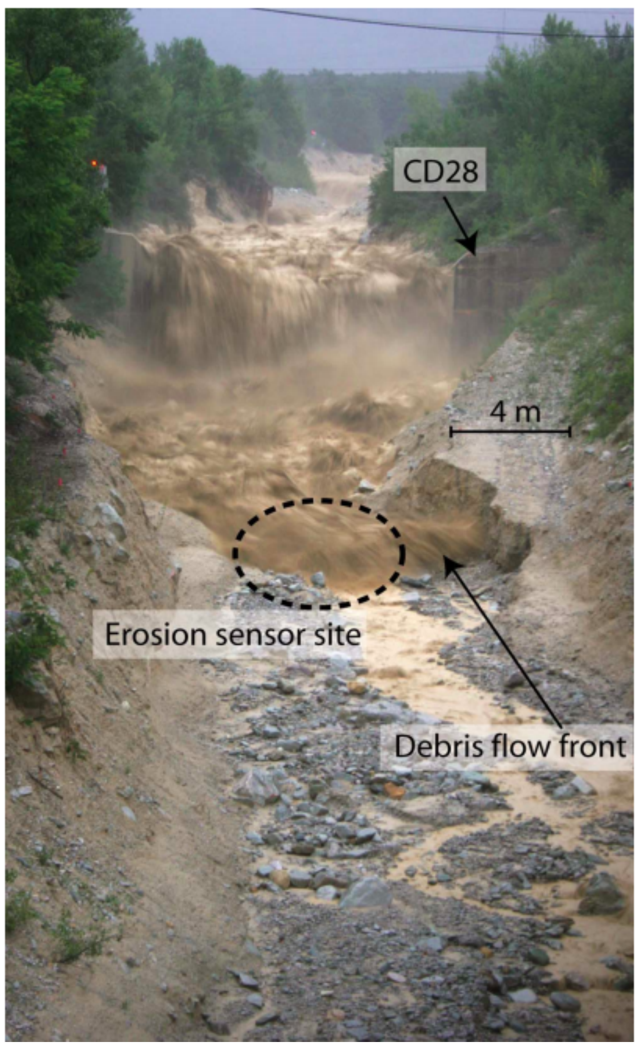


Figure 2.2: image of the debris flow front or head from an ongoing debris flow (Berger et al., 2011).

For a debris flow to happen, a few thresholds need to be overcome. Of course, a certain geology with enough loose sediment on top is required that can be mobilized for transportation (Godt & Coe, 2007; Iverson, 1997). Furthermore, enough precedential rain and a certain soil moisture content is needed. Also, the slope of the hill or mountain needs to be steep enough to make the gravitational forces overcome the internal friction of the material, and the friction of the bed beneath the material (Iverson, 1997). When these thresholds are overcome, the debris flow can be initiated and starts to flow downhill. The trigger for this initiation is mainly rainfall (Chien-Yuan et al., 2005). Another trigger could be an earthquake for example, either directly, or by lowering the critical rainfall duration for a debris flow to happen (Chein-Yuan et al., 2005). According to Godt & Coe (2007), There are three mechanisms that can ultimately cause rain to initiate a debris flow. During all these three mechanisms, enough material is mobilized in such a way that a debris flow can be initiated, but the way it is mobilized and the processes that play a role differ. One mechanism comprises shallow material that was being mobilized in thick colluvial deposits. The second mechanism was mainly due rill erosion that transported material down on steep slopes and mobilized the material at the end of the slope. The third mechanism is called the "firehose effect", which basically means the dripping or streaming from cliffs higher up onto colluvium, which can saturate the colluvium and can cause failure and ultimately initiation of a debris flow (Griffiths et al., 2004). Reid et al. (1997) discussed three hydrological triggers that focus more on slope failure. These triggers are a high-intensity rainfall event, a lower-intensity rainfall event with a longer duration, and the local inflow of groundwater. In the table below the three aforementioned mechanisms and triggers and their possible link are put next to each other.

Table 1: link between slope failure triggers and debris flow initiation mechanisms.

Debris flow initiation mechanisms (Godt & Coe, 2007)	Slope failure triggers (Reid et al., 1997)	Link
Mobilized shallow colluvial deposits	Local inflow of groundwater	Inflow of groundwater can accelerate saturation of colluvial material
Rill erosion	High intensity rainfall	High intensity rainfall is likely to cause rill erosion
"Firehose effect"	Longer low intensity rainfall	Longer rainfall can cause water dripping from steep slopes induced by saturated soils or colluvium.

Of course, also a combination of the three mechanisms and initiation can form the basis of a debris flow. Then, the combined mechanisms mobilise the sediment needed for a debris flow, and then one of the mechanisms can be the ultimate trigger to initiate the flow (Morino et al., 2019).

When the flow is initiated, it has a typical form in which it is transported downhill. The flow typically has a front or head with the biggest particle size up to boulders, which is followed by its tail, containing more suspended sediment in the form of a turbulent slurry (Berger et al., 2011; Iverson, 1997). In Figure 2.2 the head is visible on an ongoing debris flow and in figure 2.1, a schematic representation of the distribution inside a debris flow is given.

One of the things that also make debris flows hard to understand, is that the particles inside the flow go through a sudden phase change in two ways (Uchida et al., 2020). That is, in terms of behaviour of the flow: first the particles change from solid to nearly liquid, and when the flow stops, the particles change back to solid again and get deposited. These changes are largely dependent on the variation in kinetic vibrational energy (which can be seen as the granular temperature) and changes in pore pressure (Iverson, 1997), but when and why they happen exactly is partly unknown. Where material gets deposited and the mechanisms that play a role in this will be discussed in section 2.2. Besides these triggers that mainly have rainfall or groundwater flow as the direct initiating mechanism, also runoff from snow or rain that falls in one place, can indirectly lead to the formation of a debris flow in another (Kean et al., 2013).

2.2 Erosion and deposition by debris flows

2.2.1 Erosion and entrainment

Fundamental for the comprehension of debris flows are erosion and deposition. Because the pathways of debris flows are mostly studied (right) before or after the event, erosion and deposition can be good indicators of the behaviour of the flow during the event. Erosion can be seen as the scouring of the channel bed the debris flow follows (Reid et al., 2011). This happens mostly at the granular front, where coarse sediment erodes the channel bed (Schurch et al., 2011).

A mechanism that occurs often in combination with erosion or can be seen as a form of erosion, is entrainment. That is, the uptake of eroded sediment into the debris flow (Frank et al., 2017). Besides entrainment by bed erosion, entrainment can also happen when channel sides collapse and get incorporated in the flow (Iverson et al., 2011). Entrainment can have a large effect since it can incur a positive feedback to the flow volume. As more sediment is incorporated in the flow, the flow becomes bigger and channel depth is increased. From experiments, it has become clear that higher volumetric soil moisture content has a positive effect on entrainment (Iverson et al., 2011; Reid et al., 2011; Hirschberg et al., 2019).

By looking at eq. 2 (discussed in subchapter 2.3.3), it can be concluded that the shear stress increases when channel depth h is increased, which increases the erosion, which increases channel depth, and so on. In this way, the positive feedback can increase flow volumes in a rapid way and generate a much larger volume than the initial volume of the debris flow (Frank et al., 2017). This means that generally when there is a larger flow volume, there is also more erosion (Schurch et al., 2011). In the next subchapter it will be explained why this entrainment is such an important mechanism in debris flow modelling. As entrainment is affected by channel depth, logically all erosion is affected by channel depth. When multiple debris flows occur in one channel, memory effects can have much influence on erosion and deposition (de Haas et al., 2020). This memory effect means that in places with erosion there will probably be deposition in the next debris flow, and the other way around.

Besides channel geometry and debris flow volume, also sediment size is linked with erosional behaviour of a debris flow. Egashira et al. (2001) showed with experiments that overall there is a decrease of relative erosion with an increase of relative grain size of the sediment. Whereas Nishiguchi et al. (2012) stated that also the distribution of the grain size in combination with erosion and deposition can be of a wide variety. In this way, it is hard to tell if there is a straight correlation between grain size, or grain size distribution and erosion, and thus if the grain size can have a decisive effect on whether a debris flow will grow vastly in size or if the debris flow fully deposits at a certain point. The proposed parameters that affect erosion are summarized per author in the table below.

Table 2: overview of different parameters that affect erosion per author.

Author(s)	**Parameter linked to erosion**	**Type of feedback**
Frank et al. (2017)	Flow depth	Positive
Iverson et al. (2011); Reid et al. (2011); Hirschberg et al. (2019)	Volumetric soil moisture content	Positive
Schurch et al. (2011)	Flow volume	Positive
Egashira et al. (2001)	Relative grain size	Negative
Nishiguchi et al. (2012)	Distribution of grain size	Decisive
Stock & Dietrich (2006)	Inertial stress	Positive
Frank et al. (2015)	Shear stress	Positive
Schurch et al. (2011); Baggio et al. (2021)	Peak discharge	Positive
Dietrich & Krautblatter (2019)	Flow momentum	Positive

2.2.2 Deposition

Deposition is the material deposited along the pathway by the debris flow during the event. This can happen in multiple places, but overbank deposition is found to be the main type of deposition that occurs during a debris flow (Schurch et al., 2011). This is because the velocity of the flow gets decelerated very much when the sediment reaches the bank as the friction increases much as well. This is because flow depth decreases rapidly outside the channel, which brings the top of the flow closer to the friction of the bed. Of course, the process that happens when the debris flow reaches its banks can also happen along the channel. In this case, changes in channel geometry can cause the flow depth to decrease and as a result in-channel deposition can occur (Cannon, 1989). So, both erosion and deposition are strongly linked to channel geometry as well.

Figure 2.3 (Berger et al., 2011) gives an idea of the erosion and deposition patterns that become visible when the net elevation change before and after a debris flow event is calculated. The image shows a part of a well monitored debris flow channel, given for example the camera, erosion sensor and force plate in the legend. As can be seen, deposition is seen as the positive change in elevation, and erosion is seen as the negative change in elevation. In this case, it is clear that in the outer bend there tends to be more erosion, and in the inner bend there is more deposition. In the rest of this part of the channel, all other areas are calculated as erosion. Besides these observations, the check dams are very important to consider, as they are said to have much influence on the spatial erosion and deposition patterns (de Haas et al., 2020).

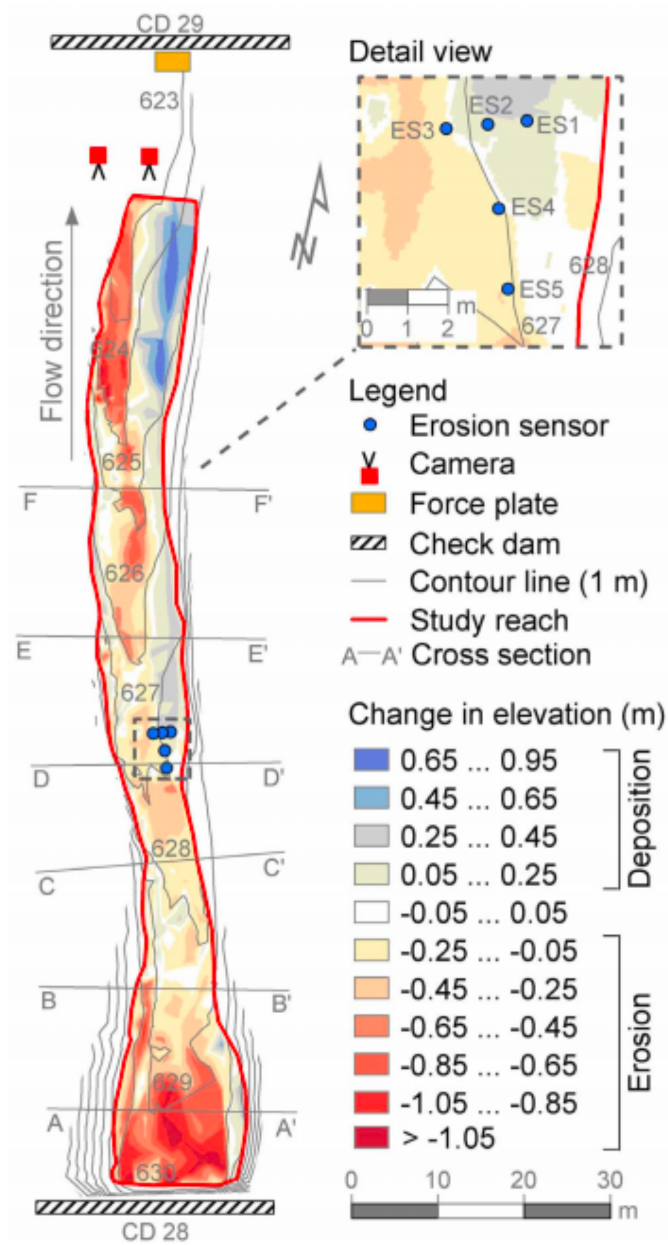


Figure 2.3: example of indicated erosion and deposition in a change map of a debris flow channel

2.3 The Rapid Mass Movements Simulation (RAMMS) model

2.3.1 Debris flow modelling in general

To get a better understanding of the behaviour of debris flows, simulation models are being used more and more. Especially in the case of debris flows this is crucial, because in models the movement of the debris flows can be simulated, whereas in the field this is very scarcely observed. With increasing calculation capacity of computers, the simulations can be done with higher resolution and thus movements of debris flows can be obtained more precisely.

Through the years, two types of debris flow simulation models have been used: empirical models, based on statistical analysis of debris flow data (e.g.: Scheidl & Rickenman 2010); and more physically based models, mostly based on resistance terms and flow equations (e.g.: Frank et al., 2015; Schraml et al., 2015; Simoni et al., 2012). Furthermore, smaller scale experiments can be executed to look at the processes that play a role for debris flows (e.g.: Iverson et al., 2011; Reid et al., 2011; de Haas & van Woerkom, 2016). Also, GIS-based or DEM-based quantifications of debris flow erosion and deposition can be used to look at the behaviour of debris flows (Scheidl & Rickenman, 2011; Schurch et al., 2011) Of course, all these types of modelling and experimenting have their own disadvantages. Of which the most important one is that models and experiments are never exact copies of actual events. This problem will be discussed more in depth for the RAMMS model in the next subchapter.

2.3.2 RAMMS

The Rapid Mass Movements Simulation (RAMMS) model is a debris flow entrainment model that estimates the runout of debris flows (Frank et al., 2015; Frank et al., 2017; Krusic et al., 2019; Schraml et al., 2015). The model can simulate avalanches, debris flows and rock fall. As with many models, it has been through a certain development over the years and has been compared to actual events to test its predictability. At the moment, multiple studies (e.g. Frank et al., 2017; Schraml et al, 2015; Simoni et al., 2012) showed that the model can successfully simulate actual events. The RAMMS model uses formulas to simulate the movement of the debris flow through a certain landscape. A Digital Elevation Model (DEM) or Digital Terrain Model (DTM) are used to simulate the terrain the debris flow will go through. As mentioned earlier, equation 3 is very important for the RAMMS model. This formula contains the friction parameters μ and ξ that can be adjusted when setting up the model. The μ parameter is linked to the normal stress, and the ξ parameter is linked to the squared velocity of the flow (Schraml et al., 2015). So, with these parameters the friction can be adjusted in such a way that the simulation is as realistic as possible. Schraml et al. (2015) found μ to be the most sensitive of the two, probably because μ is more dominant at lower speeds, whereas ξ is more dominant in turbulent areas at higher speeds. However, this sensitivity might differ between debris flows, since flow speeds and volumes can differ much between debris flows as well.

According to Fan et al. (2017), the RAMMS model has three important points where it performs better in comparison with other pre-existing models. Firstly, the flow direction of the debris flow is based on the calculation of a numerical velocity vector that is adjusted to the surface of the 3D terrain or elevation model. Secondly, RAMMS incorporates different flow heights for the different parts of the moving debris flow. Lastly, in the momentum balance equation, RAMMS has an earth pressure term. In this way, RAMMS can simulate the changes in stress on the debris flow due to topographical changes. Still, RAMMS also has some parts that can be improved. For example, it sometimes overestimates flow volumes, albeit that this overestimation can be caused by high cell size (Cesca & d'Agostino, 2008). With a higher quality DEM or DTM, this problem should be at least partly solved.

When the model simulation is run, it gives many results, among which the runout of the debris flow. In figure 2.4, an example of a few different runouts of different debris flows is given. In the foregoing chapters flow height was an important indicator of multiple mechanisms and is given as a result in the figure. With these results an idea of erosion and deposition patterns can be obtained, but it remains a model, in a given channel. However, the RAMMS manual states that the RAMMS model cannot yet make a difference between different phases, so the material is modelled as if it is one bulk flow. While in reality debris flows often have different phases within the flow over time. Moreover, even if the RAMMS model would work perfectly, it remains the challenge to translate the results of a model with a certain initial state in a (mostly) fixed channel to an actual event on a steep slope without a fixed channel but the same properties as the researched area.

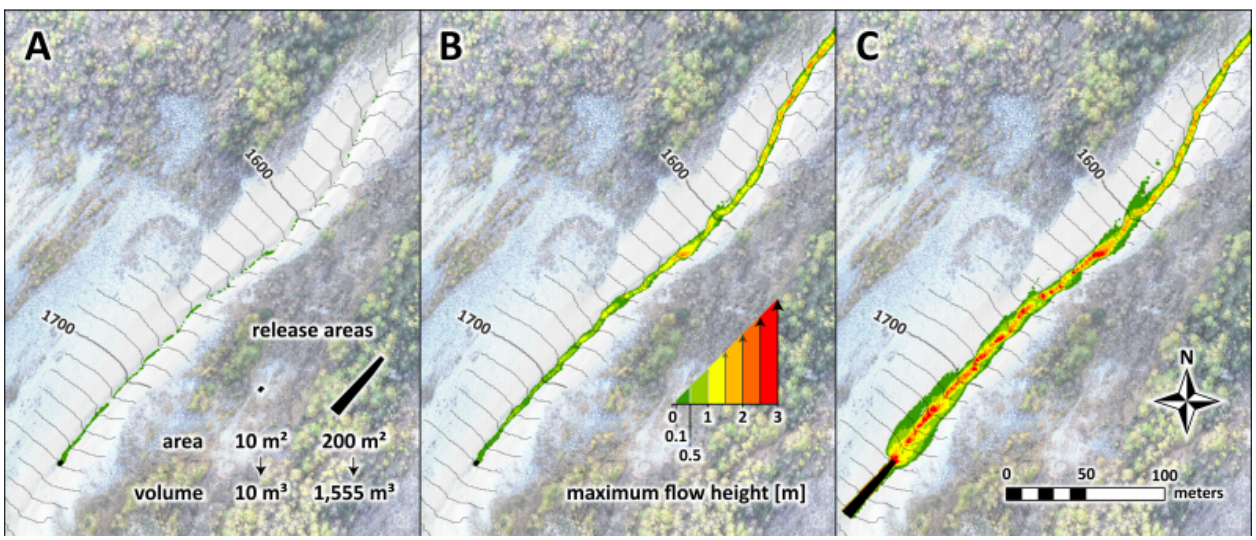


Figure 2.4: simulated runout of three debris flows with different parameters by RAMMS (Frank et al., 2017)

2.3.3 Important RAMMS formulas

To simulate the behaviour of a debris flow, also a few formulas are being used. There are of course many formulas that can describe debris flows, but there are three that are crucial for this thesis and an important part of the RAMMS model. These formulas were chosen to explain because equation 1 and 2 are mostly responsible for deposition and erosion and equation 3 is the most important equation used in the RAMMS simulation model.

The first formula to be explained is the formula for static force balance, as it describes the stress the channel bed exerts on the flow. The formula is given as follows:

$$\sigma = \rho g h \cos(\theta) \qquad \text{(eq. 1)}$$

Where σ is the basal normal stress, ρ is the flow material bulk density, g is the gravitational constant, h is the channel depth, and θ is the slope of the channel bed. (Iverson, 1997)

Nowadays, the widely accepted formula (similar to the static force balance) to estimate the shear force exerted by the flow on the channel bed is the formula for shear stress **τ**. The difference between the formulas is that the first one is from the bed's perspective, and the second one is from the flow perspective.

$$\tau = \rho g h \sin(S) \qquad \text{(eq. 2)}$$

Where S is the slope of the channel bed instead of θ (Haas & Woerkom, 2016). This formula is very important for debris flow modelling, as it describes the relation between shear stress and channel depth. This relation was more elaborately explained in subchapter 2.2.1.

Another important formula for debris flow modelling is the formula that describes the overall resistance and contains the two friction parameters μ and ξ:

$$S = \mu \rho H g \cos\varphi + \frac{\rho g U^2}{\xi} \qquad \text{(eq. 3)}$$

This is the formula that Voellmy (1955) used to describe the friction of avalanches, but also used in the debris flow module of the RAMMS model. In equation three, S is the total resistance or friction in Pa, μ is the coefficient that represents coulomb type friction, ϕ is the channel bed slope, U is the velocity of the debris flow and ξ is the turbulent drag coefficient in m/s^2 (Schraml et al., 2015; Frank et al., 2017). As can be concluded from eq. 3, eq. 1 is incorporated in this formula. In section 2.4 the formula and its importance for debris flow modelling will be discussed more in depth.

2.3.4 Erosion in RAMMS

In earlier versions of the model, erosion was not yet incorporated in the RAMMS debris flow model. In the version that is used now, there is an erosion or entrainment module inside the RAMMS model that takes erosion into account. This module is described extensively by Frank et al. (2015). In RAMMS, there are three main parameters that are responsible for the erosion of the RAMMS debris flow simulations: maximum erosion depth, critical shear stress and erosion rate (Dietrich & Krautblatter, 2019). The maximum erosion depth can be set to the maximum depth the simulated event is expected to reach, for example 2m. the critical shear stress (eq. 2) and erosion rate (in m/s) are linked to decide when erosion occurs and at what rate. Every time the critical amount of shear stress is reached, the model lets the flow erode at the erosion rate (Frank et al., 2015). This erosion rate can be defined in RAMMS with a minimum -0.025 m/s till a maximum of -0.05 m/s. After the simulation is completed, the erosion results can be obtained in various ways. The max erosion can be visualised on the grid as a map, or erosion over time can be seen in a graph. Also, the erosion and deposition can be subtracted from the DEM that was used for the simulation, which is the main method used to obtain erosion and deposition results for this research, further explained in chapter 4.

So, although an erosion module is added to the RAMMS module, which increased the ability to simulate erosion realistically, only a few studies (Frank et al., 2015; Dietrich & Krautblatter, 2019) discussed or investigated the performance of this erosion module specifically. Most of the studies investigated the performance of debris flows (Simoni & Mamoliti, 2012; Cesca & d'Agostino, 2008; Schraml et al., 2015; Gan & Zhang, 2019) tend to focus more on flow depth, instead of erosion, while erosion is probably more important when looking at the flow volume and thus the hazardous aspect of debris flows.

2.4 Literature gaps and research questions

Concluding from the aforementioned information obtained from literature, a few important literature gaps need to be stated. First of all, the RAMMS model that will be used for this research is not yet perfect. The friction parameters of equation 3 (Voellmy) still have a wide range in which they are used (Schraml et al., 2015), but could be more specific per debris flow. Furthermore, the resolution of DEM's or DTM's that are used for RAMMS are proven to affect the results and friction parameters of the model (Krusic et al., 2019), as cell size was already recognized to cause overestimation of debris flow volume by RAMMS (Cesca & d'Agostino, 2008). Secondly, the behaviour of debris flows has still some gaps to be investigated. Furthermore, when trying to recognize the behaviour of debris flows using its flow elevation, can be hampered by the shape of the channel which makes it hard to recognize flow elevation. but most importantly, there is lack of knowledge about erosion in RAMMS simulations, as the focus of studies on RAMMS performance is mainly on flow depth instead of erosion (e.g.: Simoni & Mamoliti, 2012; Cesca & d'Agostino, 2008; Schraml et al., 2015; Gan & Zhang, 2019). Where erosion is probably more important when looking at the flow volume and thus the hazardous aspect of debris flows.

The following research objectives will be investigated:

1. Quantify patterns of erosion and deposition in the Illgraben channel
2. Comparing different debris flows – testing whether RAMMS is able to successfully simulate erosion and how the different parameters affect erosion
3. Testing whether RAMMS performs better (i.e. more comparable to an actual event) when using a high-resolution DEM as input

Following these questions, hopefully more information can be obtained about the behaviour of debris flows in the study area and how RAMMS is able to simulate erosion and deposition of debris flows. It is expected that because of the high resolution of the input DEM, the model will give results that are more similar to actual data than when lower resolution DEM is used. However, it will be hard to find a balance between the time that the RAMMS model calculations take, and the resolution the model is able to simulate with. Also, these RAMMS simulations with a higher focus on erosion and deposition should give a better idea about these factors inside RAMMS, using the quantification of the actual events and the simulations as a proxy. Moreover, the relations between the friction parameters and erosion can give a better idea about how these parameters affect erosion in RAMMS. Finally, the combination of these questions can give help us to get a better understanding about the potential hazard of areas that have the same characteristics as the study area.

3. Study area

The geological setting, climate and location are always an important part in order to get a more visual idea of the study area and to put things in perspective. Also, knowledge of the study area surrounding the debris flow channel is crucial for understanding the mechanisms and processes that occur inside the channel. As stated in the literature overview, the geology is one of the external factors affecting the chance that a debris flow occurs and the way it behaves, as geology indirectly determines composition of the debris flow and the (part underneath the) channel. Climate, on the other hand, affects the upper layer of the geology and affects the landscape and its processes.

3.1 Location of simulated area measurement station

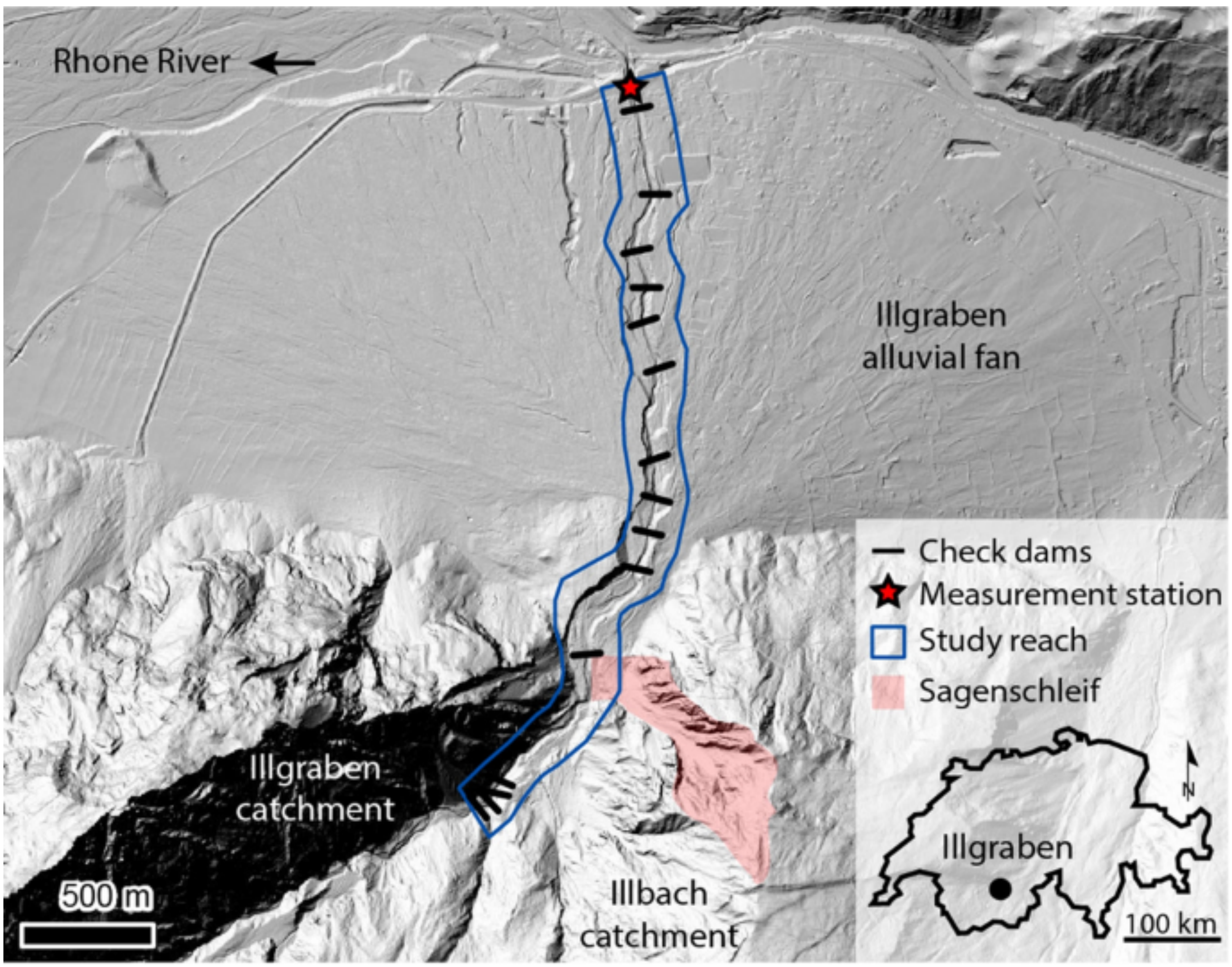


Figure 3.1: overview of the Illgraben catchment and channel, with the blue area indicating the simulation area or study reach (de Haas et al., 2020)

The study area is situated in the alps, in an area with its mountains ending in the Rhone valley in the Southwestern part of Switzerland. More specifically, the study area mainly embodies the Illgraben debris flow channel that starts higher up between the Illhorn and Schwarzhorn mountains (McArdell & Sartori, 2020). The fan at the end of the debris flow channel covers part of the Rhone valley (figure 3.1). The part of the channel that is studied covers the lower 3,5km, of which the exact boundaries of the part of the channel that is researched are indicated with a blue outline in figure 3.1. The channel is formed through the years, by yearly debris flow events that successively eroded the channel, and strongly influenced by humans (Bennett et al., 2014). There are many check dams (figure 3.1), which are dams that slow down the flow so that it does not grow big enough to be a threat for the village downhill (Remaitre et al., 2008), in addition, they prevent the flow from eroding too much and hamper lateral movement of the channel. At the end of the channel, the location of the measurement station is indicated with a red star in the figure. This is where many measurements were done that are used for this thesis. The debris flow hydrographs of the actual events (chapter 4.2 and 5.2) were measured here for example, as well as peak discharge and flow height.

3.2 Geology and climate

The area is characterized by steep slopes with highly fragmented rock mainly in the higher parts. This fragmentation is due to the Alpine orogenesis and because the Rhone-Simplon fault zone runs through this part of the alps (McArdell &Sartori, 2020). Most of the hard rock of which the steep slopes of the mountains consist are quartzite and dolomite rock. Due to the high fragmentation a lot of loose material is generated by rock weathering, which is enhanced by the climate in the area. This loose material can occur in different sizes varying from large boulders to clayey material. When the material is collected in the form of a colluvium, it can be mobilized and initiate a debris flow event as explained in the previous chapter. In some places where loose material has accumulated, soil formation made the material more cohesive and less likely to be mobilized. Figure 3.2 gives a good overview of the different rock formations and the geology of the area.

As mentioned, climate is an enhancing factor for the weathering of rocks in the area. because the area is located in the mountains, temperature differences can be large, which increase weathering. In the study area, climate is also one of the most important drivers of debris flows. Yearly precipitation rates lay between 600 mm in the valley and 1000mm in the higher region, with a temperate climate. Although this amount of precipitation on a yearly basis is not very high, in the summer the precipitation can be twice as much as in winter (Hirschberg et al., 2019). Furthermore, the precipitation can be of a convective type, and thus really intense, contributing to average erosion rates of 0.39 m/y in certain areas (Benett et al., 2012). This causes a lot of material to be mobilized, but as stated in the previous chapter, the heavy rains can also be a trigger for debris flows in the area.

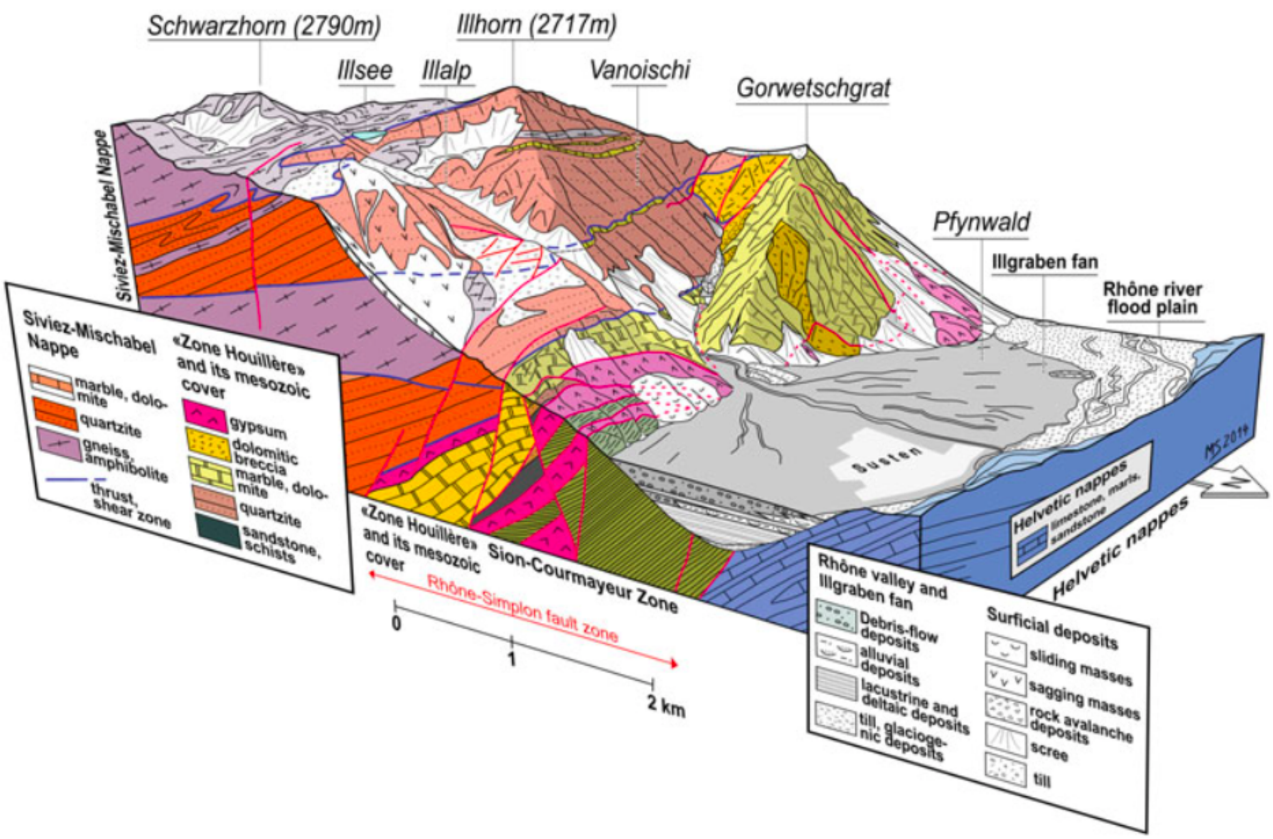


Figure 3.2: geological overview of the Illgraben area (McArdell & Sartori, 2020)

3.3 Monitoring and early warning system

When a debris flow occurs, it will most probably flow through the channel that is created by multiple debris flows and at some has become more and more affected by humans. In the year 2000, measurement devices such as ultrasonic and radar devices, video cameras and rain gauges were installed in addition to an observation station (Uchida et al., 2020). Since then, debris flow activity is being monitored closely and much data has been gathered. Especially because of the high activity of debris flows in the channel (2-5 times per year on average (McArdell et al., 2007)), the channel is a perfect area for studying different debris flow events. Besides this, debris flows can still be very hazardous. For that reason, a few measures are taken to decrease the danger, of which the most important an early warning system in addition to the check dams. This system relies on sensors that recognize hazardous events happening in the channel, such as debris flows and flash floods. When such an event happens, the system warns people to stay away from the channel (Mc Ardell & Sartori, 2020).

4. Methods

In this master thesis, several types of data from the Illgraben catchment area in Switzerland will be used for analysis to answer the research questions mentioned in the previous chapter. Two debris flow events were taken to investigate and compare: the first event was triggered 2020-06-29 and the second event was triggered 2020-08-30. The recording dates were 2020-07-02 and 2020-09-03, respectively. For the analysis, also the DEM's of the dates before the debris flows were used. To begin with, drone images of the debris flow channel were given Ground Control Points to help construct one of the digital elevation models (DEM) using Agisoft Metashape Pro. The research questions will be investigated by using the RApid Mass Movements Simulation (RAMMS) model (Frank et al., 2017). This is a debris flow entrainment model that estimates the runout of debris flow by simulating the pathway of a debris flow over a DEM. Furthermore, erosion and deposition are quantified using a GIS analysis. Finally, the results or the RAMMS model and the GIS quantification analysis results are compared and discussed. In this chapter, an overview is given of the most important steps from data acquisition to end results.

4.1 Creating DEMs from drone images

The first step for both analyses done for this thesis is creating a DEM of the study area from drone images. The DEMs that are used for this research were constructed using drone images of the DJI Phantom 4 RTK drone. This drone has an increased accuracy in comparison to earlier drones, partly because of the Real Time Kinetic (RTK) technology that it possesses (Taddia et al., 2019). The drone follows a programmed path over the study area, in this case the debris flow channel. Also, because of the RTK technology, no Ground Control Points are needed, which would normally be needed to reference the images. With the RTK technology, the images are referenced automatically. In this way, the images can be put together over the channel more easily and form an orthomosaic. From these orthomosaics, DEM's can be created by a relatively simple process but it takes quite some computing power because every elevation point has to be created. These DEM's form the basis of the debris flow simulations performed by the RAMMS model, and for the GIS erosion and deposition analysis. Prior to this master thesis, researchers Tjalling de Haas and Wiebe Neijland from Utrecht University did field research in the study area in 2020. During that research, they made drone images of the Illgraben channel before and after multiple debris flows. In the following subchapter it is explained how the DEM's from these orthomosaics are used for this thesis.

4.2 Quantitative GIS erosion and deposition analysis

This analysis is done both for the actual events and for the RAMMS simulations. It results in maps with both erosion and deposition indicated, and graphs that show the absolute erosion and deposition over distance of the channel, including erosion and deposition volumes. These maps and graphs of the actual events can then be compared to the RAMMS output for further analysis. Same as for the RAMMS simulations, the DEM's are the basis for this analysis. It is important to use exactly the same DEM of the same date as is used for the RAMMS simulations, to get similar initial conditions for the two analyses.

For the first GIS erosion and deposition analysis the DEM's from 2020-06-18 and 2020-07-02 and the DEM's from 2020-08-17 and 2020-09-02 were used, to get the change maps for the 2020-07-02 and 2020-09-02 debris flow events. The flowchart in figure 4.1 gives an overview of the steps taken for this analysis. In the black part, the subtracting of two DEM's is visualized. This step is executed by using a tool in GIS which subtracts the two DEM's and directly clips the output information to the flow channel, to create a change map (yellow part) of the channel between the two DEM dates. The change map is then, again using a GIS tool, subdivided in an erosion map and a deposition map, using the negative change for the former, and positive change for the latter. For the next step of the analysis, the green part of the flowchart is needed. This step is needed to assign the information provided in the yellow parts to specific segments of the channel, so that per segment of around 25 meters the erosion and deposition can be obtained. This step is also executed in GIS using a few additional tools. First, the thalweg of the channel needs to be drawn, along which centre points are created by the tool. These centre points are used to draw lines between different parts of the channel, after which the lines are used to draw the segments in the channel. The last step of the green part of the flow chart is to assign coordinates to the created segments. In this way, the segments get a spatial reference and the information of the maps in the green part can be obtained per segment. This will be first done in GIS by combining the attribute tables of the segmented channel with the erosion, deposition and change maps. Consequently, the tables will be exported to excel and saved in an organized way. The final step is to read out all this information from excel using MATLAB. In MATLAB, a script is used, and the information is categorized and ultimately given in a graph that shows change, erosion and deposition over distance from the end of the channel.

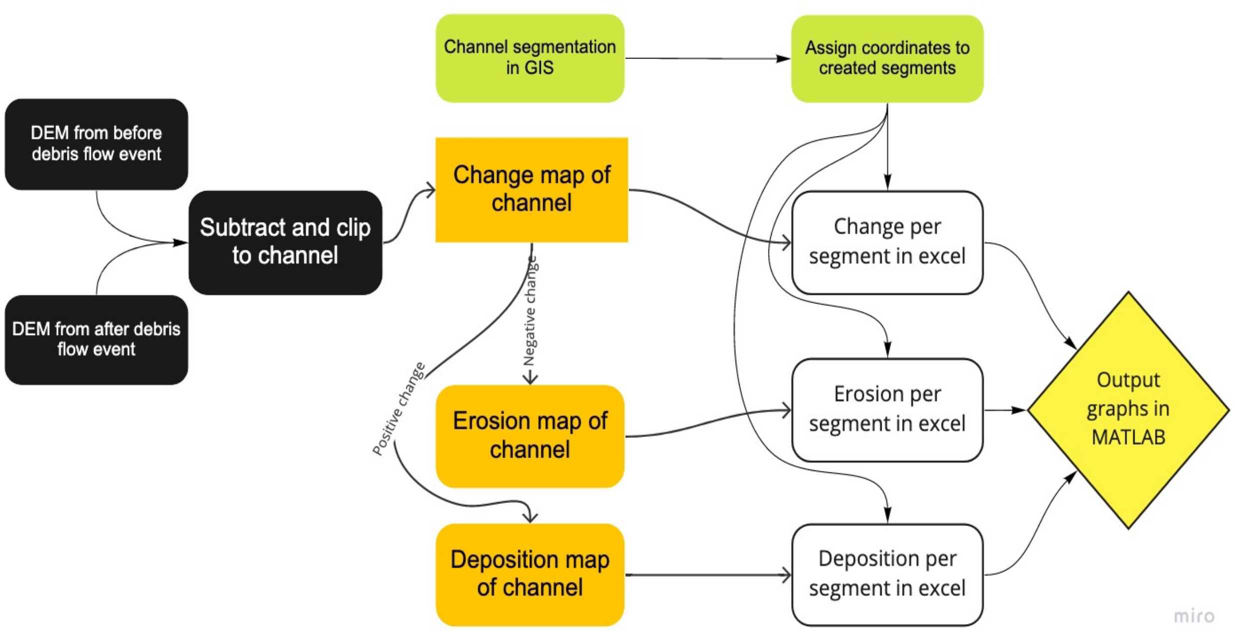


figure 4.1: flowchart of the quantitative GIS erosion and deposition analysis.

These graphs will first be made for the actual events, so with the DEM's before and after the events. After the simulations are run as given in table 2 and 3, these simulations are going through the process in the flowchart as well. In this way, a graph can be created that gives a direct overview of the overall erosion and deposition of the actual events and all the simulations. Before the RAMMS simulations can be used as input for the flowchart, one additional step is needed. From every simulation (SIM1-SIM24), the erosion and deposition need to be subtracted from the original DEM in RAMMS. Then, the original DEM and other DEM can be used for the GIS analysis. This analysis will ultimately also be used for the simulations with a higher DEM resolution.

4.3 RAMMS erosion and deposition analysis

In chapter three, the basics of the RAMMS model were explained and comparisons were made with other debris flow models. In this subchapter, the most important steps taken in RAMMS for this research are given.

4.3.1 Setting up a simulation

The first step in this process, is choosing the DEM that forms the basis of the RAMMS simulation. It is important to choose the right DEM, to create realistic initial conditions. In this case, the DEM's from 18-06-2020 and 17-08-2020 were chosen, to simulate the debris flow events from 29-06-2020 and 30-08-2020. With the DEM's from before the actual event as input, the terrain that the model uses is closest to the terrain of the actual event. In this case, the original DEM had a resolution of 0.06m, which is relatively high. However, the resolution that will be used your simulation can be chosen manually. It depends on the time you have available and calculation power of your computer how high you can set the resolution for a simulation. Given the time available for this research, for most simulations a resolution of 2m was chosen.

Because there are check dams along the channel, these need to be accounted for in the simulation as well. As the check dams cannot be eroded, erosion polygons need to be drawn in the areas surrounding the check dams. This set up with dams accounted for, can be used for every simulation. The next step is to choose the right parameters that set the initial conditions of the model and affect the behaviour of the simulated debris flow. If you have information about the hydrograph shape of the debris flow you can use recreate that as input for the simulation, otherwise you can choose block release for a predefined debris flow initiation. In section 4.3.2 it is explained how the hydrographs of the events for this research were recreated. The calibration of the most important parameters: mu and xi, is explained in section 4.3.3.

Before the desired hydrographs and mu and xi parameters could be chosen, many test simulations with different initial conditions were run in RAMMS. Especially finding the right hydrograph was hard, as a hydrograph with reasonable discharge can still be too small to cause a substantial debris flow. These test runs formed an important part of the process of getting to a realistic simulation.

4.3.2 Choosing the right hydrograph

It is very important to choose the right hydrograph for the debris flow simulation because it determines what (virtual) material input the debris flow gets from its initiation point and how long this input lasts. It represents the flow depth over time for a specific point along the channel. For this research, the hydrographs that were measured during the events could be used and recreated in RAMMS. It is important to note that the hydrographs cannot be copied but only recreated and that the hydrographs that were available for the events were from the end of the channel, whereas the hydrographs in RAMMS are the input at the beginning of the channel. Moreover, the measured hydrograph contained to peaks, where in RAMMS only one peak can be implemented. When making the RAMMS hydrograph, a measured peak discharge of 6 m^3/s, a measured flow volume of 22000 m^3 and the measured hydrograph in figure 4.2 were known. As in RAMMS the hydrograph can only be set up with discharge as unit, the 6 m^3/s had to be used. In figure 4.2, the measured hydrograph of the 2020-06-29 event can be seen. Furthermore, there was a known peak discharge of 6 m^3/s and a flow volume of 22000. A combination of this information lead to the RAMMS input hydrograph in RAMMS shown in figure 4.2. As can be seen the peak of the actual hydrograph is at a similar moment as the peak in the RAMMS input hydrograph, and the same can be said for the end of the first hydrograph. Because in RAMMS only one hydrograph can be set as input, the first one of the two hydrographs that were measured was chosen. As can be seen in figure 4.1, the peak is indeed 6 m3/s, as is the measured peak in discharge that was known.

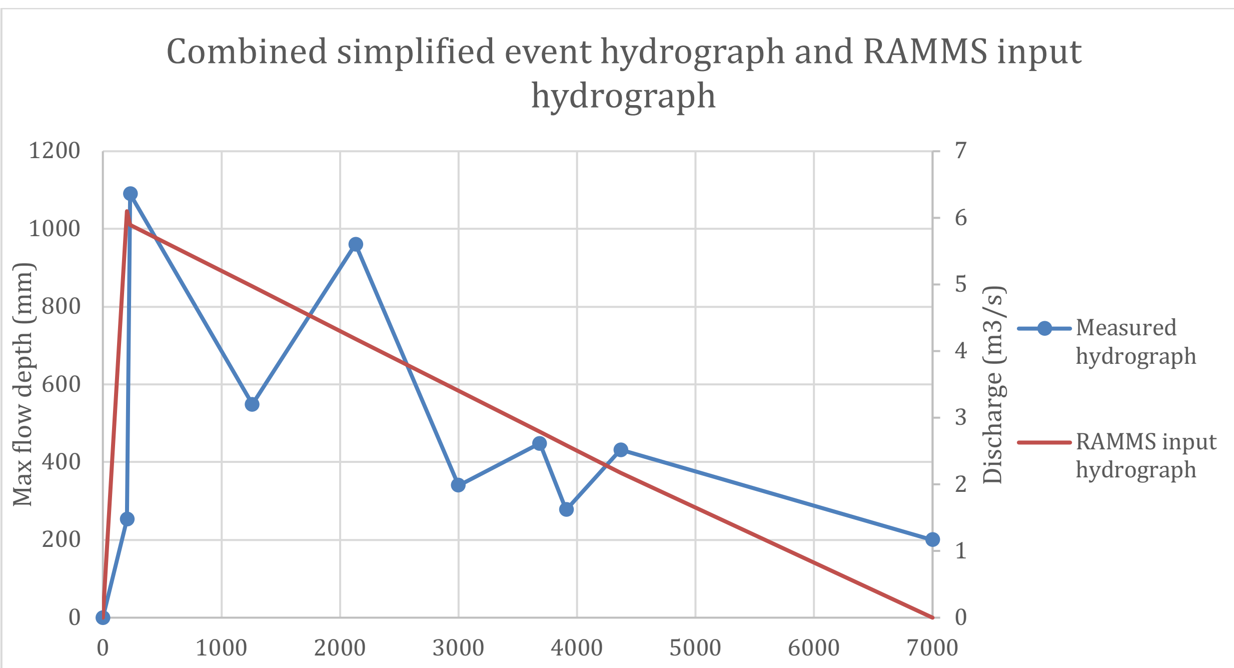


Figure 4.2: simplified measured hydrograph of the 2020-06-29 debris flow event and input hydrograph of the simulated 2020-06-29 debris flow event in RAMMS (used for simulation 1-12).

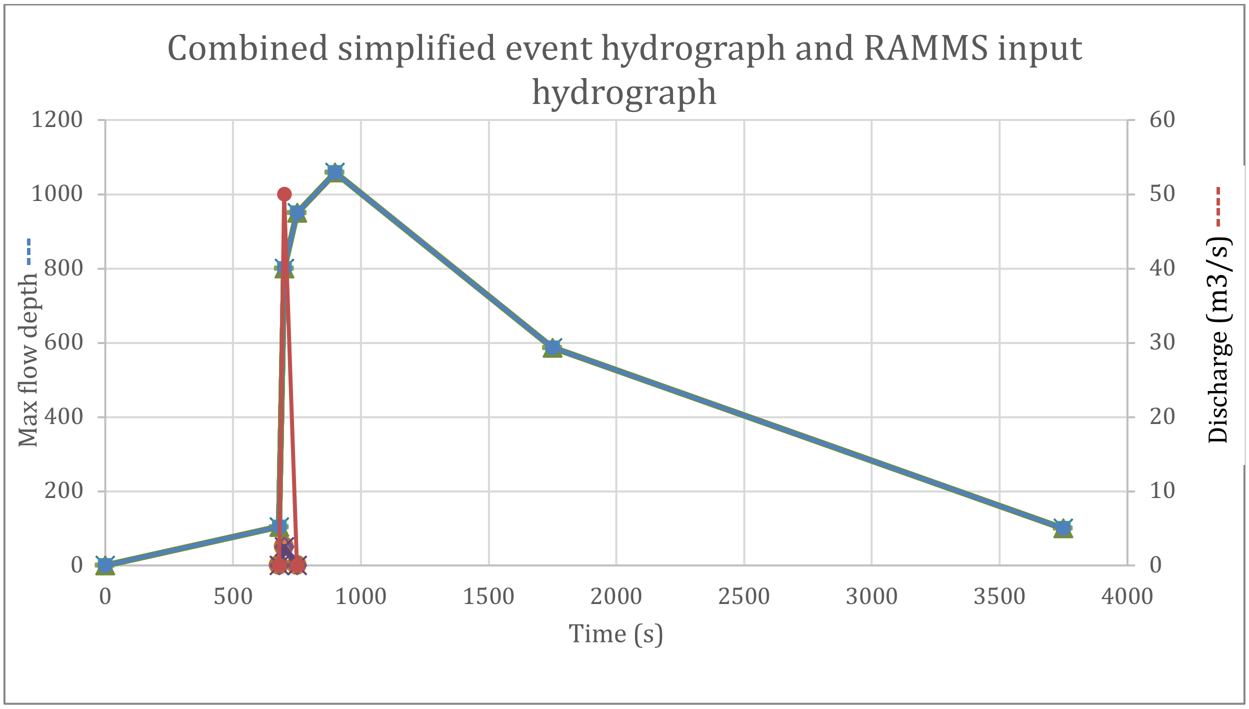


Figure 4.3: simplified measured hydrograph of the 2020-08-30 debris flow event (blue) and hydrograph of the simulated 2020-08-30 debris flow event (red) in RAMMS (used for simulation 13-24).

The hydrograph for the 2020-08-30 debris flow event (figure 4.3) was recreated in RAMMS in a way similar to the first one, but it was more difficult. This was because the maximum discharge in the actual hydrograph was higher (50 m^3/s) but the measured total volume was much smaller (6000 m^3). Because a few test runs were executed with a hydrograph that would be more comparable to the measured hydrograph and these simulations did not reach the end of the channel (which in practice they did), another way had to be chosen to still make a realistic hydrograph. So, in this case, the volume of 6000 m3 was used in combination with the maximum discharge of 50 m^3/s to make the hydrograph for the RAMMS simulation, which resulted in the hydrograph in figure 4.3. Also, the virtual time that is simulated affects the size and calculation time of the simulations. It is important to note that for SIM1-12 (table 2) a virtual simulation time of 20000s is used, and for SIM13-24 (table 3) a simulation time of 15000s is used. This is mainly because the difference in time length of the hydrographs used for the different simulations. Lastly, the RAMMS hydrograph in figure 4.3 looks like it is less steep than the other hydrographs, but this hydrograph is just over a shorter time period than the other hydrographs.

4.3.3 Calibrating mu and xi

Mu and xi are the most important parameters that affect the behaviour of a debris flow in the RAMMS model. They are also called “friction parameters” and are more elaborately explained in chapter three, but crucial for understanding mu and xi is that they are both in the total resistance formula, but mu is multiplied, and the other part of the formula is divided by xi. So, one would expect that a higher mu value would give the debris flow more resistance, and a higher xi value would give the debris flow less resistance. Because they control the behaviour of the debris flow in the RAMMS model, they are crucial in the process of simulating a realistic debris flow. In the previous two subchapters, the right hydrograph and DEM were chosen for the simulations, and in this subchapter, it will be explained how mu and xi are used to get a realistic simulation, but also how they can help showing their effects on erosion and deposition in the simulations. The RAMMS manual advises a Mu of 0.2 and a Xi of 200, and because the RAMMS model was based on and calibrated by the Illgraben channel, these values could also be used as a starting point for this research. In table 3 below, an overview is given of the RAMMS simulations of the 2020-06-29 event with the different values for mu and xi and different erosion rates. These values are relatively close to each other between different simulations, which will give a neat result on the influence of these different values on the erosion and deposition. In table 4, the same overview is given for the RAMMS simulations of the 2020-08-30 event. Different between the two mu and xi values, is that the mu values in table 3 are more focused on values higher than 0.2, and in table 4 more focused on lower than 0.2. for xi this is the other way around. This was done because of the results of the test runs, where flow depths for the 2020-06-29 event were higher than expected and for the 2020-08-30 the flow depths were lower. For the simulations to be realistic, more friction was needed for the 2020-06-29 and less friction for the 2020-08-30 event. Therefore, most of the friction parameter values of table 3 will generate more friction, and in table 4 most of the friction parameter values will generate less friction.

Table 3: different parameters for RAMMS simulations of the 2020-06-29 event.

Mu	Xi	Erosion rate(m/s)	Simulation name
0.2	210	0.025	SIM1
0.25	210	0.025	SIM2
0.25	220	0.05	SIM3
0.18	200	0.025	SIM4
0.16	200	0.025	SIM5
0.25	200	0.025	SIM6
0.30	200	0.025	SIM7
0.35	200	0.025	SIM8
0.2	200	0.05	SIM9
0.2	180	0.025	SIM10
0.2	160	0.025	SIM11
0.2	140	0.025	SIM12

Table 4: different parameters for RAMMS simulations of the 2020-08-30 event.

Mu	Xi	Erosion rate(m/s)	Simulation name
0.2	210	0.05	SIM13
0.2	180	0.025	SIM14
0.18	200	0.025	SIM15
0.16	200	0.025	SIM16
0.12	200	0.025	SIM17
0.1	200	0.025	SIM18
0.2	220	0.025	SIM19
0.2	240	0.025	SIM20
0.2	260	0.025	SIM21
0.2	280	0.025	SIM22
0.2	200	0.045	SIM23
0.2	200	0.05	SIM24

In addition to the wide variety of mu and xi values, different erosion rates were added to the different simulations. This is done because it is one of the three specific erosion parameters that can be changed, with the other ones being maximum erosion depth and critical shear stress. The maximum erosion depth for all simulations was 2m. This value was chosen because the most erosive actual event that is simulated did not exceed this value. The erosion rates differed for some simulations to see what effect this had on the quantitative erosion in combination with different mu and xi values. In this research, no different critical shear stress values were used for different simulations, because the focus lies more on the effects of the proposed relation between mu, xi and erosion rate. These relations are investigated by making plots with mu and xi versus erosion, with alternative erosion rates indicated.

5. Results and interpretation of RAMMS simulations and GIS analysis

In this chapter, multiple types of results will be discussed. Firstly, some general information about the two actual measured events are given. Secondly, the graphs that give an overview of the elevation change of the channel of the simulations and the actual events will be discussed. Next, the two simulations that are closest to the actual events are highlighted, and these simulations will be then be run another time but with higher DEM resolution. Lastly, different Mu and xi values and their erosion and deposition values are plotted, to show the effect of these parameters on erosion and deposition.

5.1 General information about the actual events

5.1.1 The 2020-06-29 event

Table 5: properties of the 20200629 debris flow event measured at the bridge.

Date, trigger	Drone data	Frontal v (m/s)	Peak discharge (m^3/s)	Volume (m^3)	Flow density (kg/m^3)
29-06-2020	02-07-2020	0.82	6.0	22000	2100

This event had a relatively normal peak discharge and a frontal flow velocity was not very fast, most other events had comparable or higher frontal velocities. The erosivity of the event was also not very high with a total erosion of -23.788 m^3 and small net deposition of 635m^3, so more is deposited than eroded. From the measured hydrograph in figure 5.4 and the information provided in 5.3.2, it can be concluded that the debris flow did not have a very steep front and then a gradual drop, but instead a more gradual front and a few little peaks in the hydrograph after the first one. Figure 5.1 on the next page gives an example of the erosion pattern of the event, zoomed in on a part located towards the end of the channel. In this figure it can be seen that the event shows a very equally distributed erosion pattern. The whole channel shows low to no erosion, also in the bends, where another erosion pattern might be expected. Furthermore, in the overview map of the whole channel almost the entire channel colours red, indicating low erosion.

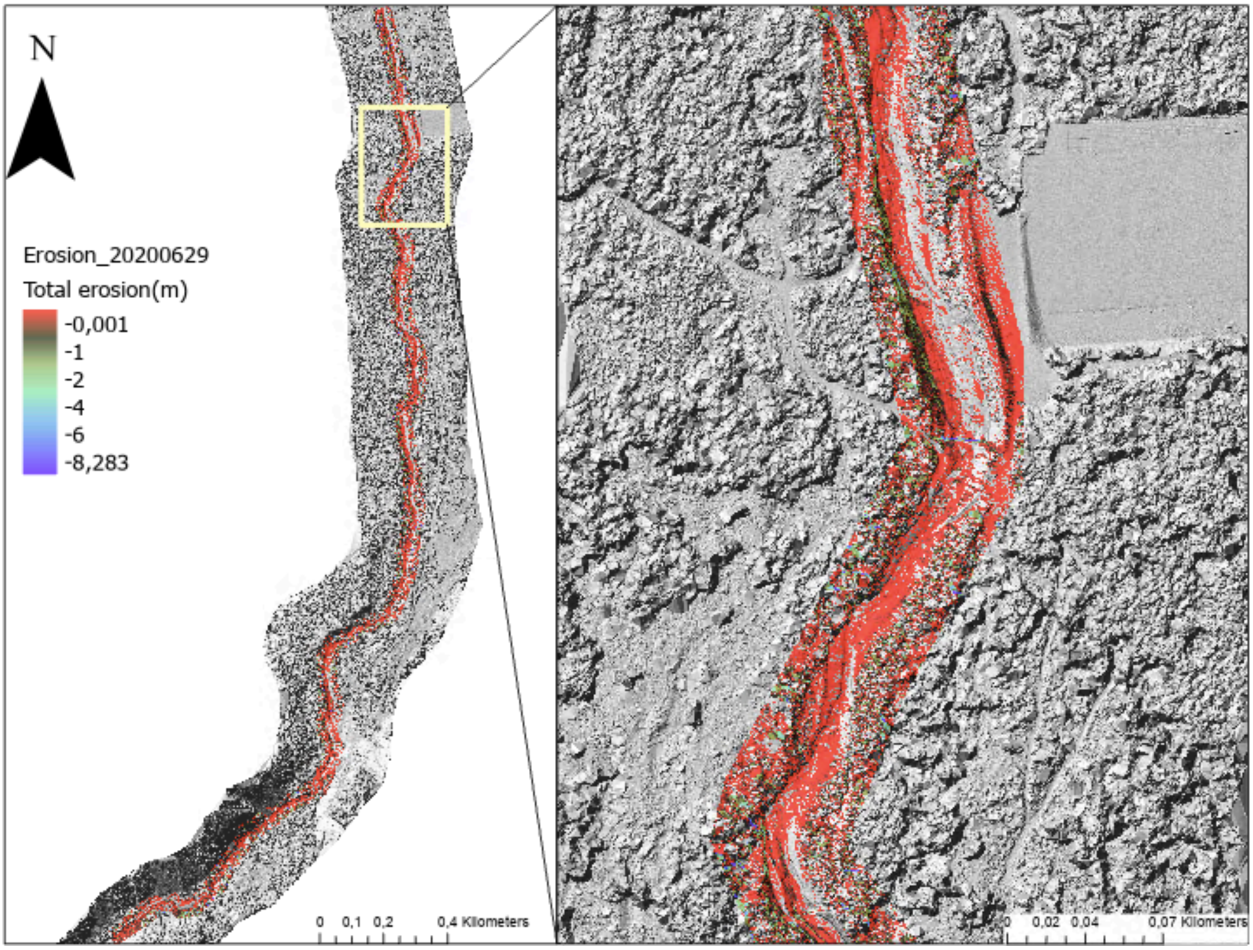


Figure 5.1: part of the erosion pattern in GIS of the 2020-06-29 event.

5.1.2 The 2020-08-30 event

Table 6: properties of the 20200629 debris flow event measured at the bridge.

Date, trigger	Drone data	Frontal v (m/s)	Peak discharge (m3/s)	Volume (m3)	Flow density (kg/m3)
2020-08-30	2020-09-02	0.7	9.2	6000	1800

When comparing the values from table 5 with the values from table 4, not many differences can be seen except for the volume. However, when looking at the erosion of this event a very different conclusion can be drawn. Both total erosion and net erosion are much higher: -42123m^3 and -25704m^3 respectively. This also comes forward when looking at the erosion on the GIS map in figure 5.2. On the overview map on the left, yellow parts can be seen, which indicate -1m or -2m erosion. When looking closer, erosion patterns can be distinguished. In the relatively sharp turn of the channel the channel erosion values of up to -6m can be seen, with the highest values clearly in the outside bend. In chapter 5.3 and 5.4, spatial patterns of the actual events will be compared to the corresponding simulations.

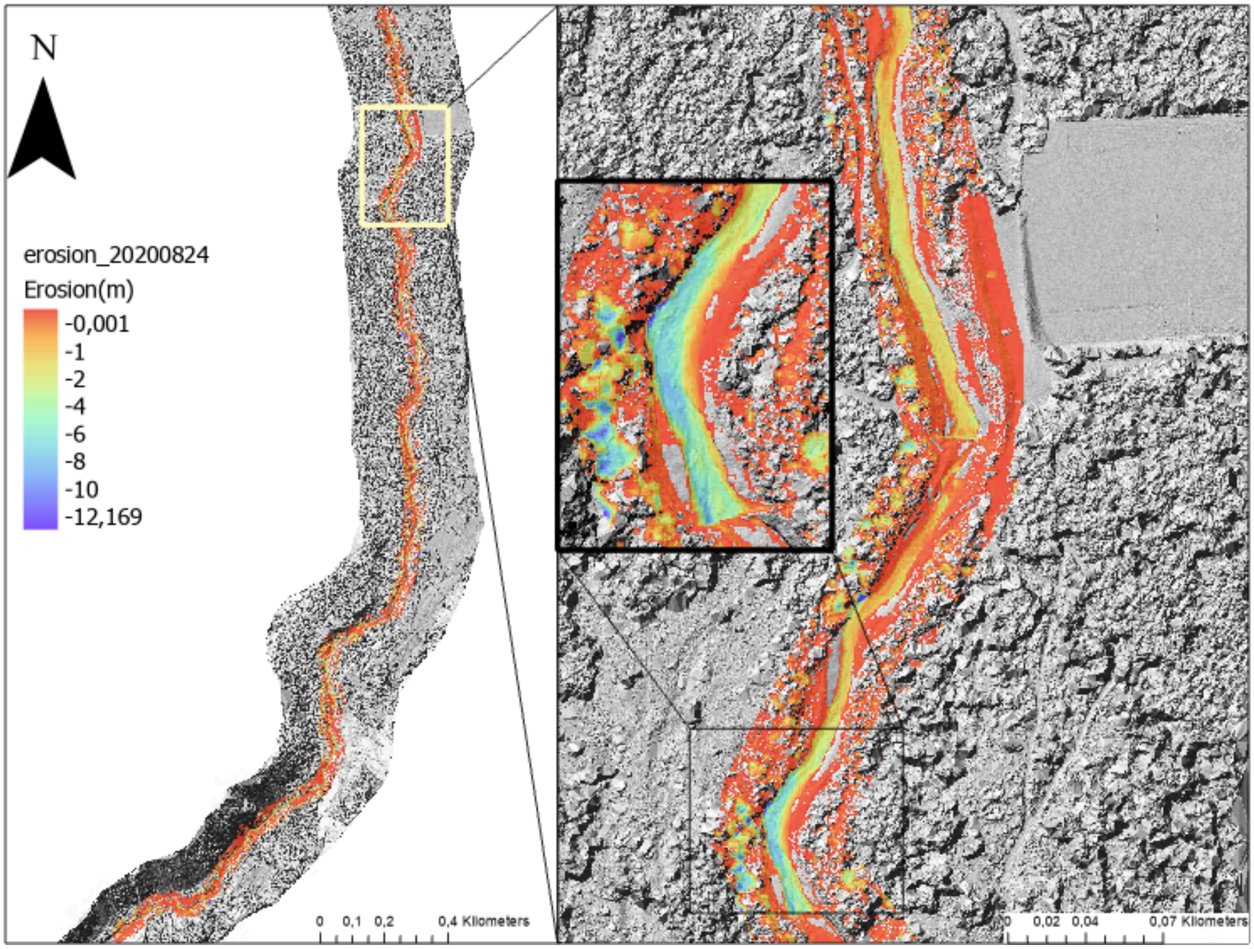


Figure 5.2: part of the erosion pattern in GIS of the 2020-08-30 event, zoomed in on the bend with up to 6m erosion.

5.1 Mean channel change graphs

The two graphs (Fig. 11 and fig. 12) that are discussed in this subchapter form the starting point of the result analysis of this thesis. These graphs give an overview of the erosion and deposition differences between the different simulations and the actual events. On the y-axis, the mean channel elevation change is plotted. This means that it shows the net elevation change, so erosion and deposition are subtracted from each other. It can thus be assumed, that negative values represent net erosion, and positive numbers represent net deposition. The x-axis represents the distance upstream of the bridge. This bridge is the most downstream point and forms the endpoint of the channel investigated for this research. In other words, in the graph, more to the right means upstream and more to left means downstream. Before choosing which two simulations will be highlighted, patterns that occur in both graphs will be pointed out. First of all, the plotted lines of SIM1-12 and SIM13-24 stay relatively close to each other, compared to the difference between the two measured events. Secondly, all the simulated events tend to show a mean channel change of zero, albeit that SIM1-12 show more negative values than SIM13-24. Furthermore, SIM13-24 show a more scattered pattern than SIM1-12, of which the mean channel change seems to stay closer together.

5.1.2 Mean channel change comparison between 20200629 event and SIM1-SIM12

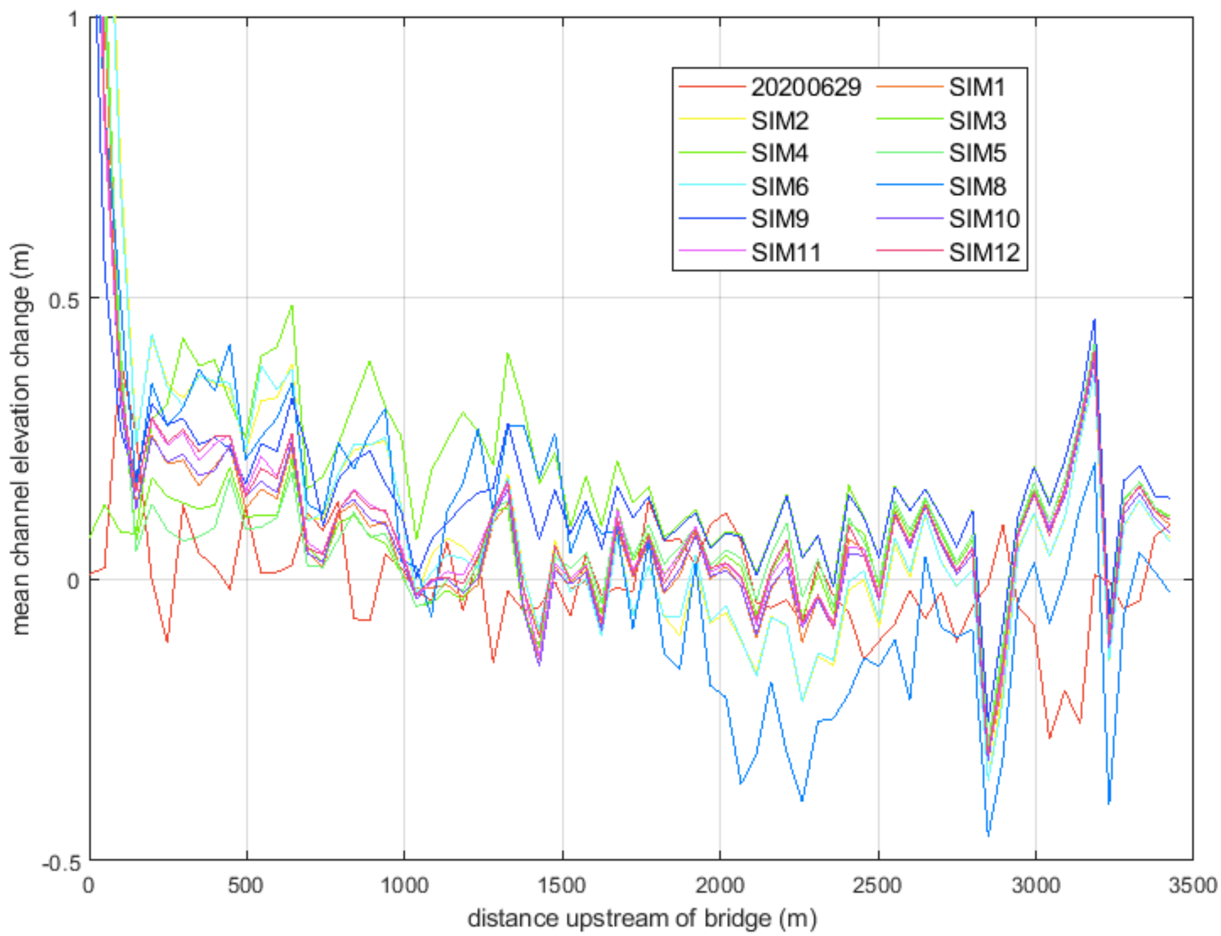


Figure 5.3: Mean elevation change over distance from the bridge of SIM1-12 and the 20200629 event in red, between 0 and 1000m below all other lines, with a negative change peak at 3100m.

Overall, a trend can be seen in the simulation lines of becoming more erosive more upstream except for a deposition peak between 3000m and 3500m from the bridge. For choosing the simulation that will be highlighted, the simulation will be chosen that is most in line with the mean channel elevation change of the measured event. In this case the upper one of the two dark blue lines is the line of the 2020-06-29 event. As can be seen, most of the lines of the simulation are quite close to the line of the actual event. The line that resembles the actual event line most simulation four (SIM4). This line most closely fits the line of the actual event from the bridge. From 2500m the line starts deviating from the actual event line, but this is the case for all the simulations. SIM 7 is not showed in this graph because no flow was simulated. From this graph it could be concluded that the RAMMS simulations show similar results for net erosion/deposition compared to the actual event.

5.1.3 Mean channel change comparison between 20200830 event and SIM13-SIM24

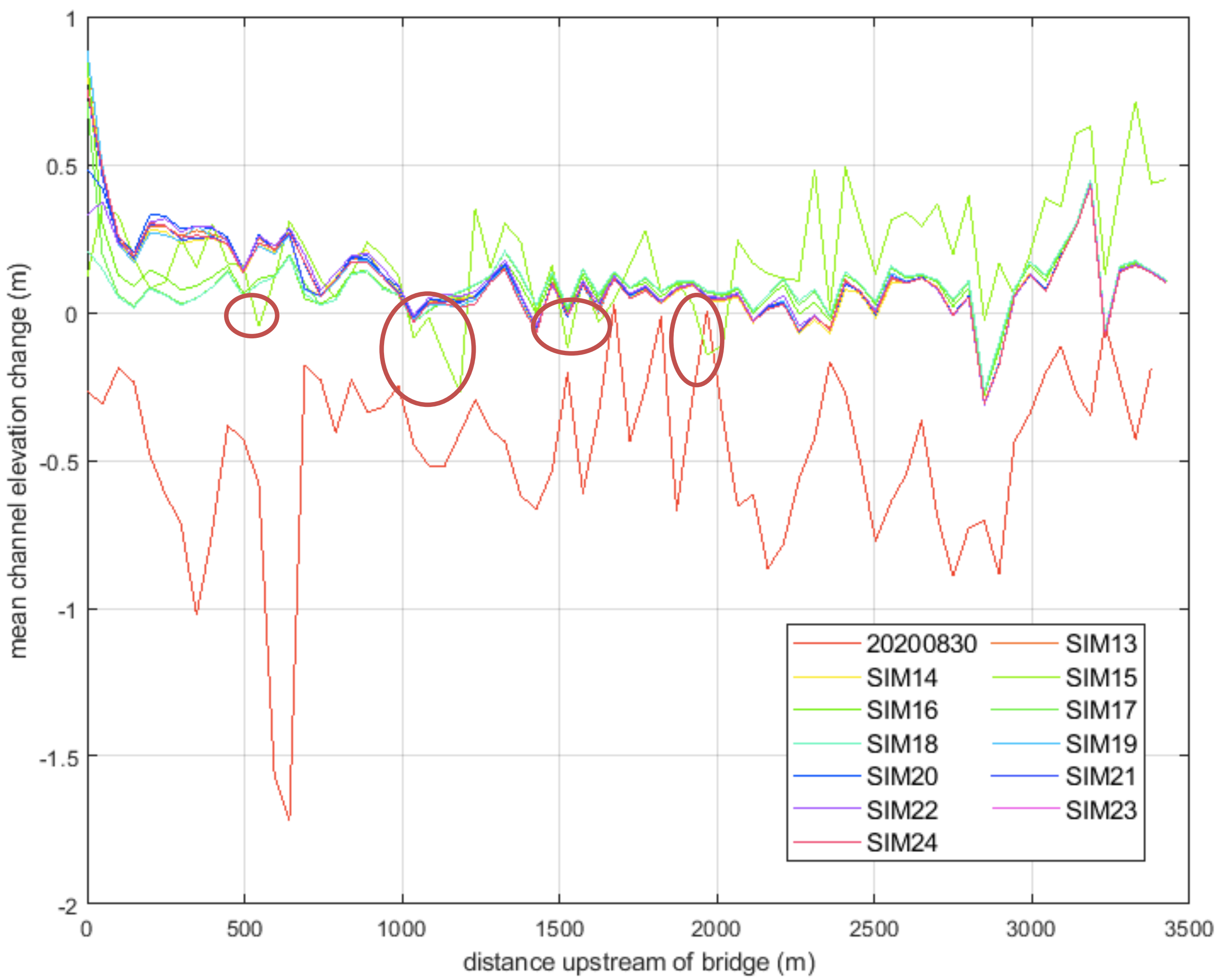
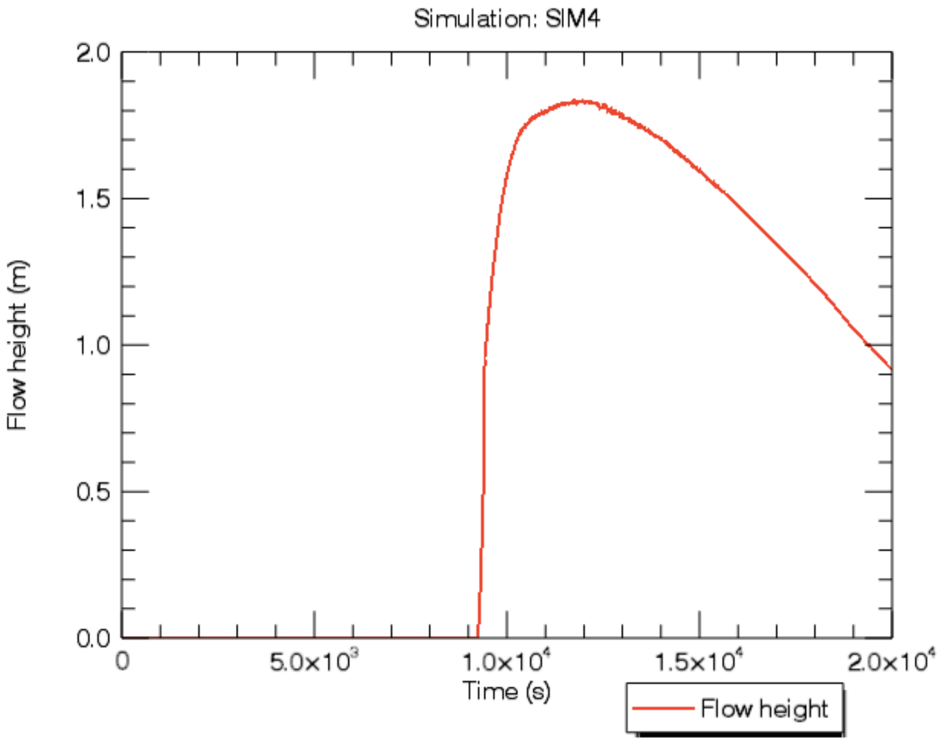


Figure 5.4: Mean elevation change over distance from the bridge of SIM13-24 and the actual event. The red circles indicate where SIM15 shows net erosion peaks. The red line below all other lines shows the mean channel change of the measured event.

As all lines of the simulations differ much from the line of the original event, the simulation was chosen that shows most erosive features. In this case, that is the line of SIM15 (marine blue). This line has four negative features in total, which is the most of all simulations, indicated on the graph in red. In addition, this simulation has the highest max erosion values of SIM 13 till SIM 24. Overall, what is remarkable in this graph is that all simulations except SIM15 show a scattered pattern until 2000m upstream of the bridge and further away from the bridge they stay relatively close together. To conclude, RAMMS did not succeed in simulating the erosion of the measured event, given that the graph of the event differs from the simulations in almost every point in the figure.

5.2 Hydrograph comparison between RAMMS output and actual events

5.2.1 Comparison between 2020-06-29 event and RAMMS SIM4 hydrograph



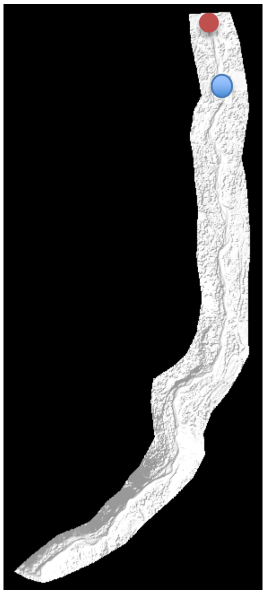


Figure 5.5: hydrograph of SIM4 (left) and measured location in RAMMS at the blue dot in the channel (right), and the measured location of the event hydrograph at the red dot.

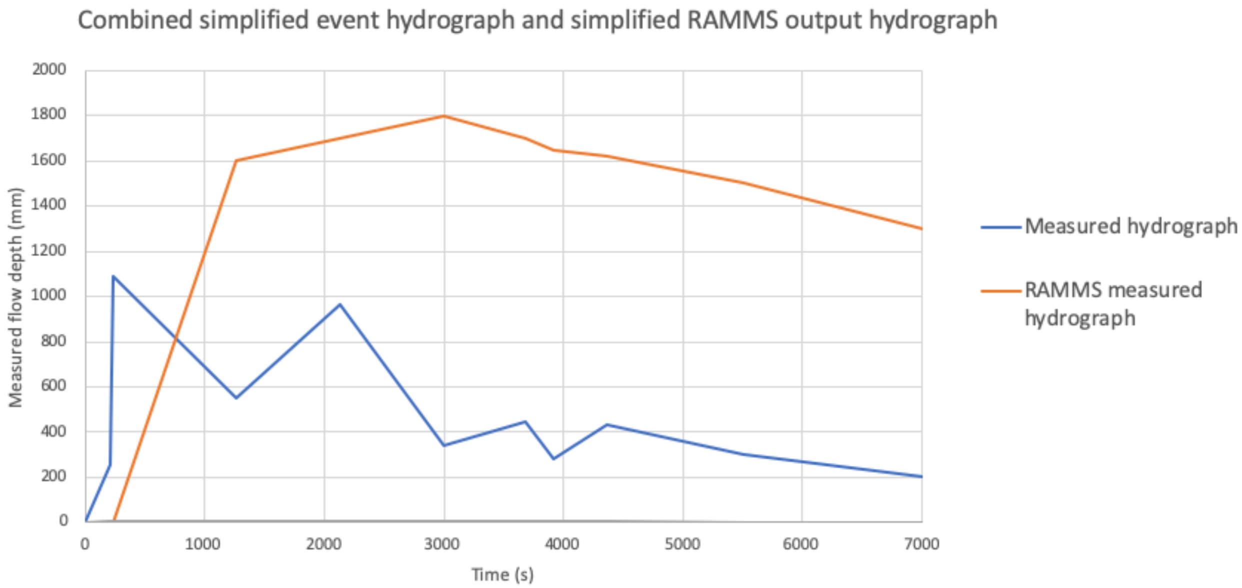


Figure 5.6: combined measured hydrograph for the 2020-06-29 event and RAMMS output hydrograph for SIM4.

the point where the virtual hydrograph of the simulation is measured is 400m from the bridge, as is indicated in figure 5.5. This location was chosen because near the bridge the hydrograph would not be complete enough to use, as it takes time for the debris flow to move through the channel, and it would take too much virtual time (i.e. data and calculation time) to make the hydrograph complete. So, the hydrograph in figure 8 is measured 400m from the hydrograph in figure 8, but still near the end of the channel.

In figure 5.5 the hydrograph is shown the way it is displayed in RAMMS, and in figure 5.6 the RAMMS hydrograph is simplified and combined with the actual event hydrograph. Logically, the difference between these two hydrographs is significant as expected, since only one of the two hydrographs could be used as input in RAMMS. For example, the peaks of the two hydrographs differ in steepness, and the measured hydrograph does not reach higher then 1.1m, albeit that some higher measurement points were filtered out when making the simplified graph. From the hydrograph it can be concluded that in RAMMS the debris flow volume is much higher than that of the measured event.

5.2.2 Comparison between 2020-08-30 event and RAMMS SIM15 hydrograph

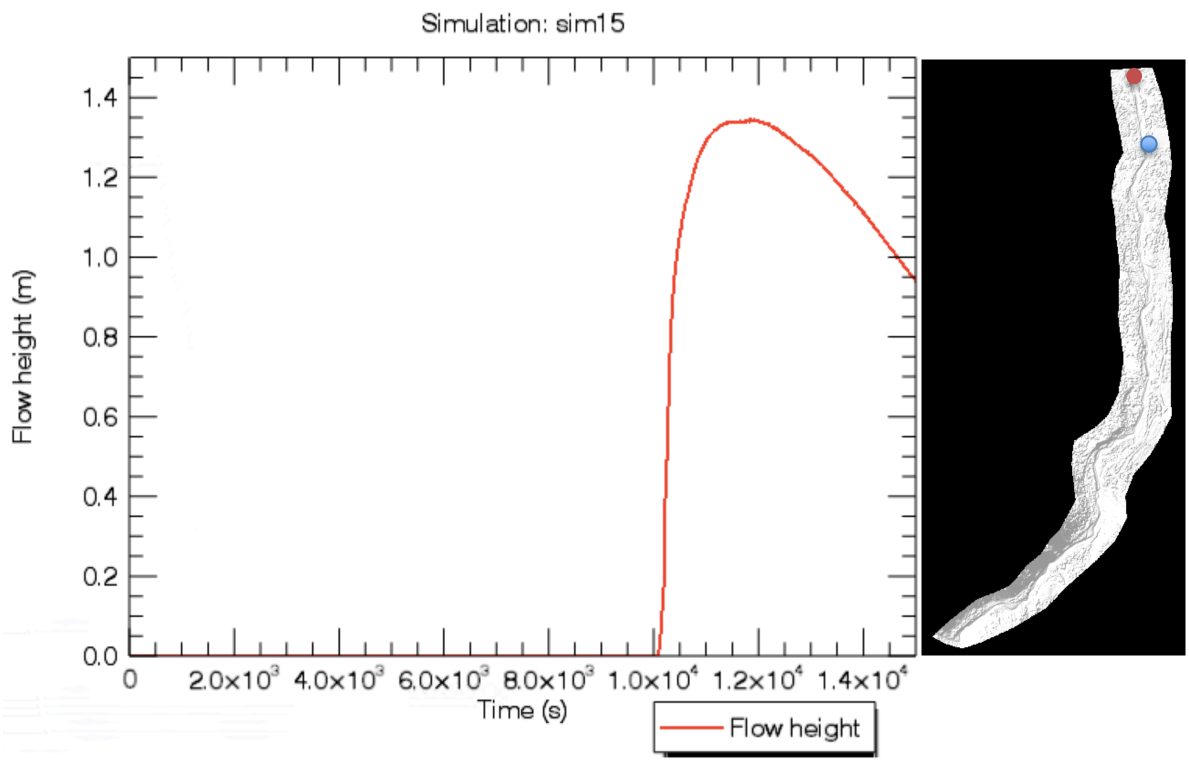


Figure 5.7: hydrograph of SIM15 (left) and measured location in RAMMS at the blue dot in the channel (right), and the measured location of the event hydrograph at the red dot.

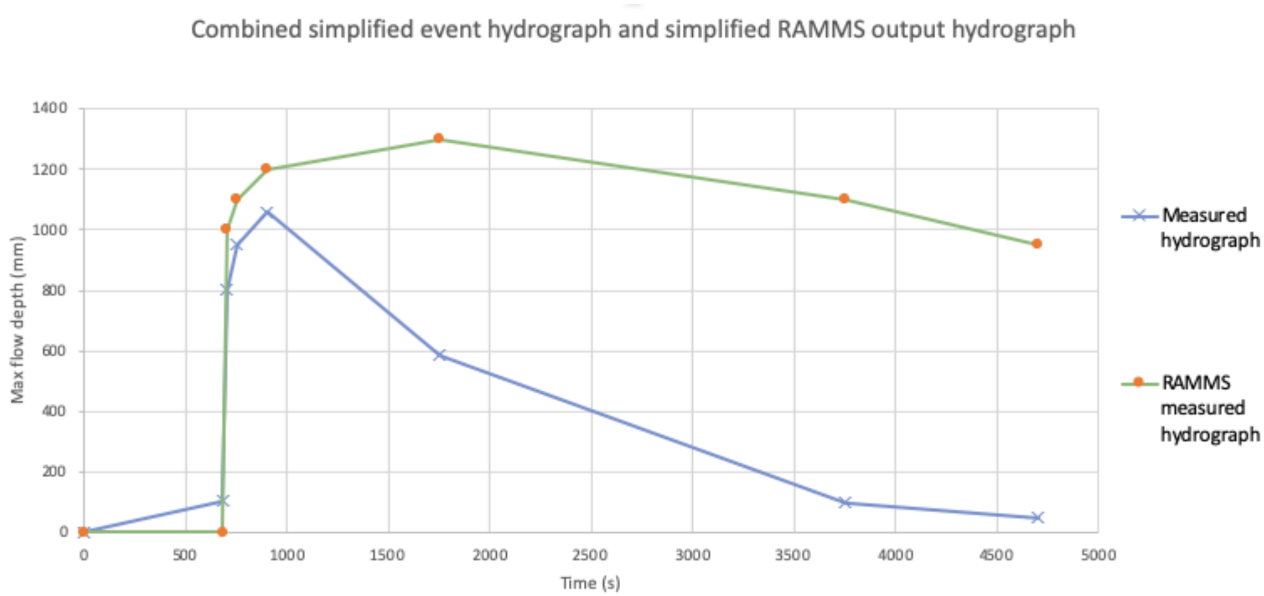


Figure 5.8: combined measured hydrograph for the 2020-08-30 event and RAMMS output hydrograph for SIM15.

In figure 5.7 is shown as a reference for how a hydrograph is displayed in RAMMS. When comparing the two hydrographs in figure 5.8, the overall trend is similar, with a steep rise at the beginning of the hydrograph towards around 1.3m flow depth and a more gradual drop after the peak. This is without considering several higher measurements in the measured hydrograph that were filtered out. On the other hand, the rate of change after the peak is different for the two hydrographs as the measured hydrograph drops much faster than the RAMMS hydrograph. The RAMMS hydrograph has not yet dropped below 0.8m when the measured hydrograph is almost at 0m. Nevertheless, the resemblance of the two hydrographs is surprising, given the difference in mean channel change between the actual event and SIM15, shown in figure 5.4. Especially because the erosion was clearly underestimated by RAMMS, a smaller flow volume and a smaller hydrograph would be expected for the RAMMS hydrograph.

To conclude, there is more resemblance between the hydrographs in figure 5.8 than the hydrographs in figure 5.8. This was not expected given the resemblance between SIM4 and the actual event in terms of erosion and deposition. That resemblance is definitely higher than that of SIM15 and its actual event. In other words: although the simulated flow height over time of SIM15 is more realistic than SIM4, and even higher than the actual event, the simulated net erosion is far too low compared to the actual event.

5.3 SIM15: 1m resolution and spatial erosion analysis

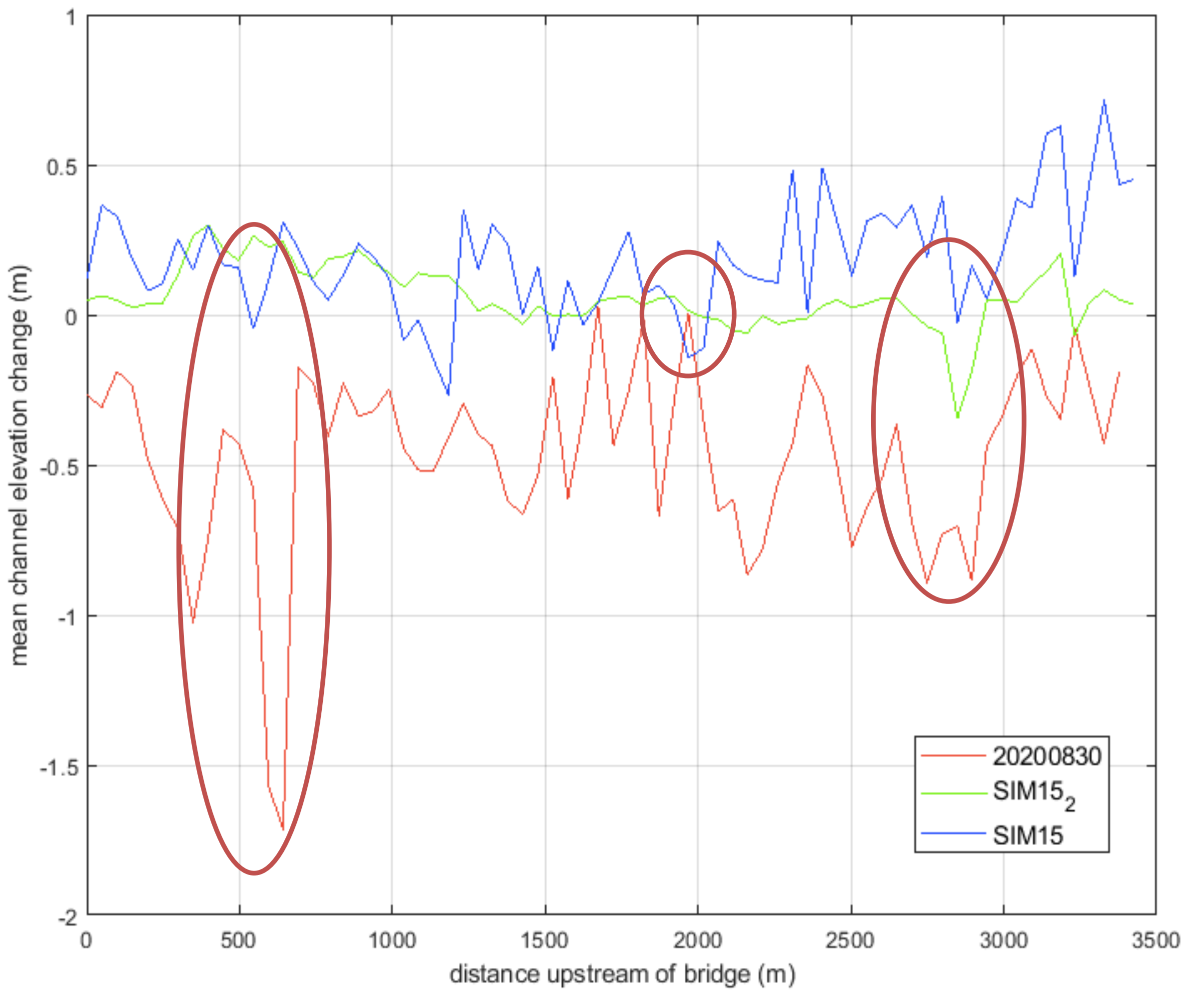


Figure 5.9: mean channel change comparison between SIM15, SIM15_2 and the actual event. Red circles indicate areas interesting for spatial analysis.

In this subchapter, simulation 5.9 is used to make a higher resolution and compare its results. This high-resolution simulation has the same parameters, DEM and hydrograph as SIM15, but the DEM resolution is 1m instead of 2m. The 1m resolution simulation is called SIM15_2. Also, spatial erosion patterns will be shown in maps form multiple locations along the channel. These locations are chosen on the basis of figure 5.9. In this figure, the mean channel elevation change for the two simulations and the actual event are plotted. First of all, there is much difference between SIM15 and SIM15_2 in terms of deposition and erosion. From 0 till 2000m from the bridge their lines intersect frequently but from 2000m differences of more than 0.5m are visible. interestingly, SIM15_2 performs better in terms of channel elevation change especially from 2000m from the bridge. The red ovals in figure 5.9 show features in the graph that are interesting to investigate spatially as well. A view on the erosion maps might explain these features. The left oval is chosen because this is the largest erosion feature the actual event while the simulated events stick quite closely together. The middle red oval is chosen because here all lines intersect in one point.

The right red oval will be investigated closer because all lines show an erosion feature here, but they still vary in absolute value.

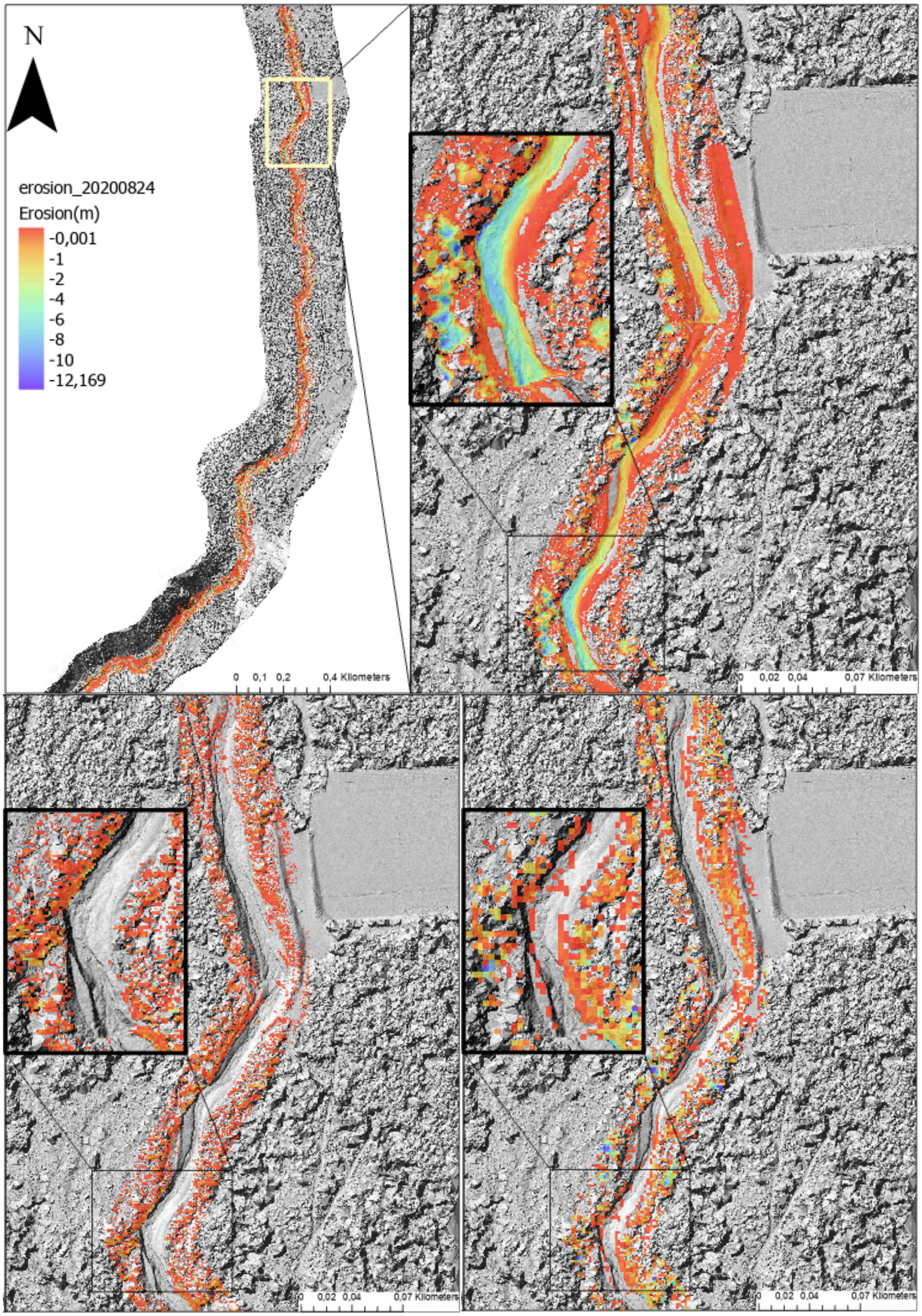


Figure 5.10: channel erosion of the 2020-08-30 event (upper right), SIM15_2(down left) and SIM15 (down right) with values from 0m to 12m erosion of around 500m from the bridge.

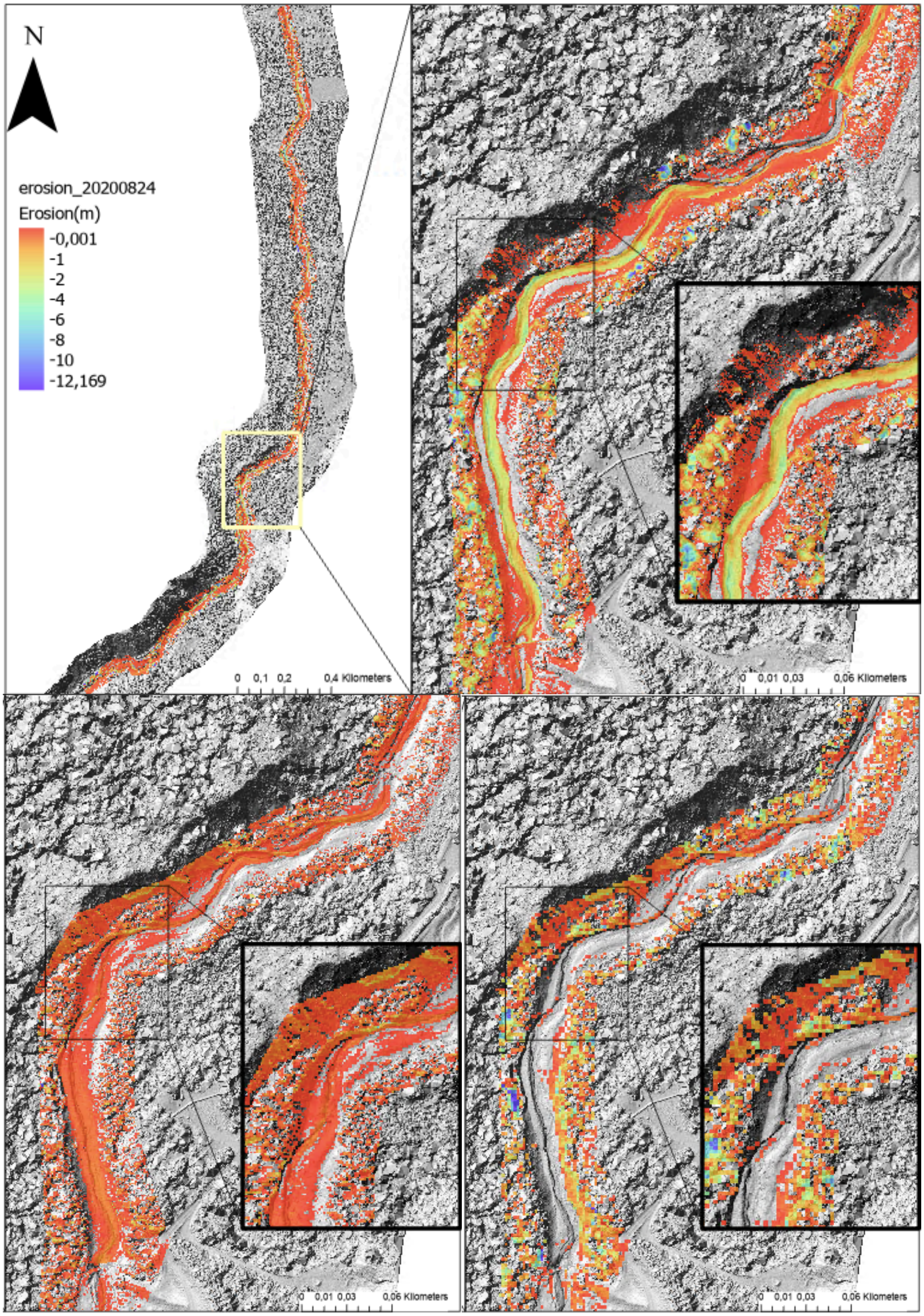


Figure 5.11: channel erosion of the 2020-08-30 event (upper right), SIM15_2(down left) and SIM15 (down right) with values from 0m to 4m erosion of around 2000m from the bridge.

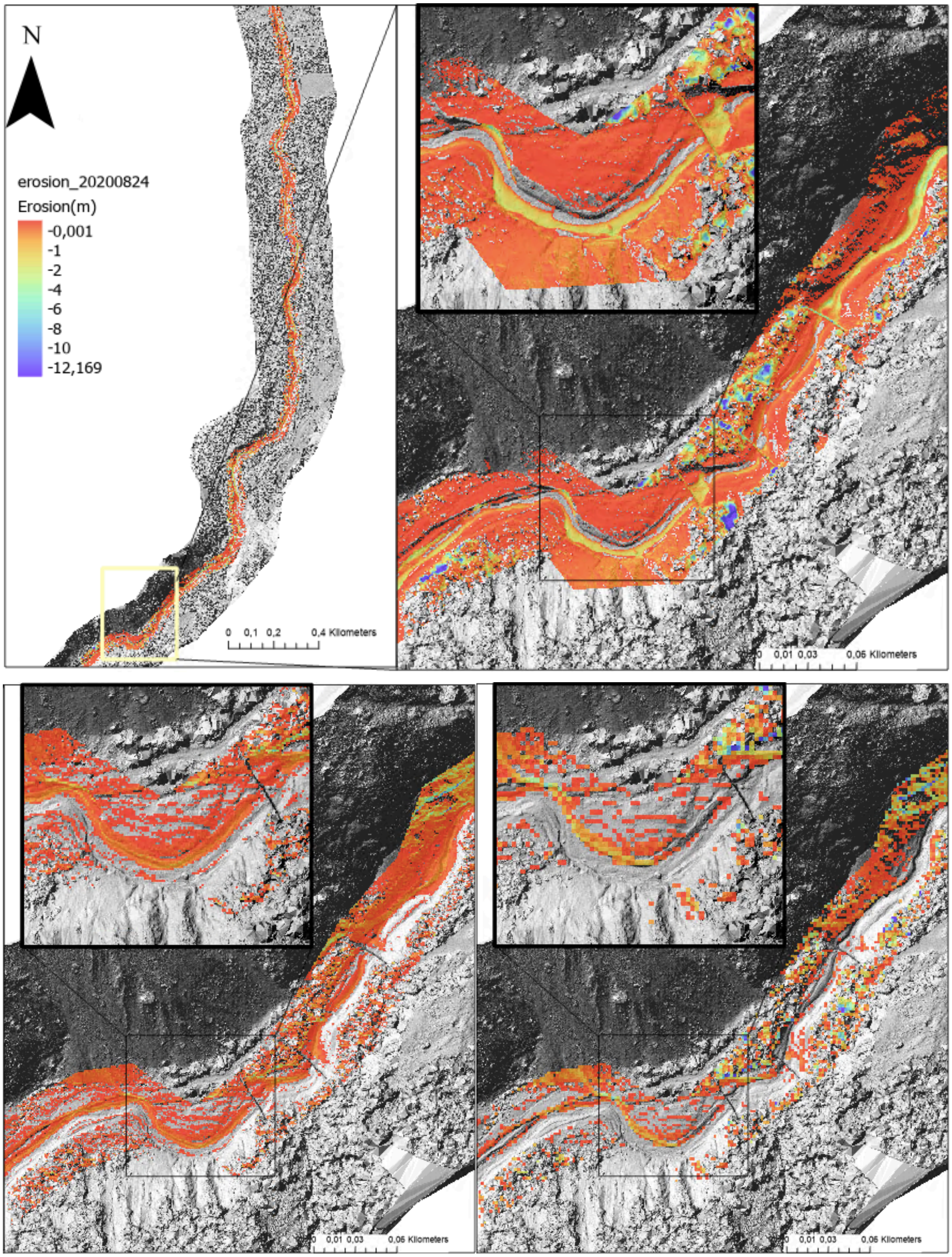


Figure 5.12: channel erosion of the 2020-08-30 event (upper right), SIM15_2(down left) and SIM15 (down right) with values from 0m to 3m erosion of around 2800m from the bridge.

The figures are placed on three consecutive pages, to make comparison easier between each place along the channel.

In figure 5.10, one the previous page, the left red oval of figure 5.9 is visualized from above. It becomes immediately clear that the actual event was much more erosive than the simulated events. On the erosion maps of SIM15_2 and SIM15 some red (around up to 1m erosion) and light-yellow (up to 2m erosion) parts can be spotted at the side of the channel, with more red and yellow spots visible in SIM15. Most of these yellow spots are outside the channel so they are assumed to be errors. In the actual event erosion map on the upper right, the complete channel is coloured yellow. Furthermore, some points in the middle, probably at around 700m from the bridge, even show a blue green part which can mean up to 6m or 7m erosion. This part, also indicated by a red oval in figure 16, probably represents the large erosion feature of the actual event in figure 15 at around 700m.

This paragraph is about figure 5.11, displayed on the next page. This part of the channel represents the middle red oval indicated in figure 5.9 at around 2000m. The red ovals in figure 5.11 indicate the location of the 2000m distance point from the bridge. The figures show different results than would be expected when looking at figure 5.9. Where figure 5.9 would suggest that both simulations and the actual event would have similar erosion, in figure 5.11 SIM15 clearly underestimates erosion. SIM15_2, however, shows a more realistic erosion pattern although it is still an underestimation of erosion. An explanation for this could be that in figure 5.9 the mean channel change is calculated, which also takes deposition into account. Moreover, the red and yellow dots that are visible outside of the channel, are small errors that occurred in the erosion map making process, which suggest erosion in places where this is not likely. These could also generate a wrong calculation in figure 5.9 for some locations. When looking closely, SIM15_2 even shows erosion in some places where the actual event does not. Unfortunately, this mostly occurs outside the channel, which means most of these erosion features are probably errors. Furthermore, a pattern can be seen in where erosion occurs for all maps, as it mostly occurs in the deeper parts of the channel, whereas the higher parts show less erosion.

Figure 5.12 shows a part high upstream the channel. This is an interesting part to take a closer look because the hydrograph has passed this area and flow depth has become, and this part is steeper so more erosion is to be expected. Earlier it was concluded from figure 5.9 that this part would show an erosion feature for both the simulations and the actual event. This indeed seems to be in line with what is shown in figure 5.12. An important difference between these features is that the erosion feature of the actual event is concentrated in the outside bend, while the erosion features of both simulations is concentrated on the inside of the bend that is highlighted in the figure. The figure also shows a more refined erosion pattern for SIM15_2 than for SIM15. Interestingly, erosion depth seems to be similar for SIM15 and and the actual event. This is a big difference between this part of the channel and the parts further downstream.

To conclude, the spatial figures confirm that erosion was underestimated by RAMMS for this event, as was concluded from figure 5.9. In addition, the erosion maps show that RAMMS mostly simulates different erosion patterns than the actual event in this case.

5.4 SIM4: 1m resolution simulation and spatial erosion analysis

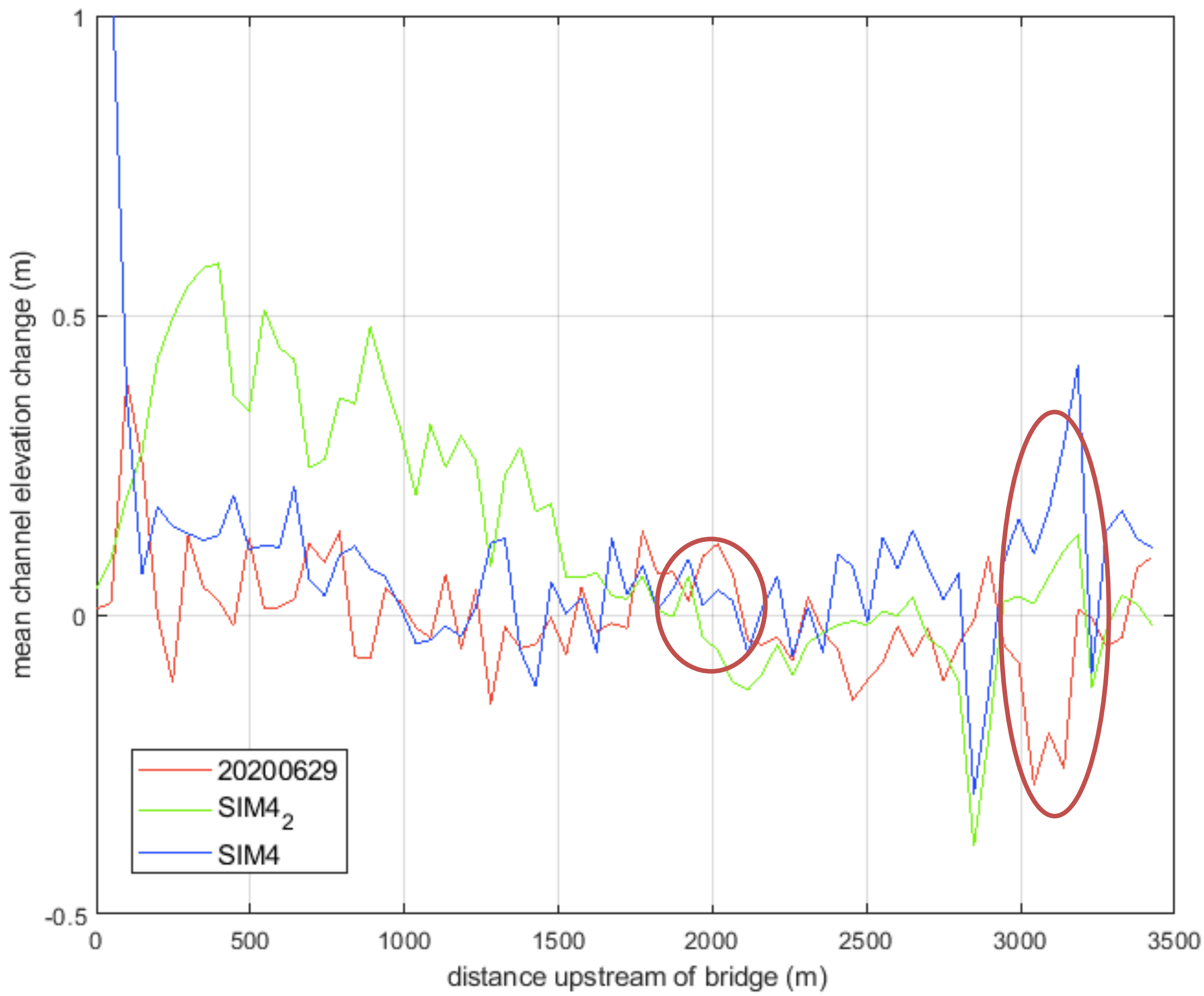


Figure 5.13: mean channel change comparison between SIM4, SIM4_2 and the actual event.

In this subchapter, the same will be done with SIM4 as was done with SIM15. A new simulation, called SIM4_2 is run with the same parameters as SIM4, but in a resolution of 1m instead of 2m. also, the virtual time used for the simulation is 15000s instead of 20000s due to a limited amount of data storage capacity. as a consequence, the amount of runout of SIM4_2 was much lower than SIM4. From the graph in figure 5.13, some locations will be chosen that will be spatially analysed in terms of erosion. As expected, the lines in this graph are much closer together than the lines in the figure 5.13 from the previous subchapter. Overall there is a trend of more deposition closer to the bridge and more erosive features more upstream. Again, red ovals are indicated at what locations erosion maps will be discussed to see erosion patterns and recognise differences between this quantitative figure and spatial patterns. The most interesting features in this figure are at the same locations as the erosion maps of the previous subchapter, at around 2000m and 2800m upstream of the bridge. These are also in this case interesting because just before 2000m the lines intersect and further upstream they divert. At the right red oval at 2800m the simulations show a distinct erosion feature, while the actual event shows a deposition feature. Lastly, SIM4_2 appears to get less erosive towards the bridge. This could be explained by the lower amount of virtual time set for this simulation.

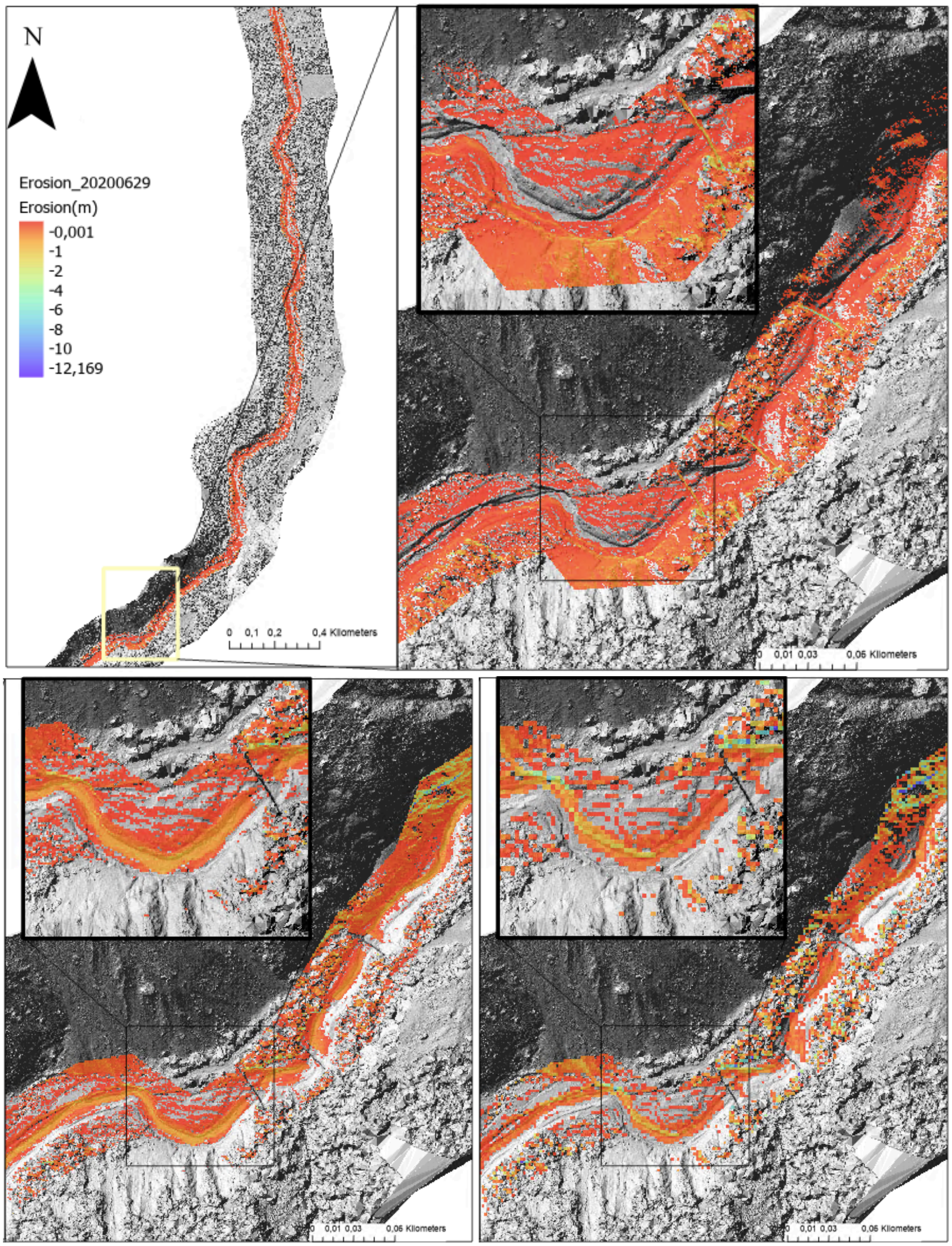


Figure 5.14: channel erosion of the 2020-06-29 event (upper right), SIM4_2(down left) and SIM4 (down right) with values from 0m to 3m erosion of around 3000m from the bridge.

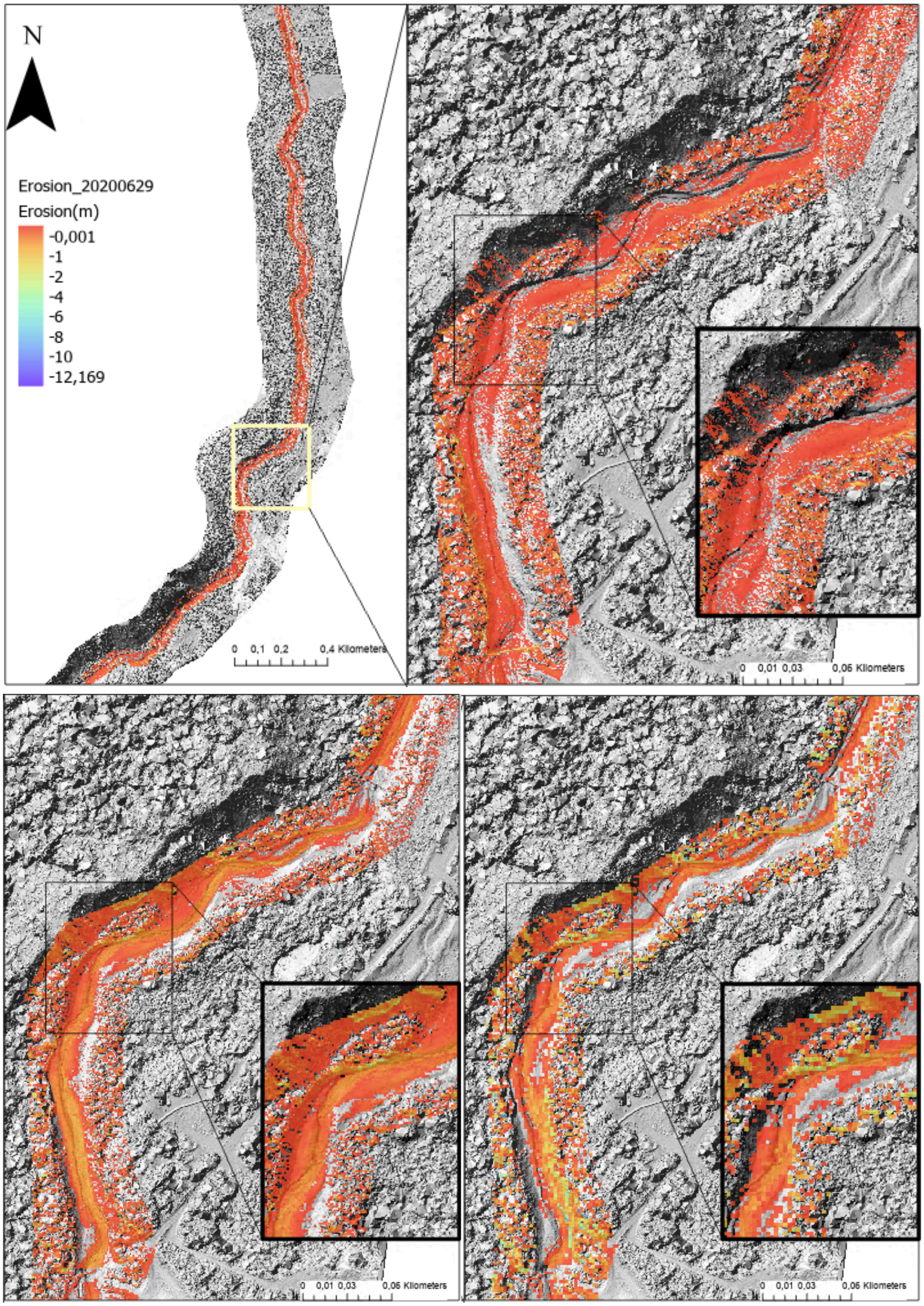


Figure 5.15: channel erosion of the 2020-06-29 event (upper right), SIM4_2(down left) and SIM4 (down right) with values from 0m to 3m erosion of around 2000m from the bridge.

Again, the erosion maps for different parts on the figure are placed after each other to make it easier for comparison.

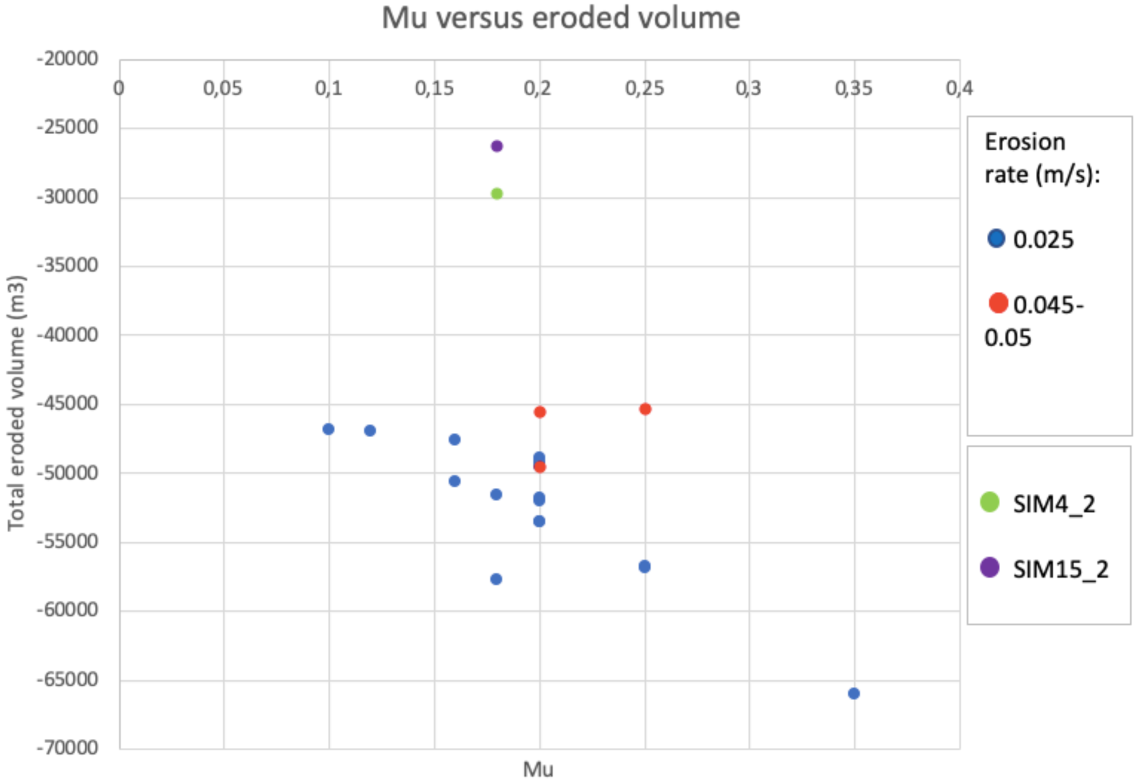
From the erosion maps in figure 5.14, it becomes clear that overall there is an overestimation of erosion of the simulations compared to the actual event. Where the actual event shows erosion up to 1m, the simulated events show parts with up to 2m erosion. This is actually in line with what was concluded from looking at figure 5.13, where the actual event had a deposition feature, and the two simulations clearly showed an erosion peak. However, the places where erosion occurs are similar for both the simulations and the actual event. Just as in the previous subchapter, erosion is dominant in the deeper parts of the channel where the flow depths are probably largest.

On the erosion maps in figure 5.15, the part around 2000m from the bridge is shown. The point of 2000m from the bridge is indicated with the red ovals. Again, the simulations overestimate erosion values in some places with a few meters. SIM4_2 shows even more erosion than SIM4. Interestingly, the erosion maps differ slightly in erosion pattern. Where in SIM4_2 quite heavy erosion seems to cover most of the channel, the other erosion maps both cover another part of the channel. South of the red oval, it is visible that in SIM4 the right part is partly eroded, while in the actual event mostly the left part is eroded. Lastly it is remarkable that most features visible in the graphs that show mean channel change in most cases go together with bends of the channel.

To conclude this subsection, also for SIM4 and SIM4_2 there is some difference with the actual event. However, this difference is much smaller than for SIM 15 and SIM15_2. Furthermore, where SIM4 does not show similar erosion patterns to the actual event, SIM4_2 does show realistic erosion patterns. This was not to be expected when looking at figure 5.13.

Another important thing that became clear when analysing erosion patterns in section 5.3 and 5.4, was that resolution clearly affected the way RAMMS simulates erosion. Generally, the higher resolution simulations (SIM15_2, SIM4_2) were closer to the actual events than lower resolution simulations (SIM15, SIM4). A possible reason for this can be that cell size is smaller with a higher resolution, which gives RAMMS a more realistic input of the terrain that the debris flow will use. For example, if there is a small height difference over 2m, there can still be a relatively big height difference over 1m, where over the other meter this difference is compensated. This can mean much for how a debris flow behaves and how erosion Is simulated. Especially when looking at eq. 1, where height and slope are important parameters affecting critical shear stress, and thus affecting erosion in RAMMS.

5.5 Correlation between mu, xi and erosion and deposition



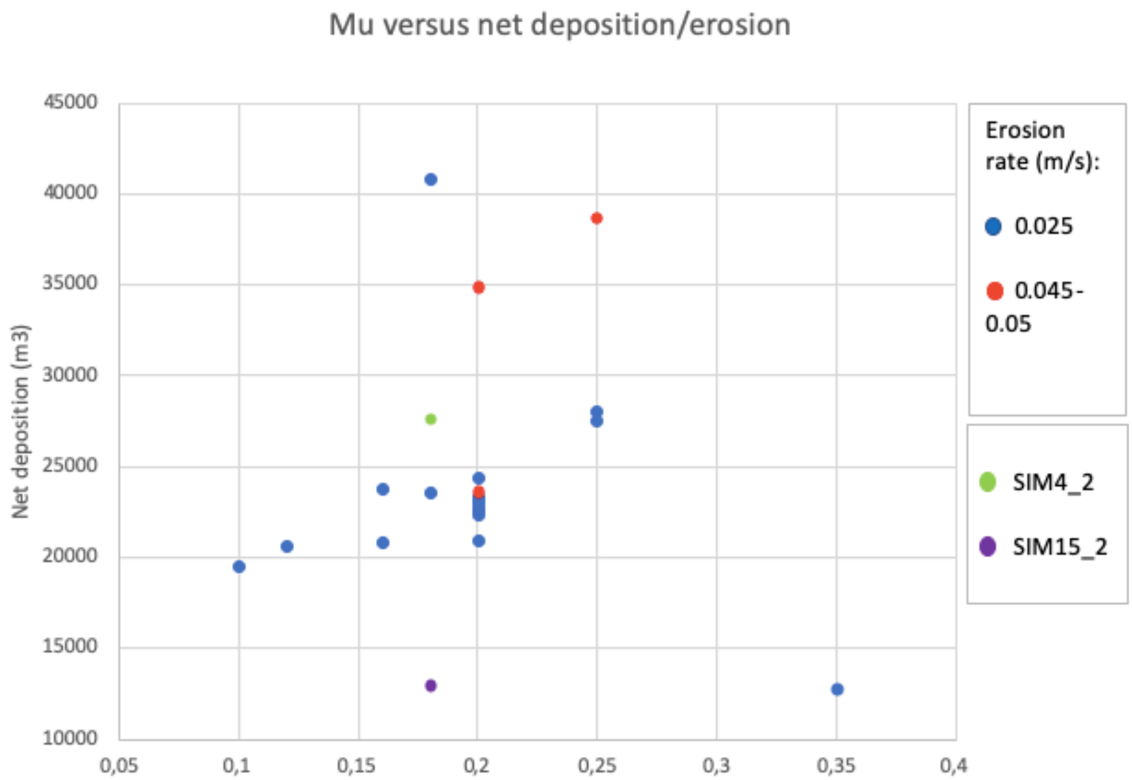


Figure 5.16: relations between Mu, erosion rate and eroded volume and net deposition/erosion. Red dots indicate erosion rates other than 0.025, green indicates SIM4_2 and purple SIM15_2.

In figure 5.16, the measured eroded volume and measured net erosion/deposition are visible per different values of mu. There is no trendline drawn because there are disproportionally many mu values of 0.2, that would wrongly affect a trendline and an R^2. However, there is a trend visible along the measured points, of a higher mu providing a higher net deposition, and a higher mu causing a lower eroded volume, so more erosion. These relations seem a bit counterintuitive, as higher erosion normally would mean lower deposition. An explanation for this could be that a higher total erosion automatically means a higher total deposition as well, because material is eroded in one place and deposited in the next. However, this is not in line with the erosion of the 2020-08-30 event, having total erosion of -42.123 m^3 and net erosion of -25.704 m^3. In the upper graph of figure 5.16, higher total erosion values can be seen than the 2020-08-30 event, but not one of them comes close to net erosion. This would also mean that the relation between mu and net deposition is more plausible, given that a higher mu would mean more friction, which would provide lower shear stress which results in less erosion. Furthermore, the effect of erosion rate can be seen. The higher erosion rates show overall less deposition than points with lower erosion rate and the same mu. Again, lower erosion rates seem to result in lower total erosion, but as explained earlier, this is probably a wrong relation. Moreover, the higher resolution simulations both show much lower total erosion than the other simulations, and a more comparable net deposition. This is an extra argument for assuming that with a lower resolution, total erosion is overestimated by RAMMS. Another reason could be that there is an error in the GIS erosion and deposition analysis for determining total erosion in maps with low resolution.

In figure 5.17, the measured eroded volume and measured net erosion/deposition are visible per different values of mu. In these graphs, a less clear trend is visible than in figure 5.16, but there are still some interesting things to be mentioned. To begin with, higher erosion rates seem to result in lower measured total erosion for the simulations, while higher erosion rates do result in lower net deposition in the end. Same as in figure 5.16, both higher resolution simulations have a much lower total eroded volume than the other simulations. What can be concluded from this, is that the friction parameters mu and xi have less influence on erosion than resolution. When comparing the graphs of mu and those of xi, mu clearly shows a more defined trend for different values. This could mean that for this channel, mu has a stronger effect on simulated erosion than xi.

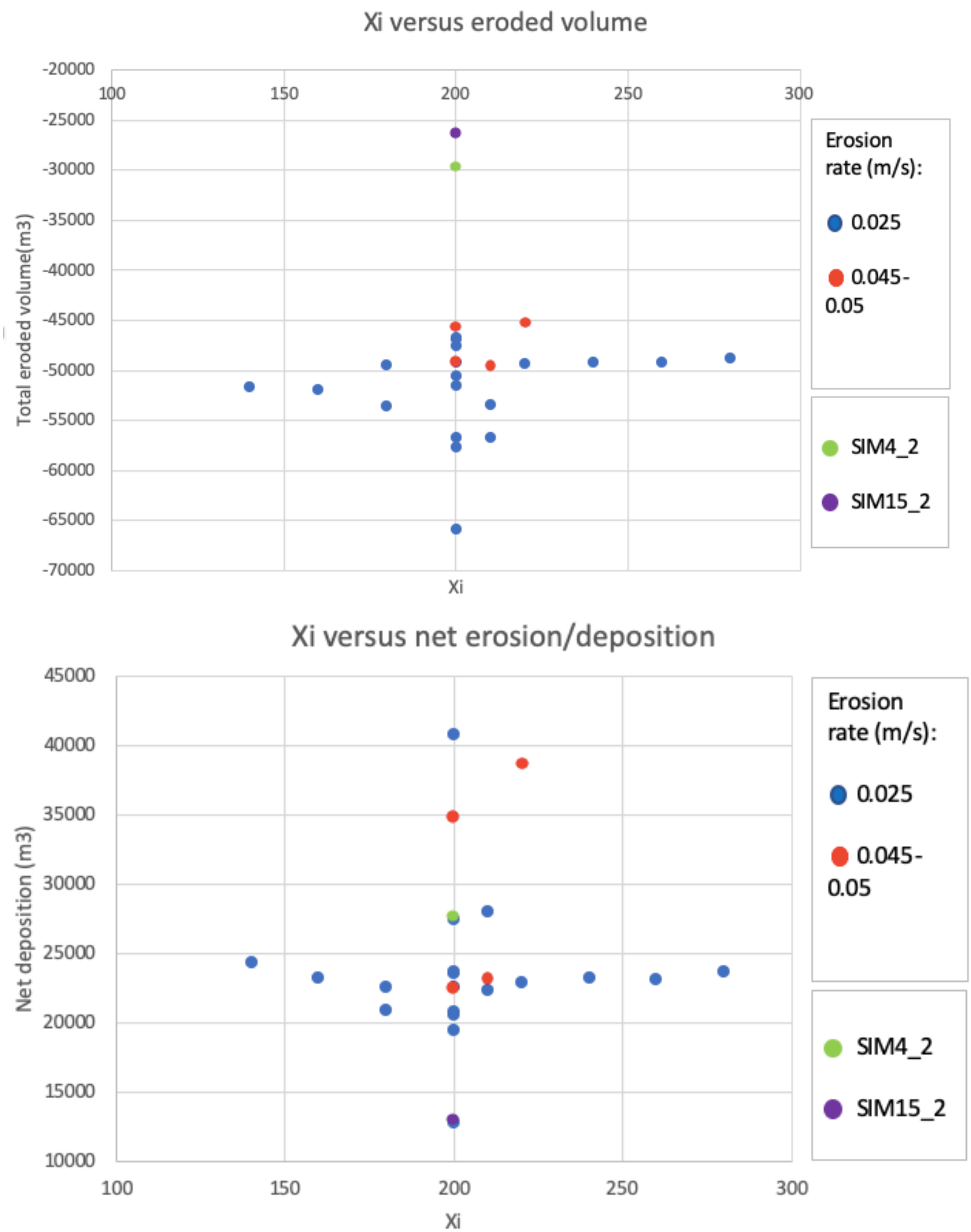


Figure 5.17: relations between xi, erosion rate and eroded volume and net deposition/erosion. Red dots indicate erosion rates other than 0.025, green indicates SIM4_2 and purple SIM15_2.

6. Discussion

The discussion will begin with an assessment of the performance of RAMMS in this research. Subsequently, the results and interpretations will be compared to studies that also compared RAMMS simulations to actual events. Thereafter, implications of the results of this research for the understanding of modelling and erosion. Finally, recommendations for future research will be done.

6.1 RAMMS performance

First of all, models can never be a perfect recreation of reality, because you are always limited by time and data capacity. However, the simulations for this research were made as realistic as possible within the time and data limits, as described in the methods. Especially data in combination with time management was a challenge in the beginning. Researching a channel with a length of 3.5km made it hard to choose the right parameters in RAMMS that did not take too much time and still preserve the quality of the data.

From looking at all results, it can be concluded that for the biggest part RAMMS did not make realistic simulations when compared to actual events. Not realistic in this case is mostly meant in terms of erosion, which is the focus of this research. The mean channel change values of SIM13-24 compared to the actual event much too high and even showed quite some deposition, while the actual event showed up till 1.5m erosion. When looking at the erosion of SIM1-12 compared to the actual event, erosion was overestimated throughout most of the channel. This comes forward mostly in the quantitative analysis, where can be seen that RAMMS overestimates and underestimates erosion volumes. Below, four possible explanations for the unrealistic simulations are given:

1. Hydrograph was retrieved from the end of the channel but given as input in RAMMS at the beginning of the channel. This is one of the difficult things about working with a hydrograph as an input in RAMMS but probably the most important one, this problem is also mentioned in Frank et al. (2015). The problem with this method is that along the channel many things happen that affect the behaviour of the debris flow, and so the hydrograph that is measured at the end of the channel. It is possible that for this reason erosion was not accurately simulated, because the used input hydrograph already underwent the erosion and deposition that instead should have happened during the simulation. Still, the difference between the simulated and measured erosion is not proportional to the difference between the RAMMS hydrograph and the measured hydrograph. Given that the RAMMS hydrograph had a larger volume, even more erosion might have been expected.
2. Critical shear stress was not varied. As the focus of this research was more on the relation between erosion rate, mu, xi and erosion, critical shear stress was not varied for the different simulations. It could have been that when lowering the critical shear stress for SIM13-24, the erosion rate would be active a bigger part of the simulation time, and the erosion volumes would be more realistic. On the other hand, it is questionable why the critical shear stress should be lower for the 2020-08-30 event, and why it should be higher for the 2020-06-29 event, where erosion was mostly overestimated, but this would be interesting for future research.

3. Optimal resolution was not used. Due to a combination of a relatively large study area, lack of computing power, and a lack of time, the optimal resolution of the DEM could not be used. This could also be one of the reasons for the simulations being more unrealistic. This becomes even more plausible provided that in section 5.3 and 5.4 the graphs and spatial maps showed that the higher resolution simulations were closer to reality than those with a lower resolution. Moreover, section 5.5 states that resolution probably has more effect on behaviour of erosion in RAMMS than the friction parameters mu and xi. Cesca & d'Agostino (2008) also state that with low cell size flow depths can be overestimated, which can have consequences for the erosion (Frank et al., 2017).
4. The 2020-08-30 was too erosive for RAMMS to simulate. It can also be that the 2020-08-30 event was an unusual erosive event in combination with the rest of its parameters. This became clear when comparing the two events in the beginning of chapter 5 (section 5.1). in this section, flow depth, front flow velocity and peak discharge did not differ that much between the two events. However, this raises the question how the event could be so erosive and not have a large peak discharge or an enormous volume that posed a threat to the lower parts. It could be that the check dams and other measures prevented this (Remaitre et al., 2008), but that such an amount of erosion otherwise would have been disastrous. This can be interesting for future research as well. In addition, in section 5.5 it becomes clear that total eroded volumes can be relatively for simulations, while the simulations show net deposition instead of net erosion.

On a few parts, the simulations were close to reality: the mean channel change of 2020-06-29 was successfully simulated, and the eroded volume was realistic. Also, the places where erosion occurred, were relatively accurate when compared to the very erosive 2020-08-30 event. One of the reasons could be the opposite of number 4 of the previous reasons. It can be that the 2020-06-29 was a more normal event where the parameters were more likely to indeed result in the amount of erosion RAMMS simulated. Furthermore, many studies have proved that RAMMS is successful in simulating events in terms of flow depth and runout, so it is likely that the erosion mechanisms in RAMMS do function, but that they still underestimate highly erosive events.

6.2 Comparison to other RAMMS erosion studies

Up till now, many studies were conducted on the performance of the RAMMS model (Simoni & Mamoliti, 2012; Cesca & d'Agostino, 2008; Schraml et al., 2015; Gan & Zhang, 2019). All these studies focused mainly on the outflow and the flow depth patterns of debris flows in testing RAMMS. However, there are some studies that looked deeper into how erosion. In this section they will be compared to this research.

Dietrich and Krautblatter (2019) found more realistic erosion rates and erosion volumes for highly erosive debris flows. In this research, far less field research was performed before executing the simulations. This shows the importance of having knowledge of the field, but also the difficulty of letting RAMMS simulate erosion in a realistic way, whereas this is crucial for future research. This is because if erosion is not simulated properly, (future) highly erosive debris flows are hard to predict. Another important difference between the research of Dietrich and Krautblatter (2019) and this thesis, is that they simulated erosion per specific section. In this master thesis, the debris flows were simulated from the start of the channel to the end. With this method, it is probably much harder to simulate an erosive event than when simulating it per section and adjusting the parameters until realistic erosion is simulated. When forecasting debris flows, it is more likely that this thesis' method will be used, as mostly not as much information is known per section as in the study of Dietrich and Krautblatter (2019). This shows that probably the RAMMS model is not yet ready to successfully forecast debris flows in dangerous areas, when there no sufficient data per section is known.

Frank et al. (2015) also studied how erosion performs in RAMMS. The first thing that stands out when comparing to this research, is that there is a large difference in discharge and volume of their events and the erosive 2020-08-30 event used for this research. This made the hydrograph that Frank et al. (2015) very different from this research, which probably had much effect on erosion. Dietrich and Krautblatter (2019) had more comparable volume and peak discharge, but they used the section approach, whereas Frank et al., (2015), simulated in a similar way as this research (table 7). The difference in peak discharge and volume could be an explanation for why the simulations of Frank et al. (2015) were more successful in RAMMS than in this research. In addition, Frank et al. (2015) used a broader range of friction parameters mu and xi. It is possible that if in this research more extreme values would have been chosen for mu and xi, more reasonable erosion values would have been simulated by RAMMS.

Table 7: comparison of peak discharge and volume between this study and other studies on RAMMS erosion performance.

Study	**Peak discharge (m3/s)**	**Volume (m3)**
This study	9.2	6000
Frank et al. (2015)	755 and 1025	45,038 and 65,037
Dietrich and Krautblatter (2019)	15	2800
Frank et al. (2015)	Block release	Block release

Frank et al. (2017) did another study on erosion in RAMMS and stated the importance of entrainment in the model. They also stated how hard it was to recreate erosion of actual events using RAMMS. Moreover, in their study RAMMS also underestimated erosion a little, but far less than in this research. Instead of using a hydrograph of input, they used a block release with a volume of 10 m^3. Interestingly, Frank et al. (2017) also did not adjust the critical shear stress threshold, while still coming with more reasonable results. They mostly relied on adjusting the friction parameters and erosion rate, which in this research did not result in the desired absolute erosion, and besides showed to have less effect on erosion than the hydrograph and resolution. Furthermore, the simulations in the research of Frank et al. (2017) were more compared with each other than with actual events.

To conclude, the other studies were more successful in simulating erosion in RAMMS than this research. Different peak discharge and volume, simulating per section of the channel, and maybe a broader range of friction parameters could be explanations for this. Another outstanding difference between the three studies and this research is that this research did more spatial analysis to test the performance of RAMMS in terms of erosion.

6.3 Implications for understanding erosion and modelling

Although in this research RAMMS did not really succeed in simulating the erosive event successfully, still some lessons can be learned about erosion and modelling from this thesis. First of all, this study shows that the erosion module of RAMMS can be improved. It is indeed possible that the erosive event used for this research was a very erosive event with unusual parameters, but the main objective of RAMMS is probably to predict hazardous debris flows in the future. For a complete prediction, also events that have some less erosive aspects, can in fact still be erosive and hazardous. When modelling in RAMMS, resolution is a really important factor when simulating erosion. It is probably better to divide a channel of 3.5km in smaller parts, both to save calculation time in the beginning, and to choose better parameters for specific parts of the channel. After all, different parts of the channel have different properties. Also, choosing the hydrograph seemed to have much influence on the debris flow simulation. Lastly, when testing RAMMS performance in terms of erosion, a high focus on the bends is needed. According to Frank et al. (2015), "The probability of erosion used as the basis for this model does not differentiate between cells where little erosion is expected (e.g., the inside bends of a channel bend) or where significant erosion can be expected (e.g., the outside of channel bends, or the channel thalweg)." In spatial analysis sections 5.3 and 5.4 it became clear that RAMMS indeed over- or underestimated erosion in the bends. If the erosion module of RAMMS would contain this probability, the performance of erosion in RAMMS would surely improve.

6.4 Recommendations for future research

Concluding from this research, a few recommendations can be made for future research. First of all, more simulations with higher resolution are needed, to confirm how much this affects erosion in RAMMS. This might also have more effect on erosion than friction parameters mu and xi. Furthermore, more simulations are needed with different hydrographs from different distances from the bridge, because the hydrographs showed to have a large effect on the erosion in RAMMS. Moreover, specific studies on erosion in bends and how this is modelled could help understanding erosion and improving RAMMS simulations. Next, testing in RAMMS if the 2020-08-30 would be erosive without the presence of check dams could help to see what effect they have on erosion and if they indeed prevent such an event from growing in volume. Lastly, it would be interesting to see what influence adjusting the threshold for critical shear stress would have on the results research, to see if this erosion parameter has more effect on erosion than erosion rate, maximum erosion and the friction parameters.

7. Conclusion

In this research, actual measured debris flows were compared to simulated debris flow events in RAMMS to take a closer look at how the RAMMS model performs in terms of erosion. Two debris flow events, one very erosive (2020-08-30) and the other less erosive (2020-06-29), were analysed using a quantitative GIS erosion and deposition analysis. In the results of SIM13-24 it became clear that RAMMS was not able to successfully simulate the 2020-08-30 event, especially in terms of net erosion and total erosion. In the results of the other simulations (SIM1-SIM12), RAMMS showed to be more successful, both in terms of spatial erosion patterns and mean channel change. Still, overall RAMMS overestimated erosion in SIM1-SIM12 compared to the 2020-06-29 event. The simulations that used higher resolution clearly performed better, showing spatial patterns and total erosion more comparable to the actual events. Furthermore, from the results it can be concluded that resolution had more effect on the net erosion/deposition than the friction parameters. Moreover, In the bends RAMMS simulates significantly different erosion patterns than the actual events show.

There are a few explanations why in this research RAMMS did not succeed in simulating the erosive 2020-08-30 event:

1. Hydrograph was retrieved from the end of the channel but given as input in RAMMS at the beginning of the channel.
2. Critical shear stress was not varied. This is another erosion parameter that would have affected erosion in RAMMS
3. Optimal resolution was not used. Although the higher resolution simulations performed better, this was not yet the highest resolution that could be used.
4. The 2020-08-30 was too erosive for RAMMS to simulate. The erosive event had some parameters that did not have erosive properties.

The simulation of 2020-06-29 possibly showed better results because it was a less erosive, which was easier for RAMMS to simulate.

For future research, more simulations with higher resolution are needed, to confirm how much this affects erosion in RAMMS. Moreover, specific studies on erosion in bends and how this is modelled could help understanding erosion and improving RAMMS simulations. Next, testing in RAMMS if the 2020-08-30 would be erosive without the presence of check dams could help to see what effect they have on erosion and if they indeed prevent such an event from growing in volume. This study showed that future research on how RAMMS performs in terms of erosion is crucial for improving the overall RAMMS performance. Erosive debris flows can be most hazardous when they grow to large volumes.

References

Baggio, T., Mergili, M., & D'Agostino, V. (2021). Advances in the simulation of debris flow erosion: The case study of the Rio Gere (Italy) event of the 4th August 2017. *Geomorphology*, *381*, 107664.

Bennett, G. L., Molnar, P., Eisenbeiss, H., & McArdell, B. W. (2012). Erosional power in the Swiss Alps: characterization of slope failure in the Illgraben. *Earth Surface Processes and Landforms*, *37*(15), 1627-1640.

Bennett, G. L., Molnar, P., McArdell, B. W., & Burlando, P. (2014). A probabilistic sediment cascade model of sediment transfer in the Illgraben. *Water Resources Research*, *50*(2), 1225-1244.

Berger, C., McArdell, B. W., & Schlunegger, F. (2011). Direct measurement of channel erosion by debris flows, Illgraben, Switzerland. *Journal of Geophysical Research: Earth Surface*, *116*(F1).

Cannon, S. H. (1989). *An evaluation of the travel-distance potential of debris flows* (No. 2). Salt Lake City: Utah Geological and Mineral Survey.

Cesca, M., & d'Agostino, V. (2008). Comparison between FLO-2D and RAMMS in debris-flow modelling: a case study in the Dolomites. WIT Transactions on Engineering Sciences, 60, 197-206.

Chien-Yuan, C., Tien-Chien, C., Fan-Chieh, Y., Wen-Hui, Y., & Chun-Chieh, T. (2005). Rainfall duration and debris-flow initiated studies for real-time monitoring. *Environmental Geology*, *47*(5), 715-724.

Christen, M., Kowalski, J., & Bartelt, P. (2010). RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Regions Science and Technology*, *63*(1-2), 1-14.

Dietrich, A., & Krautblatter, M. (2019). Deciphering controls for debris-flow erosion derived from a LiDAR-recorded extreme event and a calibrated numerical model (Roßbichelbach, Germany). *Earth Surface Processes and Landforms*, *44*(6), 1346-1361.

Dowling, C. A., & Santi, P. M. (2014). Debris flows and their toll on human life: a global analysis of debris-flow fatalities from 1950 to 2011. *Natural hazards*, *71*(1), 203-227.

Egashira, S., Honda, N., & Itoh, T. (2001). Experimental study on the entrainment of bed material into debris flow. Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science, 26(9), 645-650.

Egashira, S. (2011). Prospects of debris flow studies from constitutive relations to governing equations. *Journal of Disaster Research*, *6*(3), 313-320.

Fan, L., Lehmann, P., McArdell, B., & Or, D. (2017). Linking rainfall-induced landslides with debris flows runout patterns towards catchment scale hazard assessment. Geomorphology, 280, 1-15.

Frank, F., McArdell, B. W., Huggel, C., & Vieli, A. (2015). The importance of entrainment and bulking on debris flow runout modeling: examples from the Swiss Alps. *Natural Hazards and Earth System Sciences*, *15*(11), 2569-2583.

Frank, F., McArdell, B. W., Oggier, N., Baer, P., Christen, M., & Vieli, A. (2017). Debris-flow modeling at Meretschibach and Bondasca catchments, Switzerland: sensitivity testing of field-data-based entrainment model. *Natural hazards and earth system sciences*, *17*(5), 801-815.

Gan, J., & Zhang, Y. S. (2019). Numerical simulation of debris flow runout using Ramms: a case study of Luzhuang Gully in China. *Computer Modeling in Engineering and Sciences*, 981-1009.

Godt, J. W., & Coe, J. A. (2007). Alpine debris flows triggered by a 28 July 1999 thunderstorm in the central Front Range, Colorado. *Geomorphology*, *84*(1-2), 80-97.

Griffiths, P. G., Webb, R. H., & Melis, T. S. (2004). Frequency and initiation of debris flows in Grand Canyon, Arizona. *Journal of Geophysical Research: Earth Surface*, *109*(F4).

De Haas, T. D., & Woerkom, T. V. (2016). Bed scour by debris flows: experimental investigation of effects of debris-flow composition. *Earth Surface Processes and Landforms*, *41*(13), 1951-1966.

De Haas, T., Nijland, W., de Jong, S. M., & McArdell, B. W. (2020). How memory effects, check dams, and channel geometry control erosion and deposition by debris flows. *Scientific reports*, *10*(1), 1-8.

Hirschberg, J., McArdell, B. W., Badoux, A., & Molnar, P. (2019, August). Analysis of rainfall and runoff for debris flows at the Illgraben catchment, Switzerland. In *Association of Environmental and Engineering Geologists; special publication 28*. Colorado School of Mines. Arthur Lakes Library.

Iverson, R. M. (1997). The physics of debris flows. *Reviews of geophysics*, *35*(3), 245-296.

Iverson, R. M., Reid, M. E., Logan, M., LaHusen, R. G., Godt, J. W., & Griswold, J. P. (2011). Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment. Nature Geoscience, 4(2), 116-121.

Kean, J. W., McCoy, S. W., Tucker, G. E., Staley, D. M., & Coe, J. A. (2013). Runoff-generated debris flows: Observations and modeling of surge initiation, magnitude, and frequency. Journal of Geophysical Research: Earth Surface, 118(4), 2190-2207.

Krušić, J., Abolmasov, B., & Samardžić-Petrović, M. (2019). Influence of DEM resolution on numerical modelling of debris flows in RAMMS-Selanac case study.

McArdell, B. W., Bartelt, P., & Kowalski, J. (2007). Field observations of basal forces and fluid pore pressure in a debris flow. Geophysical research letters, 34(7).

McArdell, B. W., & Sartori, M. (2020). The Illgraben Torrent System. In *Landscapes and Landforms of Switzerland* (pp. 367-378). Springer, Cham.

NISHIGUCHI, Y., UCHIDA, T., TAKEZAWA, N., ISHIZUKA, T., & MIZUYAMA, T. (2012). Runout characteristics and grain size distribution of large-scale debris flows triggered by deep catastrophic landslides. International Journal of Erosion Control Engineering, 5(1), 16-26.

Morino, C., Conway, S. J., Balme, M. R., Hillier, J., Jordan, C., Sæmundsson, Þ., & Argles, T. (2019). Debris-flow release processes investigated through the analysis of multi-temporal LiDAR datasets in north-western Iceland. *Earth Surface Processes and Landforms*, *44*(1), 144-159.

Reid, M. E., LaHusen, R. G., & Iverson, R. M. (1997). Debris-flow initiation experiments using diverse hydrologic triggers. *Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment*, 1-11.

Reid, M. E., Iverson, R. M., Logan, M., LaHusen, R. G., Godt, J. W., & Griswold, J. P. (2011). Entrainment of bed sediment by debris flows: results from large-scale experiments. *Debris-flow Hazards Mitigation, Mechanics, Prediction, and Assessment*, 367-374.

Remaître, A., Van Asch, T. W., Malet, J. P., & Maquaire, O. (2008). Influence of check dams on debris-flow run-out intensity. *Natural Hazards and Earth System Sciences*, *8*(6), 1403-1416.

Scheidl, C., & Rickenmann, D. (2010). Empirical prediction of debris-flow mobility and deposition on fans. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *35*(2), 157-173.

Scheidl, C., & Rickenmann, D. (2011, June). TopFlowDF-A simple GIS based model to simulate debris-flow runout on the fan. In *5Th International Conference on Debris-Flow Hazards: Mitigation, Mechanics, Prediction and Assessment*.

Schraml, K., Thomschitz, B., McArdell, B. W., Graf, C., & Kaitna, R. (2015). Modeling debris-flow runout patterns on two alpine fans with different dynamic simulation models. *Natural Hazards and Earth System Sciences*, *15*(7), 1483.

Schürch, P., Densmore, A. L., Rosser, N. J., & McArdell, B. W. (2011). Dynamic controls on erosion and deposition on debris-flow fans. *Geology*, *39*(9), 827-830.

Simoni, A., Mammoliti, M., & Graf, C. (2012). Performance Of 2D debris flow simulation model RAMMS. In *Annual International Conference on Geological and Earth Sciences GEOS*.

Stock, J. D., & Dietrich, W. E. (2006). Erosion of steepland valleys by debris flows. *Geological Society of America Bulletin*, *118*(9-10), 1125-1148.

Stoffel, M., Mendlik, T., Schneuwly-Bollschweiler, M., & Gobiet, A. (2014). Possible impacts of climate change on debris-flow activity in the Swiss Alps. *Climatic Change*, *122*(1-2), 141-155.

Takahashi, T., & Das, D. K. (2014). *Debris flow: mechanics, prediction and countermeasures*. CRC press.

Taddia, Y., Stecchi, F., & Pellegrinelli, A. (2019). Using DJI Phantom 4 RTK drone for topographic mapping of coastal areas. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*.

Uchida, T., Nishiguchi, Y., McArdell, B. W., & Satofuka, Y. (2020). The role of the phase-shift of fine particles on debris flow behavior: An numerical simulation for a debris flow in Illgraben, Switzerland. Canadian Geotechnical Journal, (ja).

Voellmy, A. (1955). Über die Zerstörungskraft von Lawinen: Schweizerische Bauzeitung. *Jahrg*, *73*, 159-162.

https://ramms.slf.ch/ramms/downloads/RAMMS_DBF_Manual.pdf

Appendices

Table A1: data used for section 5.5, finding correlations between mu, xi, erosion rate and net eroded volume and eroded volume

Sim name	Mu	Xi	Erosion rate (m/s)	Net eroded volume (m3)	Eroded volume (m3)
SIM1	0.2	210	0,025	22356	-53482
SIM2	0.25	210	0,025	28026	-56799
SIM3	0.25	220	0,05	38667	-45312
SIM4	0.18	200	0,025	23556	-51607
SIM5	0.16	200	0,025	23726	-50557
SIM6	0.25	200	0,025	27491	-56715
SIM8	0.35	200	0,025	12810	-65977
SIM9	0.2	200	0,05	34959	-45652
SIM10	0.2	180	0,025	20951	-53537
SIM11	0.2	160	0,025	23247	-51983
SIM12	0.2	140	0,025	24318	-51756
SIM13	0.2	210	0,05	23210	-49524
SIM14	0.2	180	0,025	22522	-49561
SIM15	0.18	200	0,025	40804	-57676
SIM16	0.16	200	0,025	20813	-47590
SIM17	0.12	200	0,025	20588	-46915
SIM18	0.1	200	0,025	19460	-46793
SIM19	0.2	220	0,025	22919	-49339
SIM20	0.2	240	0,025	23254	-49287
SIM21	0.2	260	0,025	23110	-49225
SIM22	0.2	280	0,025	23673	-48857
SIM23	0.2	200	0,045	22599	-49262
SIM24	0.2	200	0,05	22599	-49262
SIM4_2	0.18	200	0,025	27637	-29731
SIM15_2	0.18	200	0,025	13010	-26223
20200629	x	x	x	6,35E+02	-23788
20200830	x	x	x	-42123	-25704

Statement of originality of the MSc thesis

I declare that:

1. this is an original report, which is entirely my own work,

2. where I have made use of the ideas of other writers, I have acknowledged the source in all instances,

3. where I have used any diagram or visuals I have acknowledged the source in all instances,

4. this report has not been and will not be submitted elsewhere for academic assessment in any other academic course.

Student data:

Name: Nils Roos

Registration number: 5716861

Date: 2 June 2021

Signature: