University of Zurich[UZH]

Investigating the Interaction Between Debris Flows and Groundwater and Implications for Debris Flow Erosion

GEO 511 Master's Thesis

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Abstract

Along their flow paths debris flows can grow as they entrain sediment from the bed and banks of their channels. This entrainment has come into focus in the simulation of debris flows, in order to achieve more accurate predictions of debris flow behaviour. One of the factors that influences the entrainment process is the water saturation of the channel bed. Könz (2023) has built a model that integrates this saturation into the RAMMS debris flow model. That model relies mostly on antecedent precipitation to calculate the water saturation. While precipitation is an important factor in soil moisture content there are other elements that result in the water saturation of the banks and bed of the channel. This thesis aims to improve the understanding of the importance of infiltration of water from the creek and from the debris flow itself on the water saturation of sediments in a debris flow channel. It also investigates the links between the saturation and erosion patterns. To achieve this a case study was conducted on the situation at the Illgraben. Field investigations and simulations have been conducted. From the data that was gathered a conceptual model of the water saturation around the channel has been constructed.

The ERT measurements have been instrumental in understanding the hydrogeological situation. They suggested that there is a saturated zone below the channel, that does not extend to the surface. There is also no groundwater table visible down to 20 m. The depth to which this zone extends matches the inverted groundwater table that is seen in the simulation. The resulting conceptual model suggests that there is a perched groundwater table beneath the channel. This groundwater table is partially connected to the stream. The groundwater table is disconnected from the deep groundwater table. It is limited in its depth by either an impermeable layer or an inverted groundwater table. Comparing this model to data on erosional patterns, observed at the Illgraben, it provides a possible explanation for the proportionally higher rate of erosion seen with larger debris flows. It would be possible that large debris flows erode the unsaturated layer above the groundwater and reach the saturated sediments. These more erodible sediments would then lead to an overall deeper erosion. Overall, the results of this thesis suggest, that examining the groundwater beneath debris flow channels could help in furthering the understanding of debris flow erosional patterns and thus improve debris flow modelling.

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List of Acronyms

RAMMS	Rapid Mass Movement Simulator
CD	Check Dam
ERT	Electrical Resistivity Tomography
TS	Transect

1. Introduction

Debris flows pose a significant risk in mountainous regions all over the world. A study by Dowling and Santi (2014), that assessed the death toll of debris flows between 1950 and 2011, has found around 77'800 deaths from debris flows, which due to difficulties with data acquisition might actually be much higher. As with many other geomorphic processes, debris flows are also affected by climate change. The effect here mainly comes from two factors. On one hand, debris flows, as processes that are heavily dependent on hydrological and meteorological factors, are expected to increase in frequency and magnitude with an increase in extreme precipitation events (Hirschberg et al., 2021). On the other hand, the sediment availability is also susceptible to climate change. This however is variable for different catchments. In the Illgraben for example, Hirschberg et al. (2021) are expecting a decrease due to its sediment reservoirs being mainly fed through frost-weathering. Other catchments however are expected to experience an increase in sediment availability. This is expected for example, to happen through degradation of permafrost (Damm & Felderer, 2013). One example from Switzerland, where permafrost instability was observed to cause an increase in debris flow activity is the Spreitgraben. There, permafrost degradation has caused rockfall, which has increased the sediment availability, which in turn caused a dramatic increase in debris flow activity and magnitude (Frank et al., 2019).

With increasing risk comes an increased need for risk mitigation. A central tool in the arsenal of natural hazard risk mitigation is the modelling of the natural hazards. Within the modelling of debris flows, entrainment and erosion have become an increasing concern (Frank et al., 2015, 2017; Gregoretti et al., 2019). This has happened due to the fact that debris flows can erode and then entrain the soil they flow over along their path. This can lead to a significant increase in debris flow volume (Hungr et al., 2005), which then can cause changes in their runout behaviour (Iverson et al., 2010). From experiments and the study of real events, it has been determined that, among other factors, the soil moisture content of the eroded soil has an impact on the amount of entrained material (de Haas et al., 2022; Iverson et al., 2011; Reid et al., 2011).

In order to implement the saturation of the soils, which might be eroded by debris flow, Könz et al. (2024) have developed a model that models the saturation of sediment in the river bed during a debris flow and coupled it to the widely used RAMMS software. While this can improve the performance of the software, especially when looking at flow path saturation due to antecedent rainfall, it still lacks an understanding of the interaction between debris flows and their underlying aquifers, as well as an understanding of the local aquifer. In general, groundwater has been studied extensively as a part of the triggering of debris flows (Bondevik & Sorteberg, 2021; Iverson et al., 1997). However, the interaction between debris flows and aquifers along the flow path of debris flows remain largely unstudied. This is the main gap this thesis will attempt to fill. Characterising the hydrogeologic situation at the Illgraben study site through various methods will lay the basis for simulating the infiltration process during variably sized debris flow events. The goal then is to better understand the hydrogeologic situation at the Illgraben and how debris flows interact with it.

1.1. Research Questions

The research questions for this thesis can be grouped into three sections. For the field methods, the questions are mostly about generating inputs for the simulation and the synthesis. For the simulation, the questions are mostly about the calculated infiltration from debris flows into the soil of the banks and the bed, as well as the adequacy of the chosen software for this purpose. Lastly the questions for the synthesis aim to combine all the work into a coherent picture of the hydrogeological flows at the study site.

Field Methods:

- Under what conditions is there groundwater in the banks of the Illgraben channel at the study site?
- What information about the hydraulic properties of the soil can be extracted from the data of the various field tests carried out for this thesis?
- Can electrical resistivity tomography be used to identify groundwater at the study site and if so, what can be inferred about the hydrogeological situation from this data?

Modelling:

- Is it possible to accurately simulate the infiltration of water from a debris flow into the banks and bed of the Illgraben channel using VS2DI?
- What patterns can be identified from this simulation?
- Is VS2DI the right tool for such simulations?

Synthesis

- How might infiltration from debris flows into the bed and banks of their channels influence the erosion and entrainment of these debris flows?
- What does the hydrogeological situation at the study site look like? What would the flow of water in the soil at this site conceptually look like?

1.2. Structure of Thesis

This thesis is basically divided into the two sections of field investigations and modelling. The field investigations include four methods, of which some were carried out during this thesis and others were installed previously, and the data is what they contributed to this thesis. The surveys carried out for this thesis specifically are the electrical resistivity tomography and the infiltrometer measurements. The groundwater wells and the soil moisture sensors were installed previously and their data is also used for this thesis. Additionally, there were some small assistive measurements, that will be mentioned where relevant. The groundwater and soil-moisture modelling that was carried out for this thesis using the software VS2DI used the data that was produced from the field investigations as inputs and as a way to verify the results. Both the field investigations and the modelling will be presented in this thesis as separate chapters that include all the descriptions of the work that was carried out, the results and a discussion of those results. In the synthesis chapter, the other two chapters are brought together to create a cohesive interpretation of their results.

2. Literature Review

2.1. Study Site

The Illgraben study site is located in the canton of Valais in the Swiss Alps between Sion and Visp. The full catchment has an area of 10.4 km^2. The Highest point in the catchment is the Illhorn at 2716 m above sea level (asl), while the fan starts at 850 m asl and extends down to the outlet of the Illbach into the River Rhone at 610 m asl. As is shown in Figure 1, the Illbach is fed by two sub-catchments, of which the Illgraben catchment (4.6 km^2) is the one responsible for the debris flows at this site (Berger et al., 2011). This field site has been used in many studies due to the high frequency of debris flows. With approximately 5 debris flows per year and an annual transport of around 100'000 m^3 of debris, it is one of the most active debris flow catchments in the alps (Bennett et al., 2014; de Haas et al., 2020).

The Illbach flows across the fan in an incised channel with a length of 2 km. This section and an additional section 2.8 km up into the Illgraben sub-catchment has been stabilized by the construction of a total of 28 check dams, which control the erosion and path of the flow (de Haas et al., 2020). The site of most measurements in this thesis is check dam (CD) 28 at the lower end of the channel. CD29, which lies underneath the main bridge crossing the torrent, is the site of some major instrumentation. Next to depth sensors and geophones, it includes a large force plate that measures shear forces and makes it possible to assess bulk density and mass of debris flows (McArdell, 2016).

The annual precipitation at the catchment varies from 700 mm at the lower reaches of the fan to 1700 mm at summit region and a maximum rainfall intensity of 11.4 mm in 10 minutes has been measured in 2008 in the higher reaches of the Illgraben sub-catchment (Berger et al., 2011; Hürlimann et al., 2003).

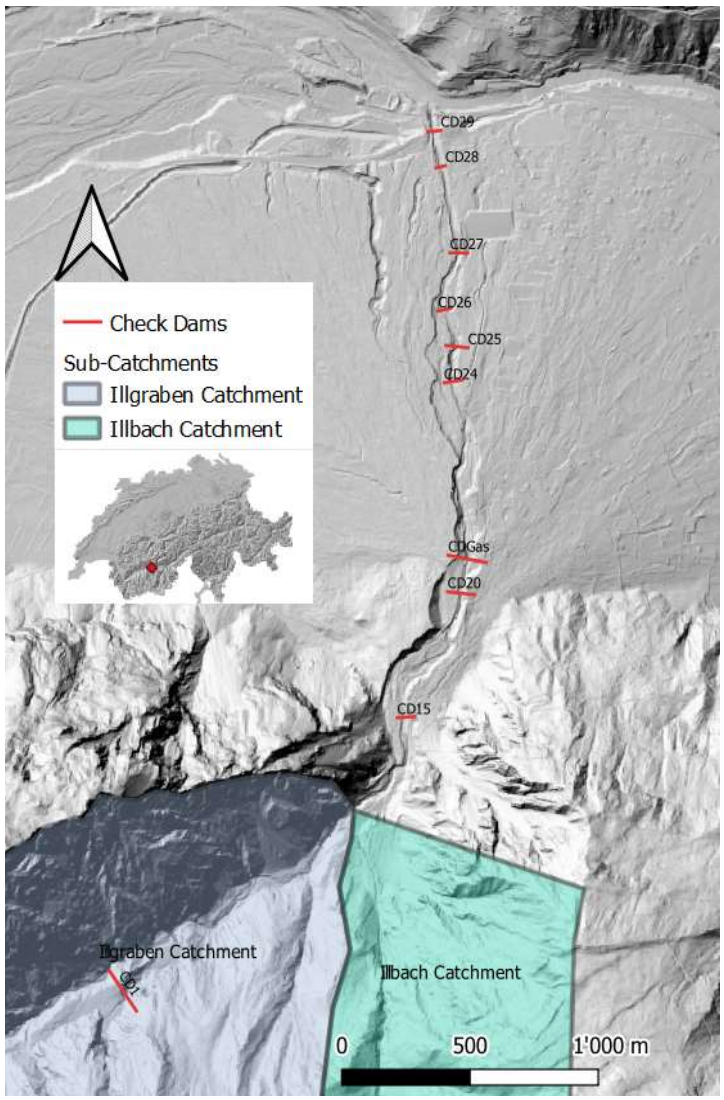

Figure 1: Situational Map of study area at the Illgraben.

Hirschberg et al. (Hirschberg et al., 2019) report that there is generally no base flow at the lower part of the Illbach, sometimes not even after rainstorms. This assessment may be true for natural flow, however there is discharge of excess drinking water by the community close to the check dam for the gas pipeline (CDGas in Figure 1). This discharge leads to an increase in flow at various times. The amount and timing of this spillage varies widely across different years, but in the debris flow season the effect in the channel is probably small (Könz, 2023).

2.2. Erosion Debris Flows

As stated in the introduction, the main reason for the investigation of infiltration from debris into the bed of their channels is the effect it has on the erosion and entrainment by these debris flows. Erosion and entrainment are important factors in determining the size of debris flows. The size of a debris flow can even be multiplied by entrainment and thus the entrainment mechanism and how efficiently it works is very important in trying to determine the potential volume of debris flows (Hungr et al., 2005).

De Haas et al. (2022) state that, along with the flow conditions the soil water content in the bed controls the erosion by debris flows. In their observations they observed among other factors, the 3-hour antecedent rainfall and the erosion depth of n=13 debris flows at the Illgraben site. The erosion depths generally correlated positively with the 3-hour antecedent rainfall. This effect however did not correlate with rainfall duration. Similar experiments by Iverson et al. (2011), although they did not fully saturate the bed sediments, have shown that the bed water content is positively correlated with the depth of erosion. Berger et al. (2011) in their study measuring erosion at Illgraben have also reported that an increase in pore water pressure might lead to liquefaction of the channel bed. This would possibly occur faster in saturated channel beds thus allowing for more erosion.

A study by Schürch et al. (2011) at the top of the fan at the Illgraben between CD 16 and CD 19 found that with increasing flow depth there is also a tendency of increased erosion depth. They have studied the change in surface elevation before and after 14 debris flows between 2007 and 2009. The change of elevation was measured in cells with a resolution of 0.2 m and they were compared against the flow depth at that position during the flow. From this they discovered that there is a trend in the median that with an increase in flow depth the erosion does not increase linearly. As can be seen in Figure 2, a flow depth above around 2 m the erosion depth increases by a larger rate than below. The amount of erosion doubles between 2 and 3 m at any probability level. They do not have a definite explanation for this phenomenon.

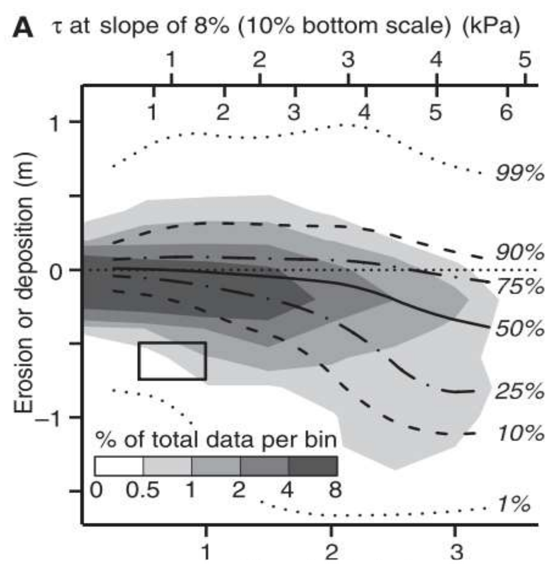

Figure 2: Plot of cell-by-cell comparison of elevation change against maximum flow depth. Gray contours show density of raw data based on bin size of 0.5 m in flow depth. Percentile lines show frequency distribution of elevation change at given flow depth (Schürch et al., 2011).

Modelling of debris flow runout behaviour has also been interested in entrainment. While entrainment has typically been ignored in earlier models that focused on flow properties and runout patterns (Könz, 2023), newer models have improved the accuracy of the modelling by including the modelling of entrainment (Frank et al., 2015). These models do not yet include the saturation of bed material, but they have laid the groundwork to make this possible. Könz

(2023), for example, has constructed an extension to the RAMMS debris flow model that enables the inclusion of bed saturation into the entrainment modelling.

2.3. Stream GW Interaction

As stated in the introduction, this thesis is attempting to establish the hydrological situation at the Illgraben study site and how it is influenced by debris flows, in order to draw conclusions about the interaction between debris flows and water in the river beds in general. Often groundwater is a central part of the water present in the soil around streams. Because of this, it is a large possible factor that could influence the infiltration behaviour in the studied situation. For this reason, the current information in the literature on the interaction between groundwater and streams in general and the situation on alluvial fans with debris flows in particular is going to be laid out here.

The most general classification of streams in relation to their connection to groundwater is based on in which "direction" the water is flowing. *Gaining streams* are defined as streams that receive groundwater from the aquifer. This generally occurs when the surface of streams lies below the local water table. *Losing streams,* on the other hand lose water to the local groundwater. The mixed form, which both receives and loses ground water, is called a *flow-through stream* (Dingman, 2008). There is also the possibility of a stream being fully disconnected from the soil by an impermeable bed, which is called an *insulated stream* (Meinzer, 1923). The insulated stream should not be confused with a disconnected stream, which will be described later on. It is also important to state that this characterization can vary along the path of a stream (Bencala, 2011).

Further streams are classified by their temporal flow pattern. Streams that flow all year are called perennial, while streams that flow only during certain times are classed as either intermittent or ephemeral streams. Intermittent streams flow seasonally during the wet season and are mostly gaining streams that receive water from the raised water table during this season. The flow in ephemeral streams occurs in response to water-input events and are normally losing streams (Dingman, 2008).

Within losing streams, the nature of the connection to the groundwater is an essential characteristic. Brunner et al. (2009) divided these into the three different flow regimes of connected, transition and disconnected. As can be seen in Figure 3, the connected regime

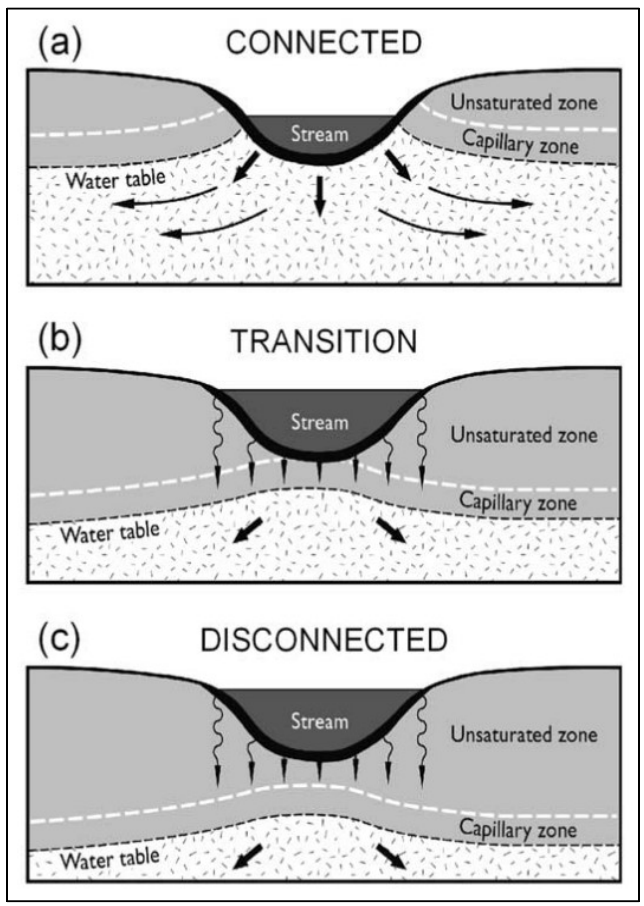

Figure 3: Figure on different flow regimes between stream and groundwater (Brunner et al., 2011).

means that the stream is directly connected to the groundwater, so the water table intersects with the stream. In the transition regime the water table lies below the stream, while the capillary zone intersects the stream. The disconnected regime has an unsaturated zone between the stream and the capillary zone. The thick black border between the stream and the bed represents what they call the clogging layer, which has a lower hydraulic conductivity than the rest of the soil, but is still permeable. This layer is necessary for this conceptualisation, as without it, a lowering water table would lead to an increased loss from the stream, eventually drying it out. Here again, it is important to differentiate between disconnection and insulation. Counterintuitively, the flux from the stream to the groundwater is actually larger in a disconnected than in a connected flow regime (Brunner et al., 2011).

The model of connection described above assumes a relatively small distance between the water table and the stream, which, under sufficiently large and long streamflow, would raise the groundwater mound to intersect with the stream. In situations where the groundwater table lies far beneath the stream, there is however another possibility. It is possible that, through the large depth, capillary effects and the relatively fast transmission of groundwater from where a mound would develop to other parts of the aquifer, a saturated zone develops beneath the stream. The boundary of such a saturated zone would then be called an inverted water table (Stephens, 1996). A low permeability streambed or a clogging layer might be necessary for the occurrence of an inverted water table, however it might be possible if a stream is very narrow and shallow and the groundwater table is very deep (Xie et al., 2014).

A further regime that could be relevant in this thesis for the interaction between stream and groundwater, is the perched water table. This again needs to be differentiated from the usage of the term, when referring to the stream as perched. The term perched there can also refer to either an isolated or a disconnected stream, as it is for example done by Meinzer (1923). Perched in this case refers to the water table just below the stream that is connected to the stream but is disconnected from any lower lying water table by an impermeable unit. Cases of such shallow perched water tables beneath streams have been reported in various conditions and due to various causes (Fleckenstein et al., 2006; Niswonger & Fogg, 2008; Palkovics et al., 1975).

The study area of this thesis is an alluvial fan and as such has some properties that differ from the plains the previously discussed flow regimes are based on. Flows, and especially smaller and ephemeral flows, on alluvial fans are relatively less studied and very complex. The stream-groundwater interactions and the flow regimes are controlled by the sedimentology of the alluvial fan to a high degree (Blackburn et al., 2021). While no general model for the stream-groundwater interaction on alluvial fans can be found in the literature, especially due to very varied depositional characteristics of different alluvial fans, there is some information on specific situations to be found. The example chosen here is a study by Blackburn et al. (2021) on an alluvial fan in Northern England. The fan is dominated by debris flow deposits and has a stream running through it. The stream is perennial at the top of the fan, but ephemeral in the rest of the fan. The study found that higher permeability at the top of the fan causes the water to infiltrate there and go deep into the fan becoming groundwater. At the lower reaches of the fan, where the permeability is much lower, the channel is usually empty and the aquifer is below the channel level. In the case of flow events, the channel fills and the water table is raised. With major or prolonged flow events, the water table is raised to the level of the channel and connection occurs. This shows that flows deep in alluvial fans are possible and reconnection of disconnected streams on such fans is possible depending on the specific situation.

2.4. Field Methods

ERT

Electrical Resistivity Tomography (ERT) is based on direct-current resistivity exploration, which uses two electrodes to inject electrical current into the ground and a different set of two electrodes to measure the difference in electrical potential that reaches them. ERT is the further development of this method, combining the results of several hundred measurements with different electrode spacings to attain a better picture of the subsurface situation. (B. Zhou, 2019)

The variety of factors that influence electrical conductivity of materials makes ERT a versatile technique that is used in many applications. To mention just a few of these it is used in the study of landslides (Perrone et al., 2014), including debris flows (Chang et al., 2012), soil water content (Q. Y. Zhou et al., 2001) and groundwater discharge (Nyquist et al., 2008).

In this thesis, the focus lies on the ability of ERT to allow for the assessment of soil water content and especially the detection of groundwater. This detection of groundwater has, for example, previously been used to locate groundwater resources in drought prone areas (Thiagarajan et al., 2018). It has however also been shown to be sensitive to differences in soil composition (Saad et al., 2012). For this thesis, this means that due to the possibility of heterogeneities in the alluvial materials of the study area the results need to be considered carefully.

Hydrogeological Survey Methods

In the assessment of the hydrogeological situation in a given study area, a large number of tests can be conducted. Here this thesis will focus solely on the methods that are possible within the limited scope of the work and instrumentation that were available. These namely are testing related to a limited array of wells, the measurement of soil moisture through buried sensors and the determination of hydraulic conductivity based on field infiltrometer test. The possibilities and advantages of other and expanded surveys will not be discussed here, but in later sections that focus on further investigation potential.

Boreholes are used widely in investigations of groundwater. As a way of accessing aquifers, they are not themselves the method used for investigation, but facilitate these methods. In a first step, the material that is drilled out can, if the method of drilling allows it, be used for mapping the geological structure of the soil or rock as well as its hydrogeological properties.
In investigations of groundwater, boreholes are probably most often used for piezometers to measure the hydraulic head in the aquifer. An example of this usage case in an alluvial fan, where piezometers were used to assess the flow regime of an ephemeral stream, can for example be found in Blackburn et al. (2021). Boreholes may also be used to measure the hydraulic conductivity of the aquifer. The two most common methods for this are the falling-head tests, where water is added to a certain head and the drop is observed, and the constant-head test, where the raised head is maintained and the required volume of water to maintain it is observed (Brodie et al., 2007).

There are many different methods to determine the hydraulic conductivity of a given soil. As such, there are both laboratory and in situ measurement techniques that are regularly carried out (Yu et al., 2013). In the case of this thesis laboratory measurements are not possible, as taking samples in the gravely soil would not be practical. Thus, the question on what methods to use is limited to the field methods. As it is generally more widely used and would also be useful in the simulations, determining the saturated hydraulic conductivity would generally also be preferable. As can be seen in a comparison of various methods to determine the saturated hydraulic conductivity by Gupta et al. (1993), these methods usually take a long time to conduct. Another approach is to use a so-called tension disk infiltrometers. These devices use perforated disc that are placed onto the ground and to which water with a specific pressure is applied. From the infiltration rate of the water, the unsaturated hydraulic conductivity can be calculated (Ramos et al., 2006). The main advantage of these infiltrometers is their simplicity and ease of use (Simunek & Van Genuchten, 1997).

3. Field Investigation

3.1. Materials and Methods

Mini Disk Infiltrometer

The hydraulic conductivity of the soil at the surface was assessed from measurements done with the Mini Disk Infiltrometer by Decagon Devices. The Mini Disk Infiltrometers construction can be seen in Figure 4. The device works by leaking water from the reservoir into the soil through the sintered stainless-steel disk at the bottom. This disk only allows leakage when it is placed on the soil and not if in contact with the air.

The device is used by first filling the two chambers with water and then adjusting the suction control tube to the desired suction rate. The suction control tube allows the suction rate to be adjusted, which is necessary to get reading intervals that are feasible for measurements. The suction rate can be varied between 0.5 and 6 cm, but generally a suction rate of 2 cm is recommended in the manual (Decagon Devices Inc., 2007a).

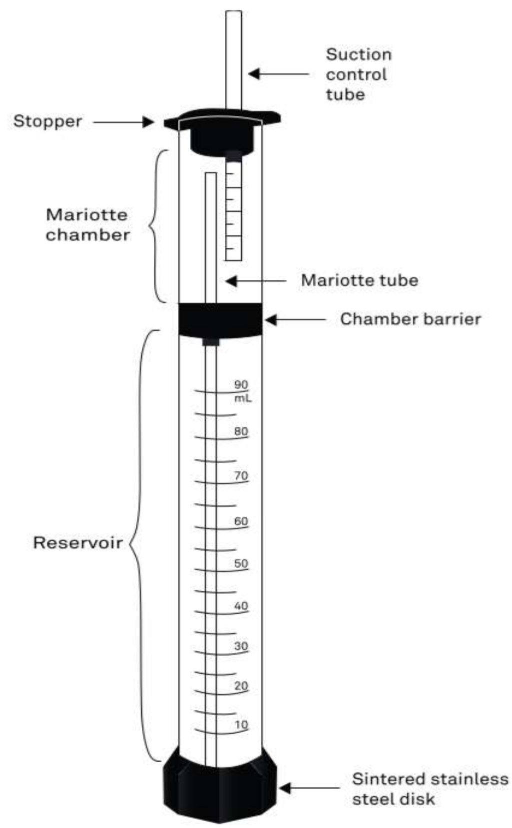

Figure 4: Diagram of the Mini Disk Infiltrometer by Decagon Devices. (Decagon Devices Inc., 2007a)

In the measurements that have been performed for this study, a suction rate of 0.5 cm with a reading interval of 60 seconds was found to be the ideal rate for the soil at hand. This was because higher suction rates and smaller intervals did not produce a drop in the water level that was sufficiently different between the readings.

After adjusting the suction to the desired rate, the device has to be placed on the soil. The measurement spot has to be smooth, so the surface of the soil should be smoothed out beforehand. This has posed a challenge in the measurements for this study, because the soil is quite heterogeneous and contains a lot of gravel, which could disrupt the smooth surface.

After a drawdown in the water level in the reservoir of at least 15-20 cm, the readings can be inserted into a spreadsheet provided by Decagon to ascertain the hydraulic conductivity. This process and the results can be found in the material properties section of this paper.

Soil Moisture Data

Approximately 25 m upstream of CD 28 on the western side of the channel, a column of soil sensors was installed in June 2022. This column includes four soil moisture sensors at different depths. Two EC- 5 soil moisture sensors were placed at 0.25 m and 0.45 m respectively. The other two sensors are Terros 12 sensors that, other than soil moisture, also report temperature and bulk electrical conductivity, were placed at 0.65 m and 0.85 m respectively. Due to channel bank erosion in the spring of 2024, some data might be unreliable. At the time of writing the sensors now are fully exposed and are no longer usable. The goal of these sensors in this thesis is to provide a framework for a realistic idea of the soil moisture profile into depth.

ERT

The survey campaign was conducted on May 3rd 2024 using a Syscal Pro Instrument by IRIS Instruments set to a dipole-dipole setting. In total, three transects close to CD28 were measured. As is shown in Figure 5, there were two transects parallel to the torrent, with one in the channel (TS 1) and one in the forest next to it (TS 2), and one across the channel (TS 3). TS 1 and TS 2 were each 97 m long with 2 m spacing between the probes. TS 3 was 47 m long with 1 m spacing between probes. Due to an abundance of gravel and rocks at the actual bottom of the channel, TS 1 had to be placed on the bank of the channel around 1 m above the bottom of the channel.

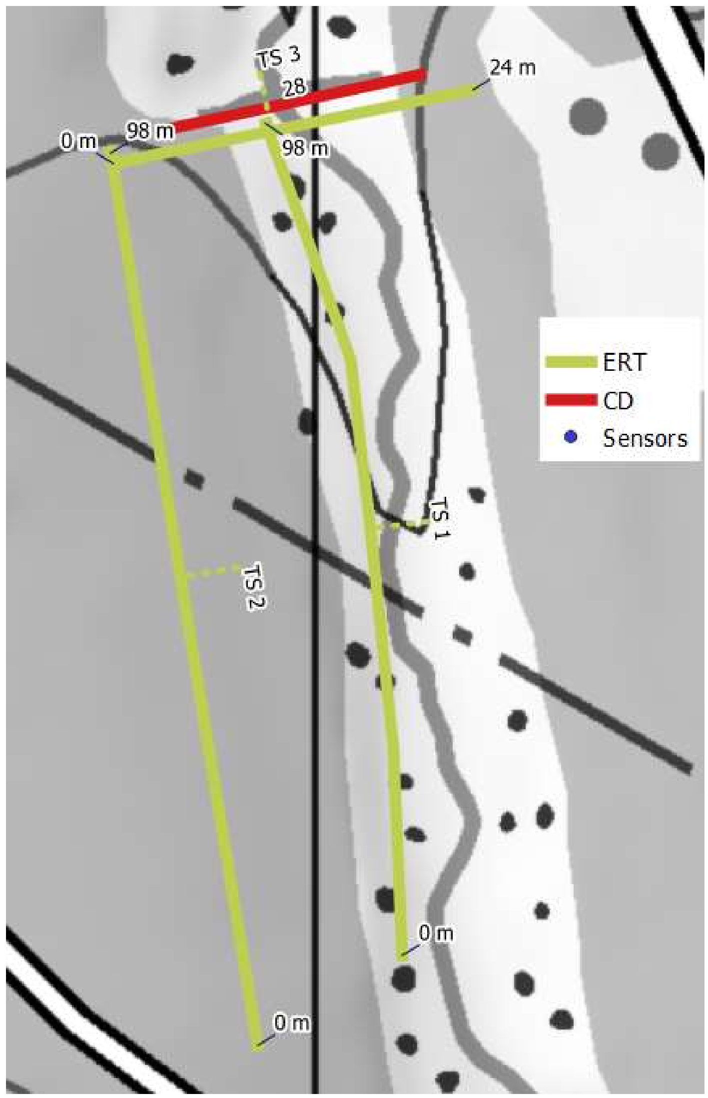

Figure 5: Map of the ERT transects close to CD 28.

For the estimation of water content values based on electrical resistivity information there are many different approaches. One important factor they have in common is that they are usually coupled with extensive combination with other hydrological methods (Brunet et al., 2010). This however is not possible in this case, because of the lack of data and time. Because of this, the resulting analysis needs to be carefully considered. This means that the resulting resistivity values are only indications of the water content of the soil and no explicit values can be taken from them. However, it can generally be said that lower resistivity is evidence of water being present (Daily et al., 1992). For the purpose of detecting saturated zones in this study, the threshold for the presence of water saturation, as expected for groundwater flow, was obtained through resistivity measurements of a sample of muddy water collected from the channel during the measurements.

Wells

In 2023 three wells were drilled at CD 28. These were drilled with the intention of monitoring potential groundwater presence and changes in groundwater level. As can be seen in the sketch in Figure 6, as well as in Table 1, the wells go down to approximately 5 m, 9.5 m and 4.5 m from the top of the casing. The sensors themselves sit at 4.9 m, 9.4 m and 4.4 m respectively. As is shown in Table 1, this leaves the sensors at 634.40, 629.99 and 635.32 meters above sea level, while the lowest point at this location in the channel lies at 635.9 meters above sea level. This means that all the sensors lie below the bottom of the channel at this point along the course of the channel. The sensors started measuring on the 8th of December 2023 and have a measurement interval of 1 min.

The purpose of these sensors in this thesis is, to provide additional information about the presence of groundwater in addition to the ERT and to potentially show the infiltration of water from debris flows, which might help to support the results of the simulations.

Table 1: Table showing depth of boreholes.

Well	Depth below casing [m]	Depth below ground level [m]	Sensor depth below ground level [m]	Ground level [m.a.s.l.]	Height of sensor [m.a.s.l.]
BH1	5.025	4.701	4.586	638.989	634.404
BH2	9.515	9.048	8.932	638.920	629.988
BH3	4.535	3.792	3.676	638.994	635.318

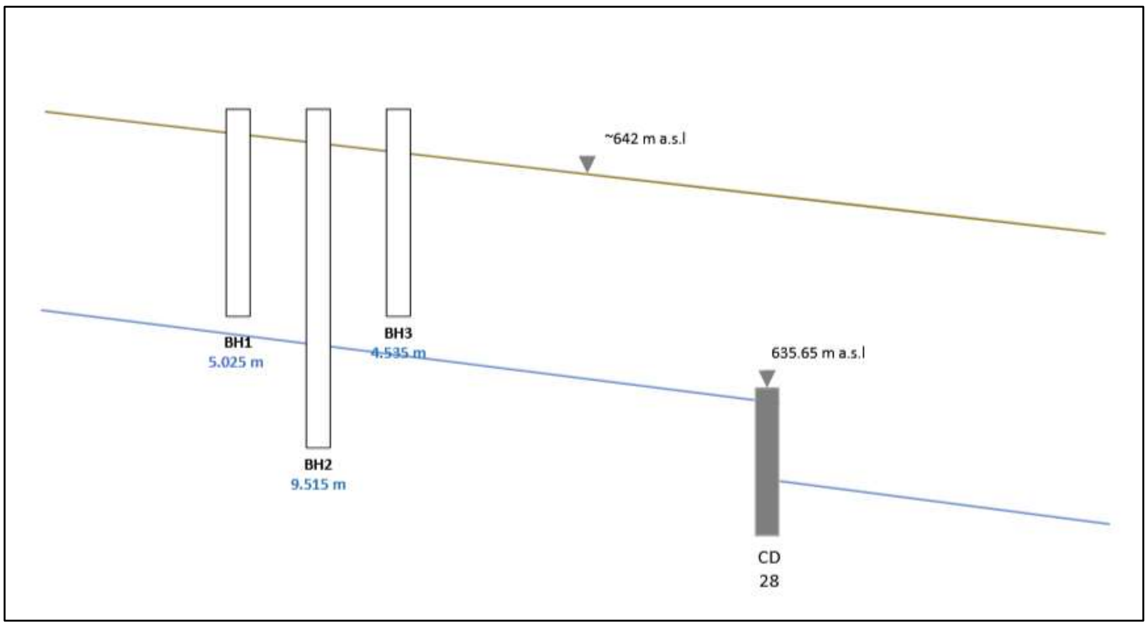

Figure 6: Side Profile showing depth of boreholes upstream of CD 28.

3.2. Results

Mini Disk Infiltrometer

The Mini Disk Infiltrometer that was previously described was used on the mud caps that can be seen in Figure 7. These are deposits of previous debris flows. The measurements were carried out at check dam 28. A total of 13 measurements were conducted at this location. The data obtained through these measurements were then analysed through spreadsheet provided by Decagon (Decagon Devices Inc., 2007b). This spreadsheet uses a numerical solution by Zhang (1997). This method is based on fitting a curve to the scatter plot created by plotting the cumulative infiltration against the square root of time that has passed. The slope of the fitted line divided by the so called van Genuchten parameters results in the hydraulic conductivity (Decagon Devices Inc., 2007a). The van Genuchten parameters stem from a paper by Carsel and Parrish (Carsel & Parrish, 1988). These parameters are governed by the disk radius, the soil texture class and the suction rate.

The results of the tests on the mud cap including the suction rate and calculated hydraulic conductivity are shown in Table 2. For the calculation with the spreadsheet the soil type "loamy sand" was selected. The results are fairly consistent with each other and are roughly in the 3.5×10^{-4} range.

Three of the tests need to be viewed with additional scrutiny, as issues occurred during those tests. Test number 1 only used 9.5 ml of water, which is too low for a conclusive test according to the user manual, which as previously stated calls for at least 15 ml of volume (Decagon Devices Inc., 2007a). Further test number 10 stopped early due to the device tipping over. This test meets the threshold, but still used very little water compared to the others. Lastly test number 13 provides a very high hydraulic conductivity value compared to the others, which after taking a closer look at the soil occurred due to the soil at location 13 consisting of a small sand lens at the top of the mud cap. This sandier soil is probably what made this result deviate from the others. Removing all three of these tests from the dataset however does not significantly influence the average, with 4×10^{-4} cm/s instead of 3.64×10^{-4} cm/s due to this I have decided to keep the resulting average of 3.5×10^{-4} cm/s for further calculations.

Figure 7: View of the channel above CD 28 on the day of the infiltrometer measurements. The mud caps can be seen on both sides of the channel. The measured mud cap is the one on the left of the image, so on the right in flow direction

Table 2: Settings and results of Mini Disk Infiltrometer testing on the mud cap at check dam 28 on 01.10.2023.

Nr.	Suction [cm]	Measurement Interval [s]	Volume used [ml]	K {cm/s]
1	2	10	9.5	3.64×10^{-4}
2	2	10	23.5	3.62×10^{-4}
3	2	30	29	2.73×10^{-4}
4	2	30	28	4.54×10^{-4}
5	1	30	30	5.17×10^{-4}
6	0.5	60	32	2.38×10^{-4}
7	0.5	60	32	3.29×10^{-4}
8	0.5	60	43	4.79×10^{-4}
9	0.5	60	36	4.58×10^{-4}
10	0.5	60	21	2.84×10^{-4}
11	0.5	60	36	3.63×10^{-4}
12	0.5	60	42	4.36×10^{-4}
13	0.5	60	66	9.51×10^{-4}
			Average	3.64×10^{-4}
			Standard Deviation	1.80×10^{-4}

Soil Moisture Data

In Figure 8, the response of the soil moisture sensors to multiple rainfall events in October 2023 is shown. What is immediately obvious is that with depth the soil moisture increases in dry conditions. It can also be seen that under heavier rainfall they all respond with an increase in soil moisture. Two problems are immediately apparent. On one hand, the sensor at 0.25 m starts off with a value below 0. This is due to an error in the sensor and has since been rectified. In the further data used for this thesis, this has been corrected. On the other hand, the rainfall seems to be around 3 hours before the response of the sensors. This is partially because the sensors seem to have different time settings and partially because the precipitation data is from a station that is a few kilometres away from the study site. The decrease of soil moisture is fairly similar between the sensor, but with an increase in depth, the recovery seems to get slower.

Table 3 displays the minimum and maximum measured water content values for the soil moisture sensors. What is most interesting about these is the fact that the range between maximum and minimum content is larger towards the top of the column.

Table 3: Soil Moisture sensors and their maximum and minimum values

Depth [m]	Sensor	Min. Water Content [m^3/m^3]	Max. Water Content [m^3/m^3]
0.25	EC-5	0.045	0.468
0.45	EC-5	0.053	0.425
0.65	Terros 12	0.108	0.361
0.85	Terros 12	0.112	0.345

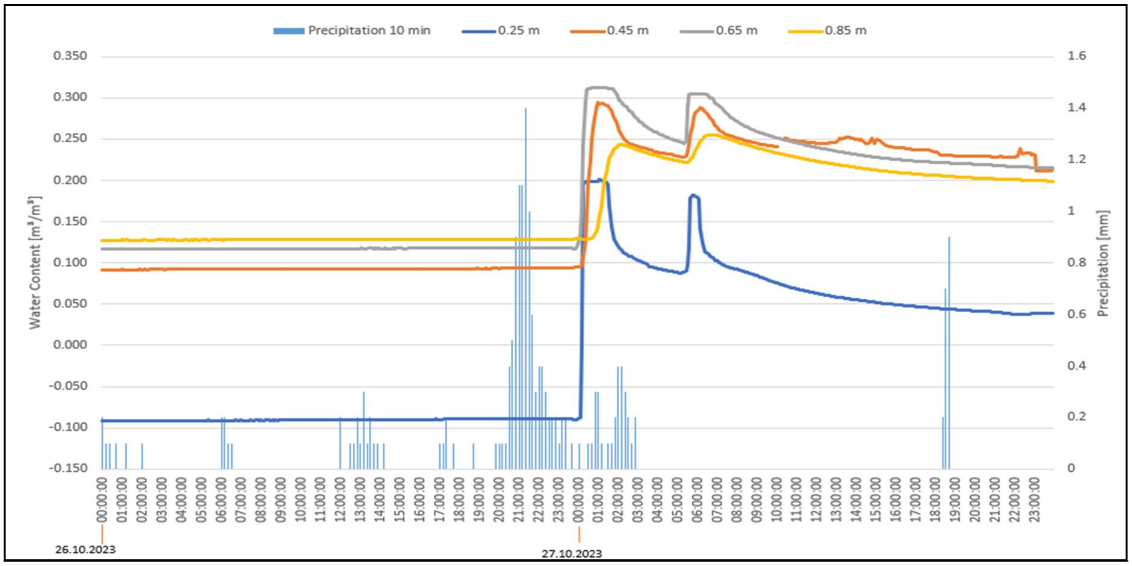

Figure 8: Soil moisture measurements and precipitation from 26.10.2023 and 27.10.2023.

Boreholes

The wells have been largely disappointing as far as results go. The main result that was visible is that there is generally no ground water present in any of the wells. Through all the measurements, the values in all three wells consistently stayed mostly below 1 cm of water.

The big and only exception to this is the period between the 12th of December 2023 and the 13th of February 2024. In this period, of which the most significant part is shown in Figure 9, there was groundwater detected in all three wells. The beginning of this period was accompanied by major precipitation. From the 8th to the 13th of December there was a total of 101 mm of precipitation at the study site. The maximum intensity of this rainfall was of the 11th and the 12th, where there were 29.7 mm and 26.9 mm of precipitation, respectively.

As shown in Figure 9, the first well to respond is number 3 with 1 being the second and 2 following later on. Well 2, the deepest well, shows only a very small value of 3.1 cm at maximum and a very quick recovery in only around 16 hours and a bounce into negative values after that. Well 2 on the other hand shows a massive and rapid increase in groundwater level up to a high point of 108.4 cm. It then recovers quite fast at first, but has several bumps back up due to smaller precipitation events. The recovery slows down and the groundwater finally recovers to 0 after approximately 1 month.

Finally, well 3 has the first increase, however 'only' reaching 28 cm. The recovery here is much slower and the bumps, that are similar to the ones in well 1, are much shallower. The final recovery occurs after 3 months, on the 13th of February 2023.

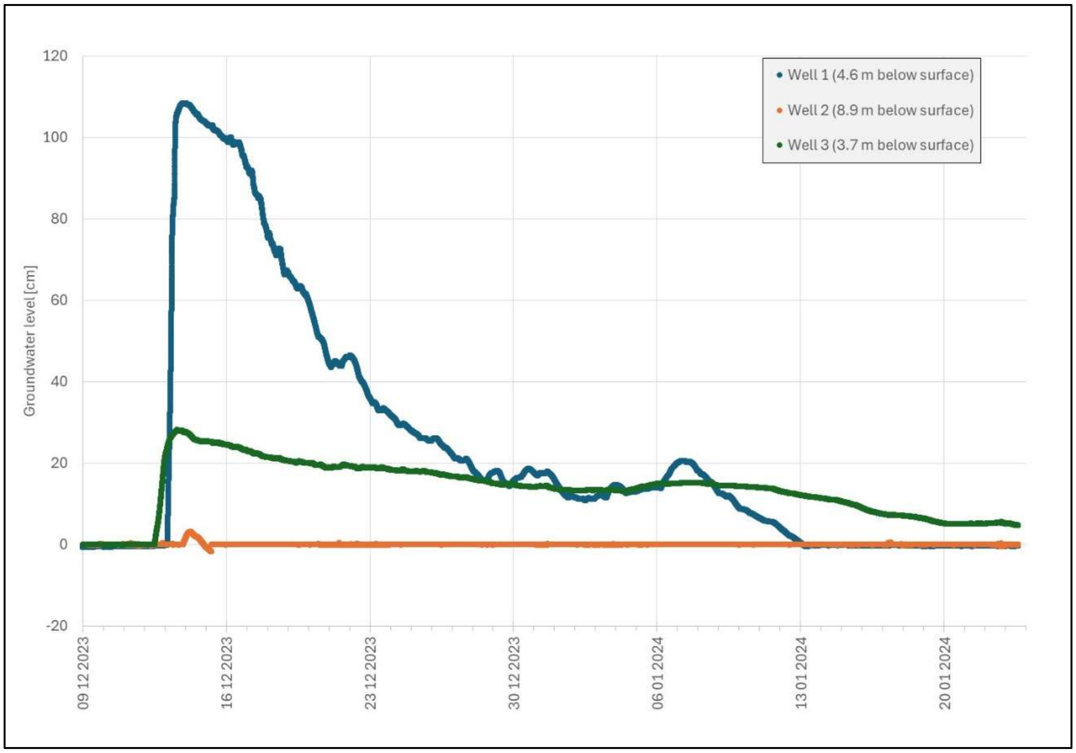

Figure 9: Measured groundwater levels in boreholes between 09.12.2023 and 27.01.2024

ERT

In order to assess the possible presence of ground water, we need to calculate the threshold for the electrical resistivity (ρ_{thold}) that differentiates between saturated and unsaturated porous media. Expressed as electrical conductivity this results in $\sigma_{thold} = 1/\rho_{thold}$.

Through Archie's law (Archie, 1941) we can define σ_{thold} as a product of the electrical conductivity of water (σ_{water}), the porosity ϕ, the cementation exponent μ, the water saturation S and the saturation exponent ω, in the following way:

$$\sigma_{thold} = \sigma_{water} \cdot \phi^{\mu} \cdot Sat^{\omega}$$

For the threshold the saturation is 1 simplifying the equation to:

$$\sigma_{thold} = \sigma_{water} \cdot \phi^{\mu}$$

The conductivity of the water was measured with a value of 238 µS/cm. This equals 0.0238 S/m.

The porosity can be derived from the wet bulk density ρ_{bulk}, which at Illgraben for debris flows has been measured to be approximately 2200 kg/m^3 (McArdell, 2016). Through the following equation, this wet bulk density can be used to approximate the porosity:

$$\rho_{bulk} = (1 - \phi)\rho_{quartz} + \phi \cdot \rho_{water} \rightarrow \phi = \frac{\rho_{quartz} - \rho_{bulk}}{\rho_{quartz} - \rho_{water}}$$

Applying a water density of 1000 kg/m^3 and a rock density of 2650 kg/m^3 this results in a porosity ϕ of 0.27.
With a high cementation factor of 1.8 this would result in:

$$\rho_{thold} = \frac{1}{\sigma_{thold}} = \frac{1}{0.0238 \cdot 0.273^{1.8}} = 434\ Ohm\ m$$

With a cementation factor of 1.5 this would result in a threshold of approximately 300 $Ohm\ m$. This leads to the conclusion that a threshold of 400 Ohm m is sensible for these measurements and will be used in the following analysis.

The data from the ERT measurements has been processed and is shown in the Figures 10, 11 and 12 with the full range and a filtered version with the threshold applied.

TS1 (Figure 10) is the transect from the channel. It shows saturated zones at the top of the profile down to approximately 4 m. Although they are not very consistent, this seems to be evidence of a saturated layer below the bottom of the channel. There are some very high resistivity spots towards the lower end of the transect. There might be some structures here that are remnants of the construction of CD 28, but this can not be confirmed, as the documentation of this construction is no longer available. Generally, it is clear that there is no groundwater table towards the bottom of the profile.

TS 2 (Figure 11) is the transect in the forest. Its distinctive characteristic is the dry layer of soil on top that covers approximately the top 2 meters of the profile. Between around 4 and 16 meters of depth, it shows a layer that has lower resistivity. This layer includes areas that are below the threshold between 300 and 400 Ohm m. This could suggest the presence of ground water in this area. This would however be perched pockets of groundwater, as they are not connected and the resistivity increases towards the bottom of the profile.

TS 3 (Figure 12) also shows saturated layers down to around 4 m below the channel. There is no direct connection visible, however this might be due to problems to the rather large spacing between probes. The warping in the saturated layer suggests the presence of a saturated bulb around the channel that follows the low resistivity zone deeper down. In this cross section of the channel, there is also no evidence of a groundwater table down to around 10 m. However, the low conductivity is probably not natural here. This again goes into the question of the construction. The foot of the CD is currently exposed on the downstream side. The depth of that is around the same as where the low conductivity zone starts, so this could be an artefact of that. Further interesting is the low resistivity zone to the west of TS 3. One possible explanation could be metal being present there from construction. It could also be water flowing around the toe of the CD.

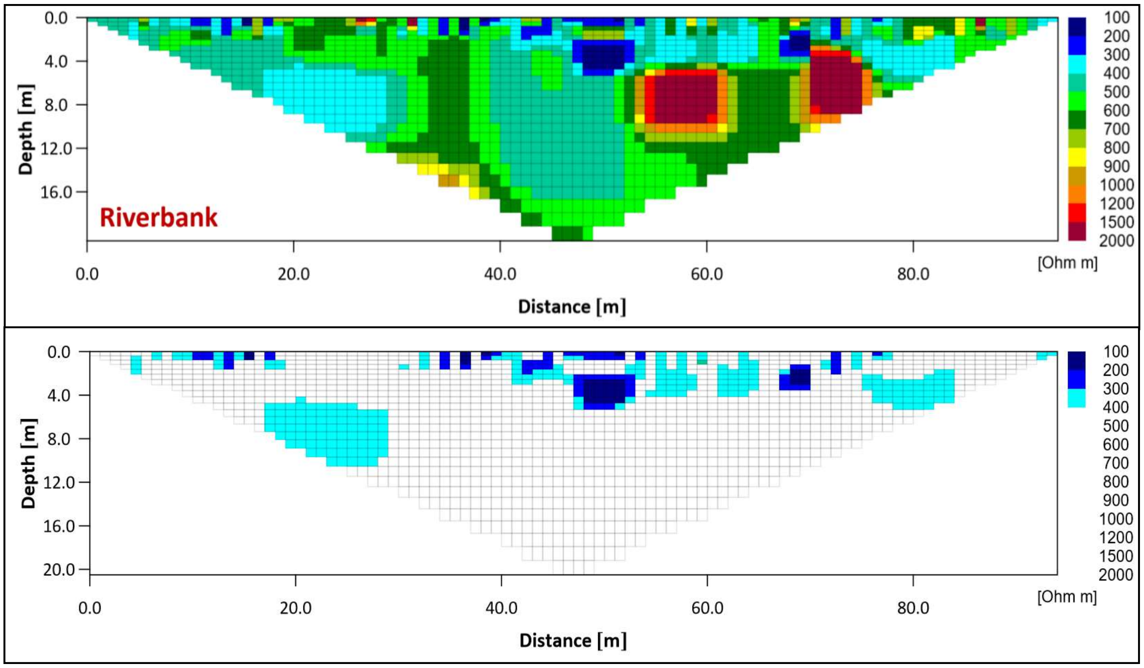

Figure 10: Processed electrical resistivity in transect TS1 in the channel. Top: Without any threshold applied. Bottom: With threshold of 400 Ohm m.

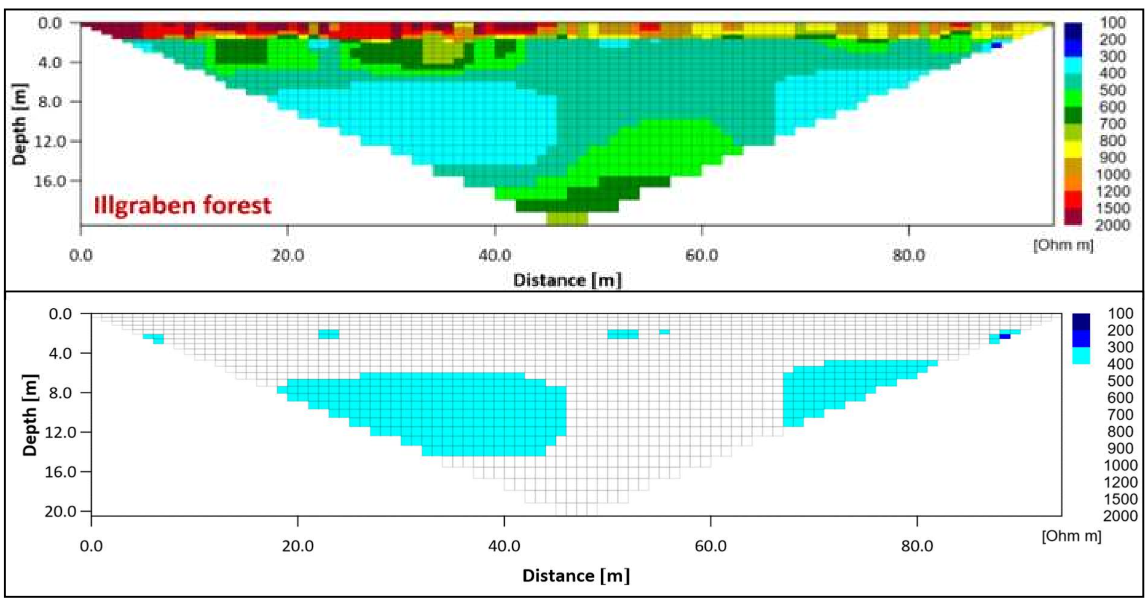

Figure 11: Processed electrical resistivity in transect TS2 in the forest next to the channel. Top: Without any threshold applied. Bottom: With threshold of 400 Ohm m.

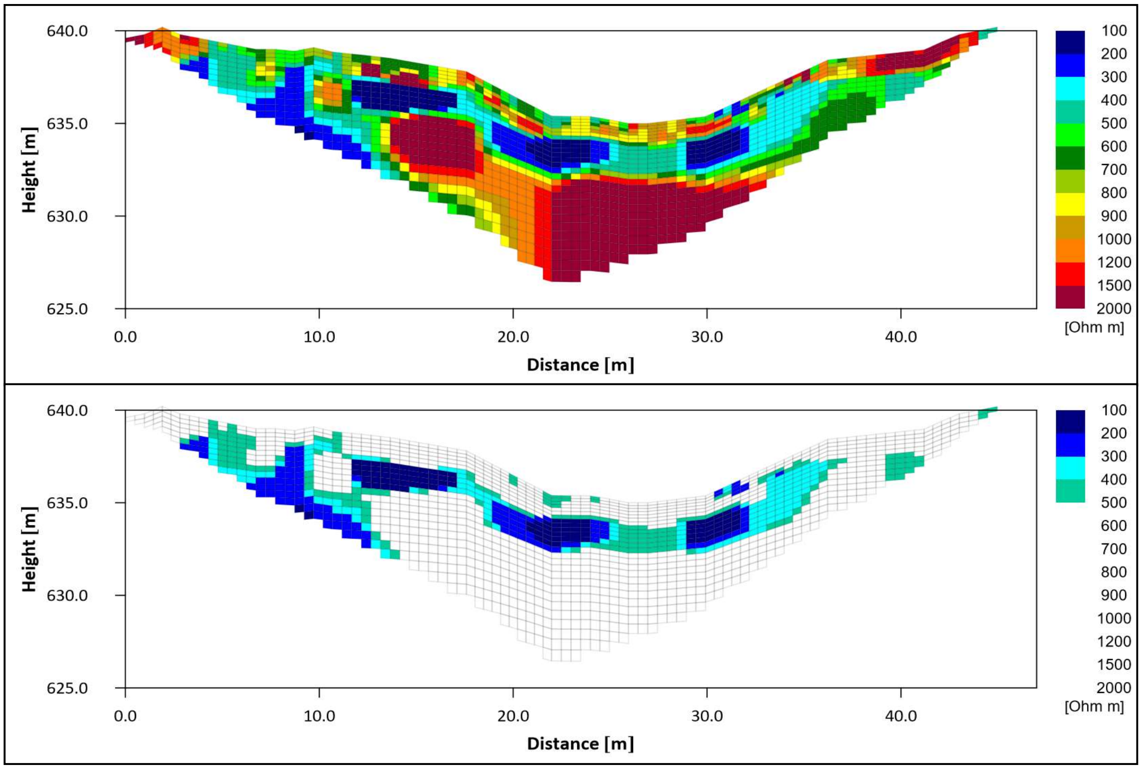

Figure 12: Processed electrical resistivity in transect TS3 a cross-section of the channel at CD 28. Top: Without any threshold applied. Bottom: With threshold of 500 Ohm m.

3.3. Discussion

Soil Properties (Infiltrometer and soil moisture Data

The infiltrometer measurements have yielded an average hydraulic conductivity of $3.64 * 10^{-4}$ cm/s. This is consistent with previous measurements by Meijer (2019) that were conducted in the upper catchment, where the material in the debris flows comes from. This also confirms the assumption by Könz (2023) that the deposits in the channel are comparable in their hydraulic conductivity to the material in the upper catchment.

Another important observation from the infiltrometer testing is the heterogeneity. Even in this small sample of relatively fresh debris flow deposits that has not been affected by further water flow through the sediment, we can observe a fair amount of heterogeneity. The sand lens that was described in the results for example shows about double the hydraulic conductivity of the average of the deposits. In addition to that, the other deposits, that in the field did not show any major differences, also show some variation that can probably be attributed to the heterogeneity in the material of the deposits.

The soil moisture data has shown that the soil moisture is responding to rainfall. How quickly this happens can unfortunately not be analysed due to issues in the time settings of the sensors. Another thing that could be observed was that the soil moisture increased with depth. This would make sense due to the effect of evaporation decreasing in depth. The same is true for the recovery speed, as it would be plausible for the soil towards the top having its water evaporate quicker. It is difficult to obtain any definitive data on what the soil moisture would typically look like just before a debris flow. Because of this, the soil moisture profile that will be used in the simulation is based on a somewhat typical progression in the depth profile that lies within the boundaries set by the soil moistures data, but not in any extreme part of the spectrum.

Hydrological Properties (ERT and Wells)

As stated in the results, the boreholes remained largely dry and there was no groundwater rise detected in response to debris flows. This suggests that that the infiltration caused by debris flows did not reach far into the bank and also would not increase the depth and width of a potential perched ground water layer below the channel.

The appearance of groundwater in the wells only after multiple days of very intense precipitation shows, on one hand the importance of rainfall in water saturation of the soils and, on the other hand, allows some insight on the material properties at the depth of the wells. Originally the goal was to conduct falling-head tests in the borehole, but this was not possible due to a lack of groundwater during the time where the tests were to be conducted. This would have made the interpretation very difficult and the unsaturated hydraulic conductivity it would have resulted in would not be as useful as was hoped. The drop in the groundwater level in the boreholes however gives some indication of a similar nature as those tests would have. Though the analysis of falling head tests is already widely discussed (Chiasson, 2005) and this is not a properly conducted test, but more a passing observation, we can however draw some conclusions. While well 2 does not have enough of a groundwater response to make any assumptions, we can compare wells 1 and 3. Even though these two are at a very similar depth and the wells are not far apart, there is a significant difference in their behaviour. The fast increase in level in well 1 and the also faster drop, compared to well 3 suggests that the hydraulic conductivity in the soil around well 1 is larger than in the soil surrounding well 3. This would imply that there are significant heterogeneities in hydraulic conductivity even in relatively small areas. We must however consider that the information here is very incomplete. During drilling, there were no records made on the soil types that were excavated and there is no exact data on the length and depth range of the screen in the casing. There might also be some issues during drilling that are not known and could have contaminated the area around the screen with fine sediment, resulting in a lower hydraulic conductivity. All of this means that, although the measurements in the boreholes provide some limited information on the groundwater situation and the soil properties, they do not provide a complete picture and with a different survey design there maybe would have been some further observations may have been made.

On the topic of the hydrogeological situation at the study site, the ERT measurements have provided some insights. It was possible to show the absence of an underlying groundwater table down to at least 20 m. There is however evidence of a variably saturated perched water table. Combining this observation with the lack of any significant groundwater being observed in the lowest well suggests this is the case not just at the time of the ERT measurements, but likely to be persistent in time. Such a disconnection between a stream and the groundwater is often caused by a clogging layer (Brunner et al., 2009). This appears to be plausible, due to the large amount of fine material in the debris flows, as well as the existing sediments. Bolliger et al. (2024) reported abundant silt and clay in every debris-flow deposit sampled (*n*=14) in lateral levee deposits, confirming that a sufficient source of fine sediment is present which could lead to clogging within the sediment bed. The potential perched water table could also be interpreted as an inverted water table, as described by Stephens (1996). It is also important to acknowledge that TS1 is not in the centre of the channel, but depending on the position variably up to 5 m away from the current location of the creek. While the exact location of the creek in the channel can vary, this would probably lead to differences in the saturation pattern. As the distance from the creek was not recorded along the transect, it is not possible to make an accurate assumption on how big this effect actually is. A more holistic interpretation including a suggestion for a conceptual model will be discussed in the synthesis chapter.

For the simulation, the most relevant findings from the ERT are that we could expect a constant saturated zone down to a depth of around 4 m during times, when only the relatively low streamflow conditions are present (e.g. only a small portion of the channel bed is occupied by flowing water). It also means that for the initial hydraulic conditions there is no need to add a water table, as long as there is no penetration of the saturated layer further down than 20 m.

It is however also apparent from the ERT that heterogeneities in the soil do have a great effect on the distribution of water in the soil. While it is not possible to accurately depict these heterogeneities in the simulation, it is important to keep this in mind for the analysis of the simulation results.

Combining the results from the piezometers and the ERT measurements, we can make some further observations. As shown in the results, TS3 appears to have a much more coherently saturated layer that is also wider than the actual channel. This seems to not be the case just 10 m upstream, where the wells are located. If there was groundwater to the extent indicated by the ERT here, we would expect to see it in well 1, which would lie in this zone. Two possible reasons for this could be that the zone actually does not extend below the banks of the channel or that, as is indicated by the discontinuous nature of TS1, these zones are highly localized. Another possible factor is the check dam. It could provide a preferential flow path along the upstream wall, which is then held back by the potential foot seen in TS3. This can not be confirmed, but check dams are used to increase infiltration in some cases and while this effect is not as great when the upstream side is filled with sediment, there is still a residual effect present (Lucas-Borja et al., 2021).

4. Modelling

4.1. Material and Methods

Software Overview

The software chosen for the simulations performed here is VS2DI version 1.3 by the USGS. This software package includes software that simulates the flow and transport in variably saturated porous media (Hsieh et al., 2000). Specifically, the components used are the VS2DTI, which is for the simulation of fluid flow and solute transport and VS2POST, the postprocessor for the software package. The solute transport component of VS2DTI was ignored for the simulations here, as only the flow is relevant.

The VS2D software solves the Richard's equation. This equation is used to model variably-saturated fluid flow in porous media such as soil, for a given set of initial and boundary conditions. To set these conditions, the software offers different options. The initial condition for the flow equation can be defined by an equilibrium profile, pressure head or moisture content. Here, the moisture content was chosen due to the availability of soil moisture data for the site. Furthermore, the calculation method for the relative hydraulic conductivity must be chosen. The arithmetic mean is the recommended method and was thus used here (Hsieh et al., 2000). Finally, for the "hydraulic characteristic functions" option the default of the van Genuchten Model was chosen. Other than the input of the initial soil moisture mentioned above, many other inputs need to be made for the simulation. These inputs and the determination of their values will further be discussed in the following sections.

Processing Pathway

In Figure 13, the processing pathway is drawn up as a flow chart. It shows the inputs into the model and the recharge periods that were simulated. The inputs consist of the previously mentioned initial soil moisture represented as the Base Moisture in the diagram. Together with the geometry of the cross section and the soil texture class, it makes up what is called the Base Model here. This Base Model represents the state of the channel without any flow.
This model is then sequentially confronted with three so called recharge periods that represent the hydrological conditions leading up to the debris flow. After this, there are two different recharge periods for different debris flow scenarios. Additionally, there is a separate path where the low flow recharge periods for one and two years are compared. This was done to find out if one year of low flow is enough to reach an approximate steady state. The details of these inputs and recharge periods are discussed below. There have also been many divergent or testing simulations made. A selection of the ones that are important for the understanding of the results will be shown in the discussion.

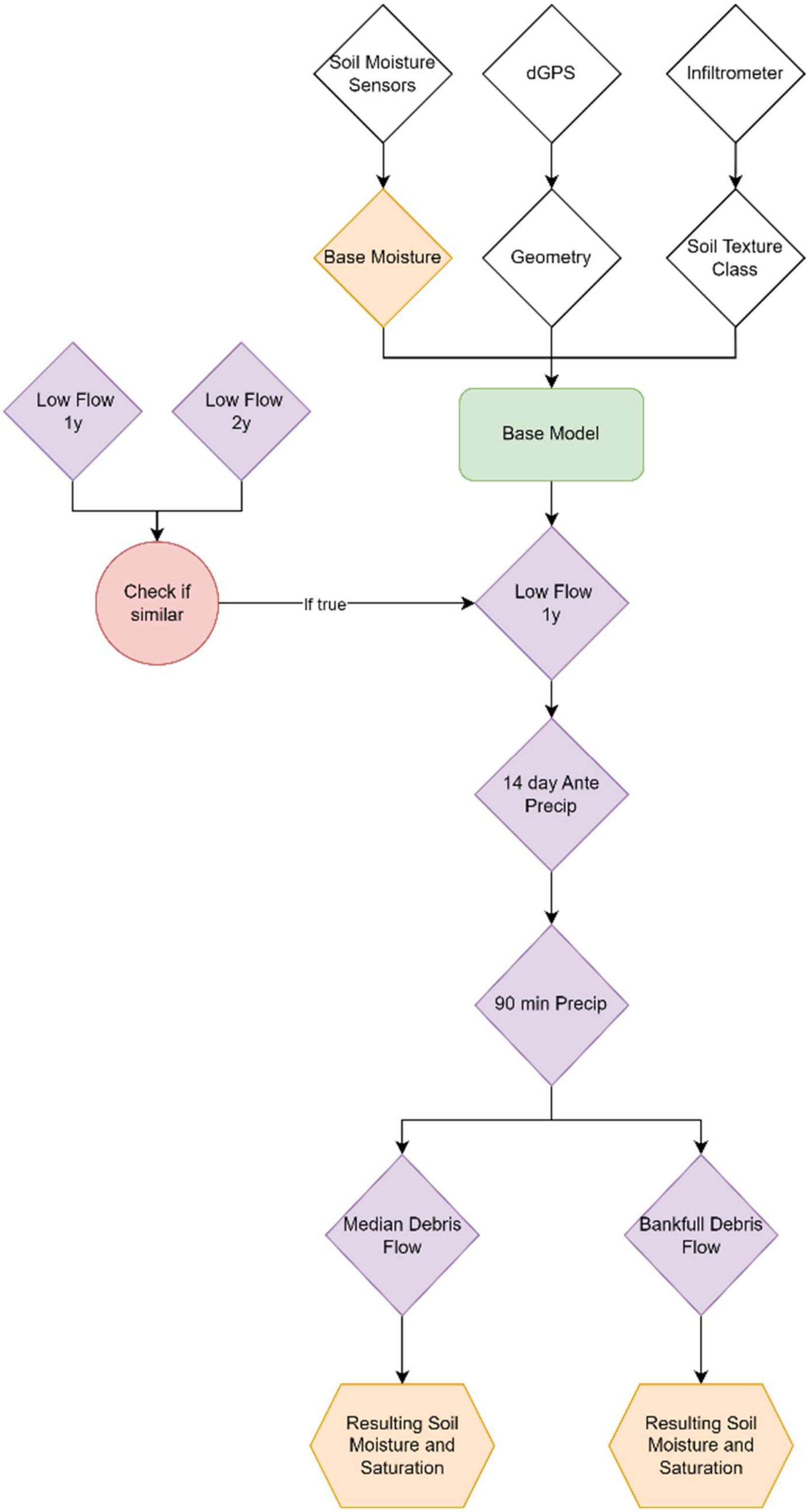

Figure 13: Diagram showing the processing pathway of the VS2DI simulations in this thesis.

Inputs

As shown in the processing pathway diagram, the geometry stems from a survey performed with dGPS on CD 28. While the CD does not show an accurate picture of the small-scale geometry of the channel, it does provide a stable geometry that represents an approximate average of the geometry of the channel along its path. This basic geometry is shown in Figure 14.

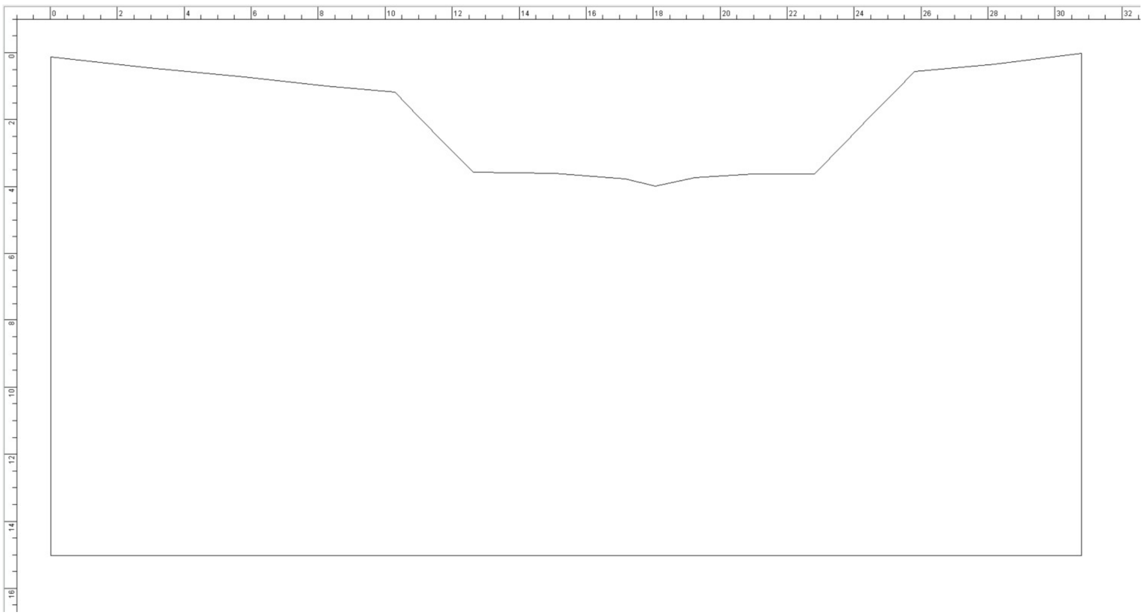

Figure 14: Geometry of the processing domain used for all calculations in VS2DI

The initial hydraulic condition for the simulations in this study was chosen as the initial moisture content. This initial moisture content was derived from the soil moisture sensors close to CD 28. As the goal is to create the moisture conditions prior to the debris flow from scratch, the lowest observed moisture content was used. This resulted in the picture seen in Figure 15 with 0.06 at the very top down to 0.085 at around 40 cm and 0.12 at approximately 80 cm. An additional line with a value of 0.1 was added at the bottom, to represent the drying observed towards the bottom of the ERT profiles. The variation that can be seen in the thickness of the layer and the distance between the moisture lines is caused by the fact that the lines have to be drawn by hand. Due to the small size of the variations, this is not expected to cause any issues in the simulation.

The choice of the soil texture was fairly difficult. Due to the complexity of input parameters in VS2DI, it was decided to use one of the preset soils in the software. In a previous study, Könz (2023) states that the soil present in the debris flow sediments is a sandy loam. Using the preset sandy loam would however not be possible, as the residual moisture content of that is above the observed values. Considering this, together with the presence of sandier spots (see infiltrometer testing), it seems reasonable to use the loamy sand texture class. This class is derived from a study by Carsel and Parrish (1988).

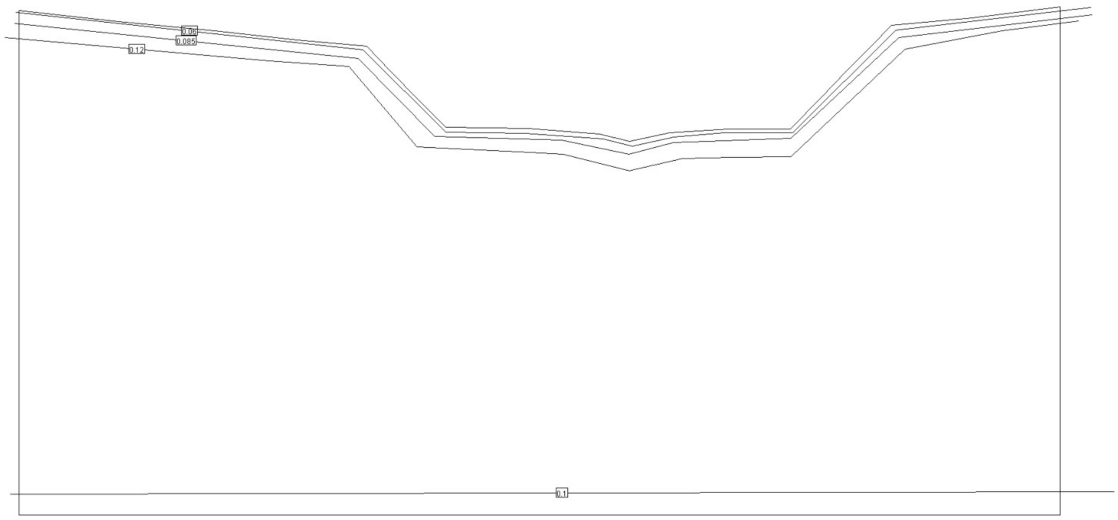

Figure 15: Initial moisture content setting of the processing domain.

VS2DI allows the simulation of water being present at a boundary of the model domain by setting boundary conditions (Hsieh et al., 2000). The types of boundary conditions relevant here are the *specified total head* for the flow of water and debris flows in the channel and the *specified flux into domain – vertical* for the precipitation as well as the *possible seepage face* for the boundaries at the sides and bottom of the domain.

To establish the baseline soil moisture for the channel, two different influxes of moisture were considered here. A baseline flow in the centre of the channel and the precipitation. The baseline flow in the channel was set to 10 cm of water in the centre of the channel, so 0.1 m of head on those sections as seen in Figure 16. This comes from the empirical observation of there being a constant small amount of flow in the channel for most of the year. There is no exact measurement of this available, but 10 cm seems like a reasonable assumption. As shown in the processing pathway diagram, a check was performed to assess if one year is enough to establish a reasonable approximate steady state. The result of this test can be viewed in the results section.

The precipitation component was derived from the average annual precipitation minus the average annual evaporation at the site. According to the Hydrological Atlas of Switzerland (2015), the average annual precipitation in the area of CD 28 is 925 mm and the average annual evaporation is 550 mm. This results in a net average annual precipitation of 375 mm. Transforming this for the required input as flux requires the use of meters and seconds due to the settings of the software. This results in a flux of approximately 1.2 x 10^{-8} m/s.

With the baseline established, the simulation essentially begins. This starts with a 14-day period before the event. This 14-day antecedent wetness is suggested as a characterization metric for debris flows by Hirschberg et al. (Hirschberg et al., 2019) and thus has been included here. From this paper, which concerns itself with the same study site an average of around 42 mm 14- day antecedent wetness can be extracted from the 52 events considered, which translates to approximately 3.5 x 10^{-8} m/s. Finally, debris flows are very commonly triggered by intense rainfall. From the study mentioned above, they had a median triggering rainfall of 9.6 mm (Hirschberg et al., 2019). As a timeframe is needed to conclude a flux for the simulation, the data at CD 28 was checked for events of around that size to find an example for the duration of such an event. The event that will be used here is from the 28th of April 2023, where a debris-flow occurred at 23:00. The corresponding triggering event started at 21:37 and had a total precipitation of 10 mm. Using this, the resulting flux is 2.06 x 10^{-6} m/s. For the simulation a slightly longer period of 90 minutes was used here. The same flux was also maintained through the debris flow.

For the two “preparatory” recharge periods, the same flow in the central channel was maintained as in the initial recharge period due to a lack of data on the time it takes for the water level to rise and to what degree it actually rises during that time.

For the actual debris flow events, two different flow depths were considered. The most extreme scenario presented here is the bankfull scenario. In this case, the lower bank lies approximately 2.4 meters above the bottom of the channel, resulting in that being the flow depth used for the bankfull event.
The median scenario is supposed to represent a typical debris flow at the site. McArdell (2016) describes multiple typical debris flows at the Illgraben site. All of these reach and/or sustain flow depths around 1 meter. Therefor this is the flow depth used in the median scenario. In Figure 16, the implementation of these two scenarios is visible in numbers 4 and 5 respectively with the side wall for the bankfull scenario being dissected into three parts. The head here has been multiplied by two, due to the bulk density of debris flows being around double that of water (McArdell, 2016).

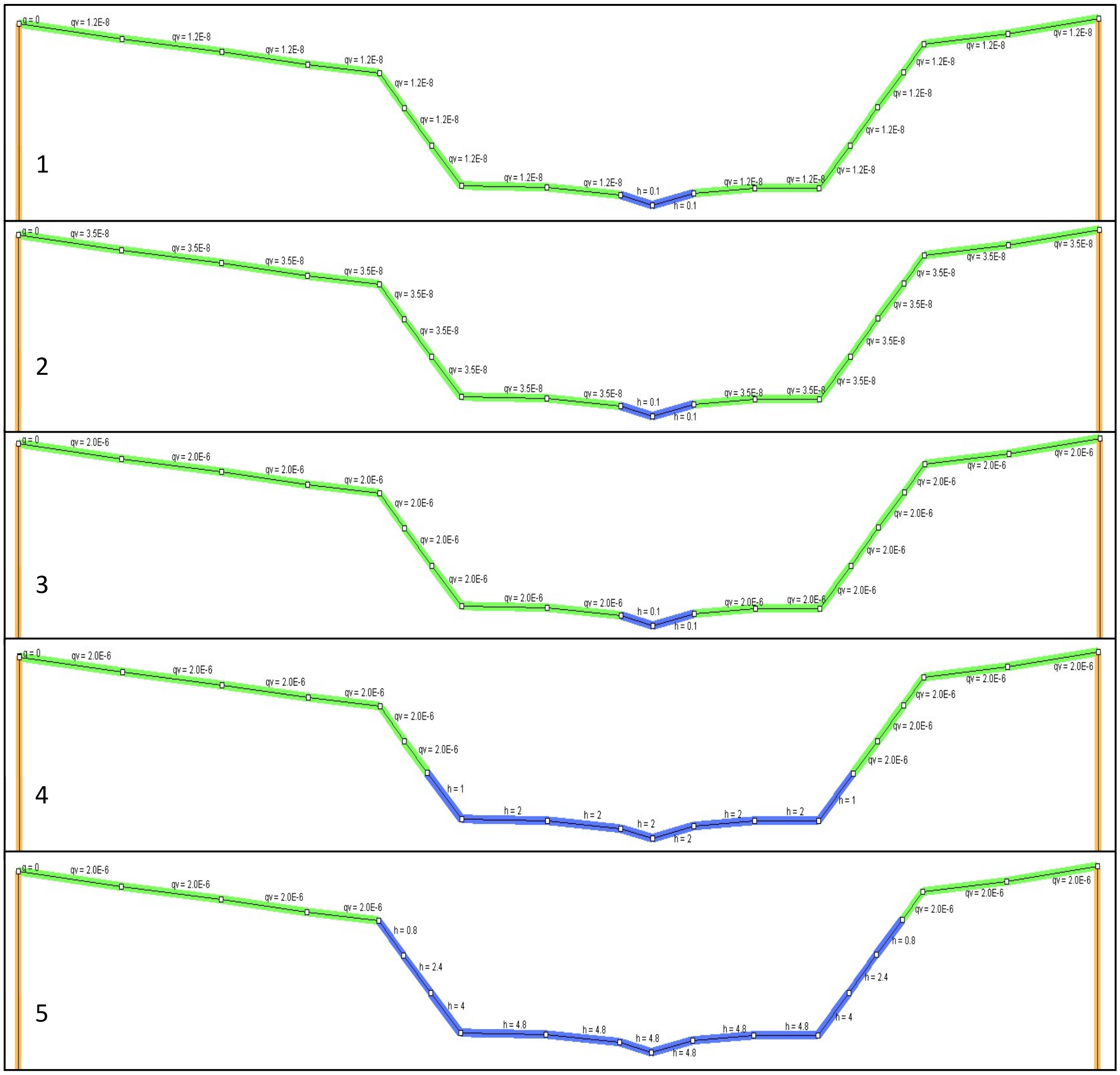

Figure 16: Boundary conditions for all recharge periods. Base flow (1), 14-day antecedent (2), 90 min antecedent (3), median debris flow (4) and bankfull debris flow (5).

4.2. Results

As stated in the processing pathway overview, there were many different parameters that had to be tested for compatibility with the software and realism. While a selection of these tests and their associated issues will be discussed in the following discussion section, the setting of the base flow duration will be mentioned here.

For the base flow duration, two different periods were tested. The saturation patterns resulting from the 1-year and 2-year period are shown in Figure 17 and 18 respectively. In these and all other figures that resulted from the VS2DI simulation, each dot represents the centre of a 10 by 10 cm square. These squares are the result of the discretisation by the software and are the units on which the calculations are based. On a preliminary visual assessment, it is apparent that they are very similar. Measuring the depths, the wetting front of the 1-year base flow reached 3.9 m below the bottom of the channel at its deepest point. The fully saturated zone for the same simulation reached 3.7 m. In the 2-year base flow simulation, the wetting front also reached 3.9 m of depth and the fully saturated zone reached down to 3.7 m as well. The width of the wetting front was 6.3 m in both scenarios. From the fact that these two simulations resulted in wetted areas of the exact same depth and width, it was decided, that the 1-year base flow scenario is sufficient to reach an approximate steady state. This means that for any further simulation scenarios in this thesis, the base flow recharge period was set to 1 year. Thus, the initial state on which the antecedent rainfall and debris flows were tested is the one shown in Figure 17.

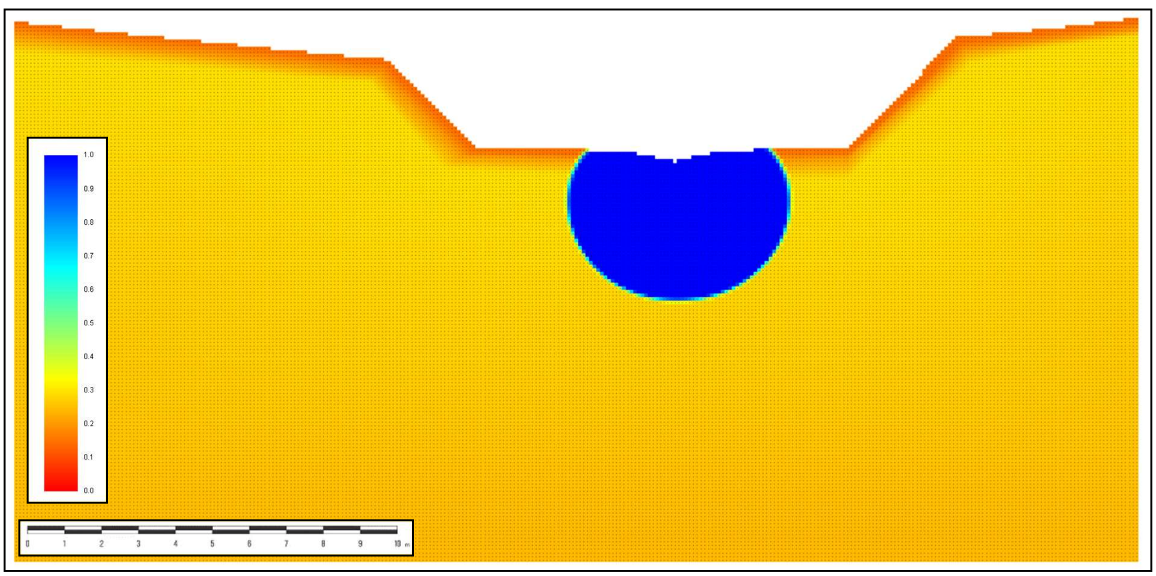

Figure 17: Saturation pattern of the full processing domain after the full calculation of the 1-year base flow scenario.

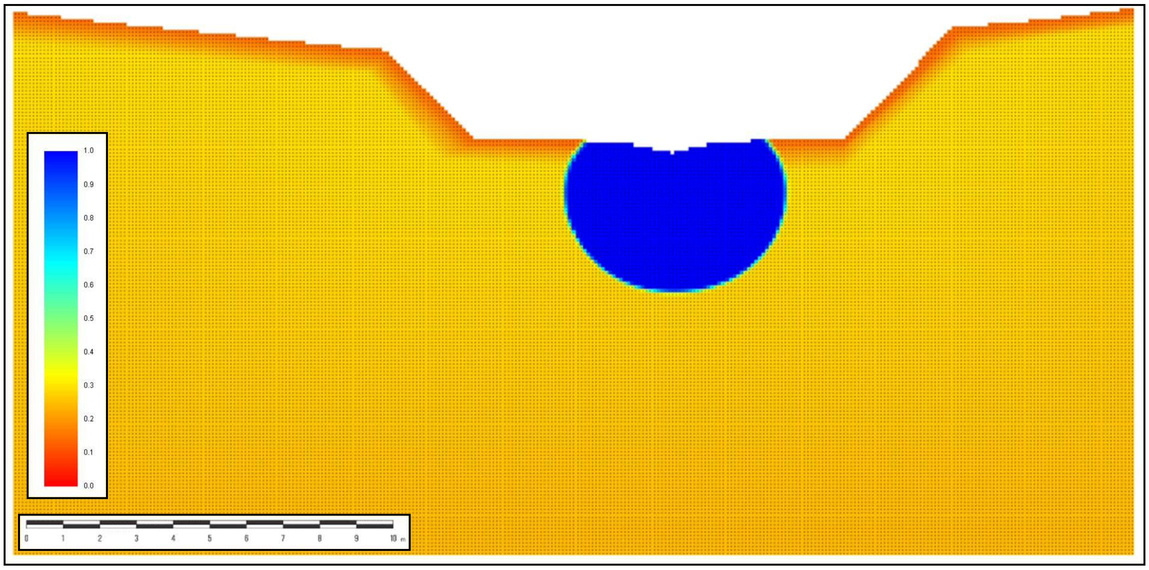

Figure 18: Saturation pattern of the full processing domain after the full calculation of the 2-year base flow scenario.

The median debris flow scenario resulted in the saturation pattern shown in Figure 19 (closeup of the central area can be found in Figure 20. In this simulation, we can clearly see the change in soil moisture in the top 10 cm of the surface that was not affected by the debris flow. This occurred due to the antecedent rainfall and the rainfall during the event. The depth of the wetting front in the centre of the channel did not change in comparison to the initial state created by the base flow and stayed at 3.9 m below the bottom of the channel. The maximum width did also not expand. In comparison to the initial state, the saturation pattern widened at the top of the wetted bulb. There, instead of a narrowing, the fully saturated zone expanded to the same width as the maximum of the initial state. The wetting front however did not expand in width at this location and the original wetting front can still be seen. The bottom and banks of the channel, where the base flow did not result in any saturation, show a fully saturated layer with a thickness between 40 and 50 cm. The wetting front is at some points 10 cm wider, but it is not fully visible everywhere. As the boundary conditions on the banks were not segmented, there is only minimal tapering of the saturated layer here. In general, the difference in penetration depth is minimal between the bottom of the channel and the banks.

In Figure 21, the resulting saturation image of the bankfull scenario is shown (closeup of the central area can be found in Figure 22). As in the median scenario, the wetting of the top 10 cm of the soil from precipitation is also visible in this image. It is however much less pronounced and around 20 % lower. The wetting front here has increased in depth everywhere compared to the median debris flow scenario. In the central wetting bulb that stems from the base flow the thickness of the wetting front has increased by 20 cm to 4.1 m. The fully saturated zone at the same location has increased in thickness by 10 cm to 4m. This bulb has also gotten wider. At the depth, where the base and median scenarios had the widest bulb, the bankfull scenario reaches a width of 6.7 m. Higher up it gets even wider, but here it is harder to differentiate between the bulb and the layer at the bottom of the channel. This fully saturated layer at the bottom and in the banks of the channel has a maximum thickness of 1 m. This tapers further up the bank to a minimum of 30 cm at the top, as the boundary conditions were segmented along the banks here.

Comparing the median and bankfull scenarios, it is apparent that an increased head in the channel during the simulated debris flow event has led to a deeper infiltration of water into the bed. It can also be seen that the wetting bulb from the base flow has an effect on the depth of saturation, through which the penetration is deeper around the initial infiltration bulb.

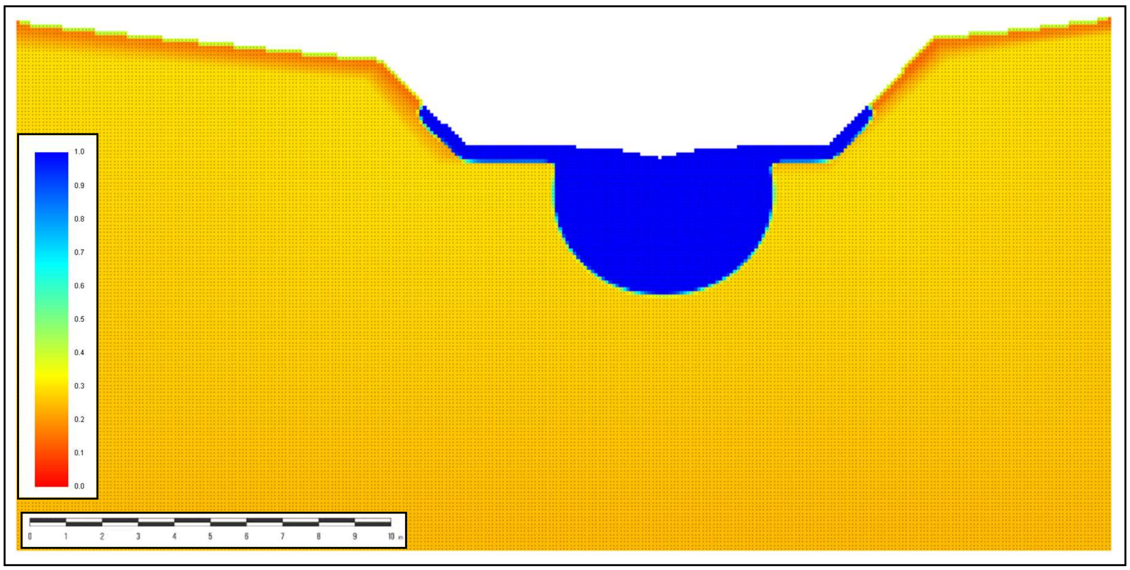

Figure 19: Saturation pattern of the full processing domain after the full calculation of the median scenario.

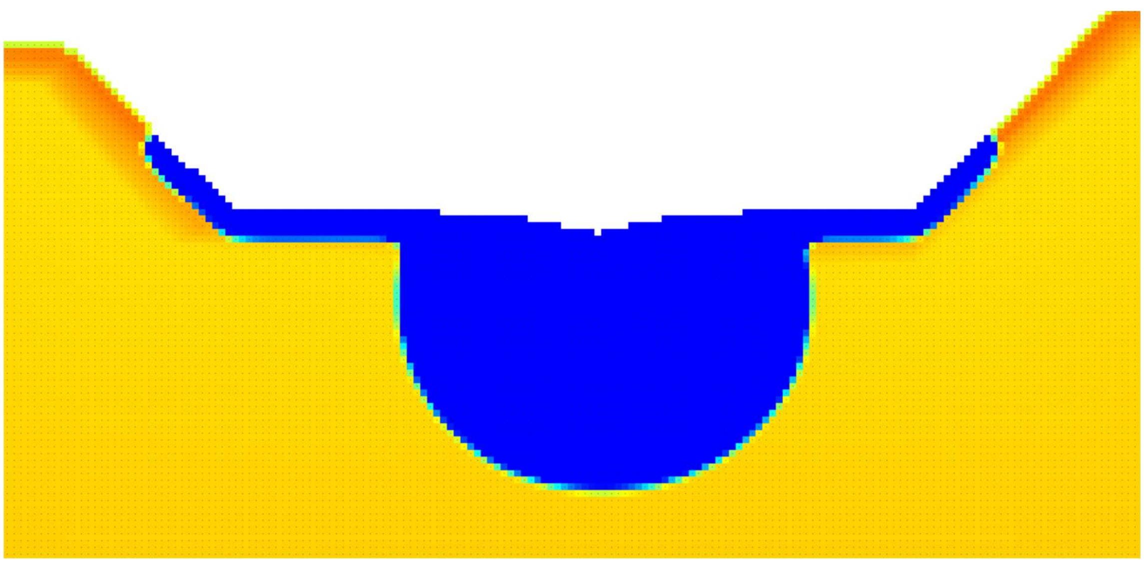

Figure 20: Closeup of the central channel from Figure 18.

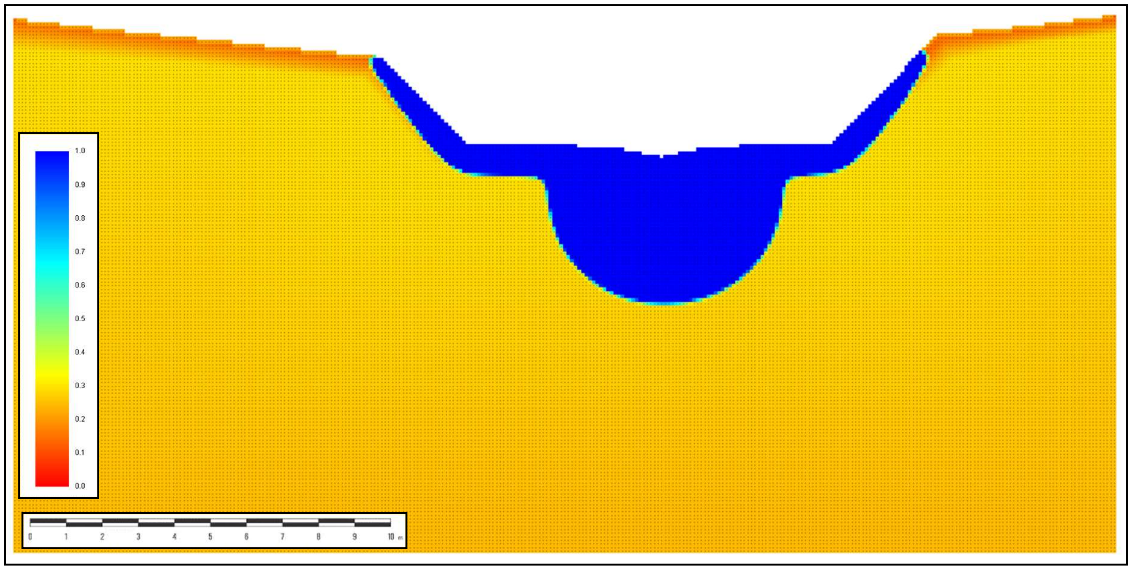

Figure 21: Saturation pattern of the full processing domain after the full calculation of the bankfull scenario.

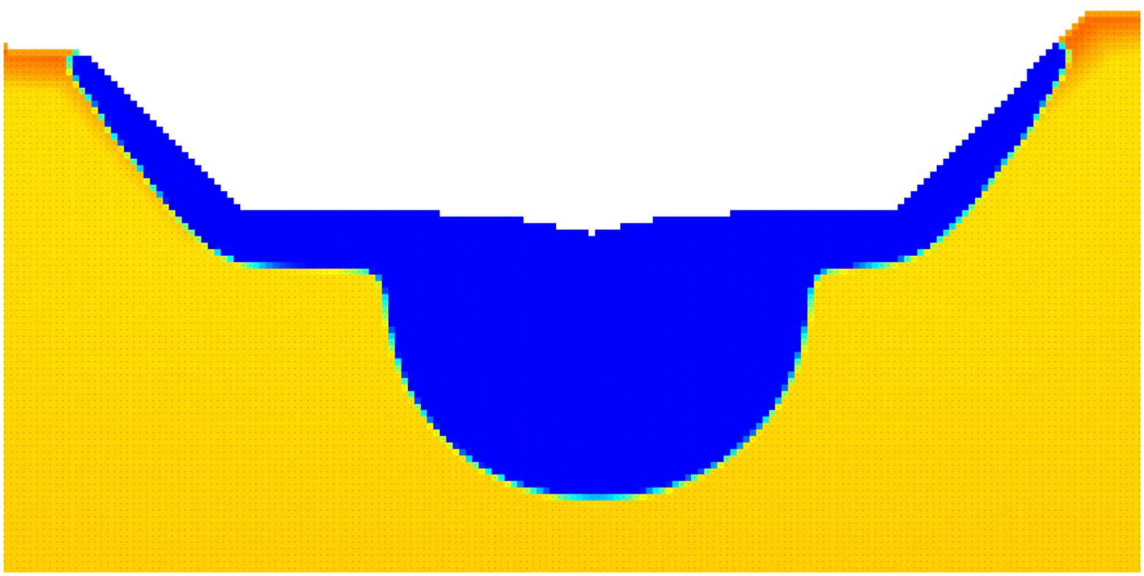

Figure 22: Closeup of the central channel from Figure 20.

4.3. Discussion

The simulations that were conducted with VS2D have shown that it is possible to simulate the infiltration of water from the base flow and the debris flows into the soil. The base flow scenarios over 1 and 2 years have shown that an approximate steady state can be reached. The debris flow scenarios have shown that infiltration in this short timeframe can reach significant depths and that an increase in flow depth is positively correlated with the depth of infiltration.

The results from the simulations in this thesis suggest that the flow depth of debris flows effect the thickness of the saturated layer in the bed. If only this infiltration controlled the erosion by the debris flows, we would have to expect larger flow depths to always lead to higher erosion. As can be seen in Könz (2023), this is not the case. While there is some corelation between flow depth and eroded volume, it is apparent that smaller debris flows can lead to higher erosion volumes. This is also confirmed by de Hass et al. (2022), who state that both the bed and the flow conditions control the erosion by debris flows. The question about the influence of soil saturation on the erosion could also be characterized as a question about timing. If we assume a situation without previous debris flows saturating the soil, then we would expect erosion to occur not mostly at the front of the debris flow, but at a later point during the flow. During debris flows it is very hard to assess the timing of the erosion they cause. Berger et al. (2010) have suggested a novel method to measure this. By burying a column of sensors in the bed of the channel at the Illgraben study site, they were able to find the time at which each sensor was eroded. In their first measurement of a debris flow with a maximum flow depth of 1.2 m, they had measured the first erosion after 44 minutes and a total erosion of 15 cm (three 5 cm elements). This however did not encompass the full erosion. An additional layer of 10 cm of sediments had built up on top of the sensors before the debris flow event. Due to this, the timing of the full erosion could not be reconstructed. From further measured events Berger et al. (2011) were able to draw the conclusion that this first event might have been more of an exception. That debris flow had produced a second more watery front and became more of a flood by the time of the erosion, which means that the erosion was not really done by the debris flow. The second and third events, on the other hand, showed erosion at the front of the debris flows and little to no erosion at the tail end. This suggests that in more standard debris flows the erosion occurs at the front of the debris flow. Due to the very limited number of events in this study, it is not certain that the results are widely applicable. There is little other data on the timing of erosion. However, flume experiments by Reid et al. (2011) have also indicated similar behaviour, especially on wet bed sediments.

All of this suggests that the wetting of soil caused by debris flows is not fast enough for the bed sediments to be sufficiently saturated to be more easily eroded. This would in turn suggest that in this scenario the centre of the channel would be more vulnerable to erosion than the more lateral parts. This has also been observed at the Illgraben by Schürch et al. (2011).

These assumptions have led to further testing. If the recharge period in which the debris flow occurs is shortened to 15 s, it results in the shallow infiltration shown in Figure 23. The bankfull debris flow shows 10 cm of full saturation on all boundaries and a further 10cm of high saturation at the bottom of the channel. Comparing this to the 50 cm and 55 cm measured at two different points in the channel by Berger et. al (2011) during a debris flow with a flow height above 2 m at the front, infiltration like it was simulated here, seems too low to be the main contributor to the erosion. As these sensors were placed in the centre of the channel the initial infiltration by the creek might however have had some effect. In the third event they observed, the infiltration from the debris flow could have had more of an influence. During this event, with a flow height of around 1.4 m during the first 3 mins, erosion was only measured at a more lateral sensors due to sediment cover at the others. This sensor was eroded by 5 cm 7 s after the front arrived. This pattern would match with the saturation pattern in the median scenario after 15 s, which is also shown in Figure 23.

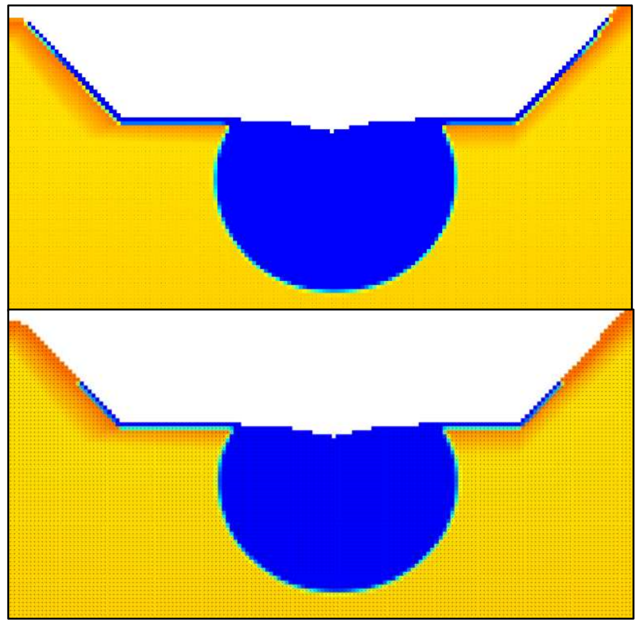

Figure 23: Saturation of the bankfull (top) and median (bottom) scenario after 15 s.

Another question that originates from these discussions is the effect the infiltration has on later debris flows. While it was not possible to simulate multiple debris flows due to processing issues, it was possible to simulate the evolution of soil moisture after a debris flow had passed. In Figure 24, the result of simulating a further 14 days of base flow conditions including precipitation after the median debris flow scenario is shown. The results here show the saturation decreasing over time in the area where only the debris flow had saturated the soil. The water seems to have seeped deeper into the soil and have marginally increased the saturation below the area where the debris flow had saturated the soil. If multiple debris flows were to occur within a relatively short time, this could potentially have an effect on the entrainment of later debris flows. While this is definitely possible, especially as debris flows tend to occur during periods of wet weather, the rate of debris flows occurrence in the Illgraben is definitely higher than at other locations. Thus, the importance of this mechanism is hard to estimate.

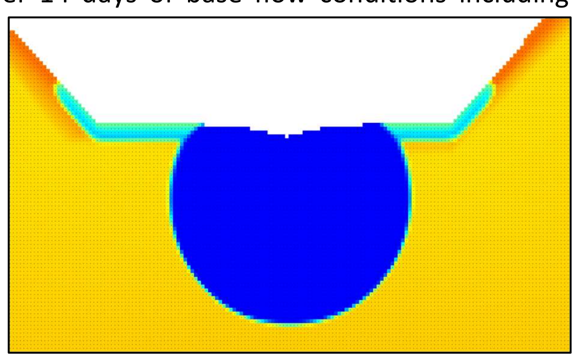

Figure 24: Resulting saturation of the median scenario with 14 days added after the event.

One issue that came up during the process of finding the input parameters, which are needed to receive a realistic pattern of saturation that is consistent between the two scenarios, can already be seen in the results section. As stated there the infiltration by the precipitation is much weaker in the bankfull scenario than in the median scenario. As the time and flux settings for the precipitation are exactly the same in both scenarios, this is not a real occurrence, but must stem from the processing. The best guess as to what causes this is that the limited number of calculation steps in every time step hampers the calculation of this infiltration. Due to the larger area of boundaries being covered by debris flow and thus more pixels having to deal with the deep infiltration by the debris flow, it appears that this infiltration is not sufficiently calculated. What effect this has on the infiltration by the debris flow is impossible to tell, but it would be reasonable to assume that this infiltration might also be smaller in the results, than could be expected. The opposite effect can be seen in Figure 25. Here, the precipitation was stopped during the median debris-flow event. This led to the infiltration by the debris flow going much deeper. The same effect could not be replicated with the bankfull debris flow. This led to the decision to continue the precipitation through the recharge period with the debris flow in order to produce the more consistent results that were used.

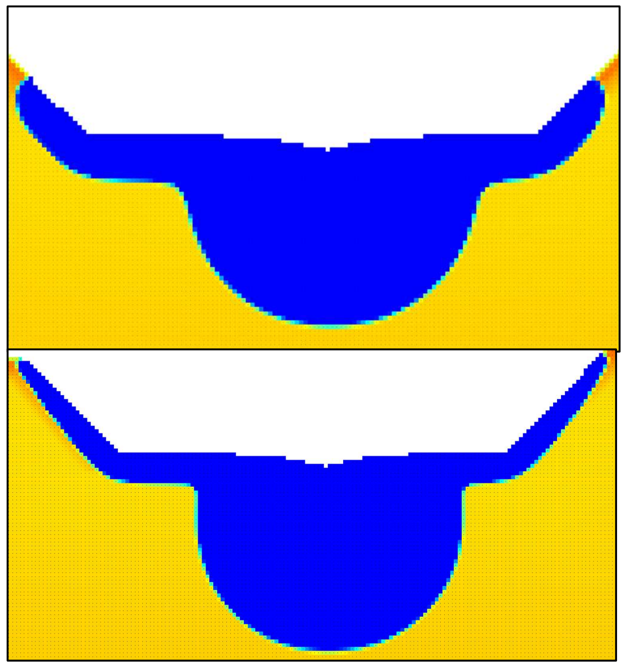

Figure 25: Top: View of resulting saturation in the median scenario without precipitation during the debris flow event. Bottom: View of resulting saturation in the bankfull scenario without precipitation during the debris flow event.

4.4. Limitations and further research pathways

The simulation conducted in this thesis has, as any other simulation, some things that have to be omitted and the software has its own limitations. Therefore, there are some issues, which can skew the results as mentioned above. Issues like these have come up in the simulations conducted for this thesis in regards to erosion, heterogeneities and the general way the simulation had to be set up. Further limitations are the product of a lack of data on the soil properties and the soil moisture at the study site. All of these will be discussed in the following section. This does not represent an exhaustive list of possible issues and limitations, but represents the most relevant parameters for this thesis.

The biggest issue for the accuracy of the simulations is heterogeneity. There are different scales at which heterogeneities in deposits can be important in hydrogeological studies and they are thus also important in simulating flow (Eaton, 2006; Heinz et al., 2003). In this thesis there are two scales at which heterogeneities are important to the simulation. Firstly, the lithofacies-scale is important, due to different units containing different units having different hydraulic properties. The variety present in these units in the Illgraben alluvial fan can be seen in a study by Franke et al. (2015) which used ground-penetrating radar and outcrop studies to identify 9 different lithofacies types. Theoretically it would be possible to implement these heterogeneities into the VS2DI simulation as different soil texture classes. This however was not practical to implement due to a lack of data. For this, a ground-penetrating radar study across the channel would be needed, as well as a full workup on the hydrogeological properties of the different lithofacies. Alternatively, cores could have been taken from the borehole and through that the properties of the soils, as well as the vertical heterogeneities of the soil column at the study site could have been assessed. ERT could also be used for such investigation, but deep sampling of the lithofacies through boreholes would still be necessary (Sudha et al., 2009). Due to the lack of any of these data sources, it was decided to use a single soil type for the whole simulated domain.

The other scale at which heterogeneity is important in the infiltration process, is boulders and other elements that can produce differences in flow behaviour. While the differences in grain size distribution in lithofacies could also be used to determine the spatial changes in preferential flow paths (Koltermann & Gorelick, 1996) and thus could be implemented in the simulation through the hydraulic properties of soil types, the effect of boulders and other such elements are impossible to implement in this software. Due to the pervasive presence of such elements in alluvial fans (Franke et al., 2015; Neton et al., 1994), it might mean that other approaches to the simulation would be more exact in simulating the infiltration in such heterogeneous environments (Eaton, 2006).

Another primary issue in the context of simulating the infiltration by a debris flow into its channel bed is at the same time part of the central questions in this thesis. As VS2DI is a software package made for hydrological questions, it does not contain the option to change the geometry of the test environment during the simulation. This leads to the issue that the erosion that would take place during a debris flow cannot be simulated. This is especially an issue considering the timing of the erosion. As was discussed in the previous section, erosion by a debris flow is likely to mostly occur at the front of the flow at least in some conditions (Berger et al., 2010, 2011; Reid et al., 2011). For the simulation this means that some of the material at the bottom of the channel would probably be eroded very quickly. With this not being possible to be simulated, this material has to be infiltrated through later in the simulation as well. It is however reasonable to assume that in scenarios, where erosion is relatively small this would not be very relevant to the results, especially because, as was shown in Figure 23, the first 10 cm are very quickly saturated with water.

As mentioned, the availability of soil moisture data was also an issue. The depth of the soil moisture sensor column went only down to 80 cm, due to it not being possible to dig down further. They are also only on the top of the bank and close to the channel. Due to this, it is not really possible to get any information on how the soil moisture situation looks further down in the soil. From the ERT it was possible to find that soil moisture decreases again further down, but this is also highly imprecise. Thus, the initial soil moisture profile only covered the very top of the profile with a more or less accurate trend. The accuracy of creating the soil moisture situation in the simulation is highly doubtful. The simulation did not actually infiltrate the water from the precipitation deeper than the first 10 cm. This does not accurately depict the response of the soil moisture in this soil (Könz, 2023). The reason for this probably lies again in the way VS2DI calculates the infiltration. There are probably also inaccuracies created in simulating the basic state after 1 year. Here, the precipitation and evaporation were averaged out and subtracted to get a constant flow rate into the processing domain. By not realistically recreating the hydrological inflows and outflows, the state that was reached is probably very inaccurate. Especially the lack of intensity in the precipitation probably leads to less soil moisture than would actually be present. This could however not be implemented in the simulation due to processing constraints.

5. Discussion and Synthesis

5.1. Internal Consistency between field and software

When comparing the results of the simulations to the field investigations, some behaviours are consistent between the two, while others are more conflicting. Comparing the approximate steady state produced by the simulation of the base flow to the ERT, we can immediately identify a major issue. In the ERT it is apparent that the saturated zone or potential inverted water table beneath the creek is not directly connected to the surface, but lies mostly around 2 m below the channel. This is not replicated in the simulations, where the saturated zone extends up to the surface. In groundwater measurements Berger et al. (2010) did also not see a permanent water level beneath the creek at around 1 m beneath the bottom of the channel. These sensors were downstream of CD 28, but it seems reasonable to assume that the situation there would be similar to the study site of this thesis, just upstream of the same CD. This leads to the assumption that, at least at locations not directly beneath the creek, but slightly off to the side, the ERT produces the more accurate picture and the saturated zone does not extend to the surface during normal flow conditions. One potential reason for this difference could lie in the heterogeneities in the soil and the formation of preferential flow paths. Pipe flow along boulders and the washing out of fines can be big factors in creating preferential flow paths in sedimentary deposits (Hencher, 2010). Both of those are possible in the environment of the study area and it is likely that this is the reason for the pattern discovered through the ERT measurements.

What is consistent between the simulations and the ERT measurements is the depth to which the infiltration of the baseflow reaches. As in the ERT, the simulation reached around 4 m of depth for the wetting front. This confirms that the settings of the soil properties in the simulation, as well as the assumption of an average flow of 10 cm are reasonable. It also gives an indication on the nature of the groundwater table. This result suggests that it could be an inverted groundwater table, as that relies on the low permeability of the soil and the deep groundwater table to be created (Stephens, 1996). It is also consistent with the assumption by Xie et al. (2014) of inverted groundwater tables occurring more often in narrow and shallow streams.

As previously stated, the soil moisture is very inconsistent between the measurements and the simulation. Similar computational issues are also the reason, why it would probably not be possible to simulate the situation that led to the groundwater in the well in December 2023. It seems however plausible that with the broadening of the inverted groundwater table seen in the bankfull scenario, it would be possible for this to also be simulated with an increased runoff causing prolonged flood conditions. This was not tested due to a lack of information about the actual flow height of the stream at the time, but it would be interesting to see if further such events produce similar readings in the future.

5.2. Comparison to Literature

When observing the totality of data that was collected and created for this thesis and comparing it back to the flow conditions that connect streams to groundwater that were discussed in the literature, some comparison can be drawn. Firstly the stream in the Illgraben can be classified as a losing stream according to the classification by Dingman (2008). This is supported by the observation that there is no groundwater reaching up to the surface. As mentioned in the description of the study site, this stream has been previously described as an ephemeral stream (Hirschberg et al., 2019). This is however not the case on the alluvial fan currently. The dumping of excess drinking water into the channel at the gas pipeline may have changed the stream type to become closer to a perennial stream, although there are times during the dry parts of the summer season when no water is visible in the channel at the location where the measurements were made (CD28). This is also supported by the fact that the simulation of base flow that assumed this has led to an infiltration pattern, which closely matches the measurements.

The situation concerning the nature of the connection between the stream and the groundwater remains somewhat unclear. There are two different frames of reference in which it could be considered. In one frame of reference, we can think of the groundwater bulb beneath the channel as connected to the channel rather than separate entity. In this case, the question about connection to groundwater would relate to a potential groundwater table, which lies far beneath the stream. From the ERT it is known that this groundwater table would lie at least 20 m beneath the channel and would be separated from the stream and its saturate soil by a large layer of unsaturated soil. This would leave the saturated bulb as a small groundwater reservoir, limited in its depth by the small pressure of water from the stream combined with a low permeability, and separated from the unsaturated soil below it by an inverted groundwater table. As these conditions match the requirements that are laid out by the literature (Stephens, 1996; Xie et al., 2014), this seems to be a realistic description of the situation. A question that remains, is if there is a clogging layer, like it is stated to be necessary according to Brunner et al. (2011). Theoretically, it should be possible for a clogging layer to form at this location. Laboratory test have shown that sand and silt are able to form such clogging layers in river gravel beds (Schälchli, 1992). Therefore, it should be possible for silt and other fines in the sediments at the Illgraben to accumulate into a clogging layer at the inverted water table. However, to confirm this, further testing at the actual location would be necessary.

The other possible frame of reference would be to think of the saturated zone as a perched aquifer that is confined at the bottom by an aquitard. In this scenario the connection to be considered is the one between this groundwater and the stream. ERT as well as the measurements by Berger et al. (2011), support the presence of an unsaturated layer between the bottom of the channel and the groundwater, making this path of analysis necessary. When looking at the options that were presented in the literature review of a gaining, a losing connected, a losing disconnected or a losing transitional stream (Brunner et al., 2009, 2011; Dingman, 2008), some options can be immediately eliminated. Under the base flow conditions, the stream can not be a gaining stream, as there is neither a groundwater table that lies above the stream and thus would contribute to the stream, nor any other source from which the groundwater could feed the stream. As discussed, both data collected and data from literature indicated that the groundwater does not reach the channel even in the centre, which further eliminates the connected losing stream. A disconnected situation is also not realistic, as there is no evidence of any other source for the groundwater. There is further evidence in the data from Berger et al. (2011) that the groundwater table rises when it is fed by the occurrence of a debris flow. This mirrors the behaviour of a groundwater mound rising to intersect the stream. This would not be possible in a fully disconnected stream (Brunner et al., 2011). This suggests that the situation at the study site is probably most accurately described as a losing stream that is in a transitional state. The two different frames of reference that were discussed here, will be unified into a single conceptual model in Section 0. in an attempt to present a holistic view on the stream groundwater interaction of the Illgraben channel.

Another aspect that needs to be discussed in relation to the stream to groundwater interaction at the Illgraben is what happens in large precipitation events like the one in December 2023. In this event, two of the boreholes have the appearance of groundwater, which took a long time to dissipate. This could lead to so called bank storage. Bank storage can occur in high flow events, when the groundwater table in the banks rises. This water then feeds back into the stream once the flood has passed, transforming it temporarily into a gaining stream until the groundwater level has again dropped below the channel (Dingman, 2008). Because the rise in groundwater in the boreholes has only been observed once so far without much accompanying data, it is difficult to assess the necessary conditions for this occurrence and if the described bank effect actually manifests.

5.3. Conceptual Model

Figure 26 presents a conceptual model of the flow of groundwater beneath the creek at the Illgraben study site. This model is based on the situation during base flow and is assumed to be at least representative of the situation just upstream of CD 28. It assumes that both the previously discussed frames of reference are partially correct and combines them into a unified model. As in the first scenario, the creek infiltrates water through a capillary zone into a perched aquifer. This aquifer is theorised to have a groundwater mound directly beneath the creek. The lateral extent of this aquifer is unknown. It could however stretch across the full channel as it is seen in the ERT results of TS2 at the CD. However, the extent in that transect is likely to be much larger than it is upstream, due to the damming effect of the CD. In the conceptual model, the perched aquifer is not limited in its depth by the typical impermeable layer, but instead ends in an inverted water table, that has been formed through the low hydraulic conductivity of the soil, the large depth to the underlying water table and potentially a clogging layer. Beneath this lies a large layer of unsaturated soil, which is at the very minimum 16 m thick. It is not currently known if there is a water table beneath this unsaturated layer, but based on the ERT measurements, it has to be at least 20 m below the channel. It is likely to be at most at the level of the Rhone River, which would be between 30 am 40 m below the bottom of the channel. As is indicated in the sketch there is still flow out of the perched aquifer into the unsaturated zone. As stated by Brunner et al. (2011), such flow from disconnected streams can be, quite large. While this model has not yet been fully confirmed, it can still be a valuable starting point in trying to understand the interaction between the water in the creek and the groundwater. While the effect of the drinking water spillage by the community on the groundwater cannot be conclusively assessed, it is possible that this additional flow increases the size of the perched aquifer.

The effect this perched aquifer would have on erosion, if the conceptual model is correct, is difficult to determine. In light of the study by Schürch et al (2011), speculations can however be made. As discussed in the literature section, this study has shown that with an increase in flow depth the erosion depth tends to increase at a higher rate than with lower flow depths. They have also seen very large erosion depths in the centre of the channel. In some events the erosion was up to 5 m deep locally. A possible conclusion that could be drawn from this is that erosion reaching the top of the aquifer causes the rate of erosion to increase. In this case, a sufficiently large debris flow would erode through the capillary zone, and as it hits the aquifer, the erosion gets much deeper than it normally would. The presence of a groundwater mount in the centre of the channel along with the rise of the water table due to flow from the debris flow into the aquifer, would in this case also partially explain the deeper erosion in the centre of the channel. While this study was done above the point, where the community dumps excess water, it still pulls the issue back to attention. If the model and its connection to increased erosion is accurate, this would suggest that anything that increases the size of the perched aquifer would lead to an increase in erosion and thus debris flow volume. The slow recovery of the groundwater level in the wells after a heavy precipitation event has shown that in this environment can take months for groundwater levels to normalize after a rise. This would suggest that even if the dumping does not continue through summer, it could still have an effect during the main season, when debris flows occur.

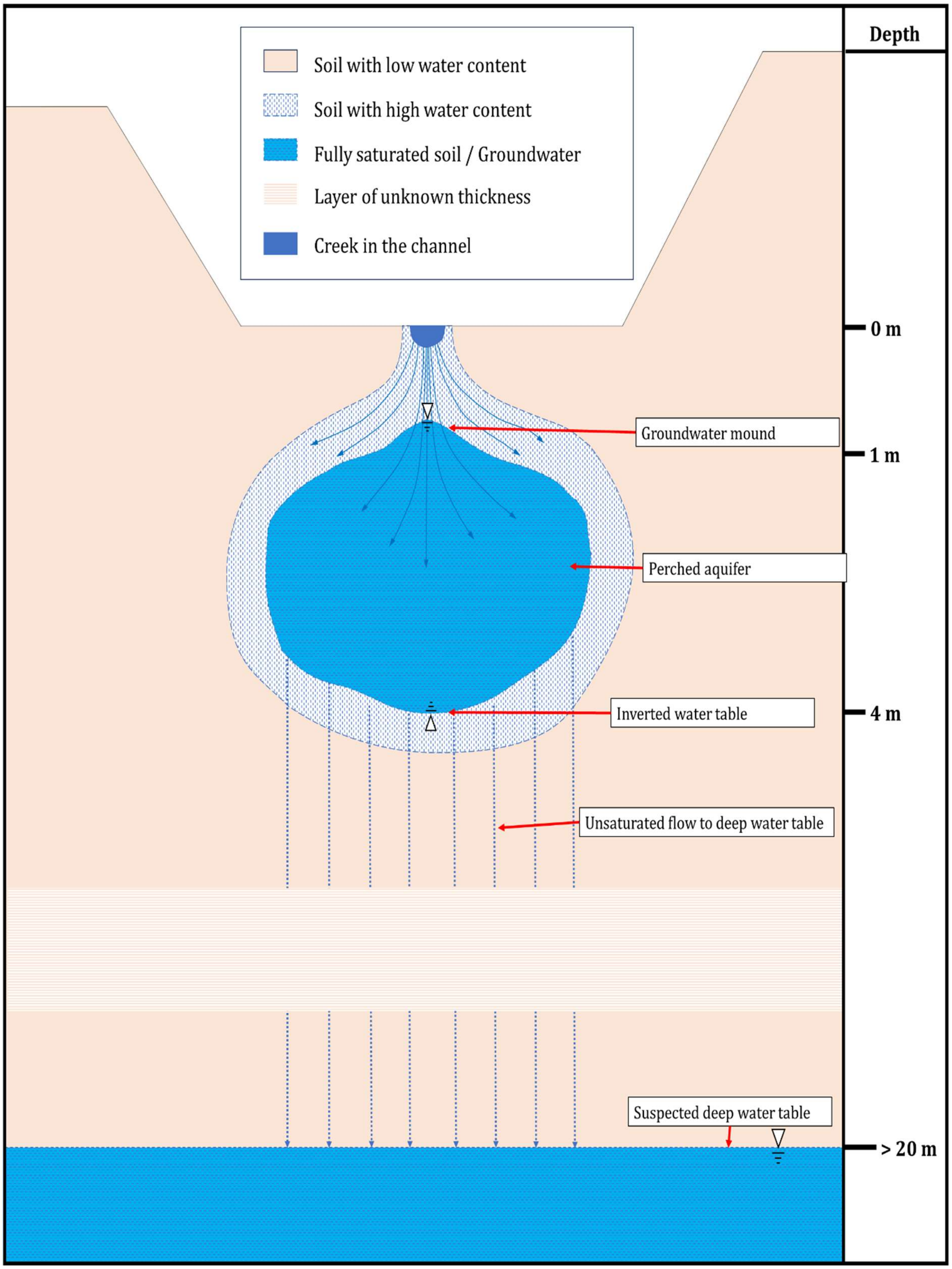

Figure 26: Sketch of the conceptual model that has been constructed from the data in this thesis. The depths that are shown on the right side are all approximate and the sketch is not to scale in either vertical or horizontal axis. The flow lines are speculative.

5.4. Limitations and further research pathways

While most limitations, especially the ones concerning the simulation, have already been discussed in this thesis, some more general issues and recommendations will be discussed here. There were some issues with a lack of data during the field investigations. It would be more ideal for the groundwater investigation beneath the channel to have angled boreholes available, so that the screens could be placed in the area of interest. If this were to be done, it would be important to also take soil samples or cores from the drilling. This would allow for a much greater understanding of the hydrological characteristics of the soil, as well as it might help with the detection of a possible clogging layer. With the lack of groundwater observed away from the channel in the ERT transect TS2, a broader study array of boreholes like it was done by Blackburn et al. (2021) would probably not be helpful. Further boreholes could potentially also allow for soil moisture measurements at depth, which would provide a clearer picture of the soil moisture profile into the depth. For this thesis, the erosion measurements by Berger et al. (2010, 2011) have been very interesting and important. Such measurements provide an important insight into debris flows. If similar systems were used in laboratory measurements, they could also provide valuable data and more precise results due to a more controllable environment. More studies, maybe including these sensors, into the effect of soil moisture into the erosion by debris flows would also aid in developing more accurate models for debris flow bulking and thus runout behaviour.

When we consider software to simulate the infiltration from debris flows into the soil, it would probably be helpful to find a software that is more attuned to the kind of heterogeneous environment that is faced when doing studies on alluvial fans. VS2DI, as used here, does not seem to be well suited for such a situation. Maybe there are also other options of simulating this situation in VS2DI that were not found by the author of this thesis.

6. Conclusion

The main conclusion which should be drawn from this thesis is that the hydrogeological situation in alluvial fans, on which debris flows are an important issue, should be studied. In the course of the research that has been presented here, it has become clear that the understanding of the flow of water in the deep deposits these fans have is important, in order to better simulate the entrainment processes of debris flows.

ERT has proven a very useful tool in the investigation of aquifer structure. Through especially this tool, it has been possible to create a conceptual model of the hydrogeological situation at the Illgraben study site. It has been able to both show a saturated zone between around 1 m and 4 m below the channel, as well as that there is no groundwater table down to at least 20 m below the channel. This has, together with the other results in this thesis, led to the creation of the model. This proposed model states that there is a perched aquifer beneath the channel. This aquifer is connected to the creek in the channel through a capillary zone during base flow conditions. In a high flow scenario, it is suggested that the groundwater mound of this aquifer rises to intersect the channel. If there is a sufficiently large and long flow, it is theorised that there might be sufficient infiltration to create a bank storage effect that keeps feeding the stream for a certain time after this event. Very interesting is also the mechanism through which this aquifer is confined from the bottom. Instead of the classical impermeable layer that occurs in many descriptions of perched aquifers, there appears to be an inverted water table. Such inverted water tables are described in very few papers and there has been even less study of them outside of modelling. The situation here however matches the opinion in the literature that they can only occur in aquifers where a small creek is separated from the underlying aquifer by a large vertical distance. There might be a great opportunity at this study site to test this hypothesis and to test the statement by Brunner et al. (2011) that a clogging layer is still necessary, even in conditions with a deep groundwater table and low permeability.

As previously stated, the software VS2DI which was chosen might not be the right choice for this kind of simulations. There is certainly the possibility of using another software that is more focused towards groundwater analysis to improve on the analysis in this thesis and especially to verify the conceptual groundwater model, which was assembled in this thesis.

The simulations done in this thesis, together with research by others (Berger et al., 2011; Reid et al., 2011), have led to the conclusion that in many cases the infiltration of water into the bed that happens during a debris flow might be less important than other factors influencing the saturation of the bed such as antecedent precipitation. This assumption has been drawn from the fact that the infiltration did happen fairly slowly. This is an issue, as debris flows are believed to mostly erode at their front, so the infiltration would not have happened to a sufficient degree to effect entrainment in a significant manner. There is however also evidence that in cases where multiple debris flows or fronts within one debris flow are present, there is an effect of that infiltration. In regards to erosion, the connection with the data from Schürch et al. (2011) might be the most important finding. As has been shown, it is a possibility that the perched groundwater table enlarges the depth of erosion, if a debris flow is large enough. If this connection could be confirmed by further research, this could have a major influence on how the erosion by debris flows is looked at. In terms of risk management, this could also have an effect, as the anthropogenic influences on the flow regime on the fan could have an influence on the entrainment behaviour of the debris flow.

There is also further research potential in the realm of infiltration and erosion by debris flows. Data on the actual timing of debris flow erosion is still scarce and could potentially be a worthwhile avenue of further research. Further information on that timing would help to better understand the influence that infiltration by debris flows has on the depth of erosion.

7. Literature

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Declaration of Originality

Personal declaration: I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

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