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Modelling the Flood Hazard in the Redtenbach Catchment in Lower Austria - Focusing on the Influence of Different Rainfall Intensities and Multi-Hazard Risk

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Abstract

Floods are one of the most disastrous hazards worldwide, with magnitudes expected to increase due to effects of climate change. Additionally multi-hazard risk is increasing in areas prone to landslides, where landslides and floods can be triggered by similar events, like heavy precipitation, and influence each other. Understanding the behaviour of floods and forecasting events can be challenging in these areas, especially if important data and historical documentations on events are missing. This study aims to understand the flood hazard for such a region, by using a novel method to model the hazard and proposes a methodology that can be used for areas with limited data availability. The study modelled 18 different rainfall induced flood scenarios, including different event intensities and the influence of a natural landslide dam. It concluded that the study catchment responds significantly to different rainfall intensities and shorter, more intense events lead to a higher flood response and exposure of buildings. The landslide dam additionally increases the flood extent and water depth at the immediate site, highlighting that landslides can accelerate flood response, and both hazards need to be incorporated into an extensive risk analysis in landslide prone regions.

Zusammenfassung

Hochwasser sind eine der verheerendsten Naturkatastrophen weltweit und es wird prognostiziert, dass sich Häufigkeit und Intensität mit den Folgen des Klimawandels weiterhin verstärken. Zusätzlich dazu steigt auch die Gefahr für sogenannte Multi-Hazards, also mehrere Gefahren die Zusammenkommen und miteinander interagieren. In Gegenden, die anfällig für Hangrutschungen sind, können Auslöser, wie zum Beispiel Starkregen, zu Hangrutschungen und Hochwasser führen. Dabei können die Folgen der Hangrutschung den Verlauf des Hochwassers beeinflussen. Ziel dieser Arbeit ist es, die Hochwassergefahr in so einem Untersuchungsgebiet abzubilden. Es wird eine Methodik vorgestellt, die speziell für Untersuchungsgebiete geeignet ist, in denen historische Berichte und Daten zu Hochwasserereignissen fehlen. Mithilfe einer neuartigen Modellierungsanwendung wurden 18 verschiedene Szenarien modelliert, die alle durch Starkregen verursacht wurden. Diese beinhalten verschiedene Niederschlagsintensitäten und den Einfluss einer natürlichen Blockade, verursacht durch eine zuvor aktivierte Hangrutschung. Es wird geschlussfolgert, dass das Untersuchungsgebiet empfindlich auf verschiedene Niederschlagsintensitäten reagiert und kürzere, intensivere Regenereignisse eine höhere Gefahr für Hochwasser verursachen und mehr Gebäude gefährdet sind. Zusätzlich dazu verstärkt die Blockade das Ausmaß des Hochwassers und die Wassertiefe rund um den betroffenen Bereich. Dies zeigt, dass Hangrutschungen Hochwasserereignisse beeinflussen können und deshalb bei ausführlichen Risikoanalysen mitberücksichtigt werden sollten.

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1 Introduction and Research Objectives

In September 2024 multiple days of heavy precipitation led to an extreme flooding event in Austria, especially in Vienna and Lower Austria. This event was classified as a HQ100 event for many party of Lower Austria (BML, 2025). This means, that an event of this magnitude statistically occurs once every 100 years and is therefore considered to be extreme. Although the flood magnitude inside Vienna was very high, reaching a peak discharge of 10.000 m³ per second the damages were relatively small (TU Wien, 2024). Experts claim that Vienna's flood management is well prepared for events of such magnitude and the impact has been well documented. But what happens in areas outside the capital of Austria? The country is generally prone to flooding as many past events have shown. And in regions that are not highly populated, reports and documentations of extreme events might not be so thorough. An interview from residents from the rural area of the district of Waidhofen an der Ybbs in Lower Austria shows how the extreme event in 2002 has impacted them. Together with lasting heavy precipitation, a mudflow has formed on the slope, where their house is located, leading to big water masses running through their house (Mr. Hornbachner, Resident of Hofermühle). Even though the local municipality has helped the inhabitants of this region to mitigate the risk and to protect their houses during the event, official reports are missing or difficult to acquire. The European Union (EU) has issued the "Flood Directive" in 2007, where every member state is required to assess flood risk and create flood hazard maps and management plans for all areas prone to floods. This assessment of flood hazards can be very challenging due to many data scarcity issues. This could include, as mentioned above, missing historical data, but also relevant parameter data such as precipitation, discharge, infiltration, etc. Apart from that, flood modelling is significantly more complex in areas that are prone to landslides, such as Lower Austria, and especially the Redtenbach Catchment, because these areas are prone to quick landscape changes that have an influence on flood behaviour. There are many different studies, methodologies and approaches to analyse flood susceptibility and a diverse availability of software to model flood behaviour. This study aims at creating a methodology for a data scarce region, in order to analyse the magnitude of potential future floods and to incorporate the multihazard risk of landslides. The chosen study area is the Redtenbach Catchment, where both risks are prevailing and where no flood hazard map including both has been created so far. For a better understanding of the flood hazard, the exposure of buildings inside the study area will be included in the methodology. The aim is to generate an overview of the flood hazard for the region, for different preconditions and to analyse, how much influence the active landslide

“Hofermühle” has for the intensity of the flood hazard and the exposure. This assessment is a critical precondition for an effective flood risk management, as only through a thorough hazard analysis, endangered areas can be identified. Over the course of this paper, four research questions will be answered:

1. What precipitation intensities refer to 30-, 100- and 300-year flood return periods?
2. How do flood magnitude, - depth and velocity change with varying rainfall intensities?
3. How does a potential stream blockage further affect the flood characteristics?
4. How does the exposure of infrastructure inside the study area change under different rainfall-induced flood scenarios?

To answer these questions, flood hazard maps for 18 different scenarios will be generated using the innovative flood simulation tool FastFlood, that is well suited especially for data scarce regions (van den Bout et al., 2023).

The first part of the paper will explain the theoretical background on floods, flood risk management and the FastFlood tool. Afterwards the study area will be introduced. The third Chapter deals with the methodology of the study in order to answer all research questions. Afterwards the results will be described and discussed, followed by an outlook into future work and conclusion.

2 State of the Art

Before presenting the workflow and results of this study, it is important to give an overview and explain all core concepts of the study. The following Chapter will dive into all relevant aspects and present the theoretical knowledge on the subject.

2.1 Floods

This Chapter focuses on the theoretical basics on flood. First it will explain what natural event is categorized as a flood and how it evolves. It will also deal with the impacts of floods. And in the second part, explore major historical flood events in Austria, to give the reader an understanding on the intensity of the hazard.

2.1.1 Definitions

Floods are among the most frequent natural disasters worldwide, with 164 events reported in 2023 alone (Galan, 2025). The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC SREX) defines floods as the overflowing of the normal waterbodies and waterstreams, and the accumulation of water in areas, where it does not occur under usual conditions (IPCC, 2012). The report further states, that the occurrence of floods in itself is a natural phenomenon, or “climatologically normal”. They can occur periodically, for example every spring during snowmelt or during annual monsoons and are therefore part of the natural water cycle (Rajkhowa & Sarma, 2021). Consequently, floods cannot be classified as disasters per se. They rather become one, when threatening human lives and everything that is associated with it, like property and livestock (Jerome Glago, 2021).

The United Nations Office for Disaster Risk Reduction (UNDRR) defines disasters as “a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts.” (UNDRR, 2017a). A crucial aspect emphasised hereby is the focus on the affected society. A disaster is defined by societies’ inability to cope independently, necessitating external assistance from beyond the affected region. This distinguishes a disaster from an emergency, where the affected local community is able to handle the negative impacts independently (UN, 2025). Within the context of a disaster, floods are defined by a considerable amount of overflowing water, that directly impacts living conditions (Uddin & Matin, 2021).

Floods occur, when the storage capacity of the soil is exhausted following heavy precipitation, or when the infiltration capacity of the soil is lower than the precipitation intensity (Disse, 2020). When precipitation falls, a significant part is taken in by vegetation or it transpires before reaching the ground, while another part infiltrates into the soil. The portion that cannot infiltrate due to saturation and runs off on the surface following slopes and curvatures is called surface-runoff (Disse, 2020). Another portion of the precipitation flows into the upper soil layers. This is called interflow. Surface runoff and interflow equal the volume of rainfall that reaches water bodies like streams and rivers directly accounting for an increasing river discharge (Disse, 2020).

The characteristics of the affected area have a significant influence on the runoff formation. Soil properties and land use and landcover are essential (Disse, 2020). Water can infiltrate better in more permeable soils, while sealed surfaces like urban areas are less permeable and thus exhibit higher runoff. The runoff concentration is determined by the terrain gradient which influences the flow time, the topography which defines the retention capacity and the vegetation that influences both flow time and retention capacity (Disse, 2020).

The classification of floods can be divided into several categories, distinguished by their formation and characteristics. The IPCC SREX report (IPCC, 2012) differentiates the following types of floods:

- River (fluvial) floods
- Flash floods
- Urban floods
- Pluvial floods
- Sewer floods
- Coastal floods
- Glacier lake outburst floods

In contrast, the UN’s classification system is more broad, categorising floods into three types according to the Peril classification (IRDR, 2014):

- Riverine floods
- Coastal floods
- Flash floods

Riverine floods are defined as the overflow of water from a water channel into normally dry land in a floodplain. Coastal floods are characterised by water levels along the coast or in lakes or reservoirs that exceed usual values. Flash floods occur when heavy rainfall, typically in a short period of time, results in excessive runoff directly at or close to the area where the rain fell (IRDR, 2014). Patt and Jüpner (2020) add that flash floods in steep catchments pose an escalating risk of damage due to the high energy levels of the flood wave, which can result in the destruction of trees, rocks, and other materials along its trajectory, and the subsequent transportation of these materials through the floodplain. In more shallow catchments, heavy precipitation events lead to a greater extent of flooding (Patt & Jüpner, 2020).

A heavy precipitation event can be defined by different parameters, generally they all refer to the amount of precipitation that rains down in a specific time, or to the rarity of the event, based on a percentile threshold or the return period of the event (WHO, 2023). The return period is defined as the estimated average duration between repeated instances of a specific event, such as a flood or intense rainfall, occurring at or beyond a certain magnitude or intensity (IPCC, 2012). Two common definition criteria are by Wussow and by Schimpf both of which define heavy precipitation by the amount of precipitation per time interval. Table 1 shows an overview of both criteria for a time interval from 5 minutes to 24 hours.

Table 1: *Definitions of extreme precipitation by time interval according to Wussow and Schimpf. (Source: Created by the author, data provided by Climate Service Center Germany (2025).*

Time Interval	**Wussow Criteria**	**Schimpf Criteria**
5 minutes	5 mm	7.5 mm
10 minutes	7.1 mm	9.1 mm
20 minutes	10 mm	10.9 mm
30 minutes	12.2 mm	12.2 mm
1 hour	17.1 mm	14.7 mm
2 hours	24 mm	17.8 mm
6 hours	42.4 mm	24 mm
24 hours	84.9 mm	35.0 mm

This paper uses the definition criteria by Wussow to categorise extreme precipitation events.

2.1.2 Impacts

When floods occur, the consequences are immediately apparent, impacting the daily lives of affected communities and enforcing economic and social pressures that persist long after the event itself (Uddin & Matin, 2021). The most immediate negative impacts are the loss of human life or injuries and damages on the infrastructure occurring during the flood (Jerome Glago, 2021). They can also have impacts on food production, when agricultural fields are disturbed for example. As floods can lead to the over-saturation of the soil, erosion and infertility, long term damage to agricultural fields is possible (Aldardasawi & Eren, 2021). Economic activity and supply chains are also threatened. Apart from that, floods can also have an impact on sanitation and on the spread of water-borne diseases (Uddin & Matin, 2021). This is due to pollutants, which can be carried by floodwater, including pathogenic microbes. These contaminants pose a risk to human health and wildlife (Aldardasawi & Eren, 2021). Furthermore, the hydrology of freshwater in affected regions can be disturbed. While the nutrient deposition may benefit some aquatic species, many others may be threatened by it (Aldardasawi & Eren, 2021).

Apart from direct effects on infrastructure and the environment, floods have direct impacts on humans themselves that exert far beyond mortality and injuries. Once a flood occurs and it's impacts reach a certain threshold, it can cause widespread displacement of the affected communities. Floods are the primary cause of internal displacements on a global scale (Uddin & Matin, 2021). This further brings social and psychological challenges, thus adding to the variety of negative impacts.

In summary, floods can be classified as the most destructive of all natural disasters, as they attribute to one third of all natural disasters and they are also responsible for a third of all economic losses worldwide (Angelakis et al., 2023). Floods are also the disaster with the most fatalities (Molinari et al., 2019).

2.1.3 Past events in Austria

Although the majority of floods occur in Asia and Africa (Salas, 2024). Austria has also experienced severe flooding in the past. The most noticeable flood events were in 2002, 2009, 2013 and most recently in autumn 2024.

The flood event 2002 was particularly disastrous due to the intensity of the precipitation and the peak discharge. Also the speed in which the flood occurred was not usual (Godina et al., 2004). These preconditions produced two flood waves in a major part of Austria with a 50-year return period, in some regions even reaching a 100-year return period (Godina et al., 2004). The event resulted in a damage of around 3 billion euros in Austria (BAW, 2025). In response, the government issued the Flood Victim Compensation and Reconstruction Act 2002, allocating approximately 250 million euros for reconstruction purposes (Hochwasseropferentschädigungs- Und Wiederaufbau-Gesetz 2002 - HWG 2002, 2002).

The next major event in Austria, mainly affecting the north and east of the country, occurred in June 2009. Consistent precipitation before the main event, led to a presaturated soil, amplifying the effects during the main event. Between the 22. and the 30. of June heavy rainfalls triggered multiple flood waves. Due to the heavy saturation, this event also resulted in numerous landslides in affected regions (BML, 2009). Lower Austria was particularly affected by these events (NÖ, 2024).

In 2013 strong precipitation triggered the next heavy event in early June. Similarly to 2009, the soil moisture was already very high due to prior rainfall, limiting infiltration capacity and favouring surface-runoff during the main event (BML, 2015). Sediment deposition could be observed in numerous settlements within the Danube catchment, further highlighting the destructive capacity of flood waves. After this event, thorough analyses accounted the total damage to approximately 866 million euros, significantly less than in the event 2002, despite the 2013 flood being categorised as more extreme due to its higher discharge values in the Danube (BMVIT, 2015).

In autumn 2024 similar weather preconditions as in 2002 resulted in a significant flooding event, particularly in lower Austria and Vienna (BML, 2025). First damage estimates on the flood event between 14. and 21. September 2024 state a damage of 1.3 billion euros. This amount covers not only the direct impact of the event, but also indirect losses such as supply chain effects and company inventories (WIFO, 2024).

When comparing the 2002 and 2013 floods, the 2013 event generally showed a lower cost of damage and less fatalities even through it was considered more intense. Also in the 2024 event, experts claim, that Austria was well prepared for events of such magnitude (WIFO, 2024). Especially in Vienna, damage could be minimised due to a good flood management system (TU Wien, 2024). This emphasises the significant advancements of flood risk management in Austria since 2002.

This improvement underscores, that an effective flood risk management can minimise the risk of damage and improve response to a potential hazard. The following section will dive further into the topic of Flood Risk Management and introduce the key concepts, placing it in the context of Disaster Management.

2.2 Flood Risk Management

Disaster Management is defined as “the organization, planning and application of measures preparing for, responding to and recovering from disasters.” (UNDRR, 2017b). When talking about Disaster Management, there are some core concepts that are always mentioned: Hazard, Vulnerability, Exposure and Risk. It is important to understand them before dealing with specific Disaster Management approaches.

Hazard: A hazard is an occurrence of a natural or human-induced physical event. A flood for example, is a hazard. The occurrence of such an event could have impacts on vulnerable and exposed elements (Cardona et al., 2012).

Vulnerability: Vulnerability describes the tendency or susceptibility to be affected by a hazard. It is a result of different conditions and processes, e.g. “historical, social, economic, political, cultural, institutional, natural resource and environmental conditions” (Lavell et al., 2012, p. 32).

Exposure: These are all people, assets, resources, etc. that are located in the area that is affected by the hazard and that can potentially be influenced by it (Cardona et al., 2012). It is important to highlight, that while all elements located in the affected areas are exposed, this does not mean, that they are vulnerable to the hazard. If risk measures are applied, e.g. a dam that protects downstream buildings from a flood, the buildings are not vulnerable to the flood while still being exposed to it (Cardona et al., 2012).

Risk: The term “risk” is defined as the product of hazard, vulnerability and exposure and directly influenced by them. It is the potential for impacts of disasters, mainly loss and damage (Khan et al., 2008). If vulnerability and exposure are low for a given hazard, risk is also decreased accordingly.

Understanding these core concepts is a foundation for an effective disaster management. A widespread model that simplifies the approaches that allow to reduce exposure, vulnerability, hazard probability and risk overall, is the disaster management cycle. The model reflects the dynamic process of disaster management through its depiction in a cycle that consists of four reoccurring phases, which follow each other in a loop. This cycle is designed to assist practitioners and planners in reducing the impact of disasters (Roder, 2020).

The initial phase of the cycle covers the mitigation, which consists of all strategies dedicated to lessening the impact of a potential hazard (Roder, 2020). This could mean a better communication of risks to a potentially affected community in order to prepare for a disaster and guarantee a better response or to identifying which regions are prone to a specific kind of hazard in order to install structural measures like dams in the case of floods or landslides. In the specific case of flood hazards, mitigation measures also include long term landuse planning in flood prone regions, minimising the exposure due to floods. In order to identify these flood prone areas, flood hazard mapping is necessary (Kumar et al., 2023).

Disaster preparedness as the second stage ensures that the community is well prepared if a hazard occurs and can quickly respond to it. Early Warning Systems are a typical example of a preparedness measure (Roder, 2020). It is also important to identify high risk zones in order to distribute more resources in this area, suggesting that in this phase, flood hazard and especially exposure mapping is a key measure (Kumar et al., 2023).

The response stage begins as soon as the disaster strikes. The stage covers all actions in order to minimise suffering (Khan et al., 2008). They often include first aid and emergency services, or evacuation of affected people (Roder, 2020). For flooding events a typical example would also include fast measures to protect infrastructure, e.g. through sandbags (Kumar et al., 2023).

After the event, the recovery stage deals with restoration of the affected areas (Khan et al., 2008). It also includes measures that improve the standards, for example rebuilding an effective area with structural measures that decrease vulnerability in case, the same hazard affects it again (Roder, 2020). This stage also includes gaining financial assistance and incorporating new policy measures (Kumar et al., 2023).

Müller and Jüpner (2020) highlight, that there are multiple variations of the risk cycle. Specifically for flood risk management, they present a cycle that is divided into three parts: Coping, Regeneration and prevention. According to that cycle, flood risk management follows four core goals (Müller & Jüpner, 2020):

- Prevention of risks before an event in the flood risk area
- Minimising of prevailing risk before an event
- Minimising the negative impacts during an event
- Minimising the negative impacts after an event

As stated in Chapter 2.1.3 damage of the Austrian floods between 2002 and 2024 could be improved due to positive advancements in flood risk management. A big impact is also the Act of Flood Risk Management, which the EU has officiated in 2007. All member states are required to assess the risk of flooding in their countries. In regions, where a significant risk could be identified, flood hazard maps, flood risk maps and flood risk management plans need to be developed.

The flood hazard maps cover the geographical areas that could be flooded. For that, usually the following classifications are used:

HQ300: Low probability floods with an expected return period of 300 years or scenarios for extreme events.

HQ100: Medium probability floods with an expected return period of at least 100 years.

HQ30: High probability floods with an expected return period of 30 years.

For each of these scenarios, the flood extent (including water depth) as well as the flood velocity should be incorporated into the map.

Flood risk maps on the other hand, also include potential damage, by incorporating information on population at risk and also the economic activities in the region. Apart from the requirements of the EU law, there are also exposure maps. Additionally to the information of a flood hazard map, they add information on exposed infrastructure, assets or people in the area of interest (Papilloud et al., 2020).

Due to the presented relevance of identifying the flood hazard in order to mitigate and prepare for floods, the following chapter will deal with different approaches for creating such maps through flood modelling.

2.3 Flood Modelling

Flood Modelling is the key in creating the different kinds of maps presented earlier. There is a variety of available methodologies and software. The most common distinction types will be briefly explained. Afterwards, the software that is used in this study will be introduced.

2.3.1 Common differentiation

There exist many different approaches to Flood Modelling that can be categorized by their methodology, dimensionality, application and data requirements. Different literature on the topic categorizes these types differently. The following section will give an overview of the most common approaches.

Flood Hazard Maps can be created by multiple modelling approaches. Most commonly they are categorized by their methodology. Physically based models use physical laws to simulate flood processes. They require detailed input parameters and are computationally intensive (Kumar et al., 2023). Empirical models use statistical and historical data to predict flooding. They require extensive knowledge on past events in the area but are simpler than physically based models (Kumar et al., 2023). Conceptual models are a balance between empirical and physically based models. They focus on a simplified representation of catchment processes (Kumar et al., 2023). Numerical models solve mathematical equations, derived from physical principles. The models can be subdivided into their dimensionality, which is also another way to categorize models in general. One-dimensional (1D) models represent flow as a function of a single spatial dimension, typically along a river or channel. Two-dimensional (2D) models extend the analysis by incorporating lateral flows, making them more suitable for floodplain dynamics and overland flow. In more complex applications, three-dimensional (3D) models are used to capture detailed hydrodynamic interactions, particularly in urban and coastal environments (Teng et al., 2017). These models provide the highest level of detail but require significant computational resources (Kumar et al., 2023).

An important categorization of flood models is their application. The common differentiation is between hydrologic and hydraulic models. Hydrologic models are usually the prerequisite for a comprehensive flood model, as they focus how precipitation interacts with the topography and leads to flooding. Rainfall-runoff models are typical to predict how much of the rainfall transfers to runoff and directly influences flooding behaviour. Hydraulic models focus on simulation the water movement in the waterbody and how floods spread. Because hydraulic processes follow the hydrologic ones, there are also integrated models, which incorporate both parts (Kumar et al., 2023)

Different models can also have different data requirements. There are models, that are heavily data driven and rely on large datasets to identify patterns and conclude flood behaviour from them. An example of data-driven models are newer models based on machine learning algorithms. Another data requirement can be geographic information systems (GIS) and satellite data. They combine remote sensing data with hydrological and hydraulic principles and can be used over large areas (Kumar et al., 2023).

2.3.2 FastFlood

This study conducts flood hazard and exposure maps with the FastFlood simulation tool, developed by van den Bout et al. (2023). It is a novel approach that is able to simulate peak flood height and velocity 1500 times faster than conventional methods (van den Bout et al., 2023). This is achieved due to a steady-state-approach, where inflow and outflow of water in the system are balanced out (zero net height change over time). Although these conditions are a simplifications of real life conditions, it allows to reduce the simulation time significantly (van den Bout et al., 2023). Due to the simplification of the methodology, it cannot be considered to be a full hydrodynamic model. Data-requirements are also very low, simplifying the application, especially in data scarce regions. Essential input parameters are event duration, rainfall intensity, the terrain characteristics through a digital elevation model (DEM) and the surface roughness, defined through the Manning’s coefficient.

Using the categorization of flood models from the previous chapter, FastFlood can be placed in the following categories:

Based on methodology and dimension: FastFlood is a highly simplified two-dimensional numerical model, that uses numerical approximations for analysing flood behaviour instead of solving complex hydrodynamic equations (van den Bout et al., 2023).

Based on application: Because FastFlood focuses on water movement across the landscape that contributes to the flood behaviour, rather than generating rainfall-runoff behaviour, it is classified as a hydraulic model (van den Bout et al., 2023).

Based on data requirements: The FastFlood webtool allows the user to download relevant data from open-source sources and to incorporate it into the model directly. Therefore, the user has low data-requirements when using the tool. Nevertheless, FastFlood is a data-driven model as it requires the input information on terrain, precipitation and surface roughness to compute the model. It can also be classified as a GIS based model, as it uses geospatial data from the DEM (van den Bout et al., 2023).

The possibility to include open-source data into the model, makes FastFlood very well suited for data scarce regions, like the Redtenbach Catchment. The data is customised to the study area extent and doesn’t need to be downloaded on the computer but is rather used locally inside the web tool. Apart from that, the fast computation time makes it easy to generate multiple models very fast, with differing input parameters. The resulting raster layers can be downloaded which makes it comfortable to postprocess the results in a GIS based software.

3 Study Area

This Chapter will provide an overview of the study area, focusing on the catchment characteristics, past flooding events and the active Hofermühle landslide.

Geographical location

The study area consists of an approximately 15 km² catchment area located about 5 km southwest of the city of Waidhofen an der Ybbs in Lower Austria. The stream "Redtenbach" is about 7.78 km long and flows in a west-southwest to east-northeast direction towards the city, where it first flows into the Schwarzenbach and then into the Ybbs river within the city borders of Waidhofen an der Ybbs (Grafinger, 2004). A road runs parallel to the stream, accompanied by scattered residential and other buildings. Figure 1 shows the study area.

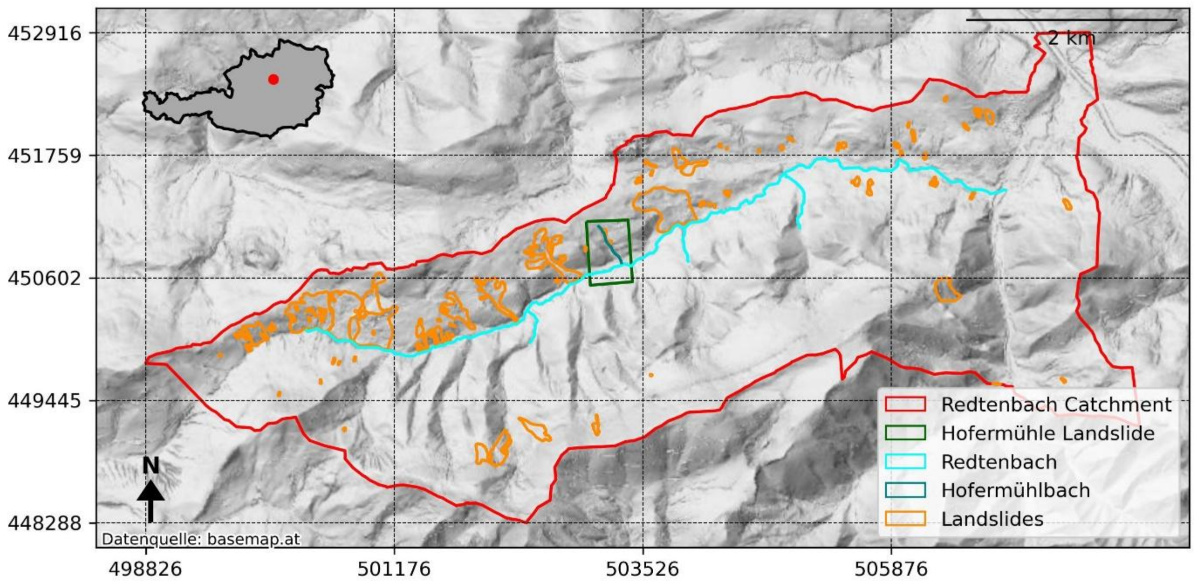

Figure 1: *Overview of study area (Source: Created by the author, landslide layer provided by Petschko et al. (2011)).*

Geology of the Catchment

Geologically, the catchment is located in the transition zone between Flysch zone and the Calcareous Alps (NoeSLIDE, 2025). The rock material in the flysch zone has a low permeability (Marinos & Hoek, 2001). The high proportion of clayey-marly material and its high degree of weathering characterises the flysch zone as landslide susceptible. In Lower Austria the highest density of landslides appears in this geological zone (NoeSLIDE, 2025). Figure 1 depicts all active landslides located inside the Redtenbach Catchment.

Climate

The area around the Redtenbach is influenced by an oceanic, temperate climate (Grafinger, 2004). The closest weather stations showing long term data are located in Waidhofen an der Ybbs and show daily measurements of temperature and precipitation for the past 100 years. The annual mean temperature between 1924 and 2024 is 9° C. The lowest average value lies at -1.37° C in January, the maximum temperature is in July with 18.83° C. Annual precipitation is at around 1136 mm. The lowest precipitation falls in February, where on average 72.57 mm are recorded. The peak precipitation of 143.81 mm in July. Figure 2 gives an overview.

According to this data, intense rainfall events (defined by the Wussow threshold of 17.1 mm per hour) last for an average of six hours in the region.

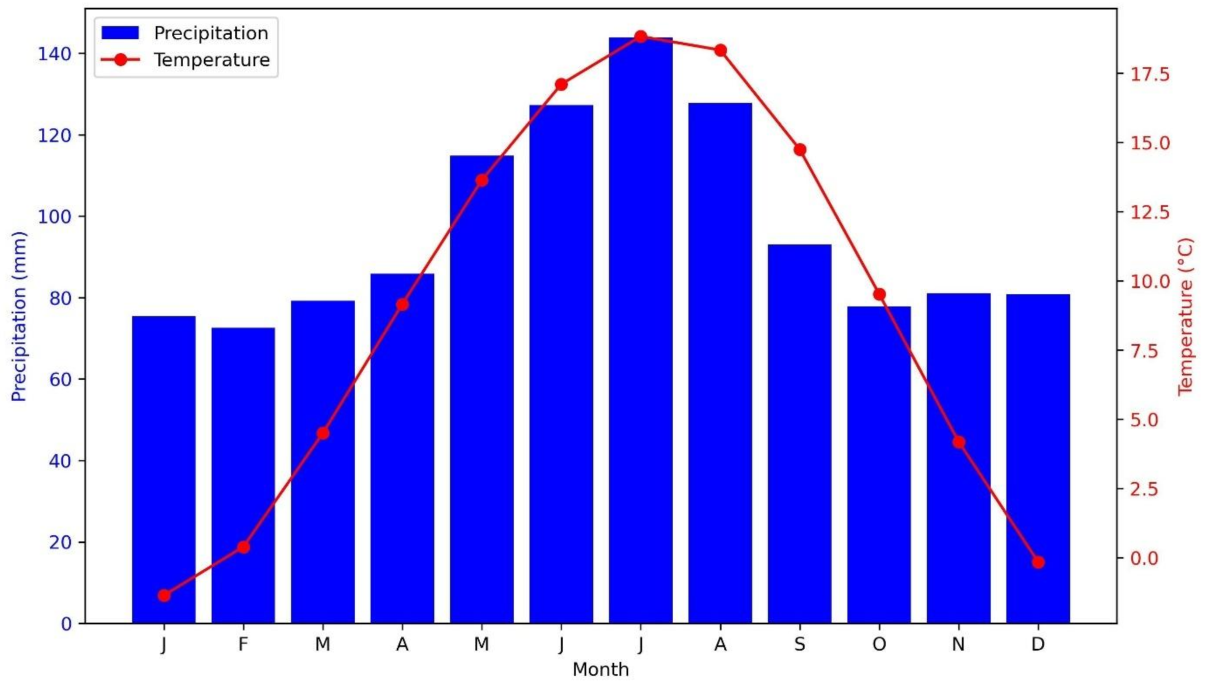

Figure 2: *Climate Diagram of Waidhofen a. d. Ybbs (1924-2024) (Source: Created by the author, data provided by GeoSphere Austria (2024b)).*

Soils

The most prevailing soil type in the whole district of Waidhofen an der Ybbs are brown earths, but also pseudogley and rendzina soils (Wenzel et al., 2016). Brown soils that are located in steep slopes are generally more susceptible to landslides, as their stability decreases. Paired with pseudogleys and rendzinas, that have a lower shear strength, the susceptibility further increases. Pseudogleys are characterized by a high water saturation. A higher soil moisture content makes the soil more susceptible to movement. Rendzina soils are generally more shallow soils, therefore providing a lower vegetation rooting. This further reduces slope stability (McColl, 2022). These factors also influence flood risk, especially in downstream areas. While brown soils favour flood risk especially in heavy precipitation events, pseudogleys favour flood risk due to their poor drainage capacity and their heavy saturation. Rendzinas' shallow profile can favour rapid runoff (Shishkov & Kolev, 2014). According to the eBod application the soils inside the study area are also mostly characterized by brown earths which consist of loamy silt or sandy loam in the upper soil horizon. With deeper soil horizon, the coarse fraction increases. The soil moisture is mostly moderately moist, with low to moderate permeability and moderate storage capacity (BFW, 2025). The lower layers also made up of strongly weathered to decomposed marly and clayey material. The weathered rocks are prone to instability, because they have a low strength and a high level of water seepage (Sausgruber, 2016).

Past flood events in the region

The Austrian torrent and avalanche control (*Wildbach- und Lawinenverbauung*) has some documentations on past events in the catchment of the Redtenbach. These reports state the occurrence of flooding for three instances: 2002, 2012 and one not dated event. For the event in 2002 and the one without a date, the report offers no further information except for an eyewitness report, stating that the Redtenbach has overflown in a specific location (Schneider, 2011). Only for the event in 2012, the documentation offers information on the intensity of the event and relevant measurements. On the 05.09.2012 there was a measured rainfall of 42 mm in only 30 minutes between 9 and 10 PM. A peak discharge of 21 m³/s was measured during the event. (Suchy, 2013). Figure 3 show the flood extent and documented damage; the photographs were provided by the torrent and avalanche control.

Figure 3: *Documented damages of the flood event in 2012 in the Redtenbach Catchment (Source: Wildbach und Lawinenverbauung Ereigniskataster (2012)).*

Hofermühle landslide

Since 2014/15, the Engage research group is monitoring an active landslide in the study area, located at the Hofermühle in Konradsheim (see Figure 1), called “Hofermühle landslide”. It is located on the southeastern slope with an inclination of 14° (Jimenez Donato, 2024). There is a small substream, called Hofermühlbach, which flows downwards into the Redtenbach. The appropriate course of the stream has been sketched in Figure 1. The occurrence and movement of the landslide has been documented long before the research project started. First activity on the slope has occurred around 1975. Already then, authorities tried to mitigate future events through forestation of the slope. In 2013 the Hofermühle landslide was triggered by heavy precipitation which lead to an earth-to-mudflow process down the Redtenbach valley with a speed of 20 m/h (Jimenez Donato, 2024). A few years later, in 2018/2019 the Austrian torrent and avalanche control installed a deflection dam to minimise further damage (Luhn et al., 2023).

A recent landslide model, developed by Jimenez Donato (2024) suggests the possibility of rupture of the landslide system, possibly triggered by intense precipitation. The landslide system consists of two subsystems. Subsystem 1 is defined by a slow-moving landslide with movement corresponding to a few cm per year. The landslide has a depth of 3.5 m according to the research group. On the other hand, Subsystem 2 is defined as a slow regressive landslide with a depth of 2 m (Jimenez Donato, 2024). In the modelled worst-case scenario, both Subsystems 1 and 2 would fail during the same event. The diversion dam installed in 2019 would not be able to avert the impact of such an event. The landslide material would move downstream along the Hofermühlbach until reaching the Redtenbach, possibly leading to a damming of the stream, or at least change the topology of the stream, which could affect flood behaviour.

Due to this possibility, the study includes this event by incorporating the modelled worst case scenario into the flood hazard map. Besides the Hofermühle landslide, there is another landslide further upstream from the Hofermühle. The so called Eckerwirth landslide is more massive than the Hofermühle landslide and is also active. So far, there is no similar rupture model for the Eckerwirth landslide, but the research group assumes, that this landslide could fail due to similar triggers. Through its higher magnitude, possibly leading to a higher alteration of flood behaviour in case of an event. The landslide can be seen in Figure 1, as being the next closest landslide upstream of the Hofermühle (left from the Hofermühle).

Given these characteristics and the research gap on a flood hazard map, the study area offers a unique opportunity to investigate flood possibilities for multiple scenarios and the influence of a multi-hazard, in this case, the rupture of the Hofermühle landslide and its interaction with a possible flood event.

4 Data and Software

To address the research questions, this study uses multiple data sources, some of which have already been mentioned in the previous chapter. To ensure clarity and traceability of the methodology, the following part will introduce all used data and software.

Flood Frequency Analysis

To answer the first research question and to conduct the Flood Frequency Analysis (FFA) both discharge and precipitation data are needed. The study uses discharge data from the donor catchment located in Schliefau in Lower Austria. The data is provided by the Austrian eHyd platform and covers daily mean measurements in m³/s at the measurement station from 1981 to 2021 (BML, 2024).

Regarding precipitation, multiple datasets are used for the FFA. The first one is also provided by the eHyd platform and includes the daily precipitation sum (in mm) for the donor catchment from 1992 to 2022. The station name is Steinholz and it is the closest station to the discharge station (BML, 2025). The other dataset covers the daily precipitation sum (in mm) for Waidhofen an der Ybbs and is used as the representative station for the study area, due to its proximity. The dataset covers a time span of 100 years, but consists of four subsets, corresponding to four different stations around the city. These subsets include:

1. Northern station: Operated from December 1, 1924 to October 31, 1988.
2. Eastern station: Active from August 1, 1989 to December 16, 2004.
3. Western station (near the city center): Collected data from October 10, 2002 to June 4, 2019.
4. Southwestern station: Currently operational, with data available from March 30, 2017 to July 14, 2024.

For further data analysis, also the hourly precipitation data for the same time interval is used. The merged datasets both for daily and hourly time intervals are provided by the Geosphere Austria Platform (GeoSphere Austria, 2024b) (GeoSphere Austria, 2024a).

The analysis is conducted using Python. The full code can be found in the appendix. The used libraries are Pandas (McKinney, 2010), Matplotlib (Hunter, 2007), Seaborn (Waskom, 2021) and SciPy (Virtanen et al., 2020). Their specific used is explained in the chapter methodology.

Flood Model

Apart from precipitation values, the FastFlood Model requires a Digital Elevation Model (DEM) as input. The DEM for the base scenario is provided by the online geoshop of Lower Austria. It has a 5-meter resolution and consists of a large area which is clipped to the study area extent (NÖ, 2025). For the landslide scenario, the result raster from the landslide model is used. This layer is provided directly by the research group.

All pre- and postprocessing steps of the result layers are done using QGIS. This also includes visual inspection of the results. For figure creation, python’s geodata visualisation libraries Geopandas (Jordahl et al., 2020) and Rasterio (Gillies, 2013) are used. The exposure analysis further uses open street map data on all mapped buildings in the study area through the QGIS plugin QuickOSM (Leroux, 2025).

5 Methodology

The methodology of this work can be categorized by three main steps. The first step marks settling the precondition that allows to perform the analysis. The study requires the identification of a suitable donor catchment which provides the necessary data that is missing in the study area. The first part of the methodology describes the workflow for that. Afterwards, the data is pre-processed to fit the requirements of the analysis. Only then the first research question (RQ) can be answered by calculating the precipitation values for different return periods. Afterwards the resulting values are used as input for the FastFlood Model. The resulting models are visualized and postprocessed with QGIS in order to answer RQ 2 and 3. In QGIS the exposure analysis is conducted which results in answering the last RQ. The following chapter will give a detailed description of the methodology for each work step.

5.1 Identification of donor catchment

The study area can be categorized as an ungauged catchment, meaning essential data is missing to perform the analysis (Odry & Arnaud, 2017). The opposite of an ungauged catchment is a gauged catchment. This describes an area, where all necessary data is available. In order to carry out a flood frequency analysis, this study uses discharge data, because peak discharge values can indicate flood events. This data is not available in the study area and also the FastFlood webtool doesn't allow to download discharge data for the study catchment. So in order to find suitable discharge data, that can be used for the study, a regionalization step is performed. This means that available discharge data is being transformed from a gauged site, where this data is available, to the ungauged site, such as the study area, where this data is not available (Odry & Arnaud, 2017). Regionalization is a common approach often used for catchments where essential information is missing (Merz & Blöschl, 2005). Through fitting certain defined characteristics, it can be assumed, that the gauged site depicts similar hydrological behaviour as the ungauged site. The data from the gauged site, or following named donor catchment, is used for the study catchment, under the assumption that the study catchment data would be similar, because of similar catchment conditions. Merz & Blöschl (2005) discuss two types of hydrological similarity: spatial proximity and catchment similarity. The paper concludes that catchments that are geographically close to the ungauged site and also share the same characteristics tend to depict similar flood generation processes and also similar flood frequency responses (Merz & Blöschl, 2005). Following these results, this thesis uses a qualitative assessment to find a donor catchment that is both spatially close and hydrological similar and where both discharge and precipitation data is available open source.

The catchment attributes considered in this study are:

- Catchment size
- Geology
- Soil characteristics
- Precipitation

A qualitative investigation of these attributes for catchments that offer available data yields one possible result for a donor catchment. Figure 4 shows the location of the donor catchment at the Schliefaubach in Lower Austria, approximately 20 km northeast of the study area.

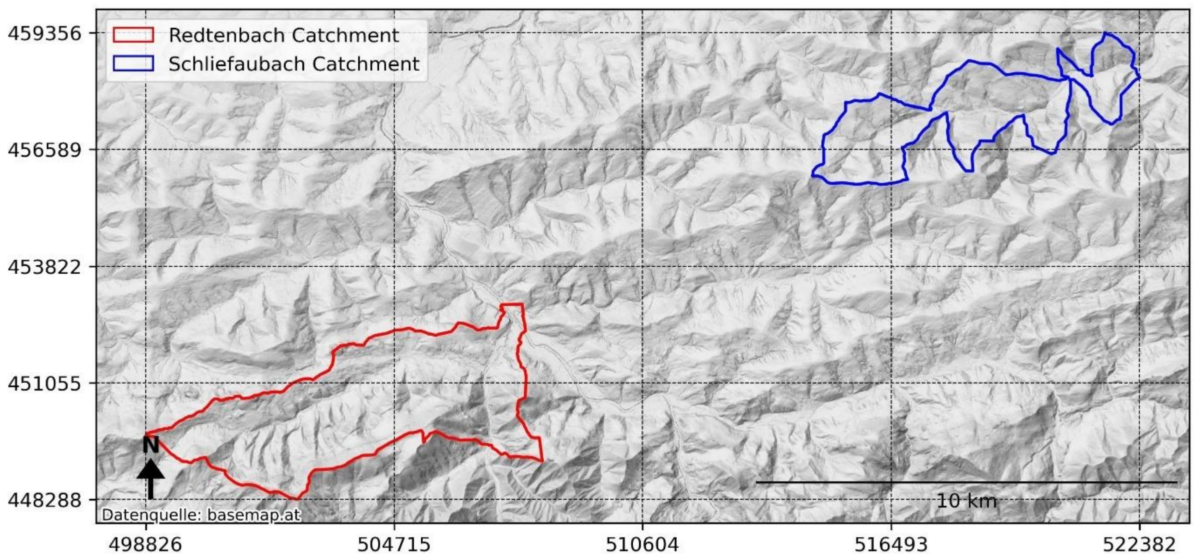

Figure 4: *Location overview of study (red) and donor (blue) catchments (Source: Created by the author).*

Specifically, the precipitation data of both catchments is compared more thoroughly to identify similarities and differences and state the mean difference between both datasets which will be used later on to modify the results. Figure 5 shows the precipitation comparison between both catchments.

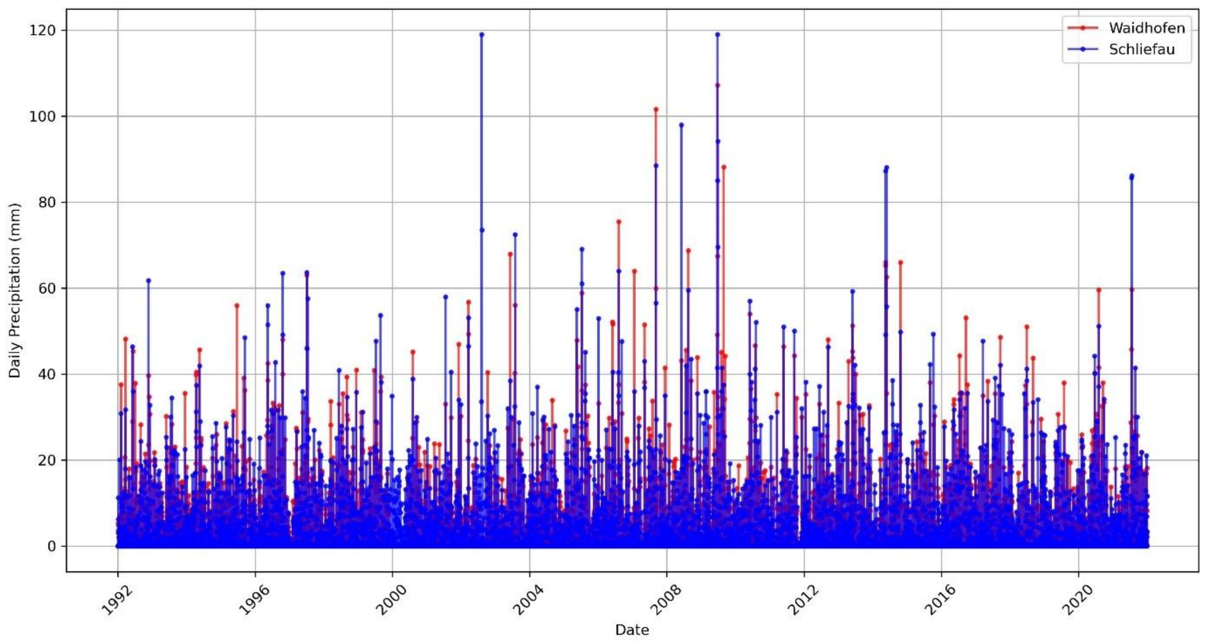

Figure 5: *Comparison of daily precipitation values for the stations Waidhofen (red) and Schliefau (blue) (Source: Created by the author, data provided by BML (2024) and GeoSphere Austria (2024b).*

For the next steps of answering RQ 1 the paper subsequently uses the discharge and precipitation data of the Schliefaubach catchment, if not stated otherwise.

5.2 Flood Frequency Analysis

After meeting all data requirements, the flood frequency analysis is performed to answer research question 1 and to obtain the essential input data for the following work steps, as precipitation is one of the two key input parameters needed for the Fast Flood Model.

This Work Step is performed in jupyter lab using multiple python libraries. The data preprocessing is done using the Pandas library (McKinney, 2010). All numerical computations are done with NumPy (Harris et al., 2020). Visualisations are conducted using the Matplotlib (Hunter, 2007) and Seaborn libraries (Waskom, 2021). The main part of the statistical analysis, consisting of interpolation and extreme value analysis are done by using SciPy (Virtanen et al., 2020).

Correlation Analysis

In the first step, the relationship between discharge and precipitation is evaluated by calculating the linear correlation. This is important because the discharge data is being used to calculate the precipitation values for the defined return periods (30, 100 and 300 years). Flood Frequency Analysis is usually conducted using discharge data and not precipitation data because not the whole precipitation that falls is directly attributed to the water inside the flooded water stream (see Chapter 2.1.1). Thus, the additional step is needed. By calculating the correlation, the study justifies the linear interpolation between discharge and precipitation in the later work steps. Using the Pandas library the correlation is determined to be 0.39, indicating a moderate but insufficient positive correlation between the two datasets. To optimise the correlation, a time lag analysis is performed to see if a delayed discharge response can be seen after an increase in precipitation between these two datasets. Time lags of up to 10 days are tested. The strongest positive correlation of 0.61 is calculated in a one-day time lag (Figure 6). This suggests that when precipitation values rise, discharge also rises significantly after one day. Due to this result, the study uses one-day lagged data for the following steps.

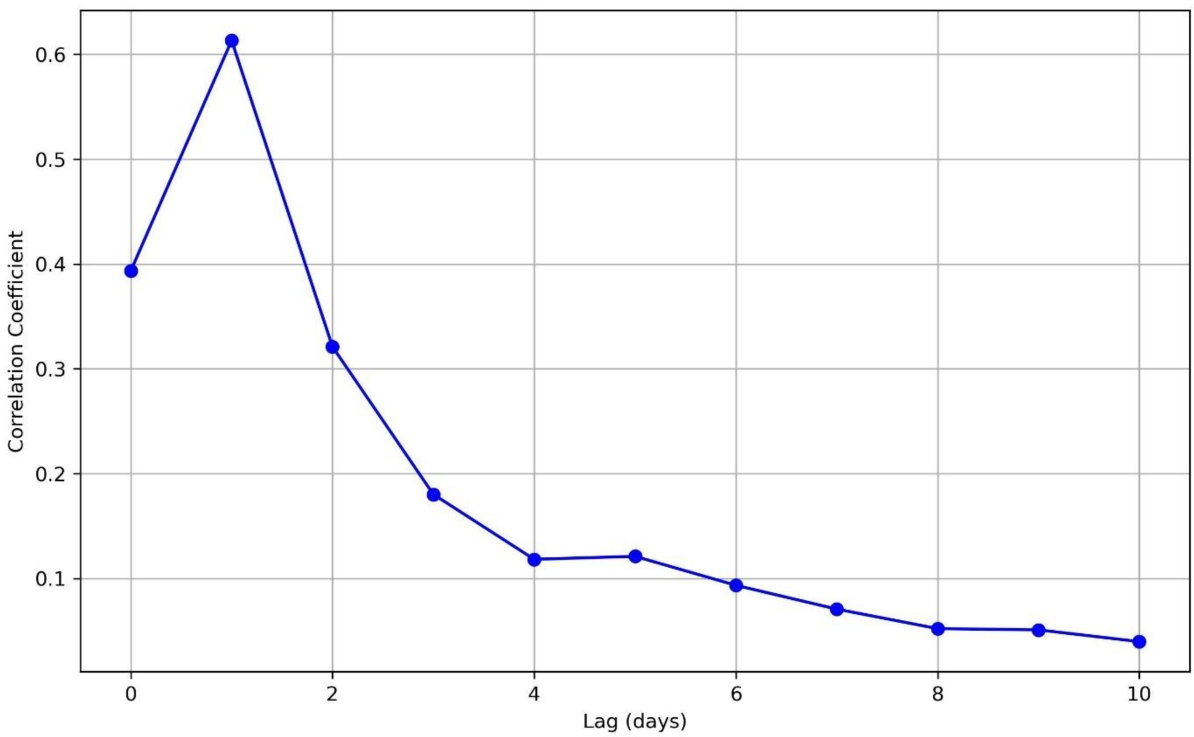

Figure 6: *Correlation between discharge and lagged precipitation (Source: Created by the author).*

Gumbel Analysis

The Gumbel distribution method is used to estimate the discharge values, corresponding to the extreme values of the return periods 30, 100 and 300 years. It is the most widely used method for calculating the reoccurrence interval of extreme events (Anghel, 2024; Shah & Pan, 2024).

To apply the Gumbel method, the dataset of discharge measurements is first processed to extract the annual maxima through Pandas' resampling function. To ensure data integrity, any missing values are dropped. Afterwards the annual maximum discharge values are fitted to a Gumbel distribution using the SciPy Gumbel fit function. This process estimates, what distribution parameters (location and scale) describe the observed annual maxima best. The percent point function from the SciPy library is then used to extract the return level for the return periods 30, 100 and 300 years.

Linear Interpolation

In the next step, the extreme discharge values identified through the Gumbel analysis are used to estimate the corresponding precipitation values through linear interpolation. As mentioned before, the time-lag of one day is now applied to the merged dataset including both the discharge and the precipitation time series, meaning that each days measured discharge is aligned with the previous day's precipitation, which likely amplifies the discharge according to the correlation. Then the dataset is sorted by the discharge values. A linear interpolation function from the SciPy library is then used to estimate the precipitation values corresponding to the calculated discharge levels. The function also includes an extrapolation step to ensure, that it can return precipitation values for extreme discharge values outside the datasets range. This is important because the discharge data only covers a timespan of around 42 years, but the goal is to find precipitation values for 30, 100 and 300 years, significantly exceeding the timespan of the discharge data.

Adjustment for catchment differences

Since the dataset originates from a donor catchment and the study focuses on another catchment, it is now necessary to adjust the resulting precipitation values accordingly. WorkStep 1 already describes the regionalization step between both catchments and highlights the comparison of precipitation values between Waidhofen and Schliefau. Calculating a mean difference between the values for the whole timeseries concludes that the precipitation is on average 0.33 mm higher in the donor catchment than in the study catchment. Therefore, this mean difference value is subtracted from the resulting precipitation values.

Conversion to hourly precipitation

The linear interpolation results in the daily sum of precipitation, but the FastFlood Model requires hourly data as input for a defined event duration. For this study the event durations 6 hours, 2 hours and 1 hour are chosen. 6 hours have been defined by analysing the available hourly precipitation data of the catchment to see how long an extreme rainfall event lasts in the catchment on average. As stated in Chapter 3 an extreme event is defined by a precipitation event, where precipitation exceeds the threshold of 17.1 mm per hour for at least one hour. The event starts as soon as precipitation is measured in one hour and ends as soon as there is no precipitation documented for one hour, so it marks a consecutive event with at least one hour where the threshold is exceeded. Therefore, this parameter is chosen due to empirical knowledge on rainfall characteristics in the study area. The other two event duration, 2 hours and 1 hour, on the other hand, are chosen as potential extreme events, based on the assumption, that future precipitation events are expected to decrease in duration but increase in intensity (Fowler et al., 2021; Marra et al., 2024).

The defined event durations lead to following data adjustments:

- 6 hour event: Daily precipitation divided by 6
- 2 hour event: Daily precipitation divided by 2
- 1 hour event: The daily precipitation is used without adjustment

This means that for a 6 hour event, the total sum of daily precipitation is split up on the six hours. The same applies to two hours and one hour respectively.

Code verification

An additional step was added to check the correctness of the code. Possible sources of problems were checked and fixed using ChatGPT (OpenAI, 2025).

5.3 Modelling

With the precipitation data per return period and per event duration now prepared, the flood model can be generated using the Fast Flood web interface. The application has been introduced in Chapter 2.3.2

The model requires a digital elevation model (DEM), which also defines the extent of the study area, and precipitation data per hour for a defined event duration in order to generate a flood simulation. There is an option to include additional data to make the model more detailed. The software offers the option to download datasets and integrate them directly into the model. For the study landuse and landcover data and infiltration data have been downloaded from the Fast Flood web interface and are included in the model to ensure a higher level of accuracy.

Fast Flood generates raster layers as results, which can be downloaded from the platform. The flood output layer shows the flood extent and depth. The velocity layer depicts the flood velocity. There are also more resulting layers, which were not considered in this study. Each scenario that has been modelled produced their own result layers. For this study 18 scenarios in total were modelled. They include all return periods (HQ30, HQ100 and HQ300) for all event durations (6 hours, 2 hours and 1 hour). Additionally, these scenarios are all modelled once for the base scenario and once for the scenario in which the Hofermühle landslide fails as explained in (see Chapter 3). To differentiate between the base and the landslide scenario, the DEM needs to be adjusted. While the base scenario is modelled using the unedited DEM in a 5-meter resolution, the landslide scenario requires an additional data preprocessing step. The raster layer showing the final deposition of material from the Hofermühle landslide is resampled to fit the DEMs resolution and aligned with it using QGIS. The DEM for the landslide scenario now depicts the change in topology due to the failure of the landslide and is used for modelling the 9 landslide scenarios. The maximum change in elevation is approximately 4 m.

Table 2 gives an overview of the modelled scenarios. All base scenarios use the original DEM and all landslide scenarios the modified DEM.

Table 2*: Overview of all modelled scenarios (Source: Created by the author).*

	Six hours		**Two hours**		**One hour**	
HQ30	Base scenario	Landslide scenario	Base scenario	Landslide scenario	Base scenario	Landslide scenario
HQ100	Base scenario	Landslide scenario	Base scenario	Landslide scenario	Base scenario	Landslide scenario
HQ300	Base scenario	Landslide scenario	Base scenario	Landslide scenario	Base scenario	Landslide scenario

For this study case a total of 36 layers are generated with the FastFlood webtool. 18 flood layers depicting depth and extent of the flood and 18 velocity layers showing the velocity of the flood.

Model Calibration

The next Work Step is meant to improve the model's accuracy by calibrating the Flood Model. Calibration describes the adjustment of the models' parameters in order to improve the models accuracy according to the individual catchment conditions (Molinari et al., 2019). Through this step the model can provide a more realistic reflection of the real catchment behaviour. Usually, calibration is performed to minimise the difference between observed and modelled flood behaviour (Molinari et al., 2019). In the case of this study, calibration cannot be performed like this, because the study does not model events that have been observed and documented in the past, but it models potential future events based on probability of occurrence. Therefore, model calibration in this study requires a different approach. The historical event from 2012 (see Chapter 3) is modelled in FastFlood, using the same DEM but the precipitation of 42 mm in a time frame of 30 minutes. As the documentation on this event states a peak discharge of 21 m^3/s for the event at the measured location, this discharge value is used for calibration. The FastFlood web interface offers the possibility to inspect values in the resulting flood model. It also offers the ability to model peak discharge values. The historically observed peak discharge is compared to the modelled peak discharge at the same location, showing that the modelled peak is overestimated. To calibrate the model and to reduce peak discharge at this location, the parameters for infiltration and roughness (Manning's values) are modified. To generate a lower peak discharge, infiltration values need to be higher, whereas roughness needs to be decreased. The parameters for the best fit (where observed and modelled peak discharge are almost identical) are identified and adapted into the original models.

Postprocessing

The resulting raster layers show the flood hazard maps that are visualised and analysed in QGIS and using the Python library Rasterio (Gillies, 2013). In order to answer the research questions 2 and 3, differences between the 18 scenarios are identified through visual inspection of the flood hazard maps. Apart from that a quantitative analysis is performed, where raster values for the same raster cells are compared using the Rasterio library to obtain differences, that are not directly visible to the eye.

Exposure Analysis

In order to answer research question 4, the exposure of infrastructure in the study area is calculated and mapped out. This part of the analysis is conducted in QGIS, where Open Street Map data on buildings is intersected with the flood layers generated by FastFlood. All buildings that are located inside the flood area are marked. In the end the number of exposed buildings is calculated for each scenario, giving an overview of the differences between the scenarios.

6 Results

6.1 Flood Frequency Analysis

The flood frequency analysis was conducted using the precipitation and discharge data of the study and donor catchment. Calculations using the Gumbel method and linear interpolation (as explained in Chapter 5.2) generated the values of precipitation per day for the different return periods HQ30, HQ100 and HQ300. These results have been modified to fit potential rainfall events for 6, 2 and 1 hour(s). Table 3 summarises the results.

Table 3: *Results of the Flood Frequency Analysis (Source: Created by the author).*

Return Period	Discharge Level	Hourly Precipitation for 6-hour event	Hourly Precipitation for 2-hour event	Hourly Precipitation for 1-hour event
HQ30	10.55	15.57	46.71	93.42
HQ100	12.49	19.97	59.9	119.8
HQ300	14.25	32.84	98.51	197.02

The results indicate that according to historical data a HQ30 event can be reached if it rains 15.57 mm per hour for a total duration of six hours. This corresponds to a total precipitation amount of 93.42 mm per day. For an event of two hours duration, the same daily value is reached when it rains approximately 46.7 mm per hour in two hours. For the 1-hour extreme scenario, the whole daily sum of precipitation falls in one hour. The peak discharge value underlying these results is 10.55 m^3/s. This value has been calculated using the Gumbel distribution.

In general, the rarer the event, the higher the precipitation value for every duration. The precipitation values for the HQ300 events are more than twice as high as the HQ30 values.

6.2 Flood Model

6.2.1 Overview

The flood model was conducted using the calculated precipitation values for the three return periods, HQ30, HQ100 and HQ300. For each of these scenarios, three different event durations have been modelled, 6 hours, 2 hours and 1 hour. In each of these events, two possibilities have been included, the base circumstances, and the landslide scenario, where the Hofermühle landslide collapses and landslide debris reaches the flooding area. This concludes 18 scenarios in total. The Fast Flood Application allows to download the raw flood layer, showing the flood extent and depth and a raw velocity layer, showing the velocity of the flood. This means that in total 36 raster layers have been conducted by the web application.

To make the results more feasible, they are visualised in a similar manner to the flood report by the ministry of agriculture, region and tourism (Wenk & Neuhold, 2020). Figure 7 shows a flood hazard map for the base scenario for an event duration of 6 hours. The map covers the whole catchment area. A zoom in shows the location of the Hofermühle in more detail for better distinction of the intensity classes.

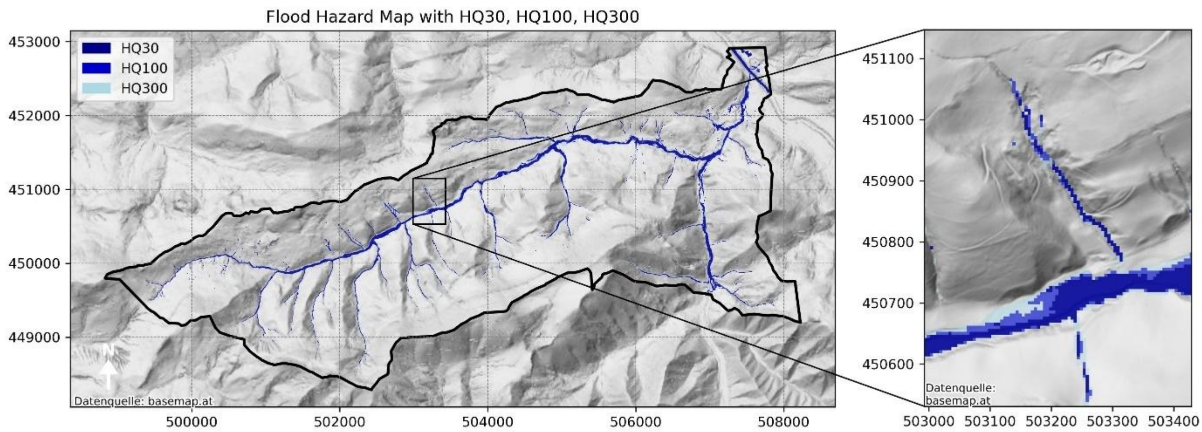

Figure 7: *Flood Hazard Map for the Redtenbach Catchment for the base scenario of 6 hours duration (Source: Created by the author).*

6.2.2 Results Flood Extent

The results reveal a clear relationship between rainfall magnitude, event duration and flood extent, where the extent of the flooded areas increases with rarer events. HQ300 consistently shows the most affected areas, whereas HQ30 the least. Depending on the exact location, differences between HQs and event durations can be higher or lower. Figure 8 displays three different observations and their localisation in the study area. Observation 1 is located downstream of the Hofermühle landslide close to the Eckerwirth landslide, which has been mentioned in Chapter 3. In Figure 9 it is visible that this area does not significantly change depending on the event duration. The flood extent is approximately the same for every scenario. Observation 2 is the location of the Hofermühle landslide. Right before the Hofermühlbach, which is flooded in the figure, a floodplain is covered with water. The size of the floodplain changes depending on the scenario. While it is significantly smaller in HQ30 than in the other scenarios, the difference between HQ100 and HQ300 is not as prominent. When comparing the different event durations (Figure 10) more observations can be made. The extent of the flooded area does not increase, but the shorter the event, the more area is already filled during the HQ30 scenario.

It is also visible, that flood extent increases for all scenarios, when additional water from the slopes reaches the Redtenbach. This is especially strong further downstream near the Bachwirtsiedlung, a small accumulation of buildings visible in Observation 3. Here, multiple rather thick contributors join the stream. The differences are visible in Figure 11 where the clear relationship between event duration and flood extent is highlighted. The shorter the event, the higher the extent. Especially an increase for the HQ30 event is visible.

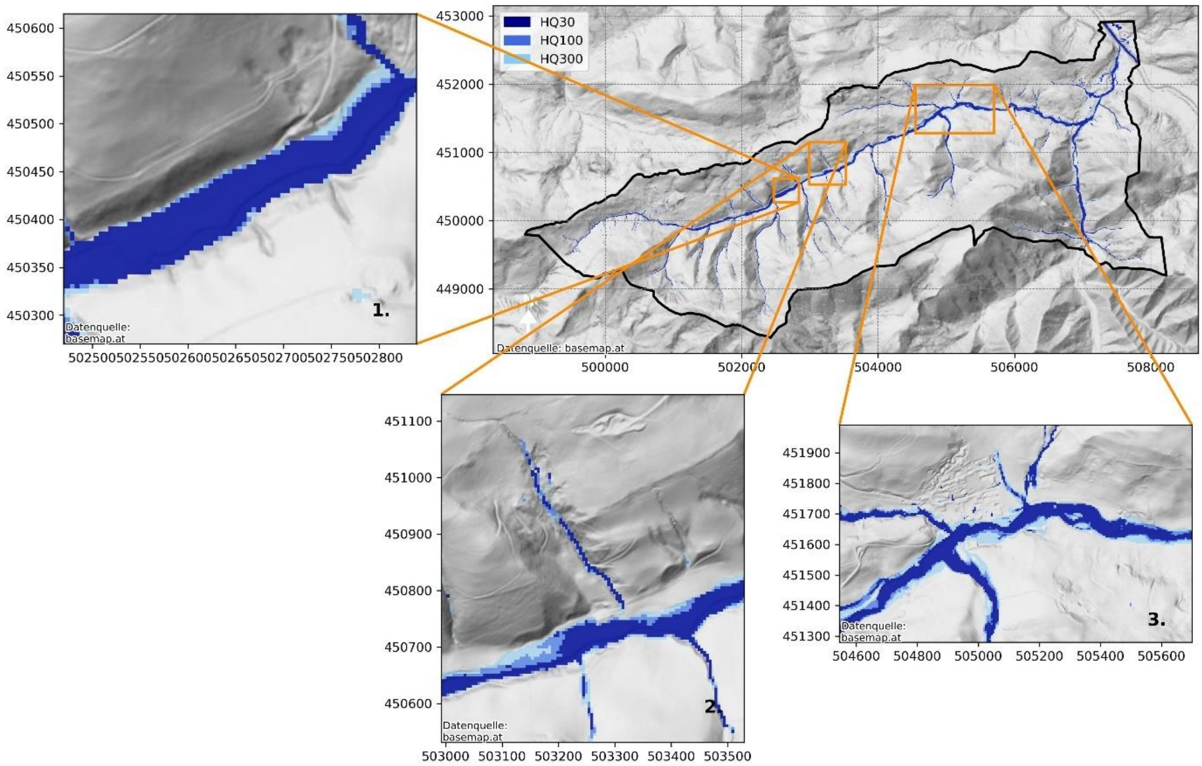

Figure 8: *Overview Map showing flood extent for all HQs for a 6 hour base event (Source: Created by the author).*

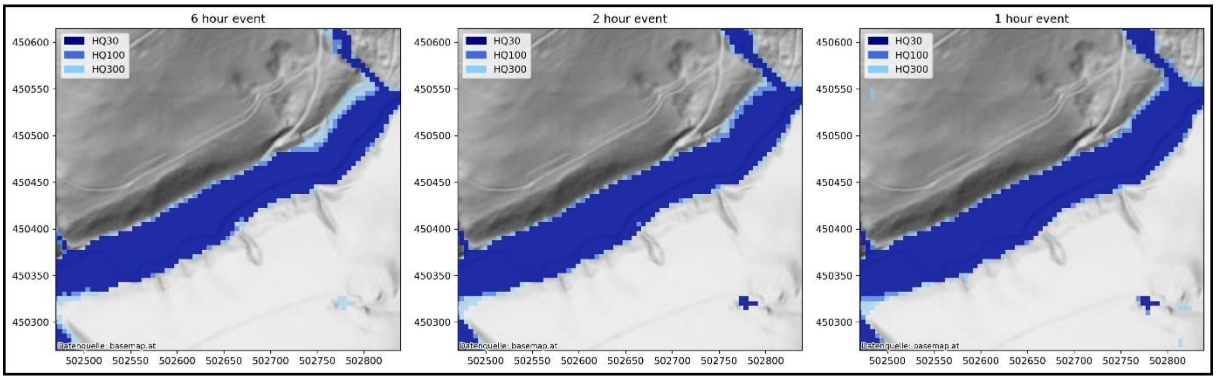

Figure 9: *Close up of Observation 1 for all event durations (Source: Created by the author).*

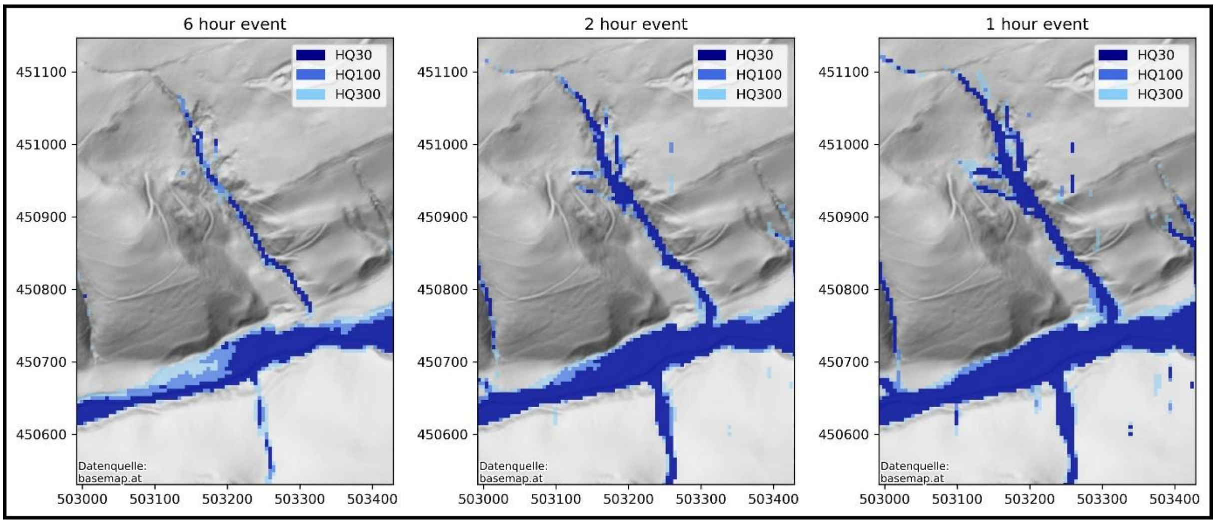

Figure 10: *Close up on Observation 2 for all event durations (base scenario) (Source: Created by the author).*

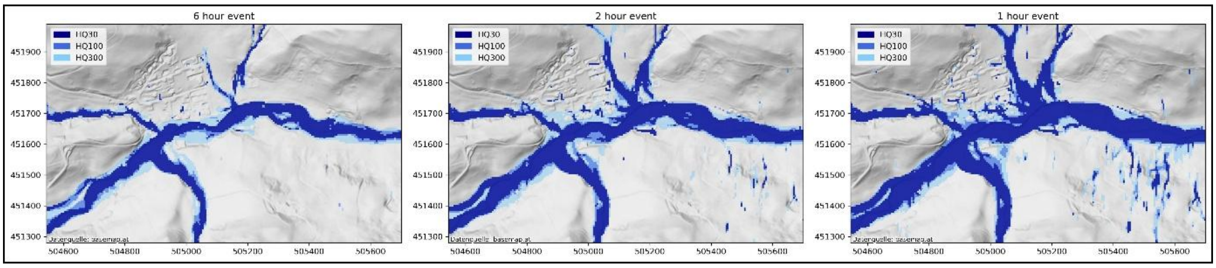

Figure 11: *Closeup on Observation 3 for all event durations (Source: Created by the author).*

The landslide scenarios amplify flood extents immediately downstream of the landslide's location (where the Hofermühlbach and the Redtenbach meet). This applies for every return period and event duration. In Figure 12, the differences between base and landslide scenarios at the Hofermühle landslide are highlighted.

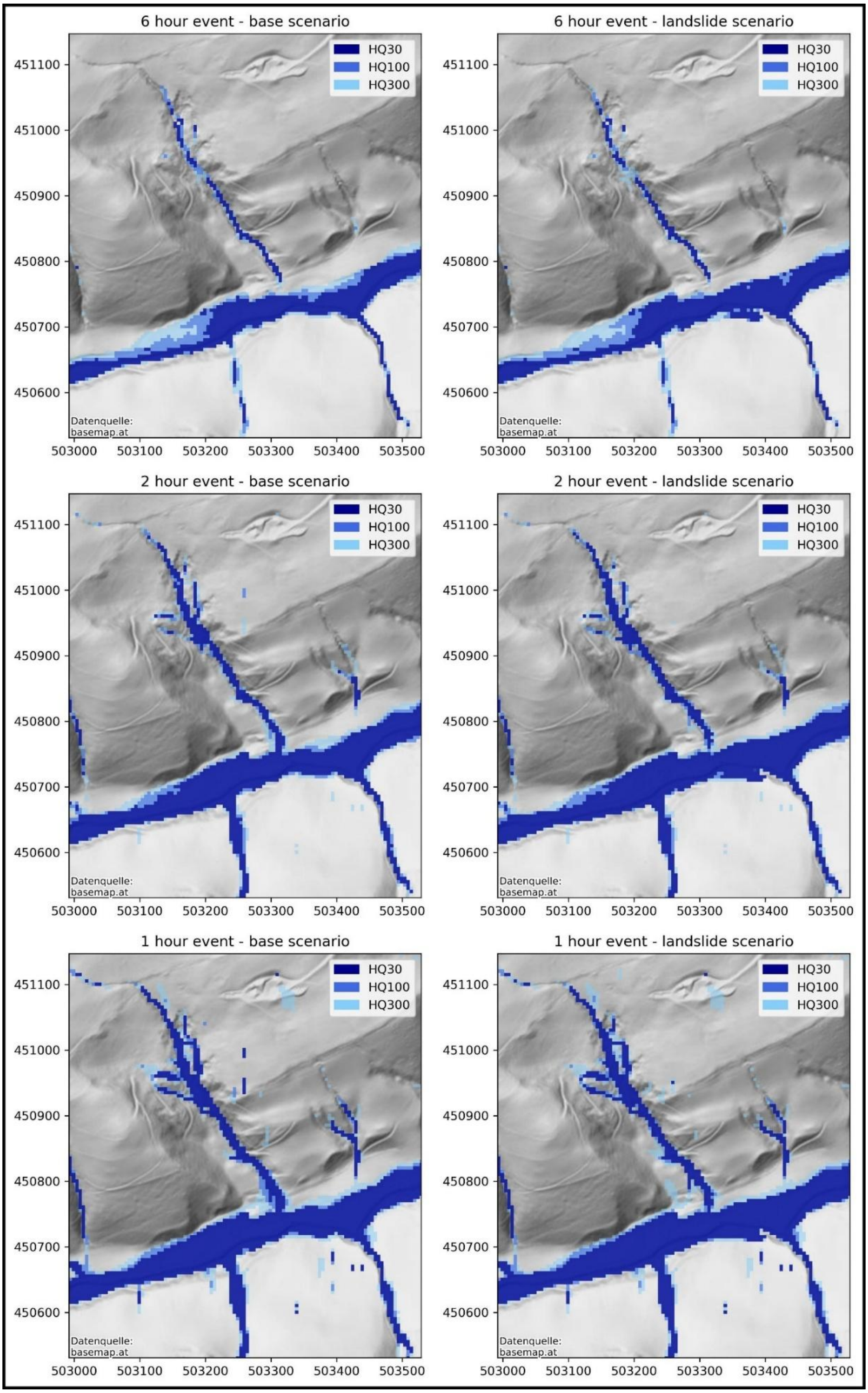

Figure 12: *Direct comparison of base and landslide events for all event durations for Observation 2 (Source: Created by the author).*

6.2.3 Results Water Depth

Apart from flood extent, the resulting raster layers also include information on the water depth for each raster cell. The 18 modelled scenarios show differences in their maximum water depth, which are summarized in Table 4.

Figure 13 shows the water depth map for the HQ100 one hour base scenario, giving an overview of the three key observations.

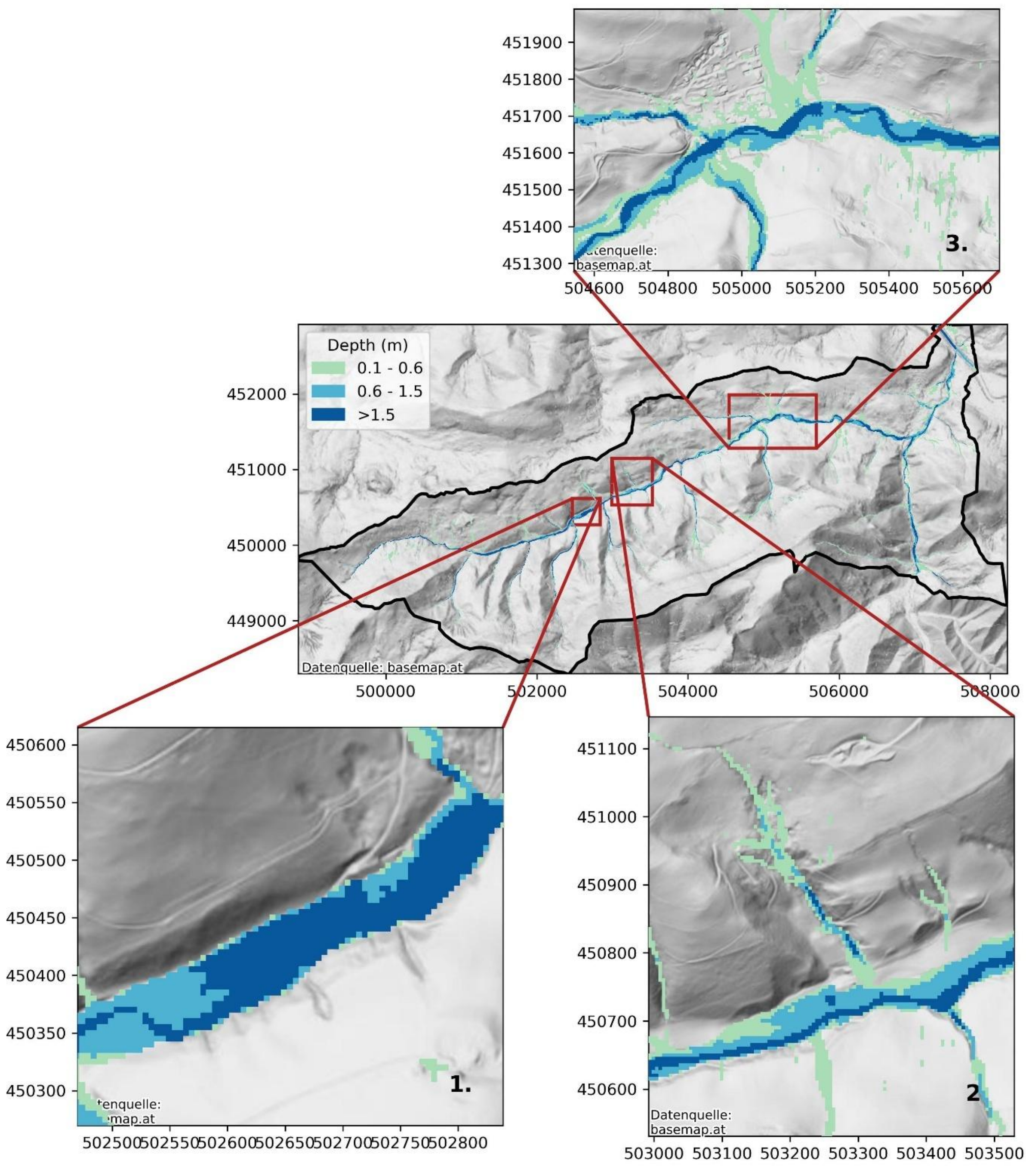

Figure 13: *Overview of water depth in the study area for a HQ100 1 hour base scenario, including three close up observations (Source: Created by the author).*

For reasons of clarity, the depth has been classified in three classes in a similar way as the ministry of agriculture, region and tourism chose for their information report on flood hazards (Wenk & Neuhold, 2020). The first class (< 0.6 m water depth) corresponds to a low water depth, which does not pose a significant risk to adults, but is possible for children. The operation of a car is not recommended even in this class (Wenk & Neuhold, 2020). The second class (0.6 to 1.5 m) poses a high risk for elderly people and children. The water level can now potentially reach building windows and water can infiltrate. The third class (> 1.5 m) can pose a major risk of injuries. The report states that areas with this water level should be evacuated. Damages on buildings can be high (Wenk & Neuhold, 2020).

General observations of the values depict some reoccurring patterns. Across all return periods, shorter event durations always result in a higher maximum water depth. For the HQ30 scenarios the highest maximum water depth lies at the 1 hour scenario, with 4.8 meters as opposed to the 2 hour event (4.3 meters) and the 6 hour events (3.66 meters). For HQ100 the values range between 5.38 meters (1 hour), 4.78 meters (2 hours) and 4.21 meters (6 hours). And lastly across the HQ300 scenarios, the 1 hour event produces a maximum water depth of 6.53 meters, whereas for the 2 hour event it lies at 5.92 meters and 5.26 meters for the 6 hour event duration.

Table 4: *Maximum water depth values for all scenarios (Source: Created by the author).*

Scenario	Maximum water depth in meters	
	Base	**Landslide**
HQ30 – 6 hours	3.66	3.66
HQ30 – 2 hours	4.3	4.3
HQ30 – 1 hour	4.8	4.8
HQ100 – 6 hours	4.21	4.21
HQ100 – 2 hours	4.78	4.78
HQ100 – 1 hour	5.38	5.38
HQ300 – 6 hours	5.26	5.26
HQ300 – 2 hours	5.92	5.92
HQ300 – 1 hour	6.53	6.53

This trend also shows, that the higher the return period, the higher the values. HQ300 consistently produces the highest values for every event duration, HQ30 the lowest. Therefore, the lowest value overall is coming from the scenario with the lowest precipitation magnitude and the longest event duration. In contrary, the highest value is generated by the scenario with the highest precipitation in the least amount of time.

Another key observation is, that there are no differences in the maximum water depth between the base and landslide scenarios. Across all return periods and event durations, the occurrence of the landslide does not change the maximum water level of the flood. Interestingly, the location of the highest water level is always the same for each scenario. This can also be seen in Figure 14, where the location of the maximum water depth cell is marked as Point A.

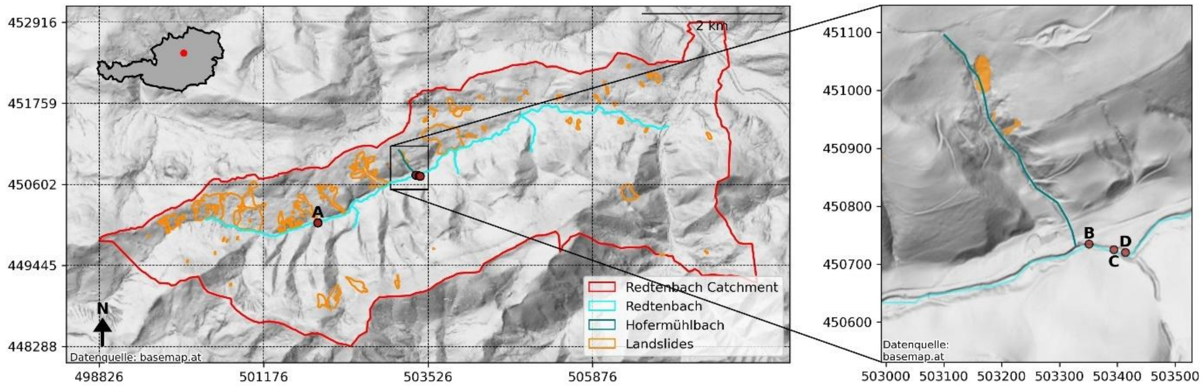

Figure 14: *Study Area and close up on Hofermühle including the location of Points A to D (Source: Created by the author, landslide layer provided by Petschko et al. (2011)).*

Point B on the figure shows the exact raster cell, where the Hofermühle landslide shows the highest net increase in elevation. Here the differences in water depth between base and landslide scenario are visible. Table 5 summarizes the results.

Table 5: *Water depth at Point B in meters for all scenarios (Source: Created by the author).*

Scenario	Water depth at Point B in meters	
	Base	Landslide
HQ30 – 6 hours	3.1	2.8
HQ30 – 2 hours	3.5	3.1
HQ30 – 1 hour	3.6	3.2
HQ100 – 6 hours	3.9	3
HQ100 – 2 hours	3.9	3.3
HQ100 – 1 hour	3.77	3.27
HQ300 – 6 hours	3.81	3.04
HQ300 – 2 hours	4.2	3.6
HQ300 – 1 hour	4.4	3.7

The values generally range between 2.8 and 4.4 meters, with the tendency of a shallower flood in all landslide scenarios, as opposed to the base scenarios. This applies to all return periods and event durations. Generally, the depth increases with higher event duration and return period, as visible in the Table.

Another observation is the difference in depth between landslide and base scenarios. For example, if comparing the two different layers for the HQ30 6 hour event, the highest difference in water depth is at 1.6 m, as seen in Table 6. The maximum difference increases with scenario intensity, except for HQ300 one hour and two hours, where the difference between base and landslide scenarios is the same. Depending on the scenario, the point of maximum difference is either located at Point C or Point D (Figure 14 and Table 6).

Table 6: *Difference between base and landslide scenarios for all events in meters and location on map (Source: Created by the author).*

Scenarios compared landslide vs. base	Maximum difference between scenarios in m	Location
HQ30 – 6 hours	1.6	Point C
HQ30 – 2 hours	1.7	Point C
HQ30 – 1 hours	1.8	Point C
HQ100 – 6 hours	1.7	Point C
HQ100 – 2 hours	1.8	Point C
HQ100 – 1 hours	1.9	Point D
HQ300 – 6 hours	2	Point D
HQ300 – 2 hours	2.5	Point D
HQ300 – 1 hours	2.5	Point D

6.2.4 Results Flood Velocity

The flood velocity maps show the flood velocity for the extent of the flood. For better visibility three categories are visualised. 0.1-0.6 m/s are considered low velocity, 0.6 to 2 m/s medium velocity and everything above 2 m/s is classified as high velocity (Wenk & Neuhold, 2020). The study chose the same classification as presented by Wenk and Neuhold (2020). In areas of low velocity, caution is required, in some areas suction effects can occur below the water. In the medium flow velocity class, some water movement can be visible on the surface. In some cases, cars can be tipped over. An evacuation is proposed. In the third high flow velocity class, dangers from turbulences in the water can be high, even in shallow water depth. Vehicles should not be used anymore in these areas. Buildings could be damaged due to the water currents (Wenk & Neuhold, 2020).

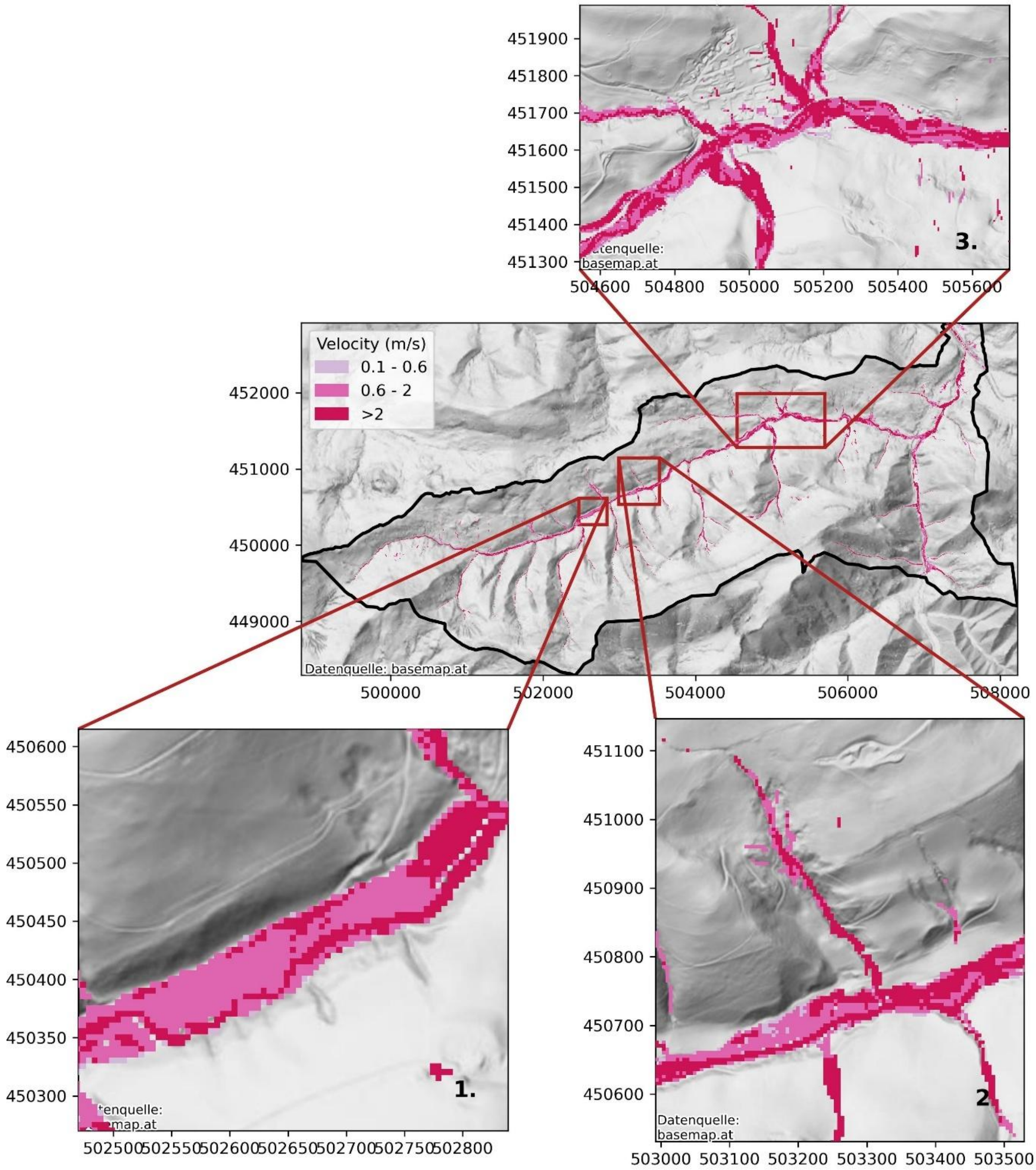

Figure 15: *Overview of Flood Velocity for the study area and three close up observations for a HQ100 2 hour event (Source: Created by the author).*

Figure 15 shows an example visualization for the HQ100 base scenario with an event duration of two hours. Between the different scenarios, distinct differences in the velocity can be described. With increasing scenario magnitude generally high velocity increases. Also, the shorter the event duration, the higher the percentage of high velocity areas. When comparing the base and landslide scenarios, differences are small, but there seems to be a tendency that landslide scenarios show a slightly higher percentage of high velocity areas, compared to the base scenario. The class of medium velocity behaves similarly to the high velocity throughout the different scenarios, but the affected area is generally smaller. While the HQ300 one hour scenarios cover shows a coverage of 3% of the whole study area for the high velocity class, for the medium class it is 2% for the same scenarios. The percentage of the low velocity class further decreases for all scenarios. Here the percentage for the HQ300 one-hour scenarios lies at around 0.2%. For this class, the distribution differs significantly from the other classes. The highest percentage of low velocity values is found in the HQ30 scenarios. HQ300 has the lowest percentage, but the difference between HQ100 and HQ300 is very low. The shorter the event duration, the lower the percentage of the low velocity class.

6.2.5 Results Flood Exposure

The flood exposure analysis describes how many buildings are exposed in each flood scenario. In total, 1587 buildings are mapped in Open Street Map for the extent of the study area. These include buildings along the Redtenbach, in the western outskirts of Waidhofen a.d. Ybbs and further away from the stream and floods area of influence. A building is classified as exposed if it intersects with the flood extent. The following table summarizes the results for each scenario. Figure 16 shows the exposure map for the example scenario HQ300 2 hour base scenario.

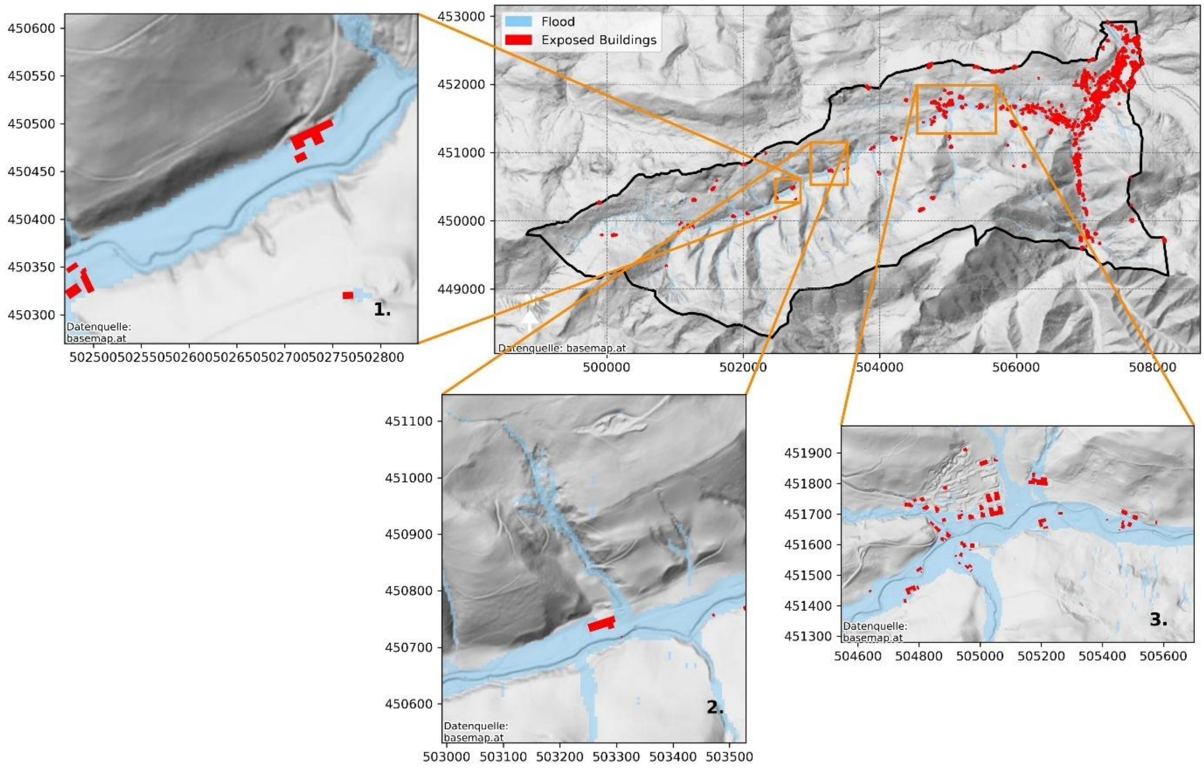

Figure 16: *Map showing exposed buildings in red for the HQ300 2 hour base scenario and three close up observations (Source: Created by the author).*

Table 7: *Number of exposed buildings per scenario (Source: Created by the author).*

Scenario	Number of exposed buildings	
	Base	Landslide
HQ30 – 6 hours	359	357
HQ30 – 2 hours	536	535
HQ30 – 1 hour	660	660
HQ100 – 6 hours	415	415
HQ100 – 2 hours	597	597
HQ100 – 1 hour	713	713
HQ300 – 6 hours	520	521
HQ300 – 2 hours	704	704
HQ300 – 1 hour	843	843

The results show that building exposure increases both with flood magnitude and also with shorter event durations. When looking for example at the HQ30 scenarios, the six-hour event duration leads to the exposure of 359/357 (base event/landslide event) buildings. If the same precipitation occurs in only two hours, the exposure rises to 536/535 buildings and increases further in an even shorter event with 660 buildings exposed. This pattern repeats itself throughout all return periods. Simultaneously the exposure always increases with return period throughout the same event duration. The one-hour scenarios show an exposure of 660 assets for HQ30, 713 for HQ100 and 843 buildings for the HQ300 scenario. This scenario also shows the highest exposure in total.

When looking at the scenarios more in depth, the comparison of the landslide influence with the base scenario shows only very little differences. Only in three occasions does the landslide show a change in building exposure. In the case of the HQ30 six-hour event the landslide scenario shows a decrease in exposure by two buildings. For the two-hour event it is one building. Contrary to that, the HQ300 six-hour event landslide scenario leads to an exposure of one additional building, according to the classification scheme.

6.3 Summary

To summarize the results, it can be said that in general, a rarer return period corresponds to a higher precipitation as seen in Table 3 (Chapter 6.1). A higher precipitation amount leads to a wider flood extent and water depth and a higher velocity. This is also reflected in the classified exposed buildings. Adding to that, the flood further increases if the same amount of precipitation rains down in a shorter period as the 1 hour scenarios consistently show wider flood extents, higher water depth and velocity and more exposure. The Hofermühle landslide does alter the flood model, specifically immediately downstream of the landslide. The differences in water depth reach up to 2.5 meters for specific locations. But building exposure does not change significantly with the influence of the landslide, only in three scenarios was there a change in classification recognized.

The following chapter will discuss the presented results, focusing on assumptions and data quality. It will further highlight advantages and limitations of the method and bring it into context of other studies regarding flood modelling.

7 Discussion

In the following chapter, the results of the study will be discussed in the context of the four research questions posed in the beginning of the study. The questions will be answered and afterwards the chapter will summarize challenges and limitations and possibilities for future work.

7.1 RQ 1

The first research question “What precipitation intensities refer to 30-, 100- and 300-year flood return periods?” is answered through performing a flood frequency analysis. The results are presented in Table 3 in Chapter 6.1. They indicate that the value for the HQ30 event is statistically reached once every 30 years, the one for HQ100 every 100 years and the HQ300 every 300 years.

When looking at the actual precipitation data from Waidhofen a. d. Ybbs, it is possible to validate these results by checking how often similar values have been reached historically over the timespan of the data. The data shows that the target value of around 93.42 mm per day (HQ30) was historically roughly reached in the dataset for one instance, specifically on the 09.08.1970 with a daily sum of 97.7 mm. Two other instances were on the 16.07.1941 and 28.08.2009, both reaching a precipitation sum of around 88 mm. The closest precipitation measurements for target value of 119.8 mm (HQ100) have been reached on the 23.06.2009 with 107.2 mm and on the 06.09.2007 with 101.6 mm. The next closest value of 138 mm was measured on the 26.05.1928. The target value of 197.02 mm for the HQ300 event was not reached over the timespan of 100 years. Statistically, the HQ300 value occurs once every 300 years. It is therefore possible, that the timeseries is too short to include a value of this magnitude. The closest values are 153 mm on the 12.08.1959 and then the already mentioned 138 mm in 1928. These two values are therefore the highest in the total data frame.

For an additional reference, the precipitation data of the donor catchment for the timespan of 30 years is also checked showing interesting trends. On the 27.06.2009 the station measured a precipitation of 94.2 mm in one day. This is the closest value to the calculated HQ30 extreme. The next closest event took place on the 04.06.2008 with a total precipitation sum of 98 mm. Another two events one on the 06.09.2007 and another on the 28.05.2014 have a precipitation of around 88 mm each.

For the HQ100 event, the calculated precipitation value of 119.8 mm was almost exactly hit in the historical data two times. The first instance was on the 07.08.2002 with 119 mm per day and the other on the 23.06.2009 with also 119 mm in one day. This is the exact same day, the closest to HQ100 value was also reached in Waidhofen a. d. Ybbs.

Across the 30-year timespan of the data, this value is the highest, ever reached. Therefore, there is no precipitation value, close to the HQ300 value. This is likely to the fact that the data only covers 10 % of the statistical timespan, in which the value should occur.

If placing the memorable flood events in Austria in the context of these findings, some observations can be made. The 2009 even has been identified in both locations as the closest to a HQ100 event and in the donor catchment as HQ30 only a few days prior. It is not possible to identify if this event has been classified as a HQ30 or HQ100 event in reality as peak discharge and precipitation differ significantly in different areas and there is no distinct information about the annuality for this specific catchment.

The 2002 event appeared in the mentioned values in the donor catchment once. With 119 mm in one day, it is almost exactly the calculated HQ100 value. It seems highly unrealistic, that a similar value is not measured at the station in Waidhofen but diving deeper into the reasoning reveals the first major limitation of the study. This regards the availability of data. Between the end of June and October 2002, the station in Waidhofen a. d. Ybbs does not provide a single daily measurement except for one day in 21.08.2002, where a precipitation value of 5.6 mm was measured. This suggests that the station was likely damaged by the heavy precipitation event and was not working for a considerable amount of time. It is likely that exactly the events that are relevant for this study might be the reason for issues, because these heavy events can lead to damage of the measurement stations and are therefore not documented. In contrary, for the timeframe of the 2013 event, there are available precipitation measurements for both weather stations. But the single values per day are not high enough to be placed in the defined range of the HQ30 and HQ100 events. So, although there has likely been a heavy precipitation event in the study and donor catchment, it might not have been that strong in that specific area. The fourth major event mentioned in Chapter 2.1.3 was the recent flooding event in September 2024. The data that was used for the FFA only covered a timeframe up until the 16.07.2024, meaning it could have not included the last major event. But looking at the most recent data from the same data source, it appears, that the event has been measured in Waidhofen a. d. Ybbs. From the 12.09.2024 a high daily precipitation sum has been recorded. Table 8 shows an excerpt of the data, with the intense increase of precipitation over the period of the flood event.

Table 8: *Excerpt of daily precipitation measurements for Waidhofen a. d. Ybbs station (Source: Created by the author, data provided by GeoSphere Austria (2024b).*

Date	Measured daily sum of precipitation in mm
10.09.2024	2
11.09.2024	16.1
12.09.2024	33.5
13.09.2024	63
14.09.2024	75.3
15.09.2024	27.2
16.09.2024	53.8
17.09.2024	1

The data suggests that the event was also evident in Waidhofen a. d. Ybbs, although not strong enough to be classified as a HQ30 event according to the presented results.

Considering these comparisons with real historical data, the results are validated and are rated as sufficient to answer the first research question. Due to some missing data of past events, such as the 2002 event and the 2024 event it can be assumed that the values might even be slightly higher in reality.

7.2 RQ 2

The results of RQ 1 are used as input data to answer research question 2: "How do flood magnitude, - depth and velocity change with varying rainfall intensities?" for the flood hazard maps of different scenarios.

The general findings show, that in all scenarios, a higher amount of precipitation results in a higher flood. The rarer the event, the higher the impact and also for the same amount of precipitation, the faster it falls, the higher the impact. This is visible in all parts of the study area, where the topology of the catchment allows the water to expand. One visible exception from this is Observation 1 in Figure 9, which highlights that the topology of the catchment has an influence on the flood behaviour. It is assumed, that in this specific location steep slopes close of the stream on the sides and there is not much space for water to expand. The area is already quite flooded during the HQ30 event, and there is not much change in flood extent with increasing intensity. But there is a change in water depth, as it increases consistently with rising flood intensity, underlying that the flood hazard is increasing in this area if the precipitation increases.

As Chapter 2.1.1 explained, not all precipitation falling directly contributes to flooding. Depending on the soil characteristics, more or less water is infiltrated, before it can run off to influence water height changes in the waterbody. Important factors are the permeability of the soil and already prevailing soil moisture in the moment of the event. For less severe events, these preconditions can have a big influence on the amount of rainfall, that leads to floods (Brunner et al., 2021). A study by Brunner et al. (2021) argues, that there might be a catchment specific threshold, where, if exceeded, rainfall water strongly influences flood magnitude. In this scenario, rainfall is so intense, that the capacity to absorb water by the soil is exceeded so quickly, that much more water is directly transformed into runoff, thus contributing to flooding. Under these preconditions, soil characteristics have hardly any influence on flood formation (Brunner et al., 2021). This thesis has not analysed, whether such a threshold exists in the study catchment and how high it is, but still, the different results on flood intensity show, that indeed, rainfall intensity has a crucial impact on flood behaviour in this region. Figure 17 compares two scenarios, that seem very similar visually, but with very different rainfall conditions. The HQ300 6-hour event is based on a precipitation of 32.84 mm per hour for a duration of 6 hours, making a total of 197.02 mm. For the HQ30 1 hour event it is a precipitation of 93.42 mm per hour for 1 hour. That means that in total, the HQ30 event is based on an input of approximately 100 mm less precipitation, but the extent of the flood inside the Redtenbach is very similar. Even more striking is the observation that the flooding inside the Hofermühlbach appears to be more intense for the HQ30 event, than for the HQ300 event. So even though the total amount of rainfall contributing to this event is a lot higher in the HQ300 scenario, the hourly precipitation is three times higher in the HQ30 scenario. The modelled behaviour of the flood, especially the increased runoff though the Hofermühlbach in the HQ30 scenario, indicates, that there might indeed be a threshold reached if just looking at the hourly precipitation. It has to be emphasised, that for all flood models, the settings for soil infiltration and roughness are the same, so different preconditions cannot be the reason for the observed differences in flood responses. During the longer event, more water falls in total, but the timespan is longer, which indicates that the soil has more time and capacity to absorb water and minimise the impact, whereas during the short event, the capacity is quickly exceeded, leading to a more intense runoff response.

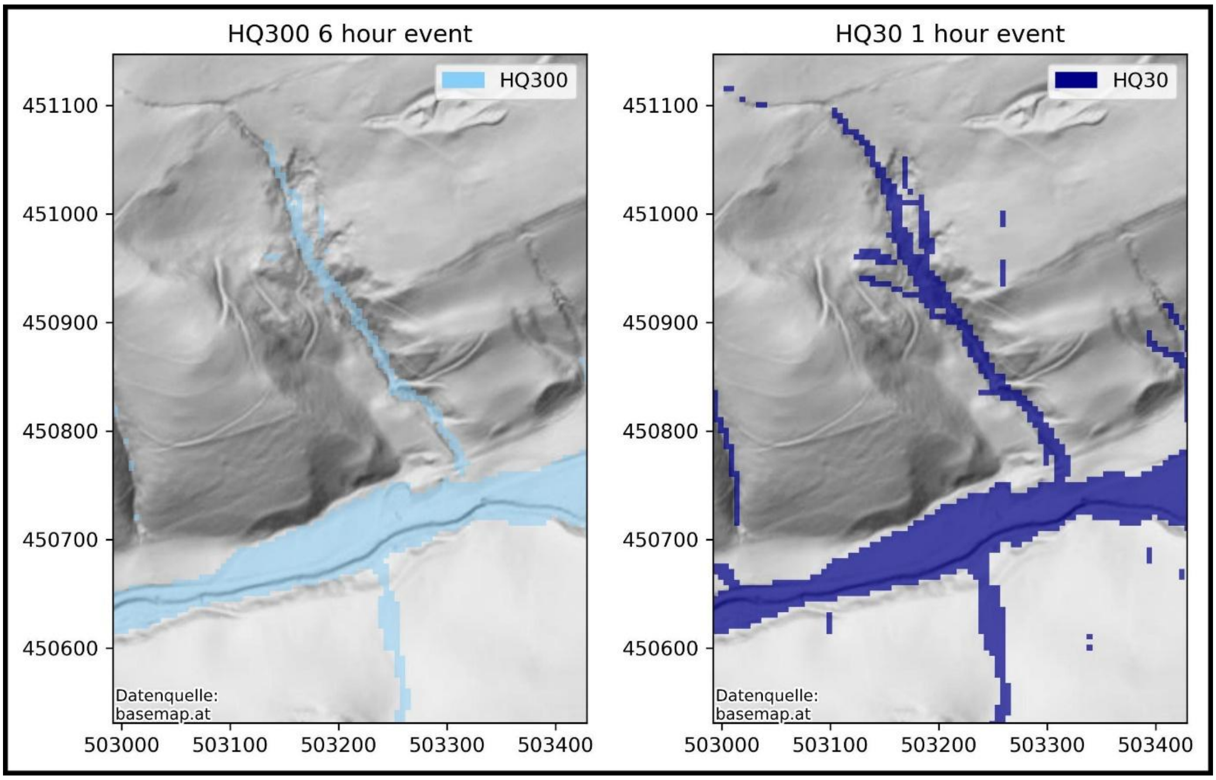

Figure 17: *Direct comparison of the extents of HQ300 6 hours and HQ30 1 hour base events (Source: Created by the author).*

With climate change, it is expected that extreme precipitation events shift and that events become shorter and more intense (Haslinger et al., 2025). This is due to the changes in the water-holding capacity of the atmosphere according to the Clausius-Clapeyron relationship (Marra et al., 2024). A recent study by Haslinger et al. (2025) analyses changes in short precipitation events in Austria and concludes that since the 1980s these events increase in Austria and specifically in catchments smaller than 50 km² have a significant effect on flood occurrence. The decision to include short duration extreme events of 2- and 1-hour durations in the study highlights that this expected shift could enhance flood risk greatly, as the magnitude of the floods increases significantly even for comparatively lower events like the HQ30 events, compared to HQ100 or HQ300. A future extreme event with the intensity similar to the 2002 event for example, could have significantly higher impacts if occurring in a smaller time frame. This emphasises that the expected changes in rainfall patterns through climate change need to be included in future flood risk management practices.

7.3 RQ 3

"How does a potential stream blockage further affect the flood characteristics?"

The Hofermühle landslide showed a difference in the scenarios immediately at the affected site. For no scenario where there differences in flood extent, depth and velocity outside of the area of Observation 2, indicating that the landslide alters the flood only in the immediately affected area but does not have further implications downstream. The results show, that for the landslide event, flood extent becomes wider, whereas water depth decreases right at the point where the landslide material meets the Redtenbach (Point B in Figure 14). These findings suggest that the landslide acts as a natural dam inside the stream. The water is hindered by the landslide material and has to move around the debris, which leads to a bigger extent in this area. In the area, where material is accumulated, the water level becomes shallower. Right before the natural dam, the water depth is actually increased in the landslide scenario, further suggesting that the water builds up in front of the dam, before it expands on the sides. This can be seen in Figure 18, where the base and landslide scenarios are contrasted for a better overview. Similar behaviour can be observed in multiple studies dealing with landslide dam breaching. A paper by Song et al. (2022) for example, models how water is building up in front of the a natural landslide dam in a river and ultimately leads to an outburst flood due to the dam breaching for three cases (Song et al., 2022). In all three analysed cases, the outburst flood leads to an accelerated flood and a high peak discharge (Song et al., 2022). Another study, that deals with landslide dam breaching in Burundi finds similar results (Nibigira et al., 2018). Although the preconditions are similar in the Redtenbach study case, an acceleration of the flood cannot be confirmed here. The flow velocity values for the extent of the Hofermühle area (Observation 2) are actually slightly lower in the landslide scenario, then in the base scenario. The maximum flow velocity for this extent is at 58 m/s for the base, and 56 m/s for the landslide scenario. Further of looking at the values more detailed for the single raster cells, the velocity values are not higher after the landslide, as opposed to the base event. This observation indicates that the natural dam is not breached in the modelled results, and it withstands the flood event. But it is very important to note, that this observation could be due to the fact, that the chosen model is not able to distinguish landslide debris from plain digital elevation. Van den Bout et al. (2022) deal with the complexity of modelling multi-hazard events, as there are many hazard interactions that are not included in the modelling tools. An important factor that is often not included is for example, that the sediment content of water changes in case of a dam breach (van den Bout et al., 2022). The water might behave differently if more sediment is included and it could have very direct implications for flood damage, especially if coarse debris is included. To analyse the dam breaching a tool is needed, that analyses both the landslide and the flood in an interconnected manner. Using only the result from the landslide model FastFlood does not automatically assume, that the increase in elevation could be due to loose material damming the stream and does not include the possibility that this material could move in a way a outburst flood would do.

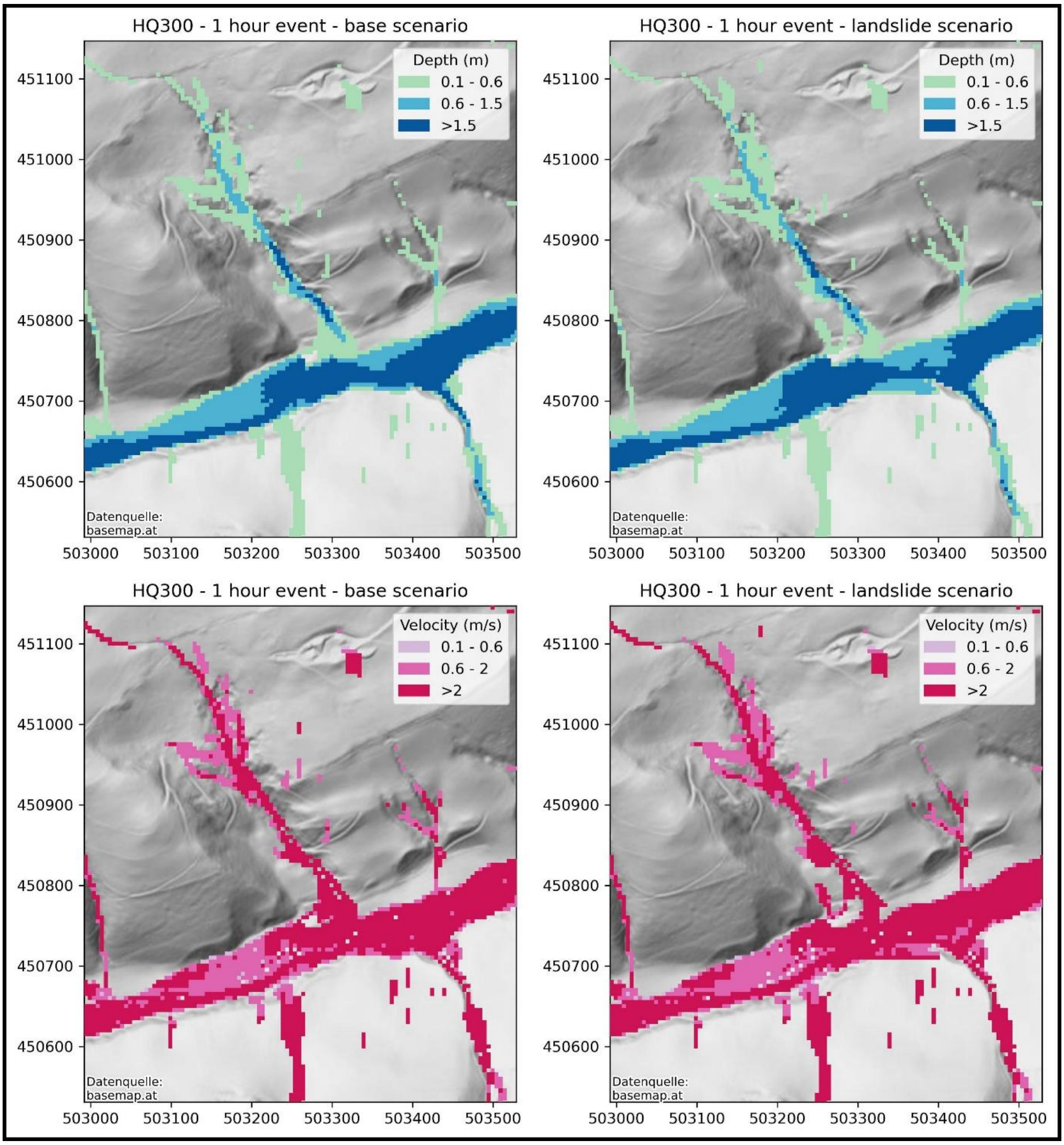

Figure 18: *Direct comparison of flood extent and water depth (first row) and velocity (second row) between base and landslide scenarios for HQ300 1 hour (Source: Created by the author).*

Another factor which is also not included in the study is the influence of other landslides in the region. As stated in the Chapter 3 the landscape is prone to sliding and multiple active landslides are mapped out (see Figure 1). If a potential damming of the stream is modelled for the Hofermühle landslide, the possibility for the same effect to appear at other active landslide sites should be considered as well. And if a landslide prior to the Hofermühle landslide already changes the topology of the stream, there is a chance that the impact of the Hofermühle landslide will look different, because of differing preconditions. This probability of a "domino effect" highlights that flood risk assessment and forecasting can be really challenging in an area prone to landslides. Due to quick landscape changes in this area, similar events can have very different outcomes. So using past precipitation events is not enough to assess the flood risk in this area. Coupled methods that include both landslide and flood risk are necessary to understand the complex interplay of these hazards and to understand, how they influence each other. What adds to that, are the effects of climate change on landslide probability. The earlier section already explained, how climate change influences rainfall behaviour and increases the risk extreme rainfall events and subsequently floods. Due to the just established complex relationship between landslides and floods it is also important to mention the effects of climate change on landslide probability. Specifically, the increased precipitation rates can trigger more landslides in Austria (Offenthaler et al., 2020) because the increased moisture in the soil increases pore water pressure, which reduces the shear strength of the slope (McColl, 2022).

7.4 RQ 4

The last research question deals with "How does the exposure of infrastructure inside the study area change under different rainfall-induced flood scenarios?" So, for this question, the earlier discussed results are coupled with available data on buildings in the study area in order to see, how many buildings are exposed per scenario. Because these results are based on the same input raster layers as the other two research questions, the results follow the same general pattern. The higher the flood magnitude, the more buildings are exposed, because more area is covered by the flood. But that alone does not give an implication on the severity of the exposure. A building might be classified as exposed, but the water level only reaches a few cm, while another building might just not be classified as exposed at all, because of just one pixel. This leads to a lot of uncertainty regarding the results. How sensitive the results are, can be seen very clearly when comparing the landslide and base scenarios. As the results chapter described, there are only three instances where the landslide and base scenarios show differences in the number of exposed buildings. These are the HQ30 6 hour and 2 hour scenarios and the HQ300 6 hour scenario, For the latter, one additional building was marked as exposed for the landslide scenario. Figure 19 shows a close up of this building.

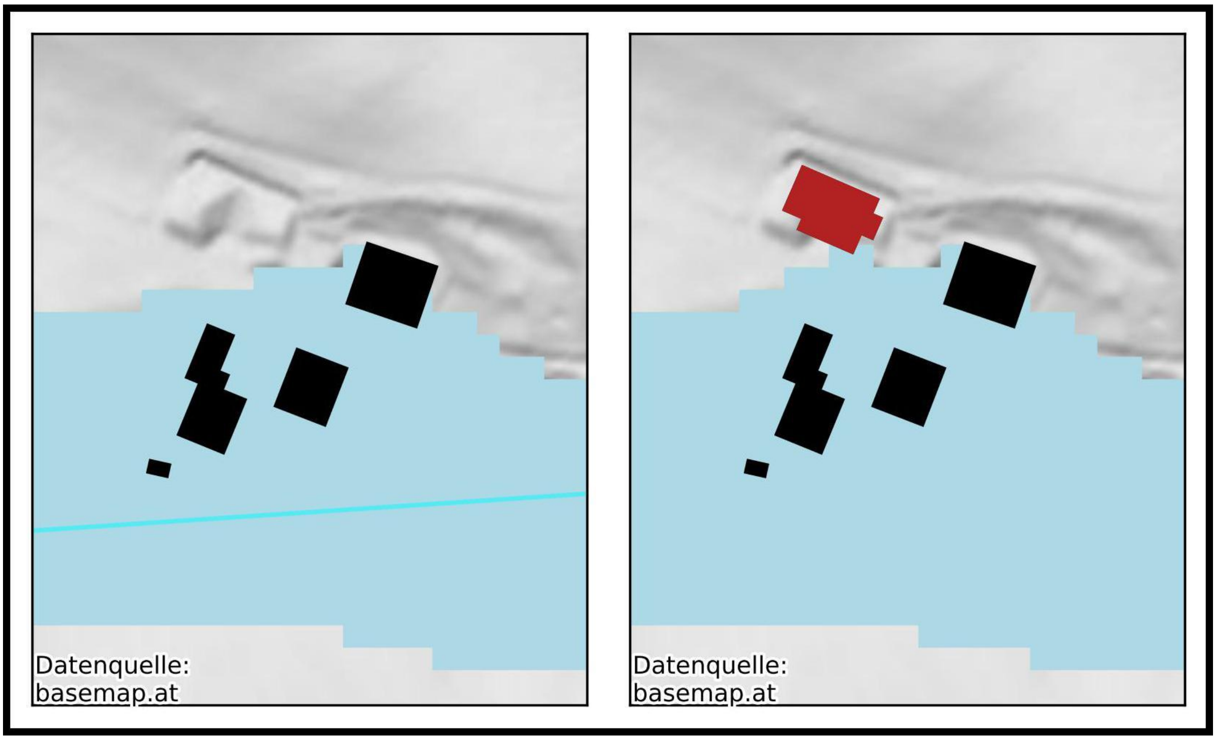

Figure 19: *Comparison of exposure analysis for HQ300 6 hours base (left) and landslide (right) scenarios. The red building displays the additionally classified building (Source: Created by the author).*

It can be seen that the red building in the figure was classified for the landslide scenario, even though the difference in the flood layer is fairly small. An additional flood layer pixel just barely intersected with the building, therefore marking it. Of course, under real circumstances the flood does not move in pixels and borders would be slightly different. It is therefore difficult to make a clear statement about whether this building is really exposed or not. The same pattern could be observed for the other two scenarios where base and landslide had different exposure outcomes.

So in general this study concludes that the landslide has no influence on the exposure of the buildings. This result aligns with the previous statement, that the effects of the landslide are only provided close to the landslide itself. And in this area of influence, there is only one house, the Hofermühle, which is inside the flood extent in every presented scenario, regardless of the landslide or not. But once again, it needs to be emphasized, that exposure could change quickly, if the preconditions in the study area change, for example multiple landslides are triggered during one event.

The thesis concludes that the exposure analysis is prone to many limitations and should not be taken as a given but rather as an overview of the intensity of the flood events. The exposure analysis can help grasp the intensity and magnitude of the analysed events, as it is easier to relate to an object that is immediately affected by the event, rather than just seeing the extent on a map, because the object directly mirrors the effects the flood would have on humans and not just on the landscape.

7.5 Limitations

The presented methodology of the study was able to generate strong results and answer all four research questions. But as it has been touched on before already, there are many limitations and assumptions that where necessary in order to generate these results. It is important to explain these limitations and to emphasize that the study is very data sensitive and different data available would have likely led to a different outcome.

Data availability

Data scarcity is a big limitation in this thesis, especially the absence of discharge data for the study catchment. And because all research questions build on each other, this data limitation has an effect on all results in this study. To counteract this, a commonly known approach named regionalization is used. But the regionalization step itself is again subject to limitations as it strongly builds on assumptions. Apart from that, other data such as land use and landcover data and information on infiltration inside the study area is missing. This data is necessary for a thorough flood model. Gladly, the innovative modelling program FastFlood allows to download infiltration and land use data directly from the website and automatically incorporate it into the model in order to minimise the scarcity issue. But this global data doesn't have a very high resolution for the specific study area.

Regionalization

As mentioned before, generated results are based on a regionalization step due to data scarcity. Without using a donor catchment's data, it would have not been possible to calculate extreme precipitation values, which were relevant to generate the flood hazard maps using FastFlood. But the whole regionalization step was performed in a rather qualitative way and not using clear, defined conditions. As described in Chapter 5.1Identification of donor catchment a suitable donor catchment in this study is chosen by fitting spatial proximity and catchment characteristics, both of which are very subjective and don't have a clear definition. The chosen donor catchment in Schliefau is approximately 20 km north-east of the study area and is classified as close enough in regards to spatial proximity. But that decision cannot be supported by a clear definition of what spatial proximity is. Same applies to the chosen catchment characteristics which are considered to align in both study and donor catchment. But this thesis is not supported by clear definitions of how similar precipitation values should be in order to be similar enough. To a certain degree, the regionalization step is subjective and someone else might have chosen a different donor catchment, which can ultimately lead to very different results.

Flood Model

The data used for the flood model in FastFlood has a direct influence on the resulting flood hazard maps. First of all, the used DEM has a resolution of 5 m. Even though there was a better DEM available with a resolution of 1 m, the 5 m DEM was used for modelling, because a higher resolution DEM led to computational difficulties. It was not possible to generate results with the 1 m DEM because the computational time of the model would be exceeded, and the site would crash. This shows that even when data availability is not the issue, computational difficulties can still be a limitation.

The model calibration step is another limitation, as there is only limited information available on past flooding events in the region. Although major events such as 2002, 2009, 2013 and 2024 have affected Lower Austria, for the immediate study area, there is only one available report that includes both precipitation and discharge value for an event in 2012. This event makes it possible to calibrate the model, but what is missing is information on damages, that could help to also validate the model and to make it more accurate. It also appears that at least some of the major events like 2002 where not documented in the precipitation measurement station, as mentioned in Chapter 7.1. Because of this, valuable information on extreme events is missing and is not included in the results. It can be expected that the calculated precipitation extremes might be higher in reality, because it is likely that multiple high values are not displayed in the data.

7.6 Perspectives

After discussing the results in the context of the research objectives and explaining limitations of the study, it is also relevant to discuss gaps and opportunities for future research. As explained earlier, the landscape is quick to changes, especially with the increasing effects of climate change that favour heavy precipitation, floods and landslides. These factors together create complex interconnected disasters, that threaten an increasing amount of people and economic value, due to urbanization. Due to this increasing vulnerability, a next step should include a more thorough analysis in the catchment including similar landslide models, as the one of the Hofermühle. The Engage research group is already working on modelling the Eckerwirth landslide failure. This could be a next precondition to include into a flood model in order to include more possibilities of how a flood event could look like. In an ideal scenario, the catchment and all active landslides inside should be seen as a unit, focussing on how different triggers (like one extreme precipitation event) might affect all slopes in the area and what implications that would have on a flood. And this is where the next steps of disaster management can connect to the results, as proposed by the EU directive.

After identifying areas that are prone to flooding and where buildings are exposed, specific analyses on the risk in the identified regions should be identified by experts. A risk assessment includes not only the buildings but also the economic value of the potentially affected buildings, how many people would be in danger in case of a flood and how high damage estimates would be. It might be identified that certain protection measures could help to minimise overall risk and to increase preparedness for a future event. This ties into the disaster management cycle, described in Chapter 2.2.

Apart from immediate follow up steps, this approach can also be used in different catchments, especially where data might be limited. Even with little data, general observations can help in gaining an impression on the intensity of flood hazards and sensitising the population and relevant decision-makers.

8 Conclusion

The presented thesis analysed the flood hazard and exposure for the Redtenbach Catchment in Lower Austria. In order to do that, first a thorough preprocessing step of available data was necessary to identify the precipitation values, that need to be reached for flood events corresponding to a 30-, 100- and 300-year return period. Also, the study focussed on the extreme events for different event duration, specifically precipitation events that last 6 hours, as this is the calculated mean duration of extreme events in this catchment and 2 and 1 hours. Latter reflect potential future extreme events, that tend to decrease in duration but increase in intensity, due to climate change. Adding to that, a multi-hazard scenario is included, where prior to the flood, a landslide is triggered, and material accumulates inside the stream. The results conclude that flood intensity generally increases with increasing precipitation input. Therefore, the rarer the precipitation event, the more intense the flood response inside the catchment. Another key finding of the study is that flood response is significantly stronger, when the same amount of precipitation falls in a shorter amount of time. The third key finding is, that the active landslide can act as a natural dam, in the case that it is triggered, and the material reaches the dam. The flood water jams in front of the dam and water is slowly going around the dam, which leads to a shallower but wider flood shortly after the landslide area.

The study states, that the results can be used as a first step for a thorough flood risk analysis in the region. The necessity for further work in the region has been made clear. First of all, there are multiple studies that prove that the ongoing effects of climate change influence precipitation patterns and lead to shorter, more extreme events. The results highlight, that this observation increases building exposure in the area significantly, thus likely also increasing flood risk in the western outskirts of Waidhofen a. d. Ybbs and neighbouring settlements. What adds to that, is the continuous changing environment due to the susceptibility to landslides. Changing preconditions make it difficult to predict the impacts of floods, because landslides are able to alter flood response significantly as shown by the results. Flood mitigation structures might not withstand future events, that change severely in intensity as presented in the study. Therefore, the study concludes that a consistent monitoring of the area is necessary in order to adapt to changing conditions and to evaluate if structural measures are necessary in the region.

9 References

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10 Appendix 1: Python Code FFA

```
In [1]: import pandas as pd
        import seaborn as sns
        import matplotlib.pyplot as plt
        import numpy as np
        from scipy.stats import gumbel_r
        from scipy.interpolate import interp1d
```

1. Preprocessing Data

In this first step, the data is loaded in and formatting is adjusted so that it is easy to work with both datasets.
Specifically, it is ensured that both datasets have only the two relevant columns: `"date"` and `"precipitation"/"discharge"`.
The `"date"` column needs to have the same format for merging both datasets. In the end the two datasets are merged into one named `"merged"`.

```
In [3]: # Loading discharge dataset
        discharge = pd.read_csv(r"C:\Users\ju_mu\Documents\Master\sem4\Masterarbeit\Data\Q-Tagesmittel-209403.csv",\
                                sep=";", skiprows=20, encoding='latin1', names=['date', 'discharge'], header=None, decimal=",")

        discharge['date'] = discharge['date'].astype(str)


        # Changing format of date column to datetime format
        discharge['date'] = pd.to_datetime(
            discharge['date'],
            errors='coerce',
            dayfirst=True
        )
```

```
In [4]: # Loading precipitation dataset
        prec = pd.read_csv(r"C:\Users\ju_mu\Documents\Master\sem4\Masterarbeit\Data\N-Tagessummen_Schliefau-116210.csv",
                           sep=";", skiprows=21, encoding="latin1", decimal=",")

        # Remove everything except the first two columns
        prec = prec.iloc[:, :2]

        #Renaming columns
        prec.columns = ["date", "precipitation"]
```

```
In [5]: # Converting 'date' to string
        prec['date'] = prec['date'].astype(str)

        # Changing format of date column to datetime format
        prec['date'] = pd.to_datetime(
            prec['date'],
            errors='coerce',
            dayfirst=True
        )

        # Converting 'precipitation' to string
        prec['precipitation'] = prec['precipitation'].astype(str)

        # Removing any non-numeric characters like commas and replacing them with periods if needed
        prec['precipitation'] = prec['precipitation'].str.replace(',', '.', regex=False)

        # Converting the 'precipitation' column to numeric
        prec['precipitation'] = pd.to_numeric(prec['precipitation'], errors='coerce')
```

```
In [6]: # Removing time aspect in date column for merging
        discharge['date'] = pd.to_datetime(discharge['date']).dt.normalize()
        prec['date'] = pd.to_datetime(prec['date']).dt.normalize()
```

In [7]:
```python
# Merging the two datasets on the 'date' column
merged = pd.merge(discharge, prec, on='date', how='inner')
```

In [8]:
```python
# Displaying the first 5 rows of the merged dataset
merged.head()
```

Out[8]:

	date	discharge	precipitation
0	1992-01-02	0.182	0.0
1	1992-01-03	0.182	0.0
2	1992-01-04	0.182	3.1
3	1992-01-05	0.789	6.3
4	1992-01-06	1.960	11.3

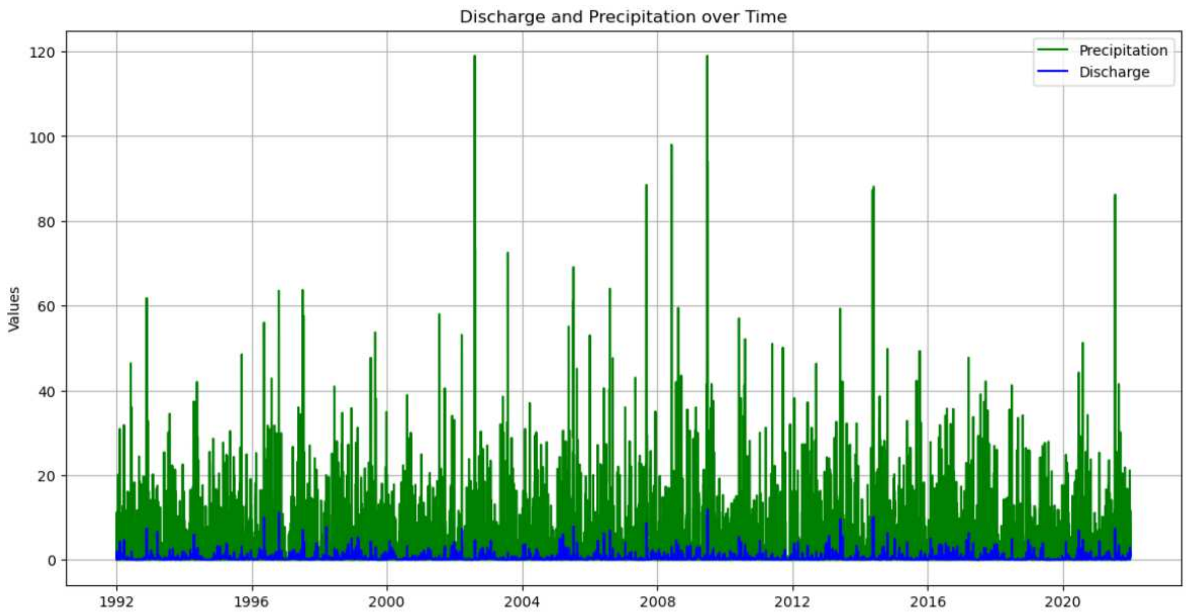
2. Calculating and Plotting Correlation

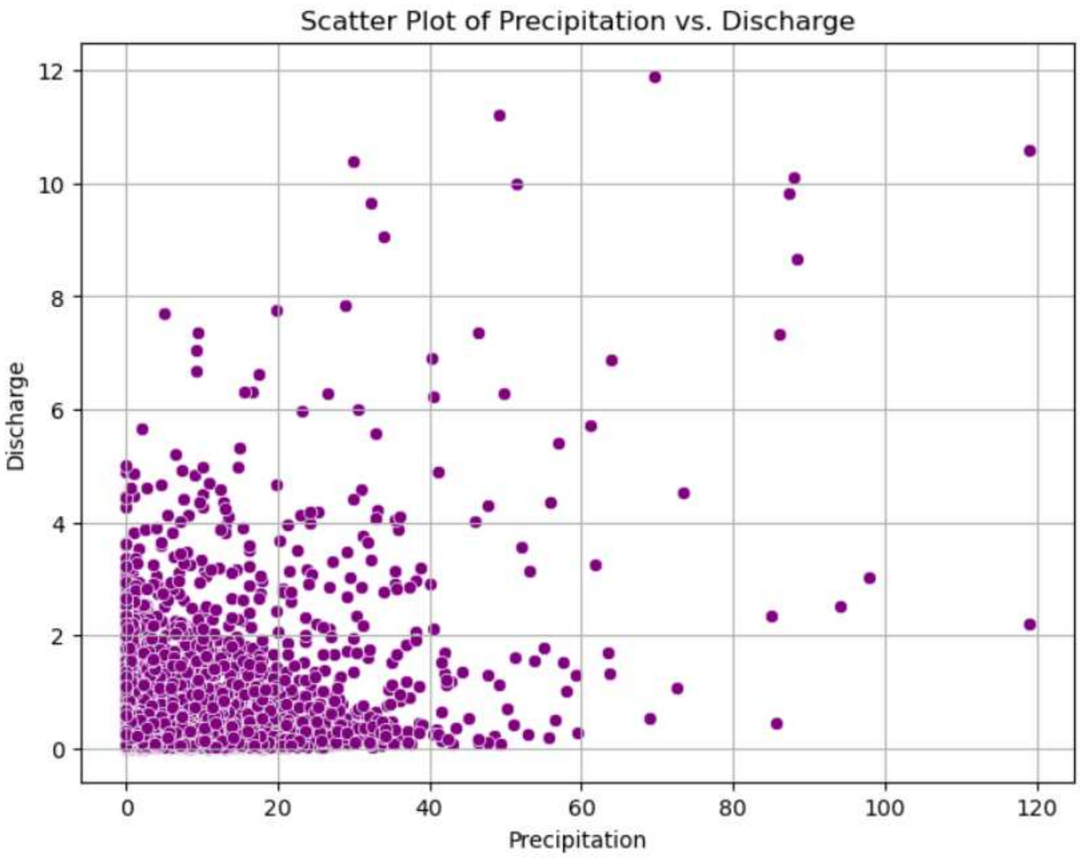
Now, the `"merged"` dataset is used to calculate the correlation between `"discharge"` and `"precipitation"`. Because the initial correlation is unsatisfying a Time Lag Analysis is included to find the best correlation.

In [10]:
```python
# Calculating the correlation coefficient
correlation = merged['discharge'].corr(merged['precipitation'])
print(correlation)
```

```
0.39344794216442586
```

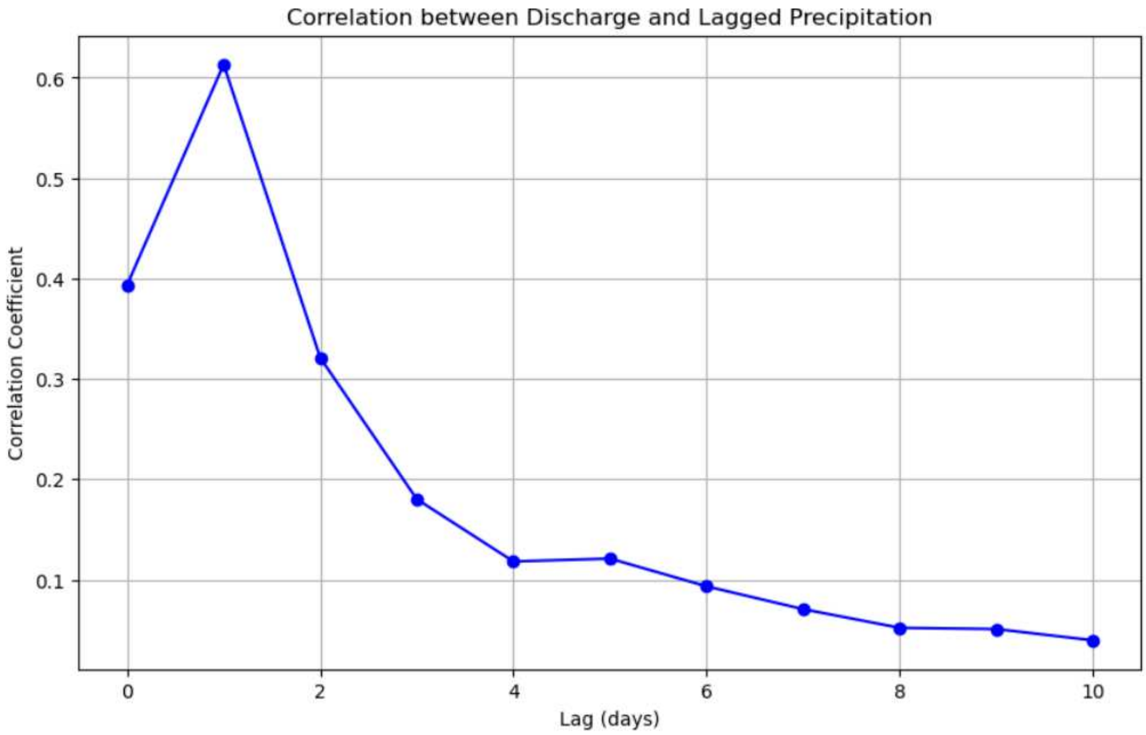
In [11]:
```python
# Plot precipitation and discharge over time for visual inspection
plt.figure(figsize=(14, 7))
plt.plot(merged['date'], merged['precipitation'], label='Precipitation', color='green')
plt.plot(merged['date'], merged['discharge'], label='Discharge', color='blue')
plt.title("Discharge and Precipitation over Time")
plt.xlabel("Date")
plt.ylabel("Values")
plt.legend()
plt.grid(True)
plt.show()

# Plot a scatter plot to visualize the correlation
plt.figure(figsize=(8, 6))
sns.scatterplot(x='precipitation', y='discharge', data=merged, color="purple")
plt.title("Scatter Plot of Precipitation vs. Discharge")
plt.xlabel("Precipitation")
plt.ylabel("Discharge")
plt.grid(True)
plt.show()
```





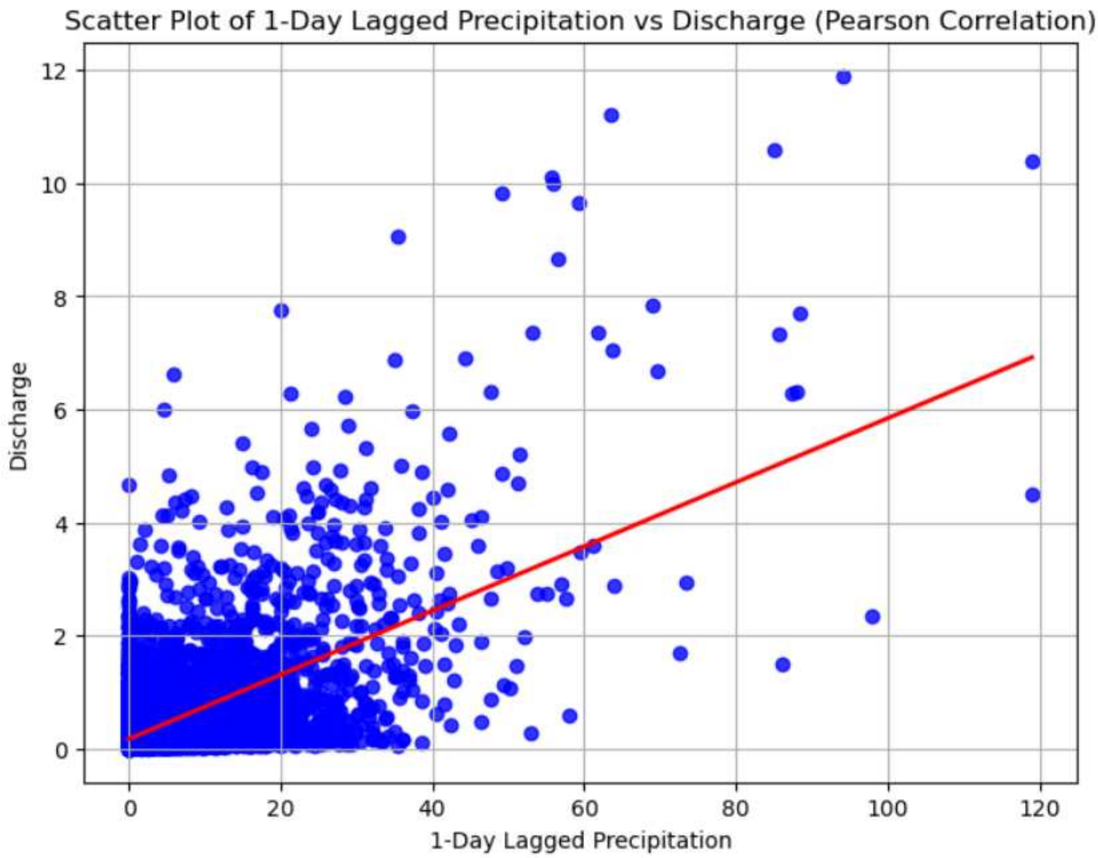
In [12]:
```
# Time Lag Analysis with a maximum of 10 days
max_lag_days = 10
lag_correlations = []

# Calculating correlations for each lag
for lag in range(0, max_lag_days + 1):
    merged['precipitation_lagged'] = merged['precipitation'].shift(lag)
    lag_corr = merged['discharge'].corr(merged['precipitation_lagged'])
    lag_correlations.append((lag, lag_corr))

# Finding the best lag
best_lag, best_lag_corr = max(lag_correlations, key=lambda x: x[1])
print(f"Best correlation ({best_lag_corr:.2f}) occurs at a lag of {best_lag} days.")

# Plot the correlation coefficient over different lags
lags, correlations = zip(*lag_correlations)
plt.figure(figsize=(10, 6))
plt.plot(lags, correlations, marker='o', color='b')
plt.title("Correlation between Discharge and Lagged Precipitation")
plt.xlabel("Lag (days)")
plt.ylabel("Correlation Coefficient")
plt.grid(True)
```

```
Best correlation (0.61) occurs at a lag of 1 days.
```



In [13]:

```
# Pearson correlation with 1 day lagged precipitation data
merged['precipitation_lagged_1day'] = merged['precipitation'].shift(1)

# Droping any rows with NaN values (from lagging)
lagged_1day_data = merged.dropna(subset=['precipitation_lagged_1day', 'discharge'])

# Scatter plot for 1-day lag Pearson correlation
plt.figure(figsize=(8, 6))
sns.regplot(x='precipitation_lagged_1day', y='discharge', data=lagged_1day_data,
            scatter_kws={'color': 'blue'}, line_kws={'color': 'red', 'linewidth': 2}, ci=None)
plt.title("Scatter Plot of 1-Day Lagged Precipitation vs Discharge (Pearson Correlation)")
plt.xlabel("1-Day Lagged Precipitation")
plt.ylabel("Discharge")
plt.grid(True)
```



3. Gumbel Analysis

First the annual maxima values from the `"discharge"` column are extracted into `"annual_maxima"`. Then the Gumbel distribution is fitted to the values and the values for HQ30, HQ100 and HQ300 are calculated. Afterwards interpolation between discharge and one day shifted precipitation data is calculated and the precipitation values for the return period are extracted. The values are then modified.

In [15]:

```
# Setting date column as index for easier resampling
discharge.set_index('date', inplace=True)

# Extracting annual maxima
annual_maxima = discharge['discharge'].resample('Y').max()

# Converting annual maxima to numeric, coercing errors to NaN, then dropping any NaN values
annual_maxima = pd.to_numeric(annual_maxima, errors='coerce').dropna()

# Checking the data type and confirm no remaining NaNs
print(annual_maxima.dtypes)  # Should be float or int
print(annual_maxima.isna().sum())  # Should be 0
```

```
float64
0
```

In [16]:

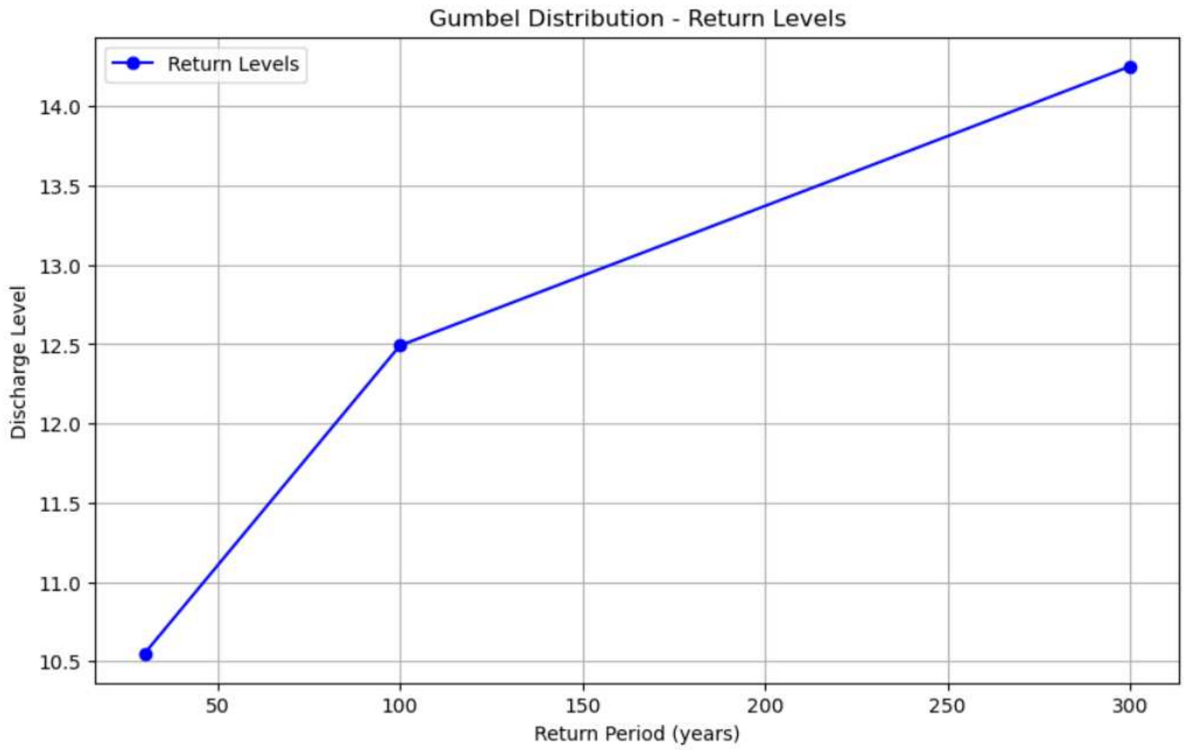
```
# Fit Gumbel distribution to annual maxima
params = gumbel_r.fit(annual_maxima)

# Calculate return levels for given return periods
return_periods = [30, 100, 300]
return_levels = gumbel_r.ppf(1 - 1 / np.array(return_periods), *params)


# Create a DataFrame for the results table
results_table = pd.DataFrame({
    'Return Period (years)': return_periods,
    'Discharge Level': return_levels
})

# Display the table
results_table
```

Out[16]:

	Return Period (years)	Discharge Level
0	30	10.548507
1	100	12.491259
2	300	14.252032

In [17]:
```python
# Plotting results
plt.figure(figsize=(10, 6))
plt.plot(return_periods, return_levels, marker='o', color='b', label='Return Levels')
plt.xlabel('Return Period (years)')
plt.ylabel('Discharge Level')
plt.title('Gumbel Distribution - Return Levels')
plt.grid(True)
plt.legend()
```

Out[17]: <matplotlib.legend.Legend at 0x1fe400ff890>



In [18]:
```python
# Shifting precipitation by 1 day to match the time lag
merged['precipitation_lagged_1day'] = merged['precipitation'].shift(1)

# Dropping any rows with NaN values that could occur because of the lag
lagged_data = merged.dropna(subset=['discharge', 'precipitation_lagged_1day'])

# Sorting data by discharge to apply interpolation correctly
lagged_data = lagged_data.sort_values(by='discharge')

# Defining a function to calculate precipitation for a given discharge level
def calculate_precipitation(discharge_level):
    interp_function = interp1d(
        lagged_data['discharge'],
        lagged_data['precipitation_lagged_1day'],
        kind='linear',
        fill_value="extrapolate"
    )
    return interp_function(discharge_level)

# Adding a new column for precipitation values using the discharge levels
results_table['Precipitation Value'] = results_table['Discharge Level'].apply(calculate_precipitation)

# Adjusting precipitation by subtracting the mean difference between study and donor catchment
adjustment_value = 0.3328300784814747
results_table['Precipitation Value'] = results_table['Precipitation Value'] - adjustment_value

# Adding a column dividing the adjusted precipitation values by 6
results_table['Precipitation Value / 6'] = results_table['Precipitation Value'] / 6

# Adding a column dividing the adjusted precipitation values by 2
results_table['Precipitation Value / 2'] = results_table['Precipitation Value'] / 2
```

In [19]:
```
# Displaying the final table
results_table
```

Out[19]:

	Return Period (years)	Discharge Level	Precipitation Value	Precipitation Value / 6	Precipitation Value / 2
0	30	10.548507	93.421054	15.570176	46.710527
1	100	12.491259	119.798116	19.966353	59.899058
2	300	14.252032	197.020588	32.836765	98.510294

11 Appendix 2: Modelling Results

11.1 All Scenarios Hazard Maps

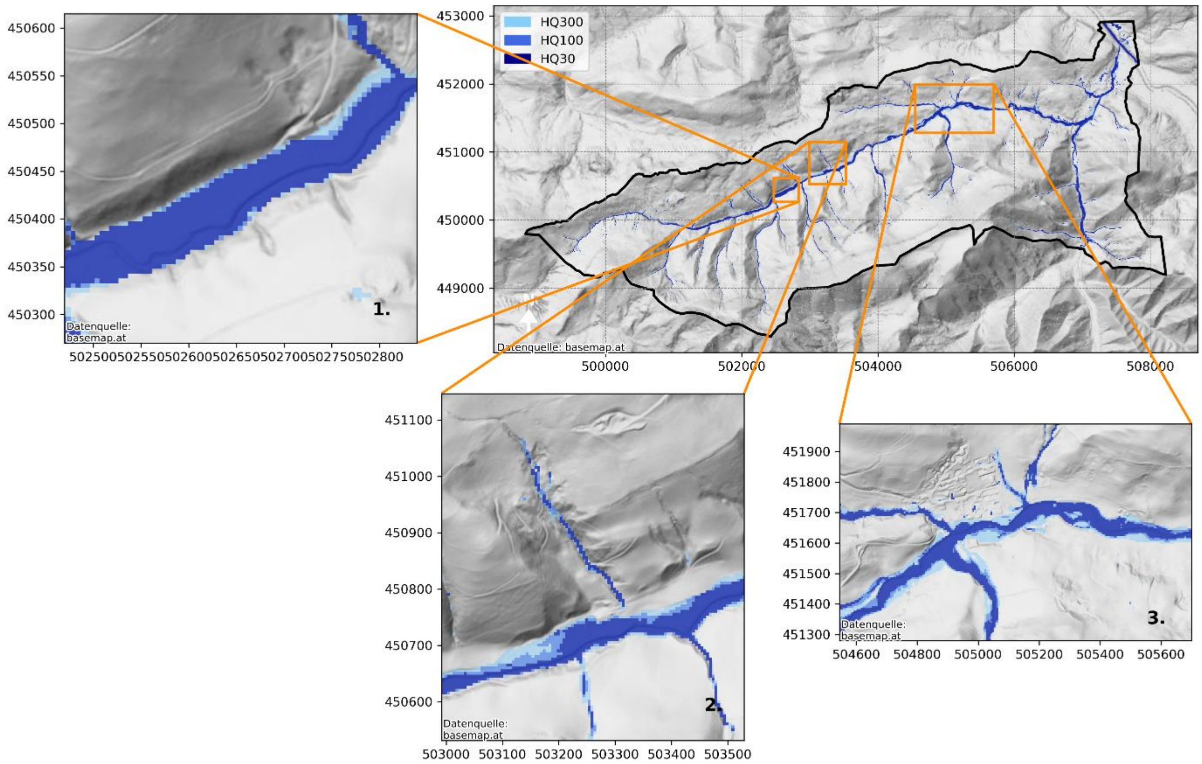


Figure A 1: Flood Hazard Map 6 hours base (Source: Created by the author).

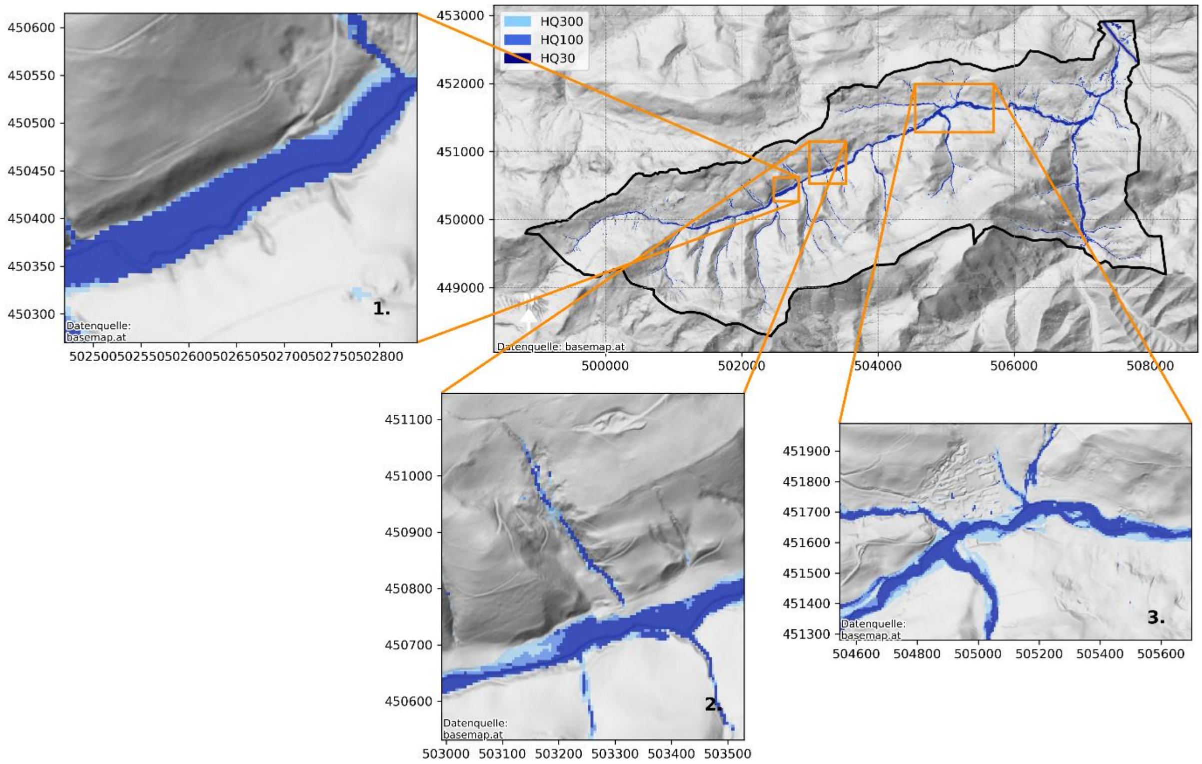


Figure A 2: Flood Hazard Map 6 hours landslide (Source: Created by the author).

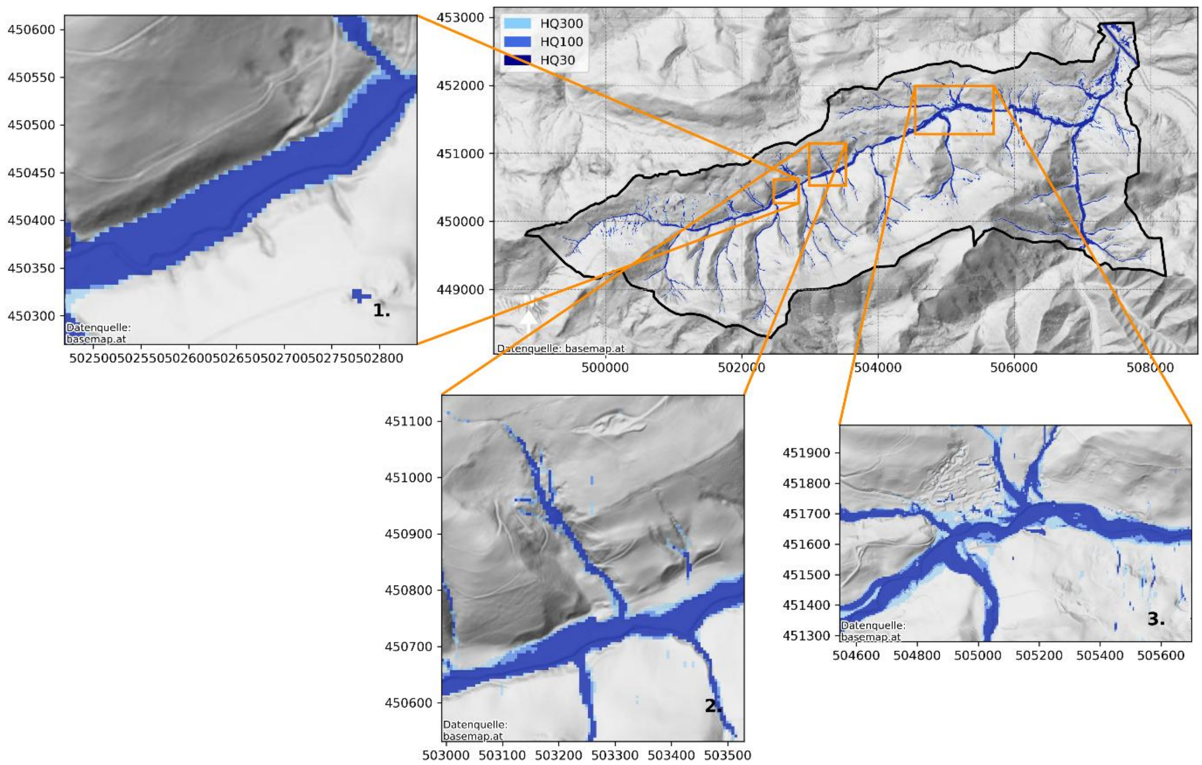


Figure A 3: Flood Hazard Map 2 hours base (Source: Created by the author).

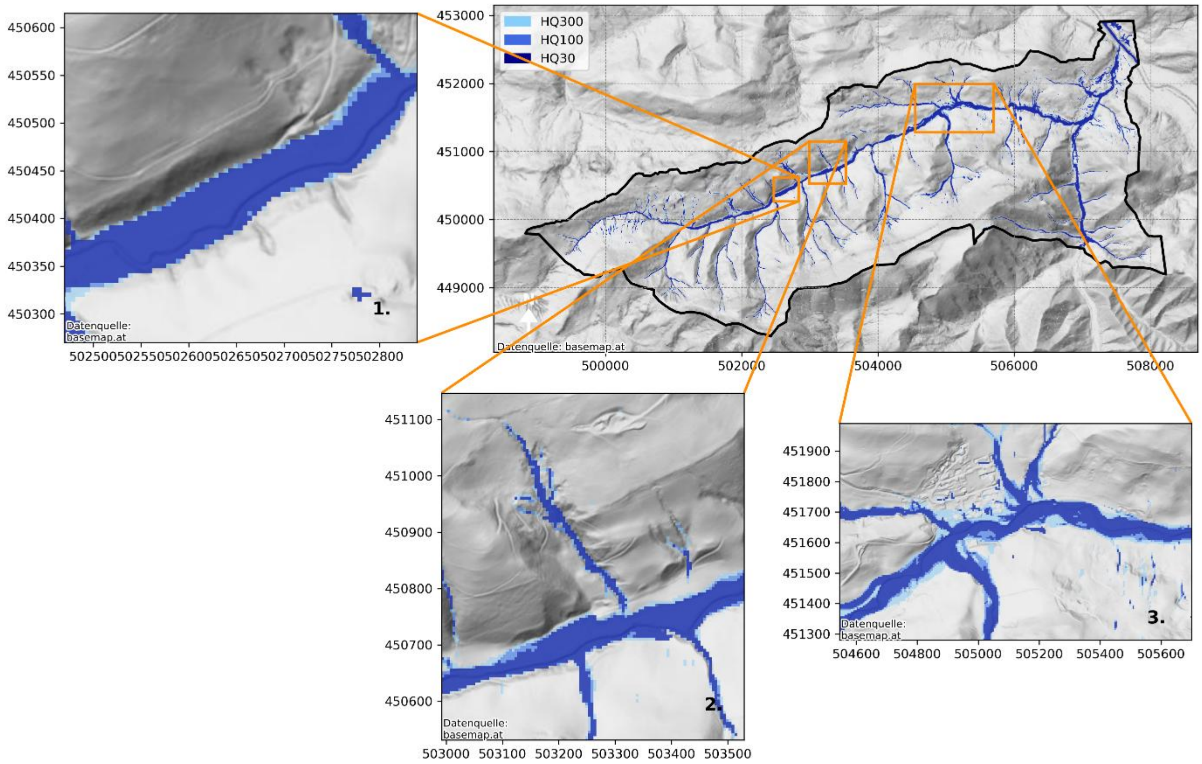


Figure A 4: Flood Hazard Map 2 hours landslide (Source: Created by the author).

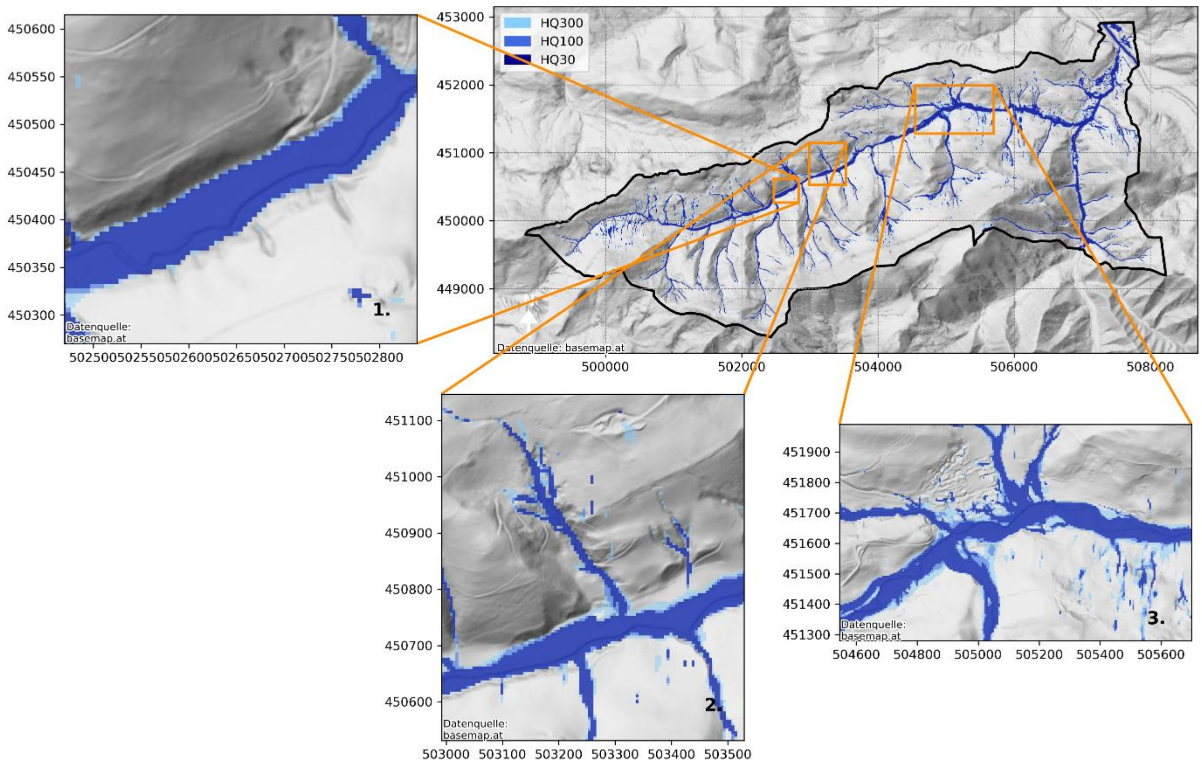


Figure A 5: Flood Hazard Map 1 hour base (Source: Created by the author).

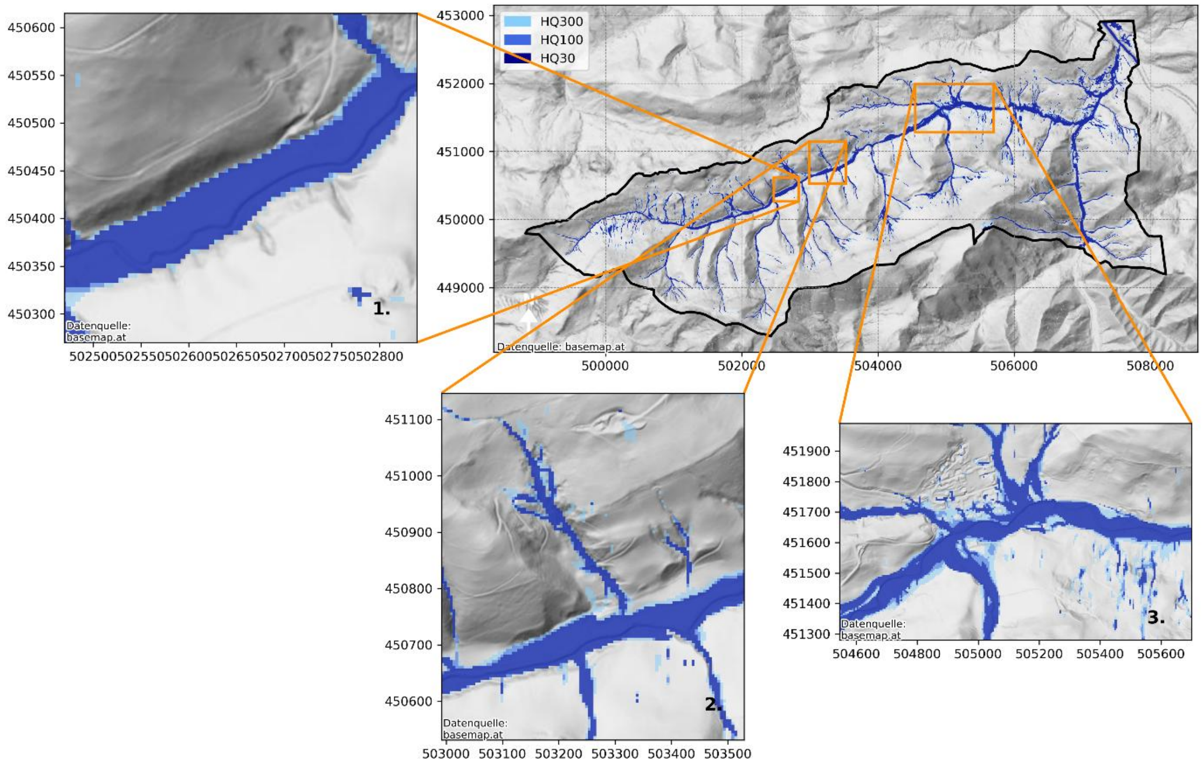


Figure A 6: Flood Hazard Map 1 hour landslide (Source: Created by the author).

11.2 All Scenarios Water Depth

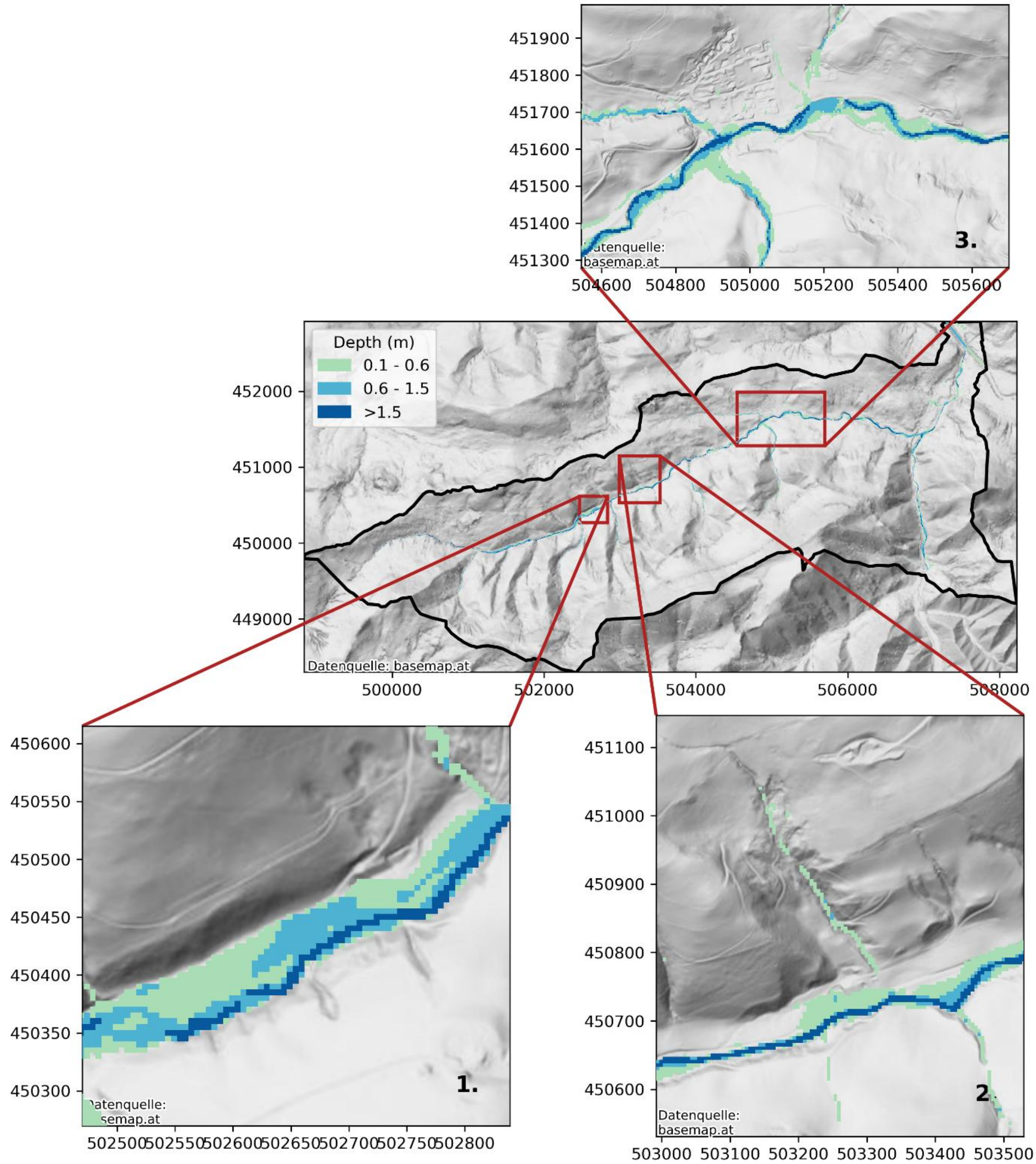


Figure A 7: Water Depth HQ30 6 hours base (Source: Created by the author).

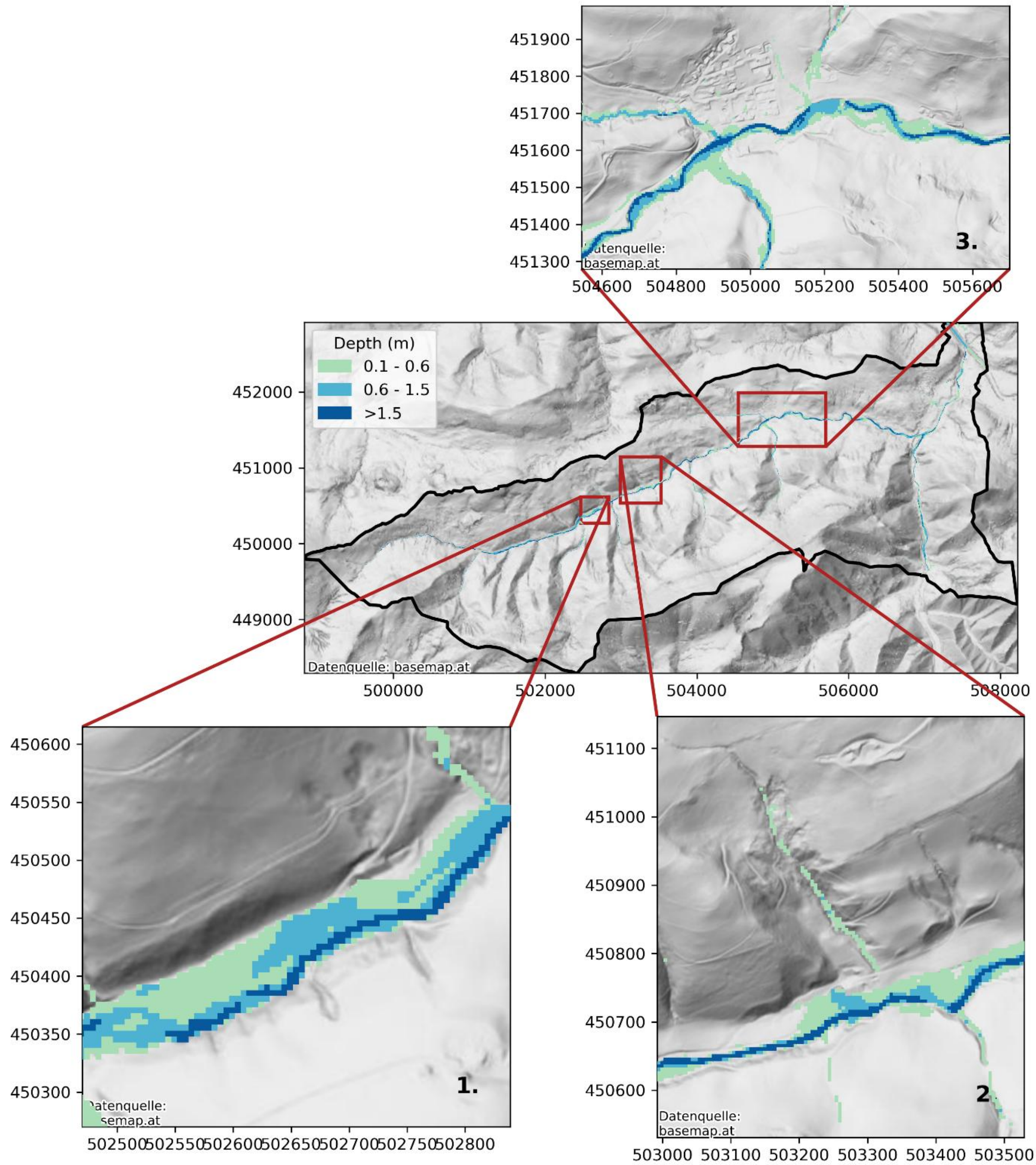


Figure A 8: Water Depth HQ30 6 hours landslide (Source: Created by the author).

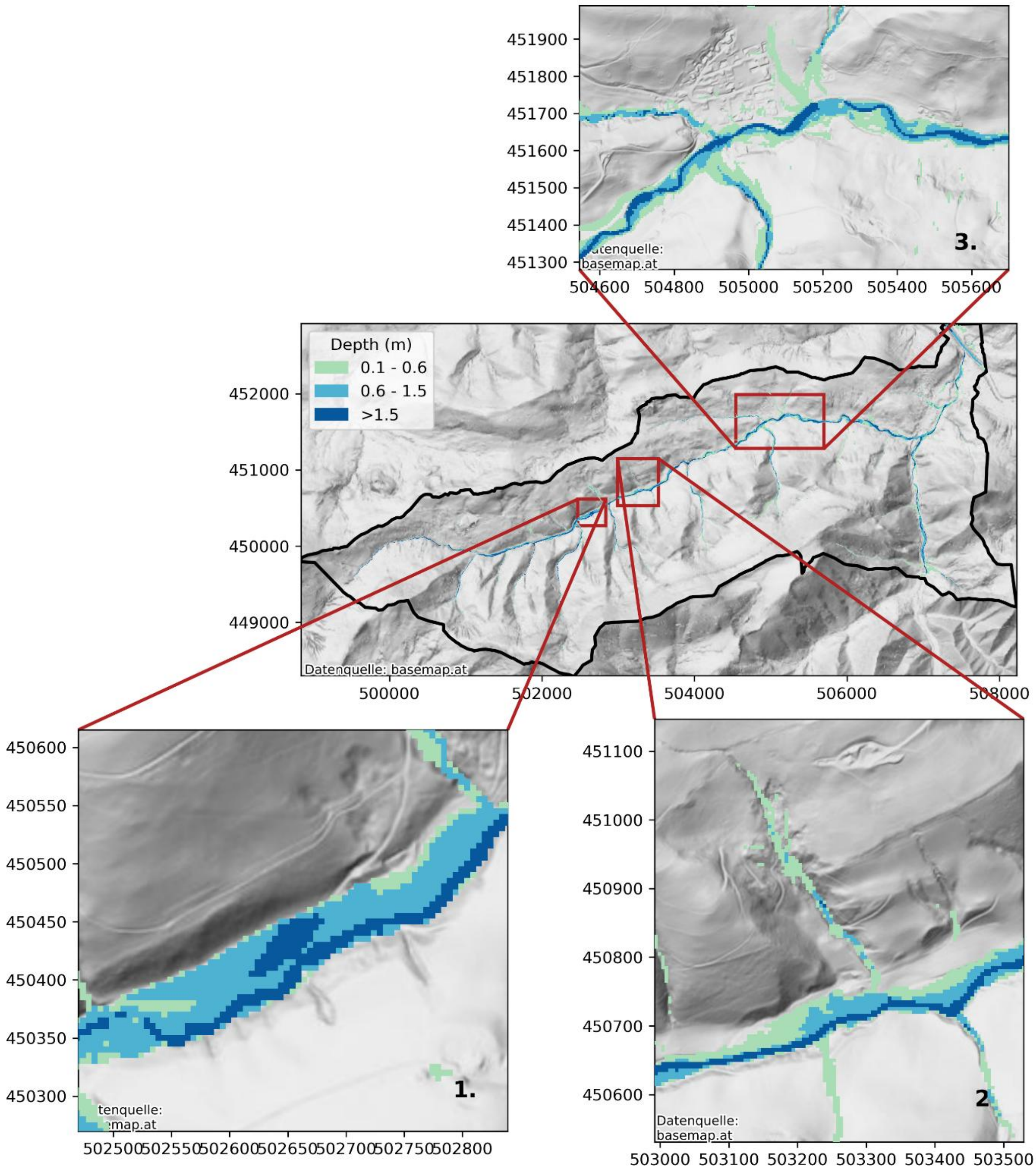


Figure A 9: Water Depth HQ30 2 hours base (Source: Created by the author).

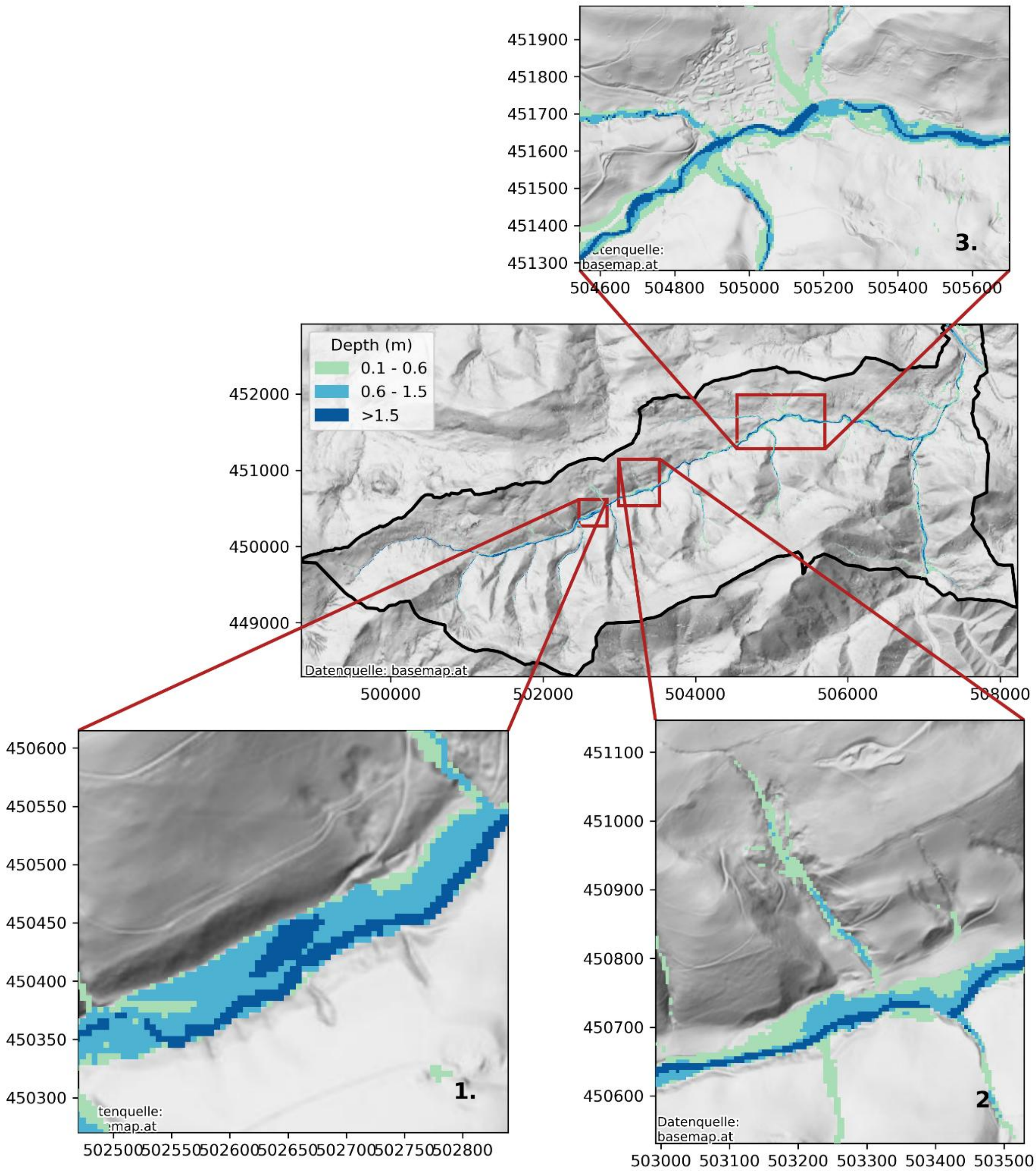


Figure A 10: Water Depth HQ30 2 hours landslide (Source: Created by the author).

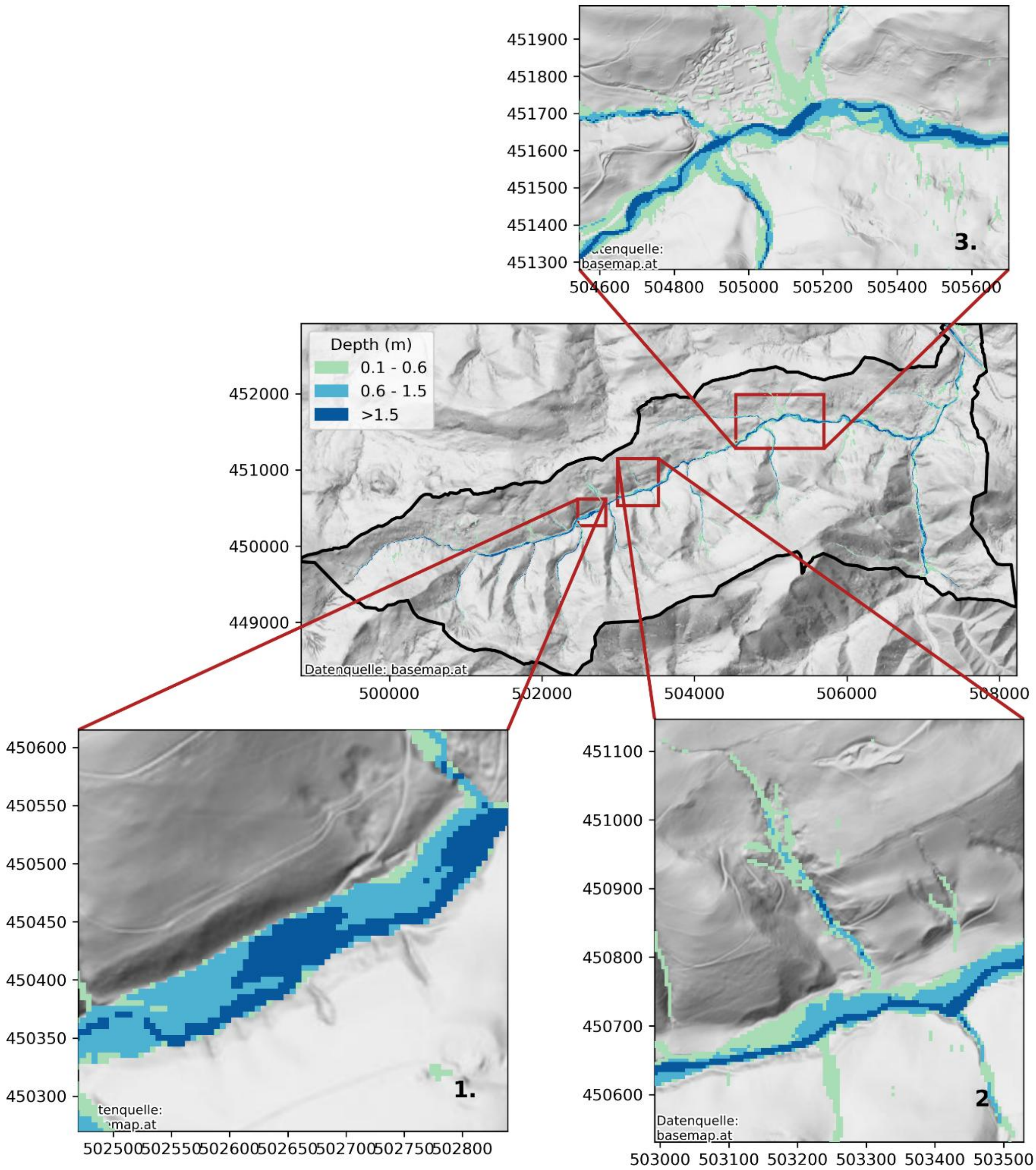


Figure A 11: Water Depth HQ30 1 hour base (Source: Created by the author).

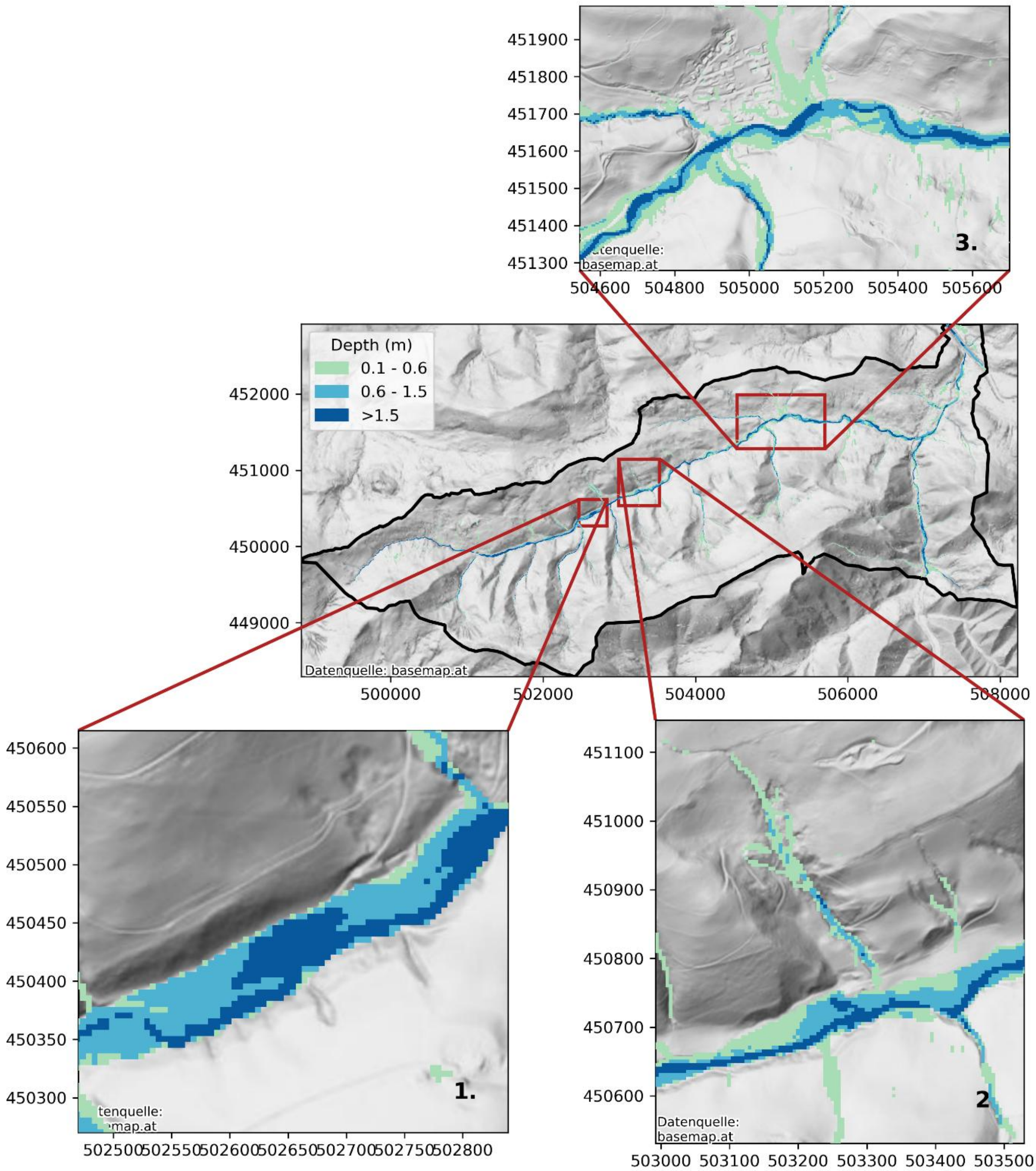


Figure A 12: Water Depth HQ30 1 hour landslide (Source: Created by the author).

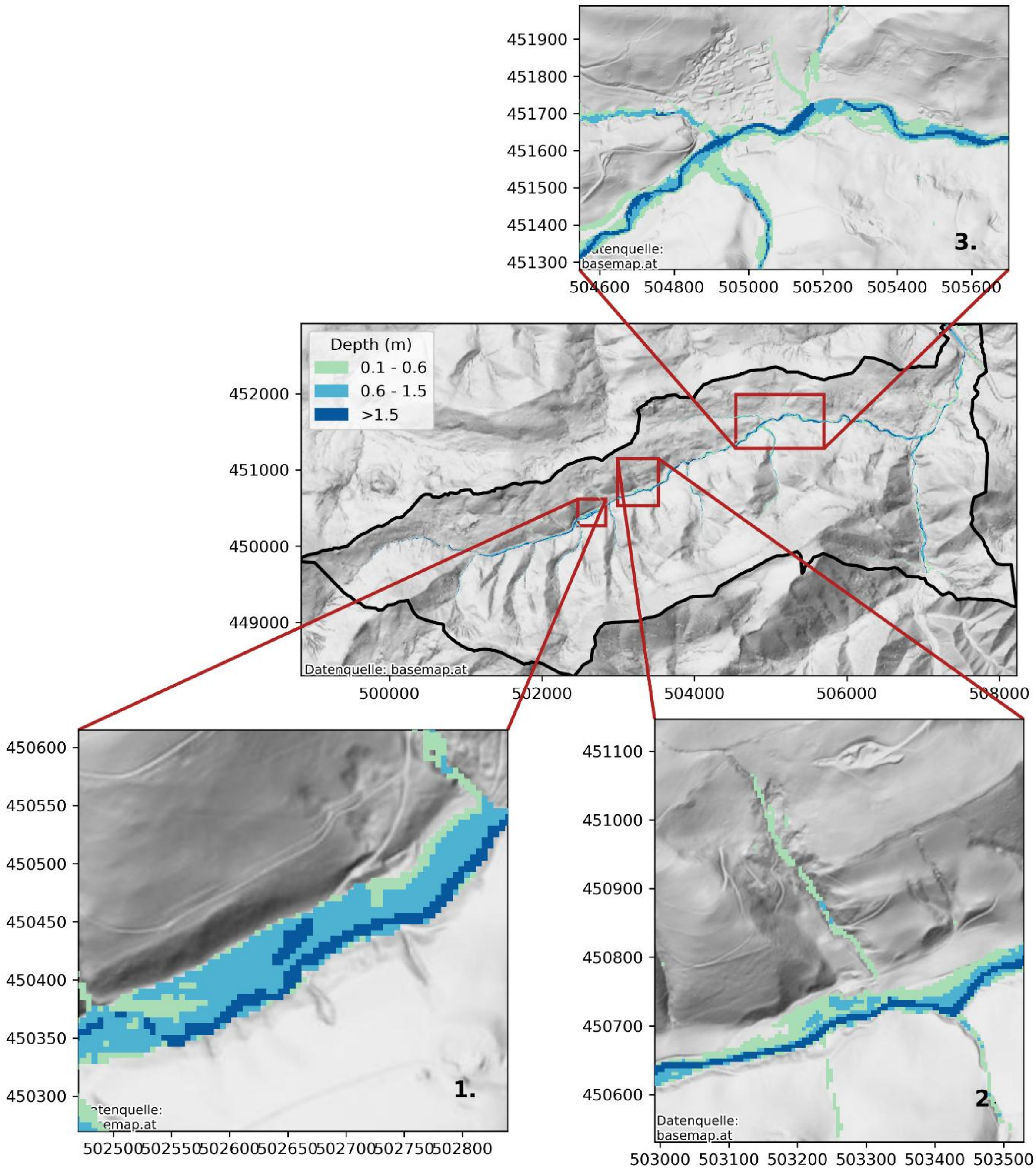


Figure A 13: Water Depth HQ100 6 hours base (Source: Created by the author).

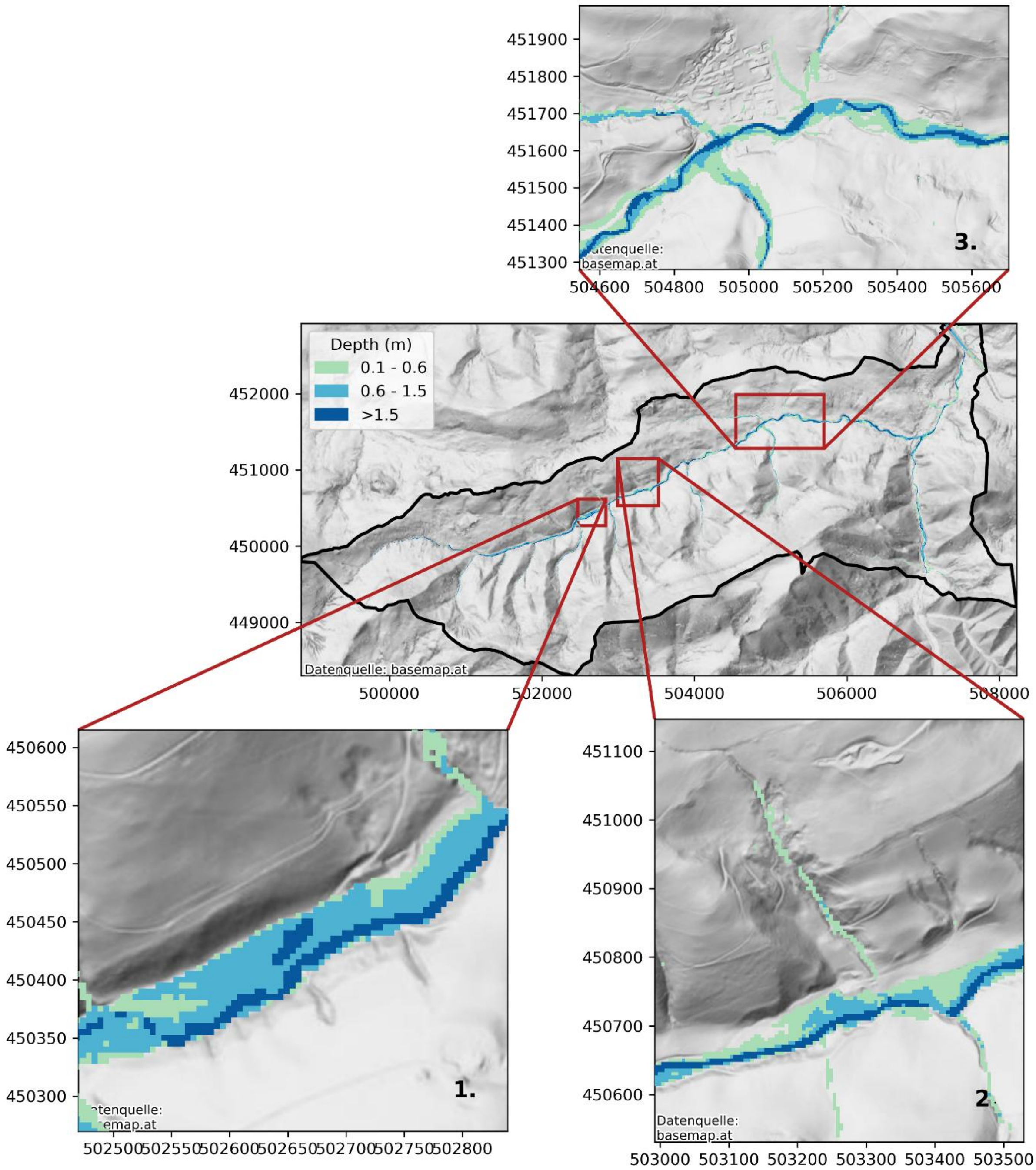


Figure A 14: Water Depth HQ100 6 hours landslide (Source: Created by the author).

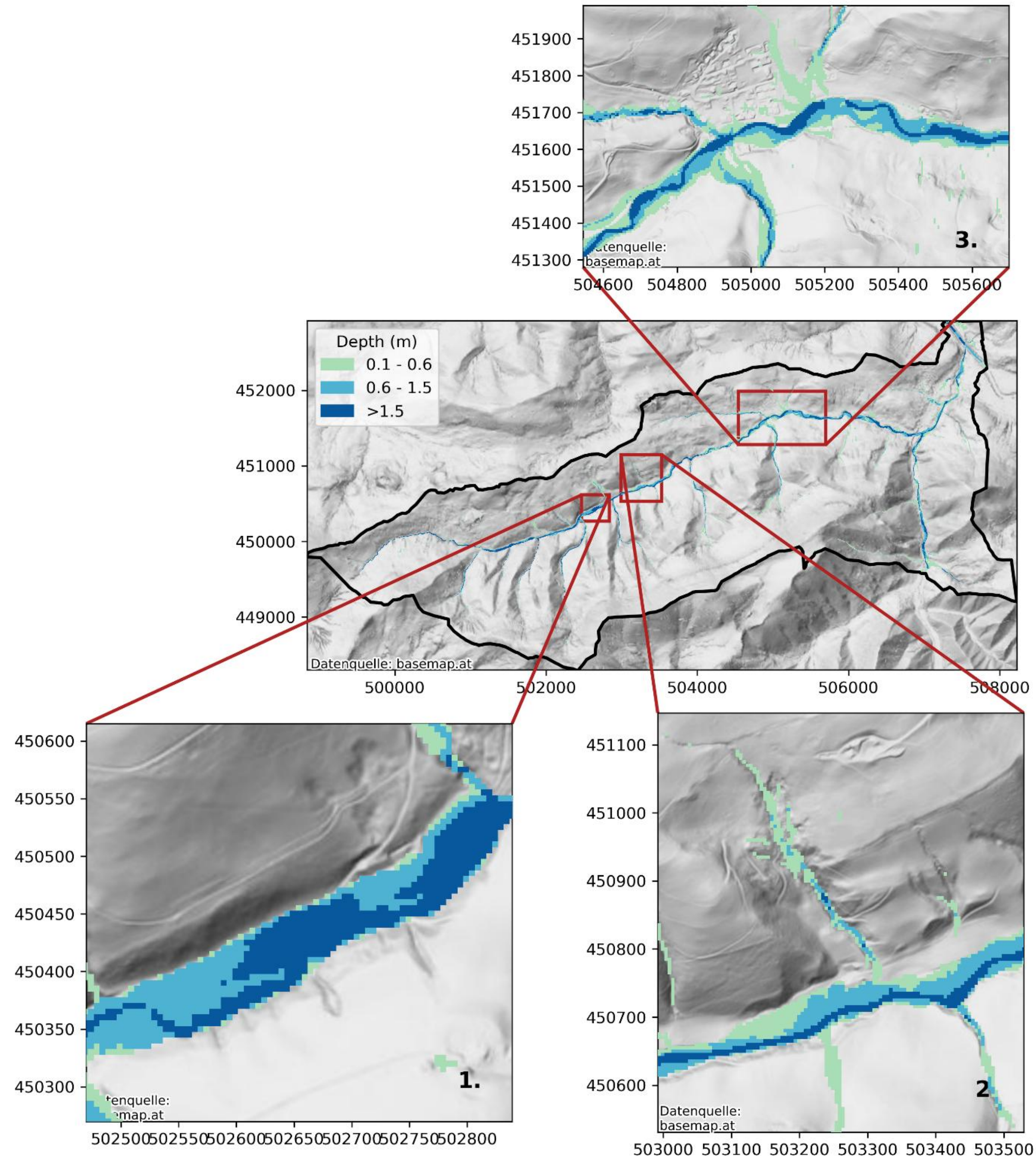


Figure A 15: Water Depth HQ100 2 hours base (Source: Created by the author).

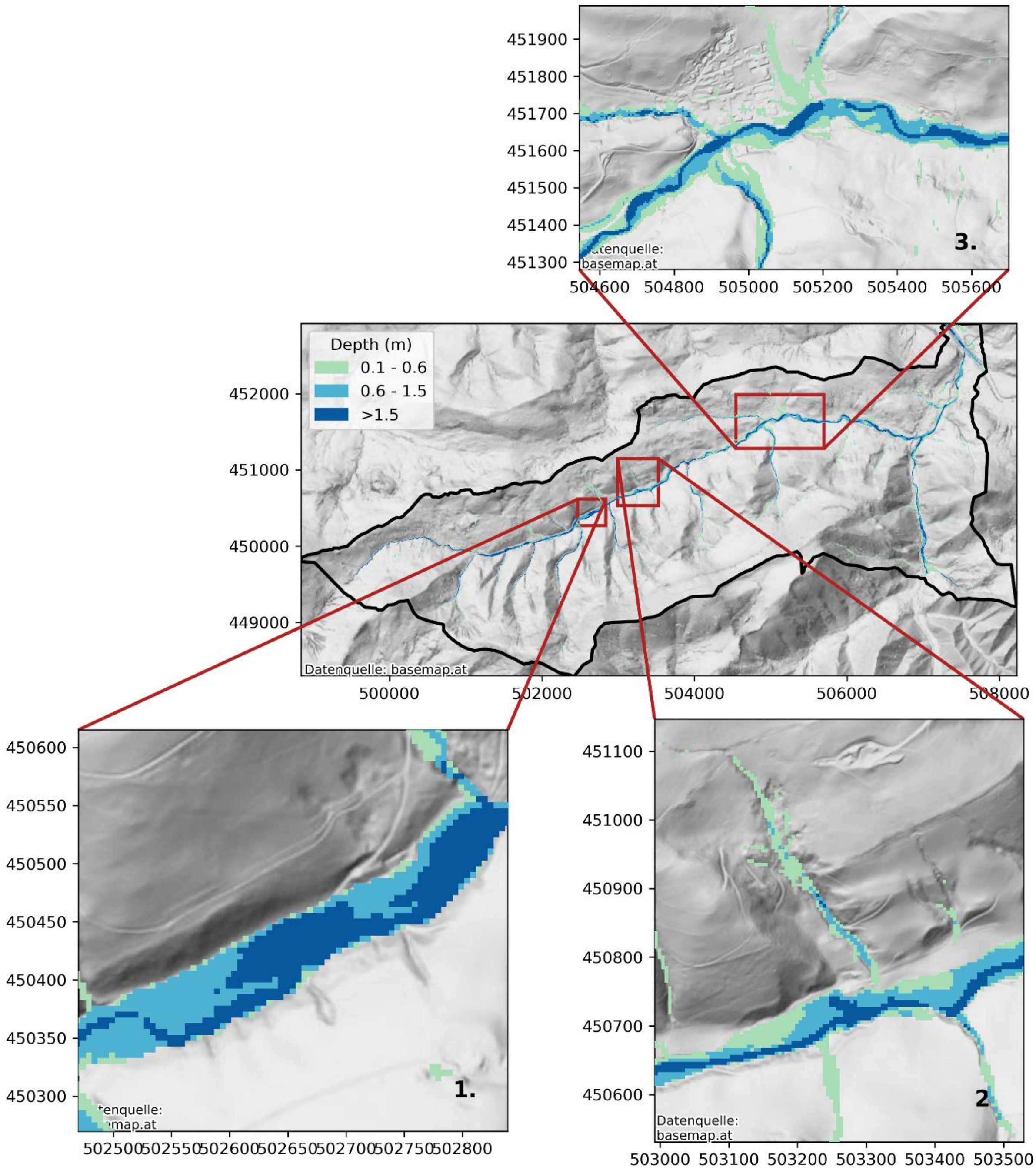


Figure A 16: Water Depth HQ100 2 hours landslide (Source: Created by the author).

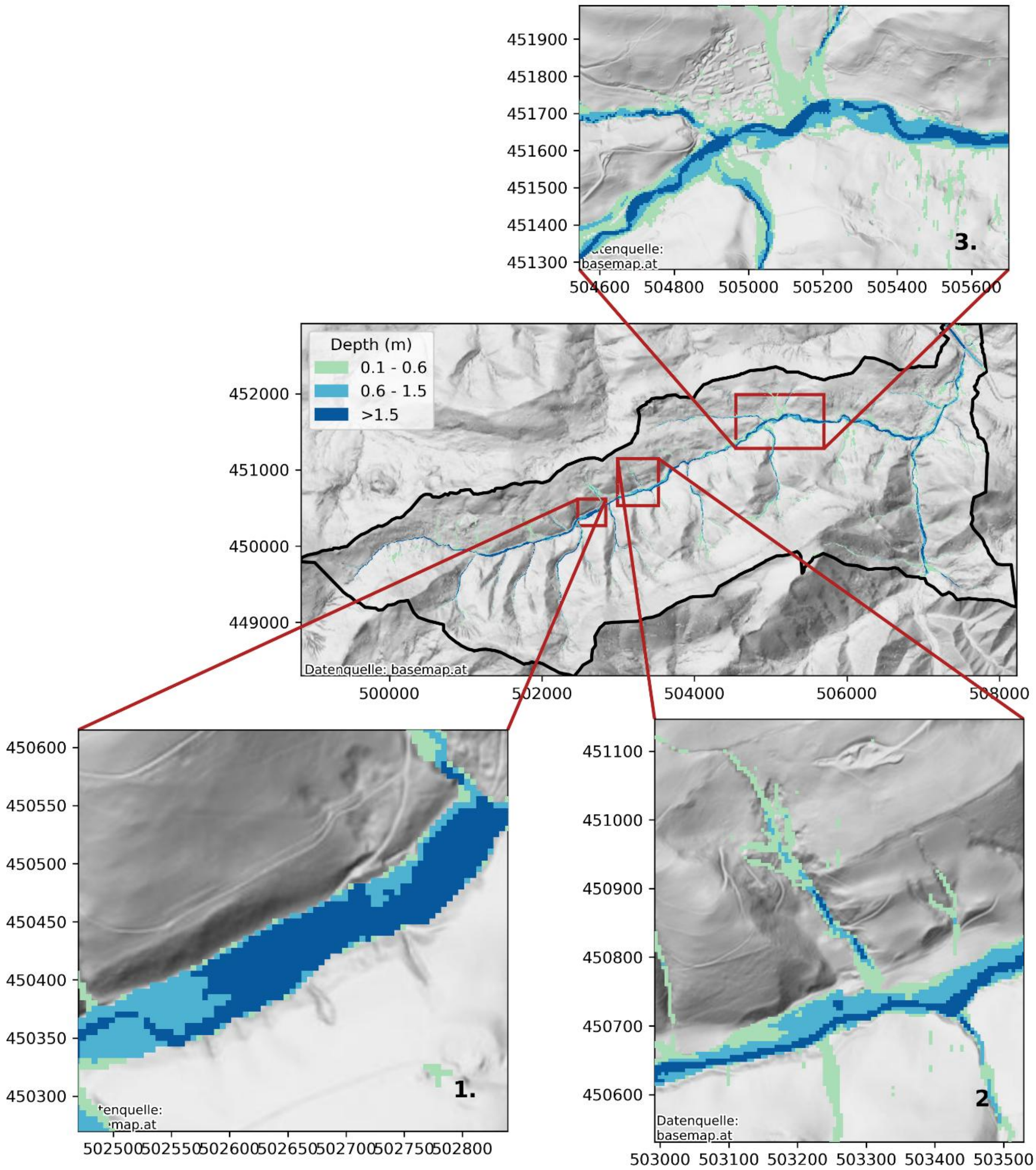


Figure A 17: Water Depth HQ100 1 hour base (Source: Created by the author).

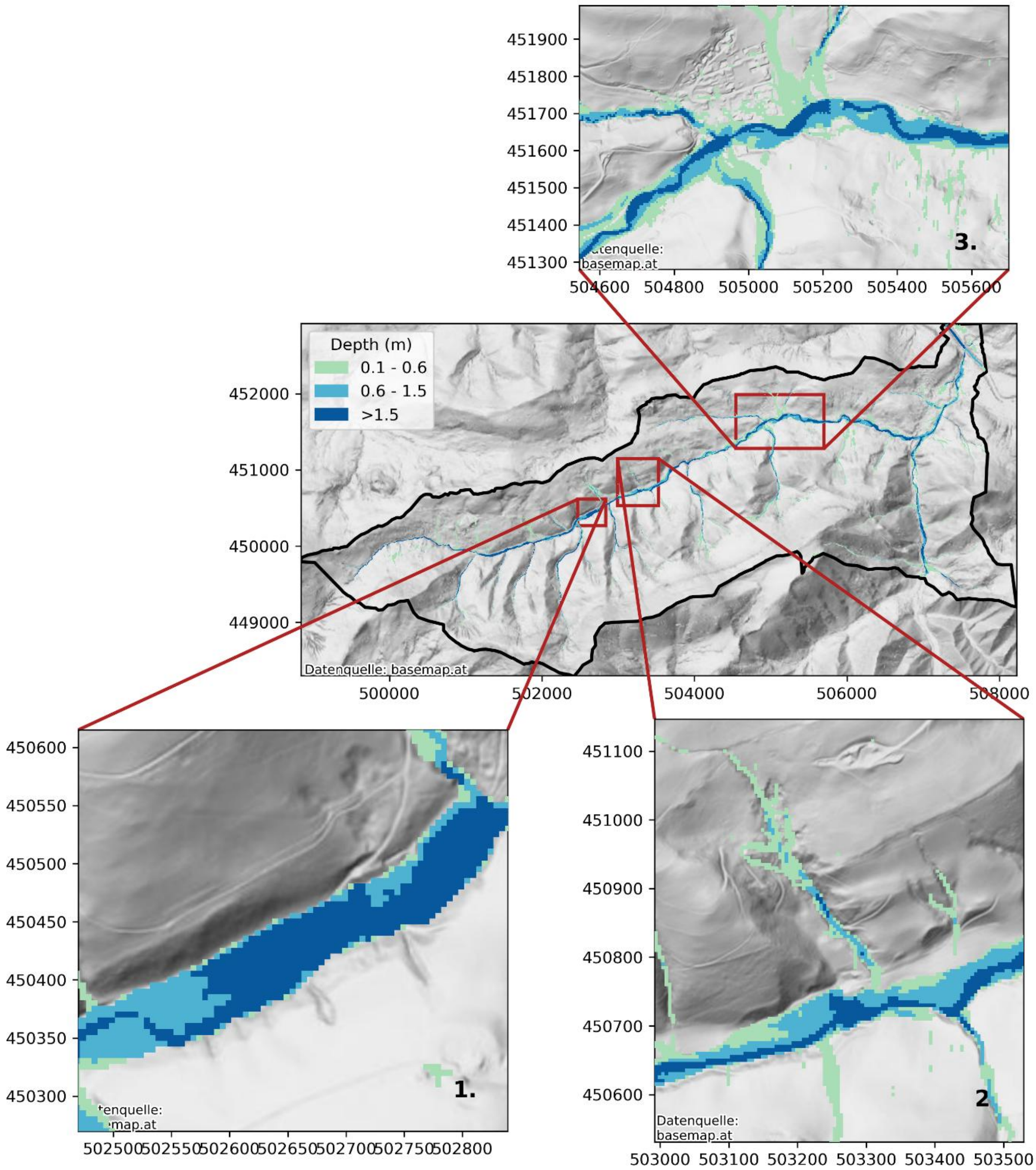


Figure A 18: Water Depth HQ100 1 hour landslide (Source: Created by the author).

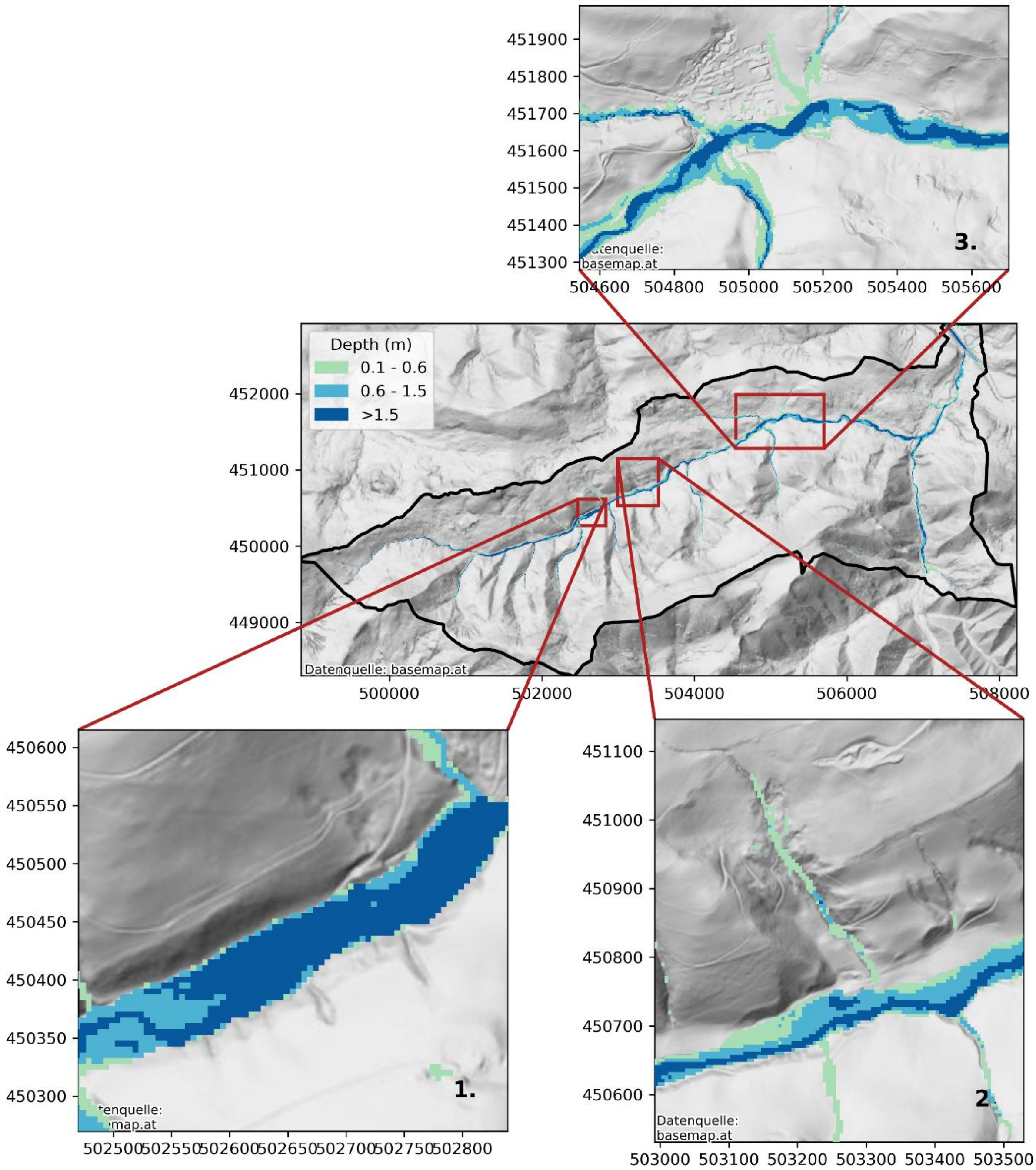


Figure A 19: Water Depth HQ300 6 hours base (Source: Created by the author).

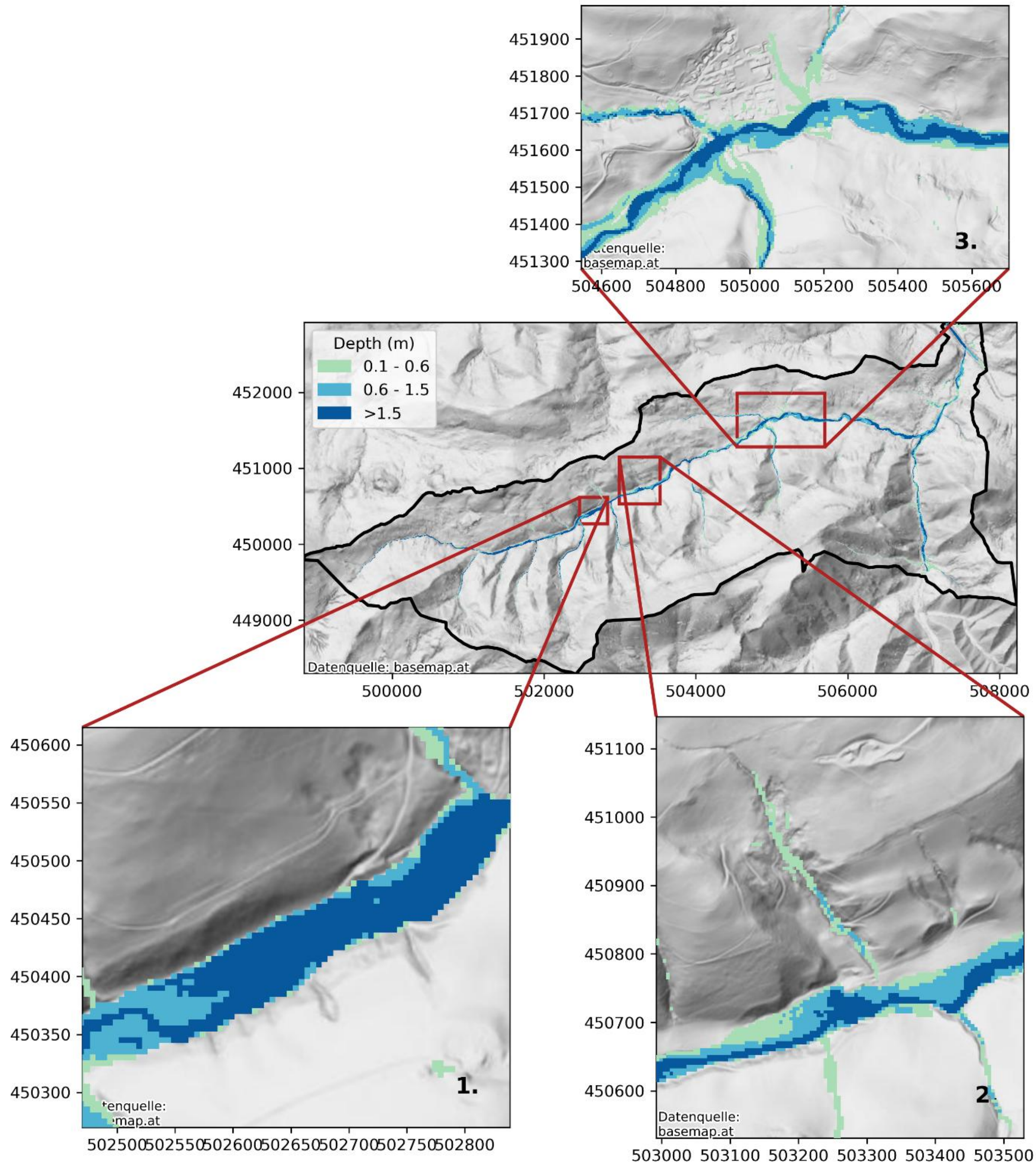


Figure A 20: Water Depth HQ300 6 hours landslide (Source: Created by the author).

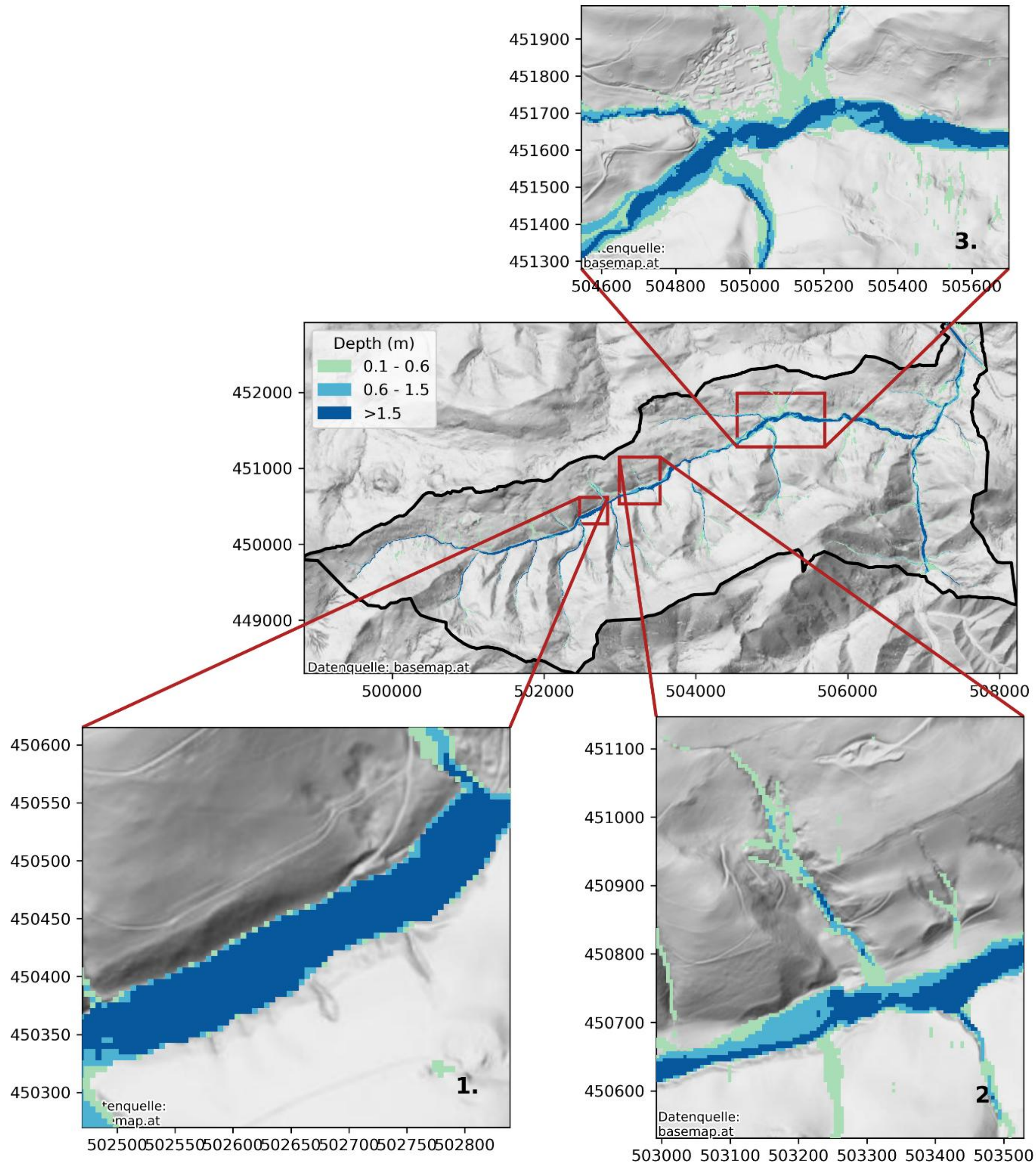


Figure A 21: Water Depth HQ300 2 hours base (Source: Created by the author).

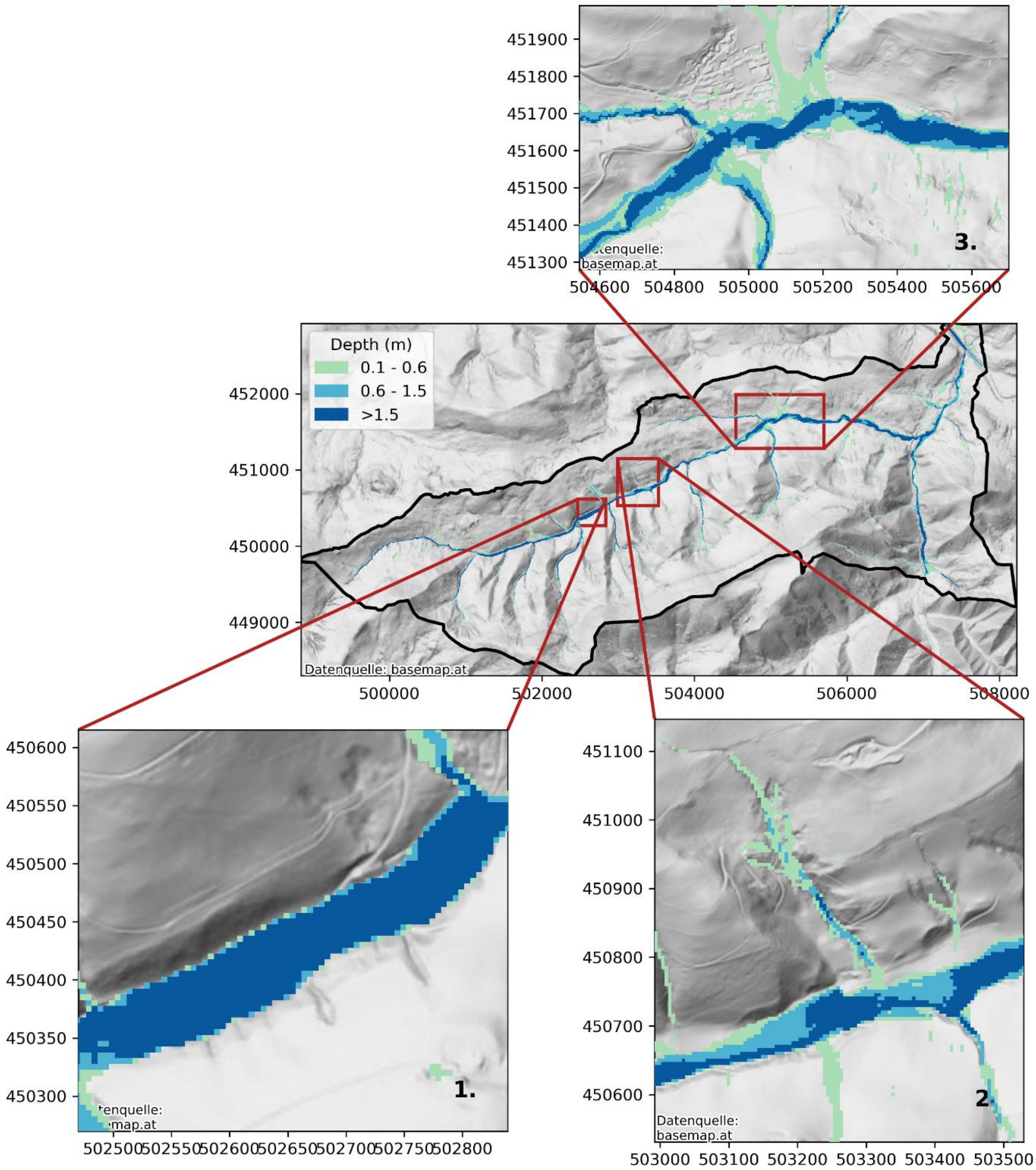


Figure A 22: Water Depth HQ300 2 hours landslide (Source: Created by the author).

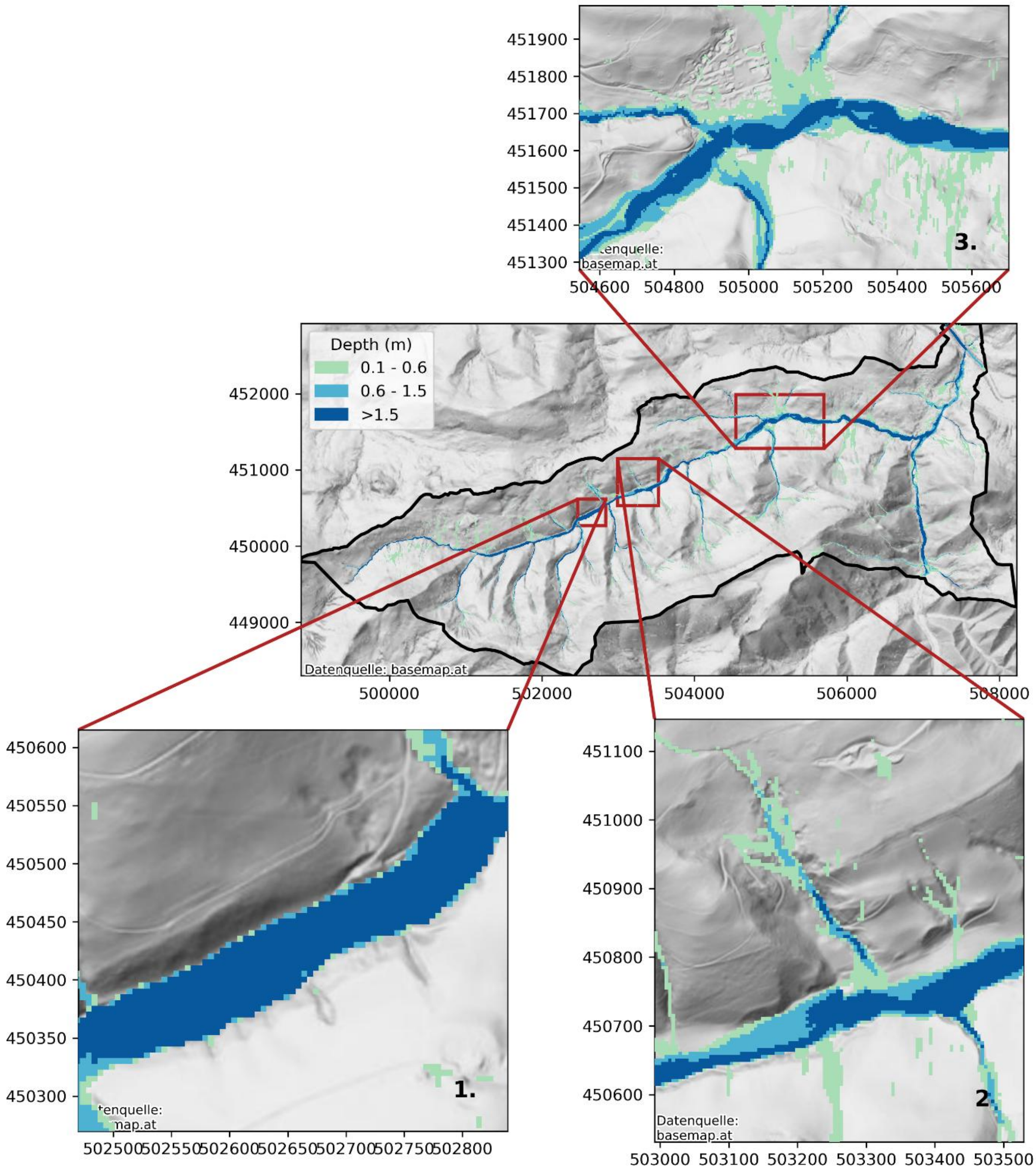


Figure A 23: Water Depth HQ300 1 hour base (Source: Created by the author).

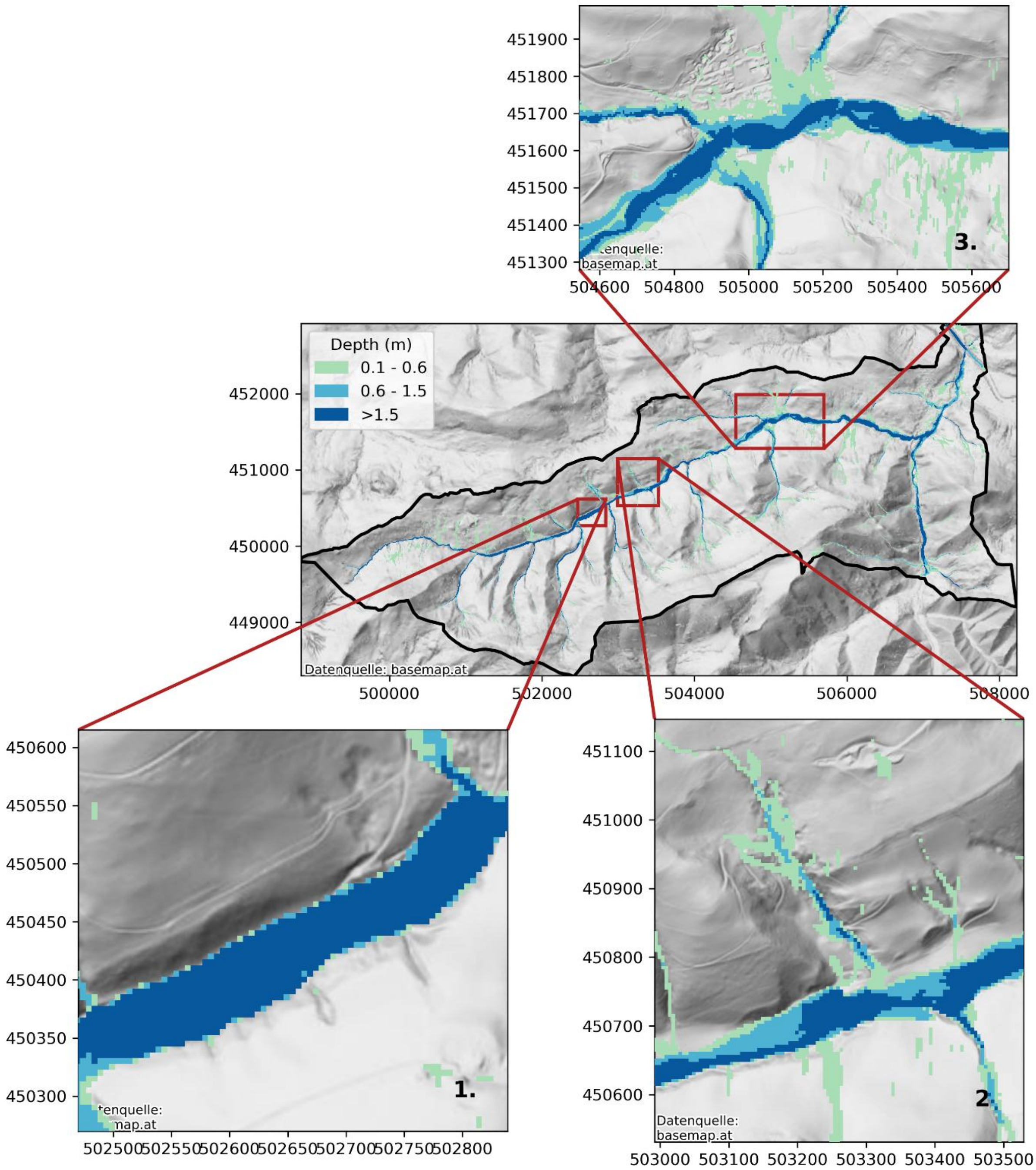


Figure A 24: Water Depth HQ300 1 hours landslide (Source: Created by the author).

11.3 All Scenarios Flow Velocity

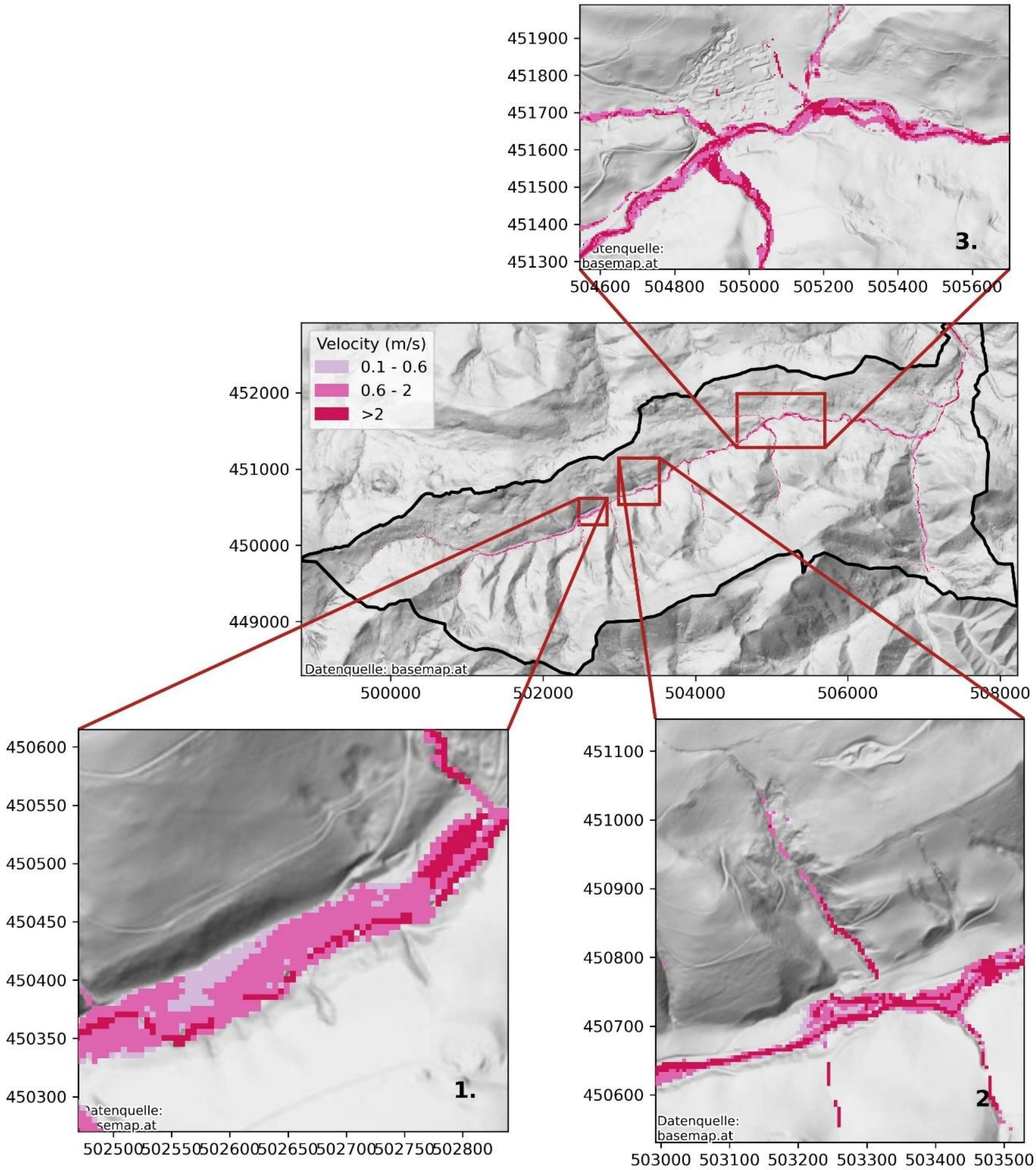


Figure A 25: Flow Velocity HQ30 6 hours base (Source: Created by the author).

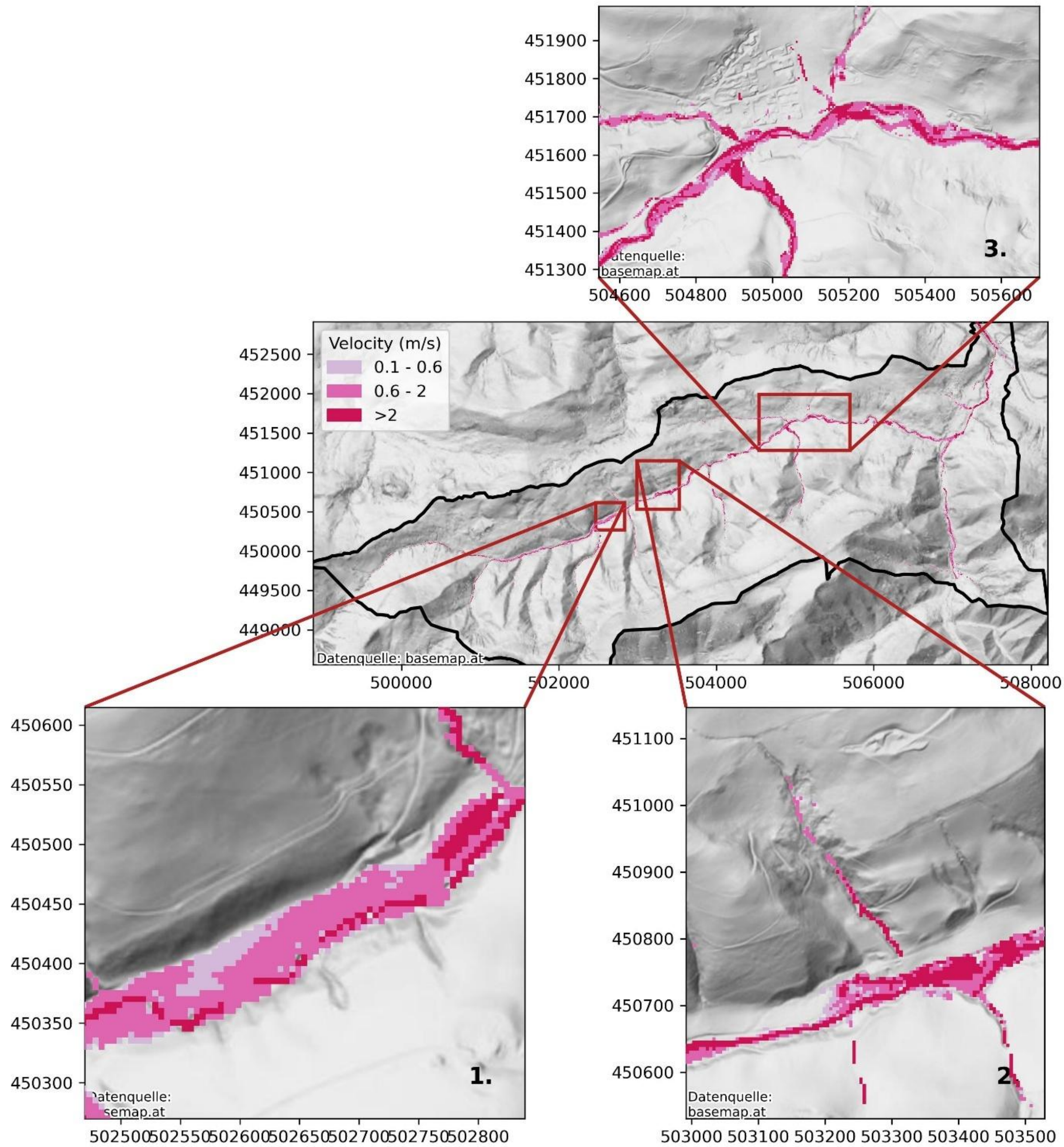


Figure A 26: Flow Velocity HQ30 6 hours landslide (Source: Created by the author).

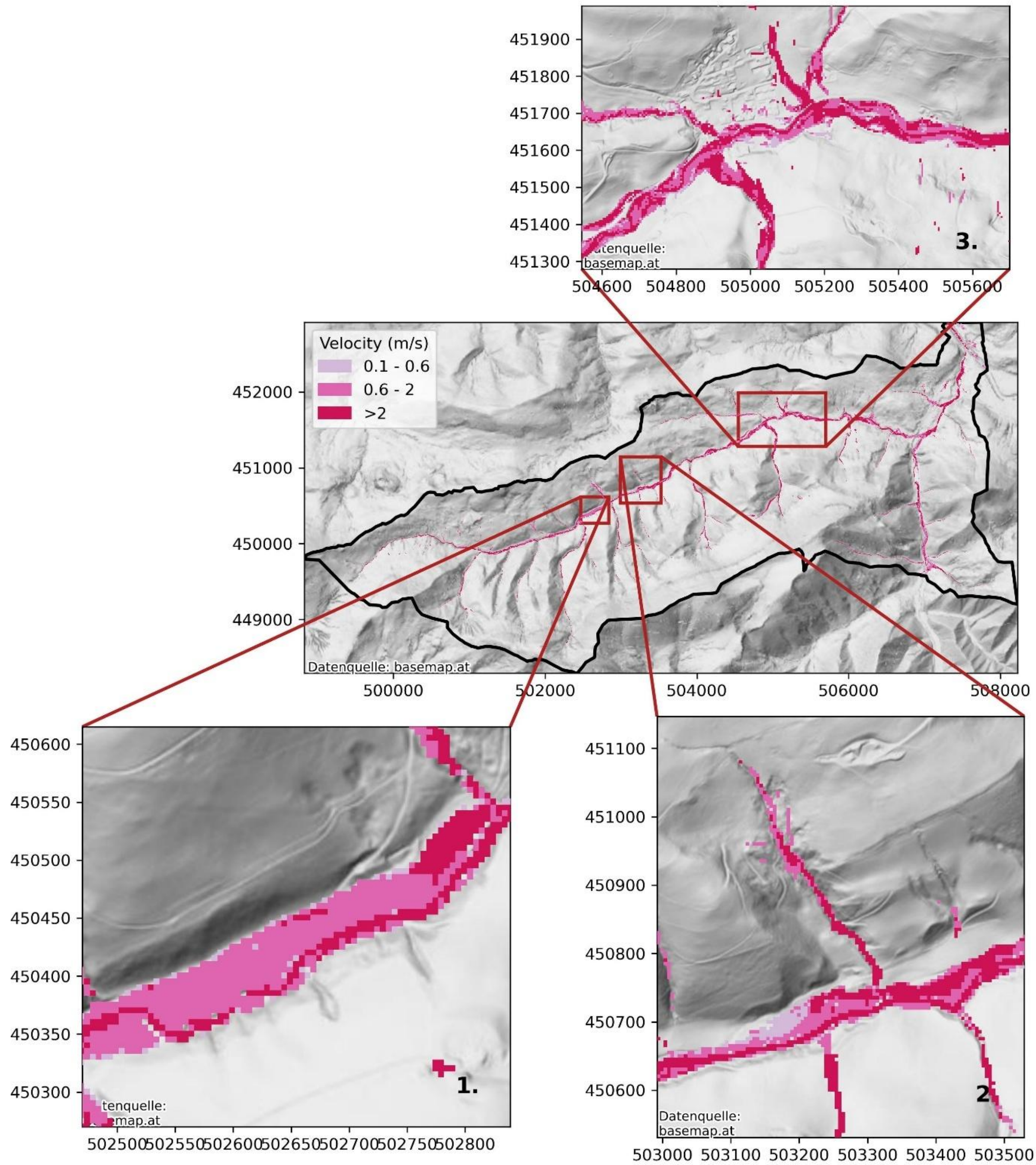


Figure A 27: Flow Velocity HQ30 2 hours base (Source: Created by the author).

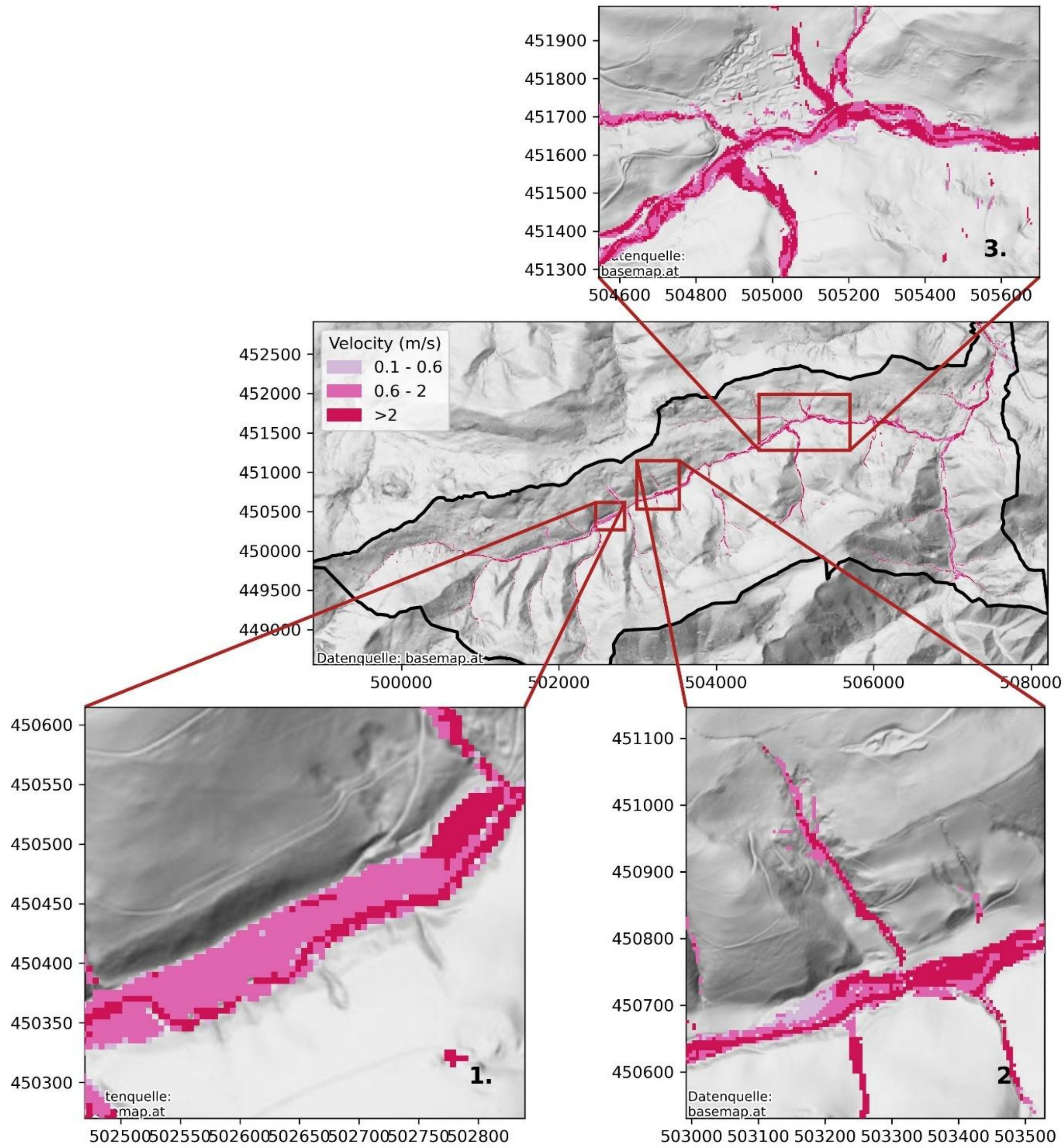


Figure A 28: Flow Velocity HQ30 2 hours landslide (Source: Created by the author).

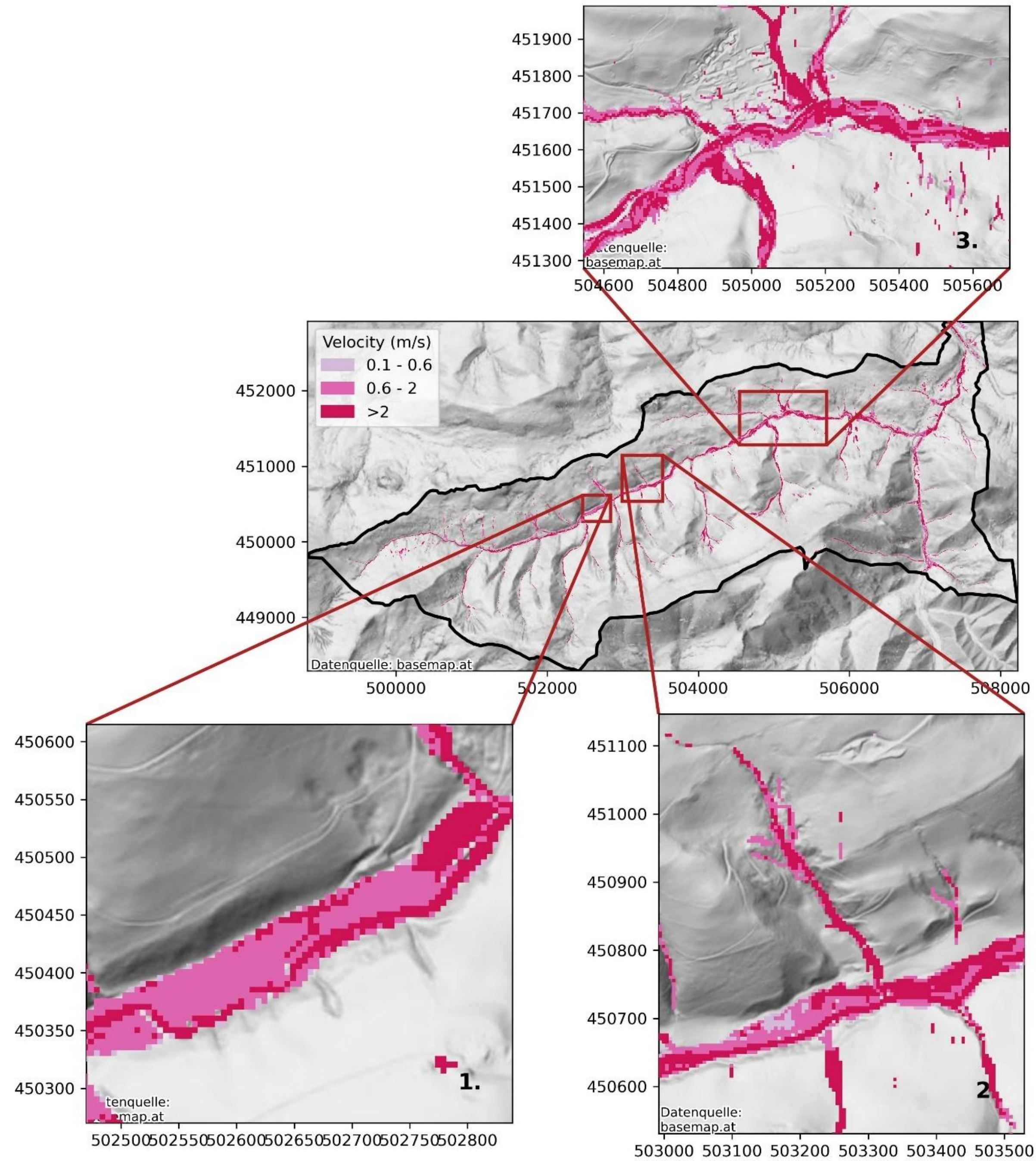


Figure A 29: Flow Velocity HQ30 1 hour base (Source: Created by the author).

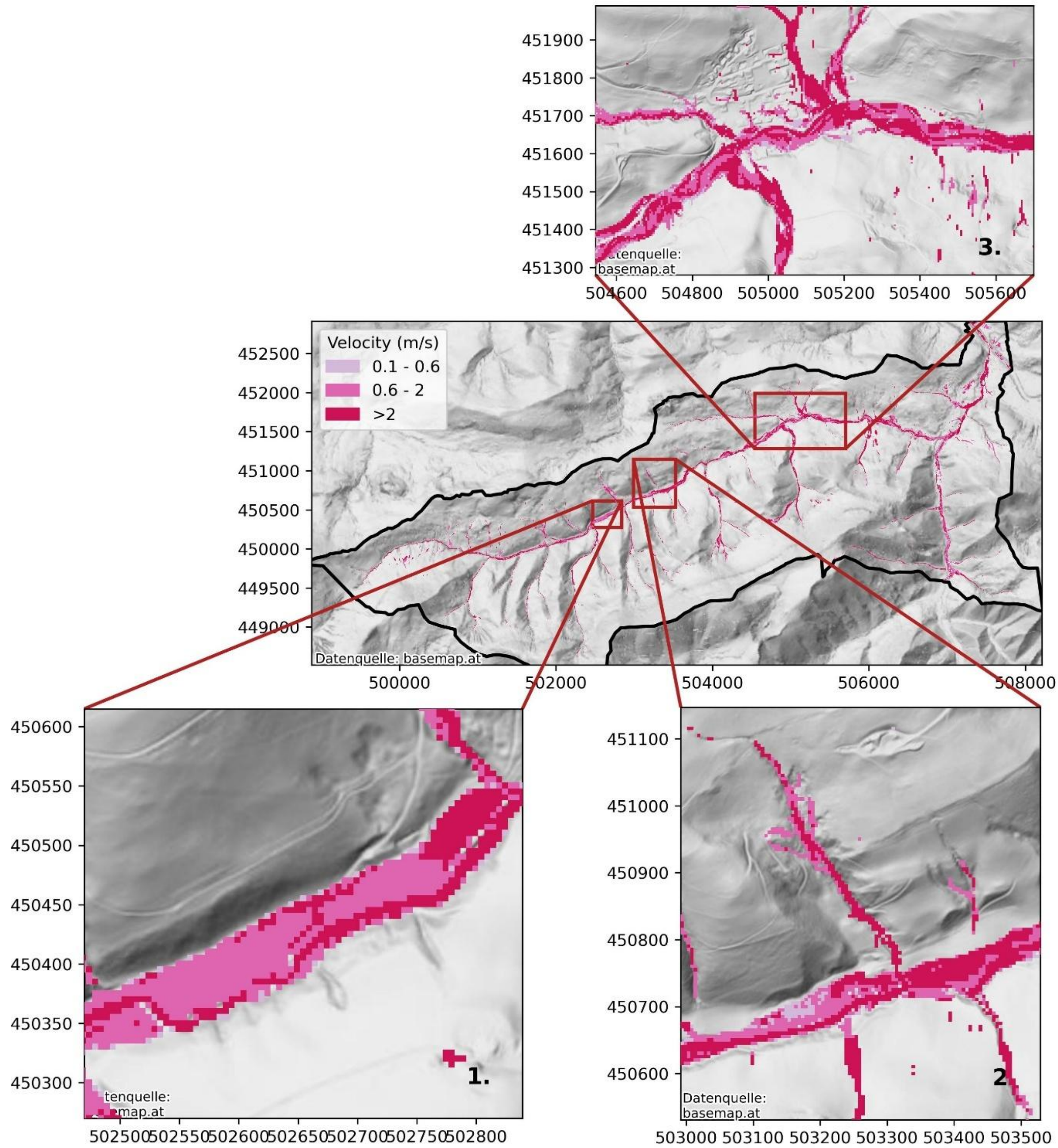


Figure A 30: Flow Velocity HQ30 1 hour landslide (Source: Created by the author).

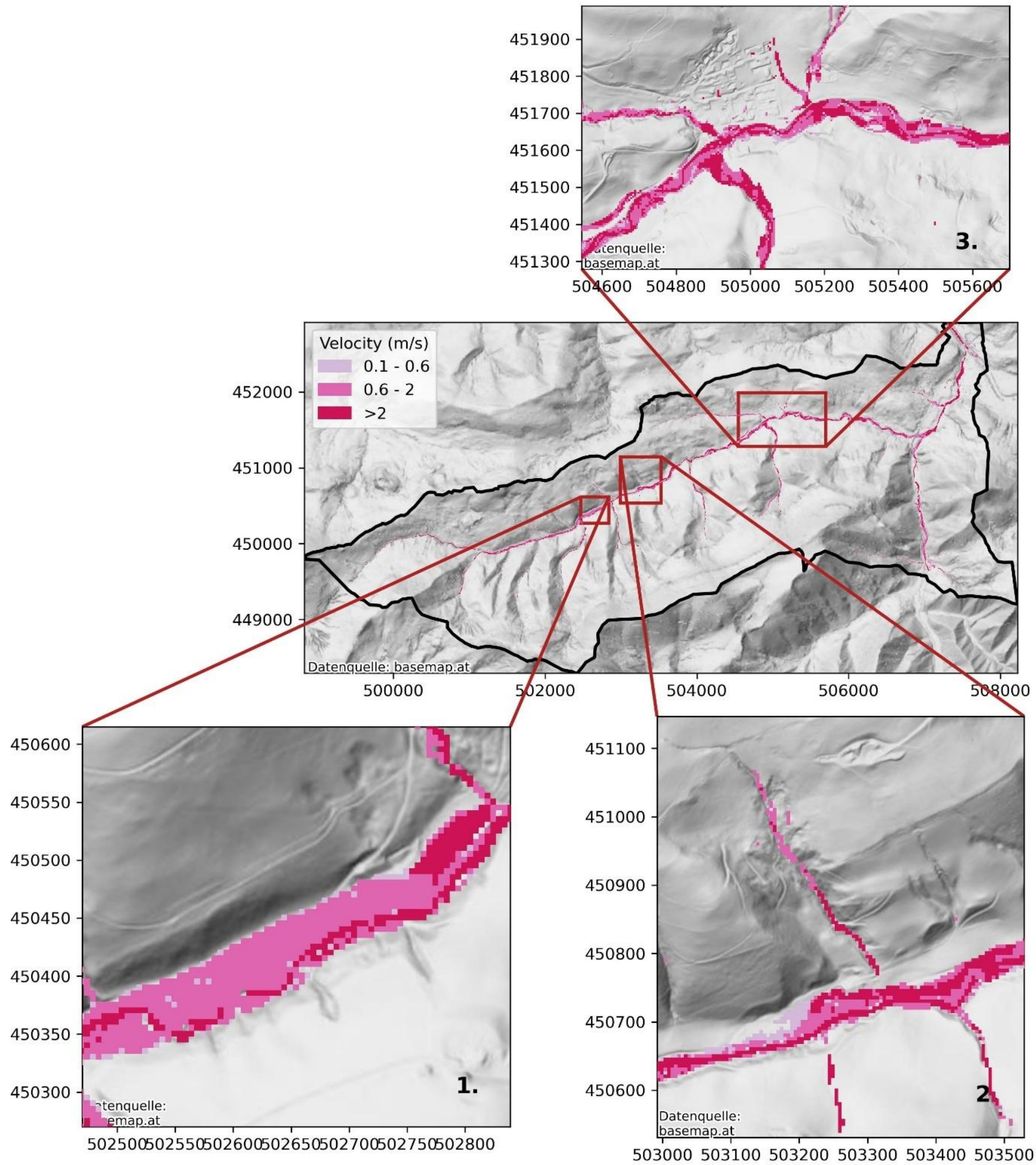


Figure A 31: Flow Velocity HQ100 6 hours base (Source: Created by the author).

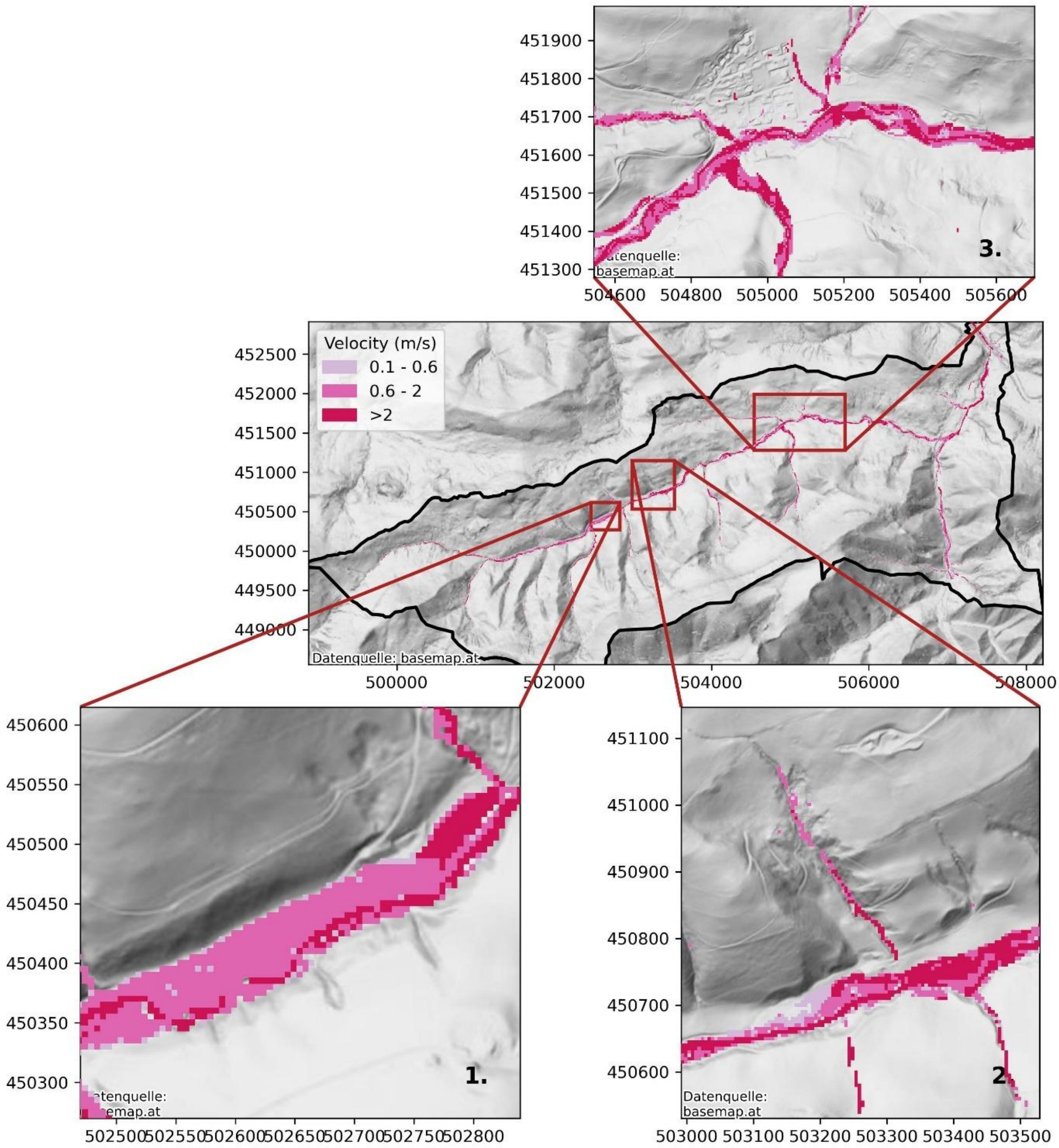


Figure A 32: Flow Velocity HQ100 6 hours landslide (Source: Created by the author).

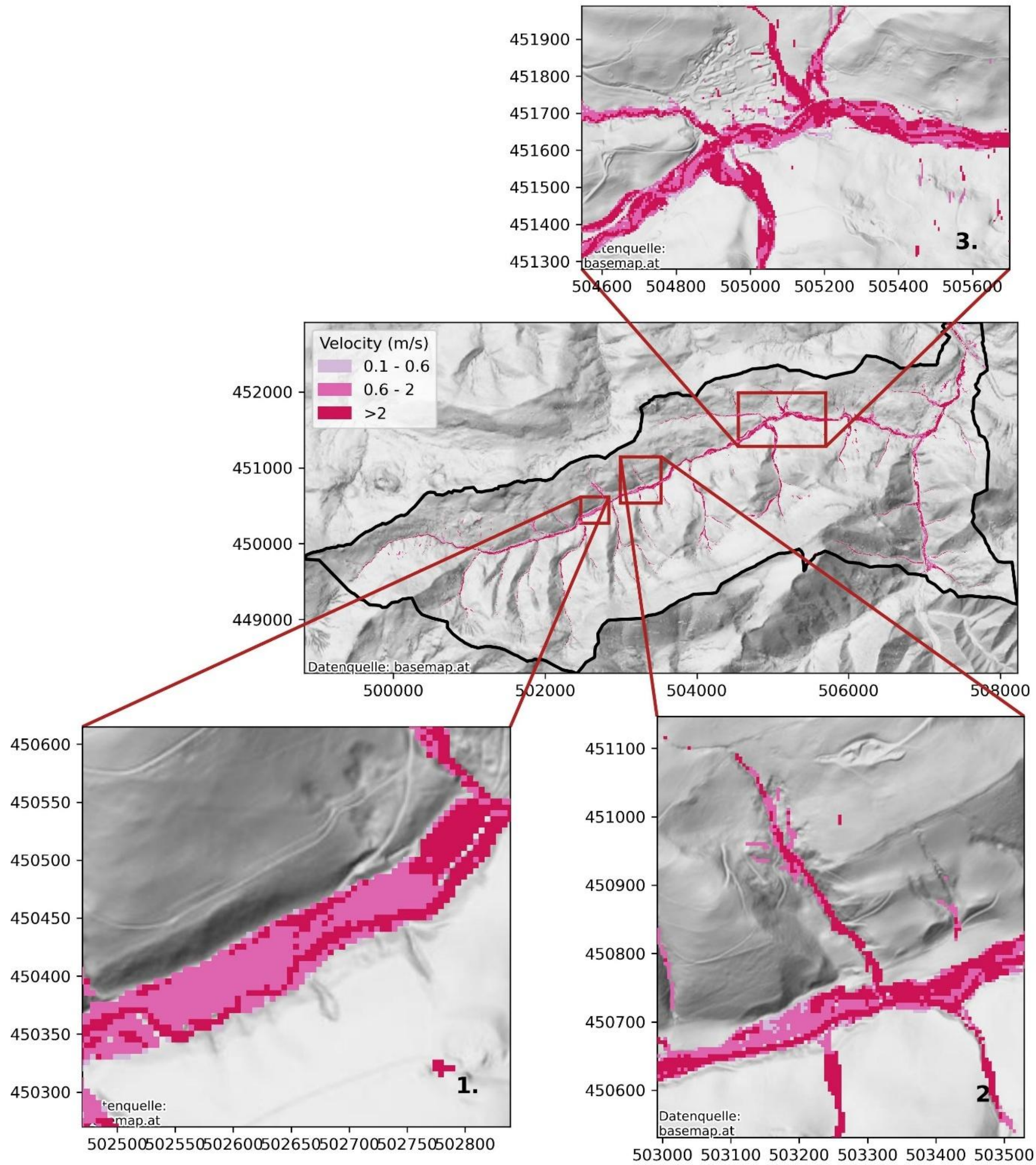


Figure A 33: Flow Velocity HQ100 2 hours base (Source: Created by the author).

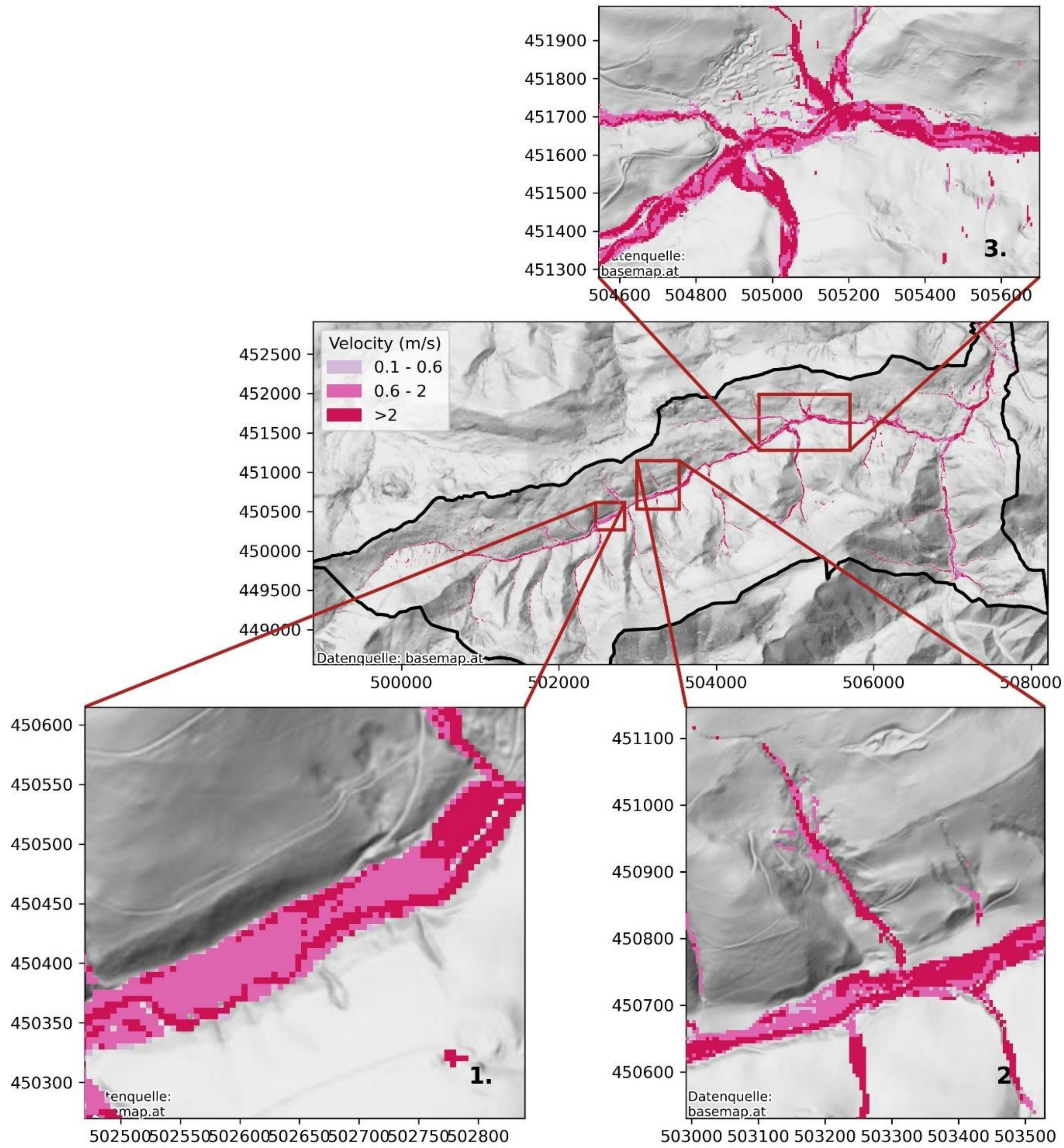


Figure A 34: Flow Velocity HQ100 2 hours landslide (Source: Created by the author).

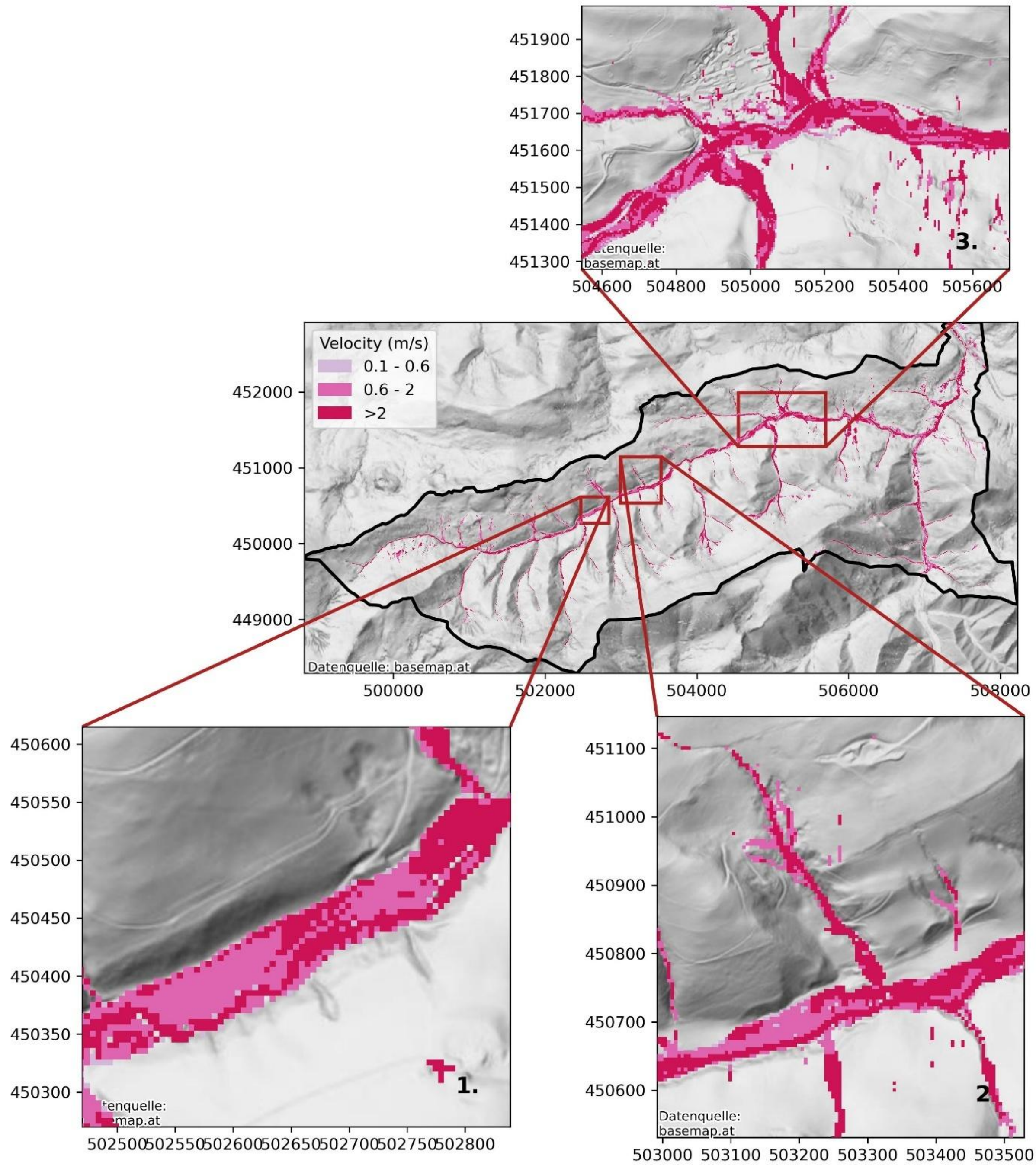


Figure A 35: Flow Velocity HQ100 1 hour base (Source: Created by the author).

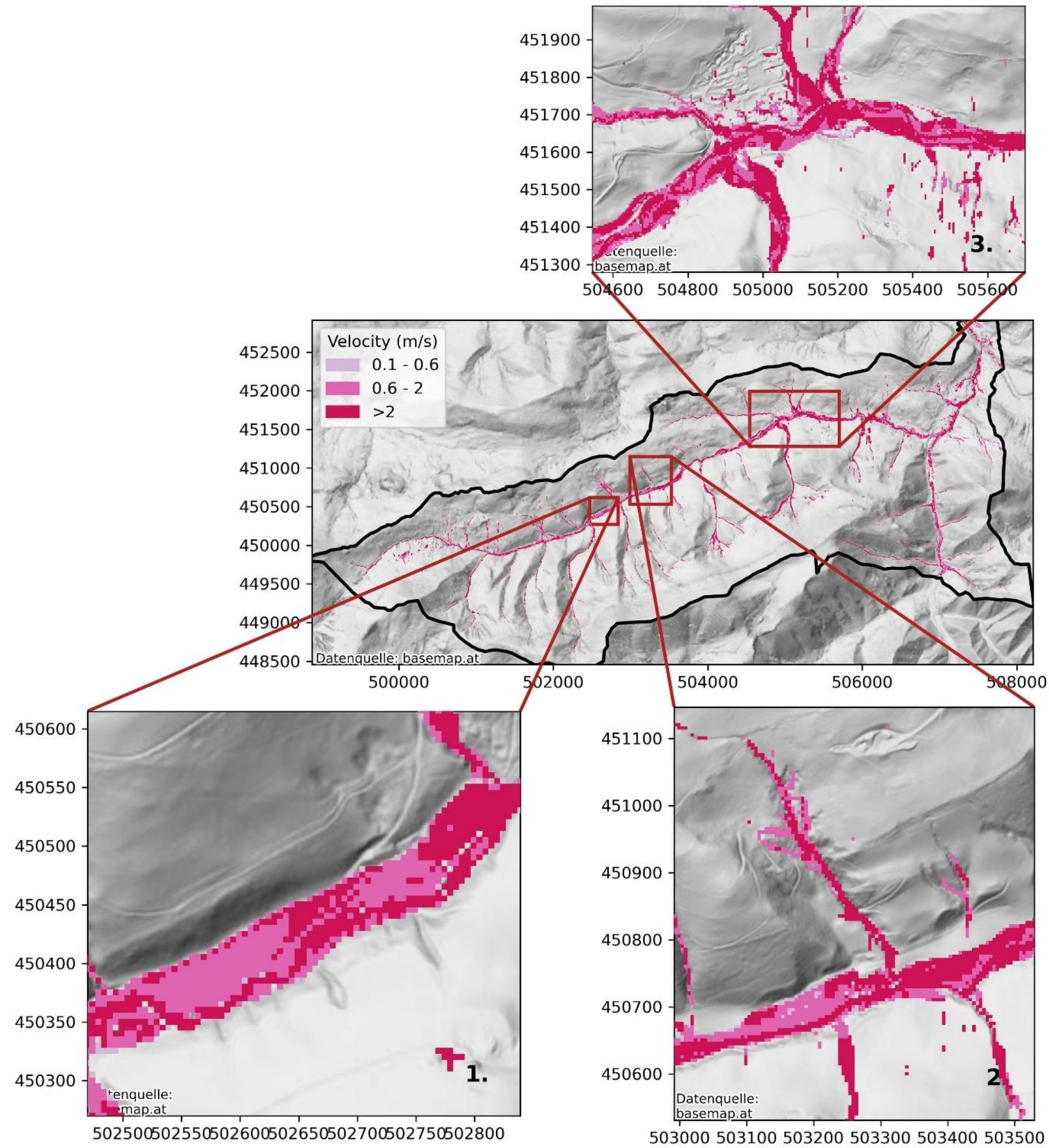


Figure A 36: Flow Velocity HQ100 1 hour landslide (Source: Created by the author).

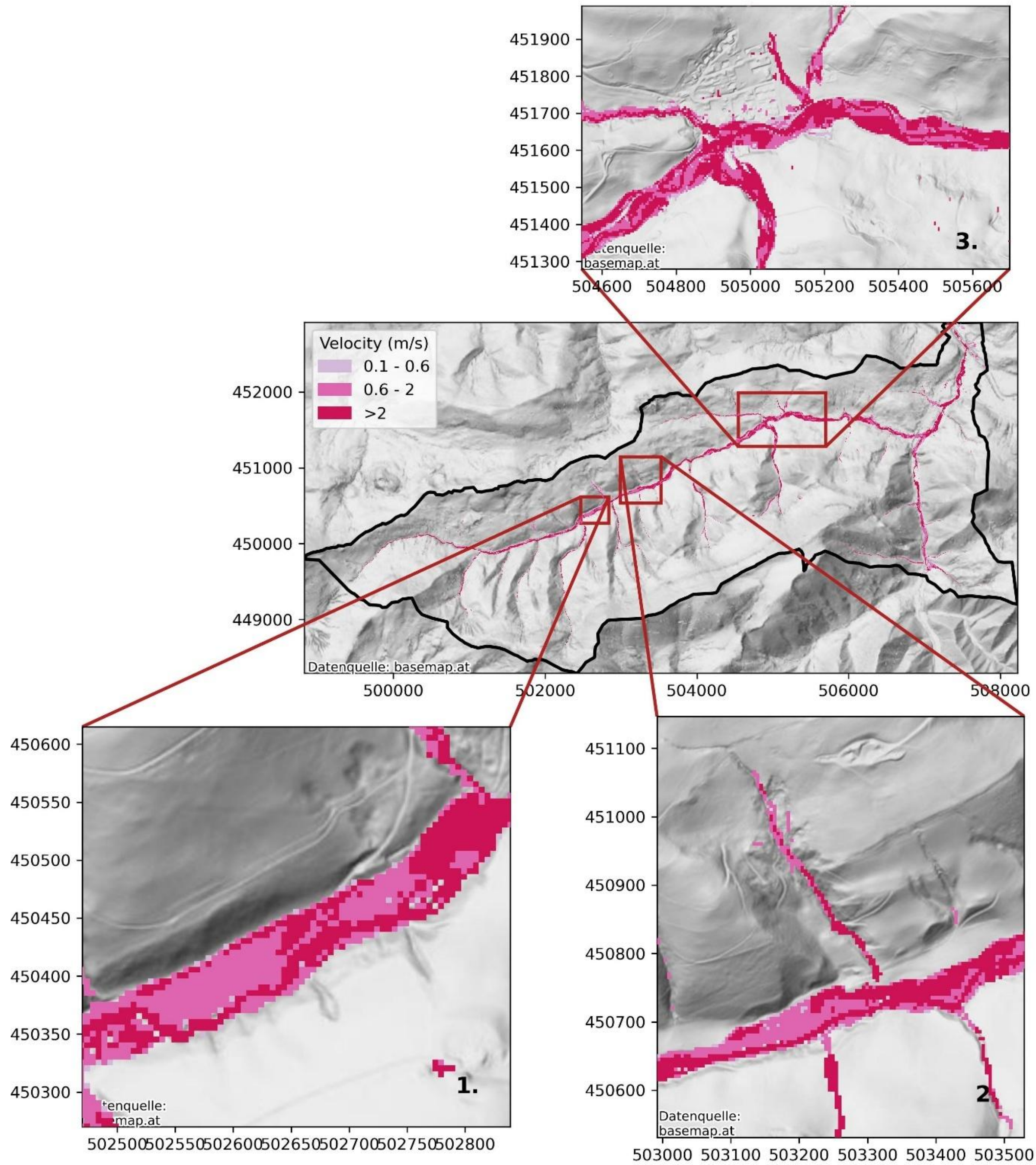


Figure A 37: Flow Velocity HQ300 6 hours base (Source: Created by the author).

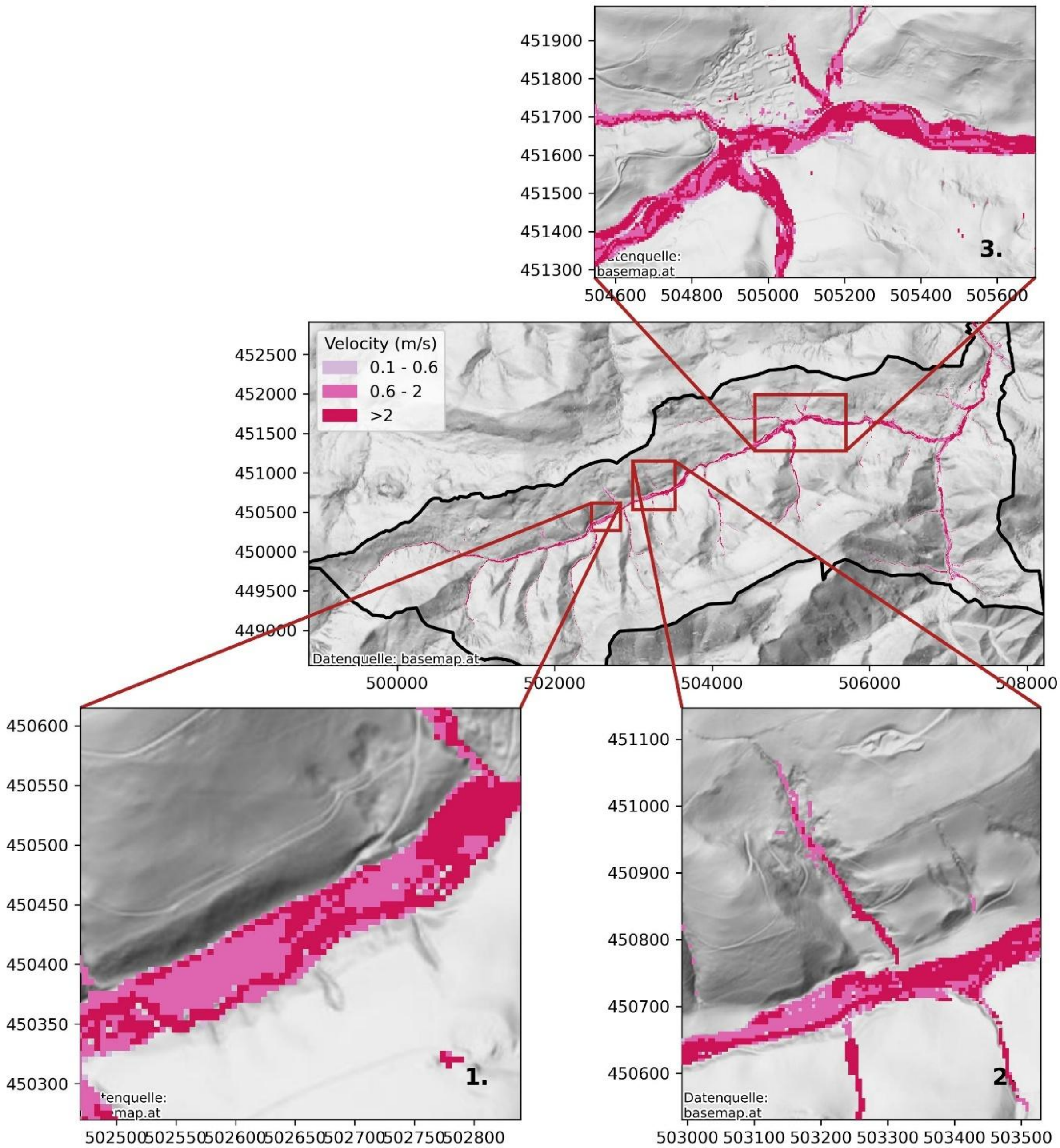


Figure A 38: Flow Velocity HQ300 6 hours landslide (Source: Created by the author).

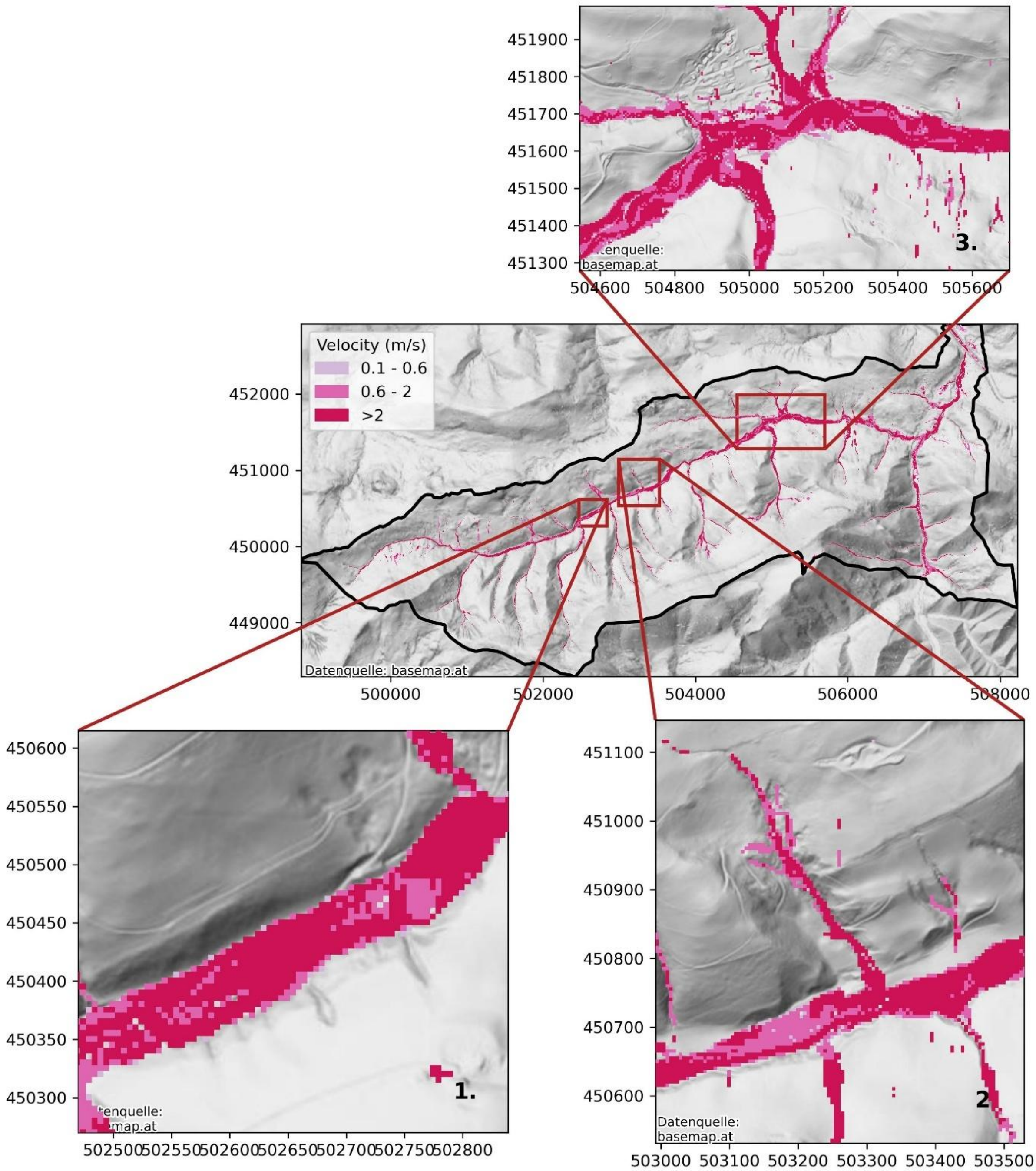


Figure A 39: Flow Velocity HQ300 2 hours base (Source: Created by the author).

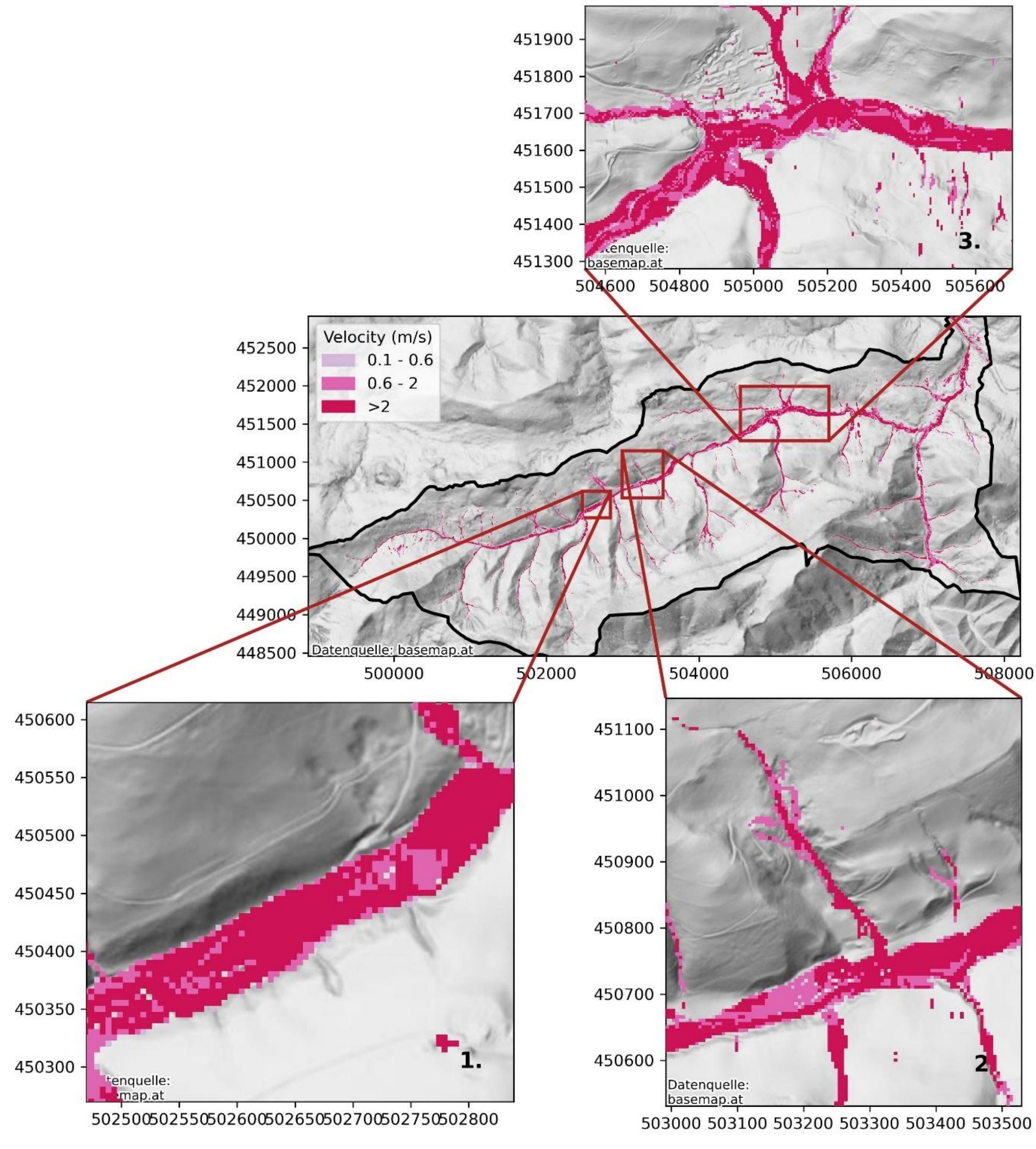


Figure A 40: Flow Velocity HQ300 2 hours landslide (Source: Created by the author).

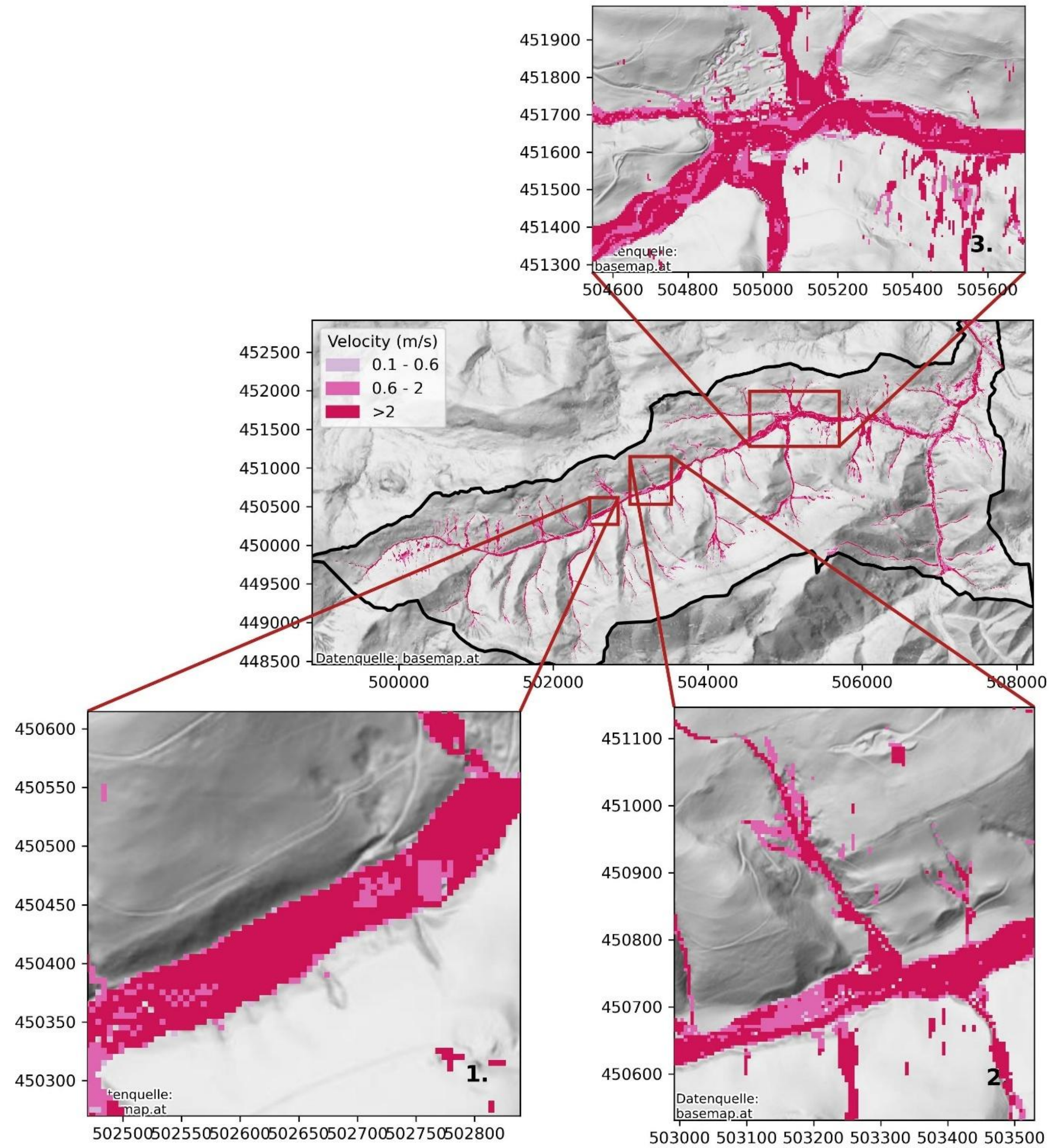


Figure A 41: Flow Velocity HQ300 1 hour base (Source: Created by the author).

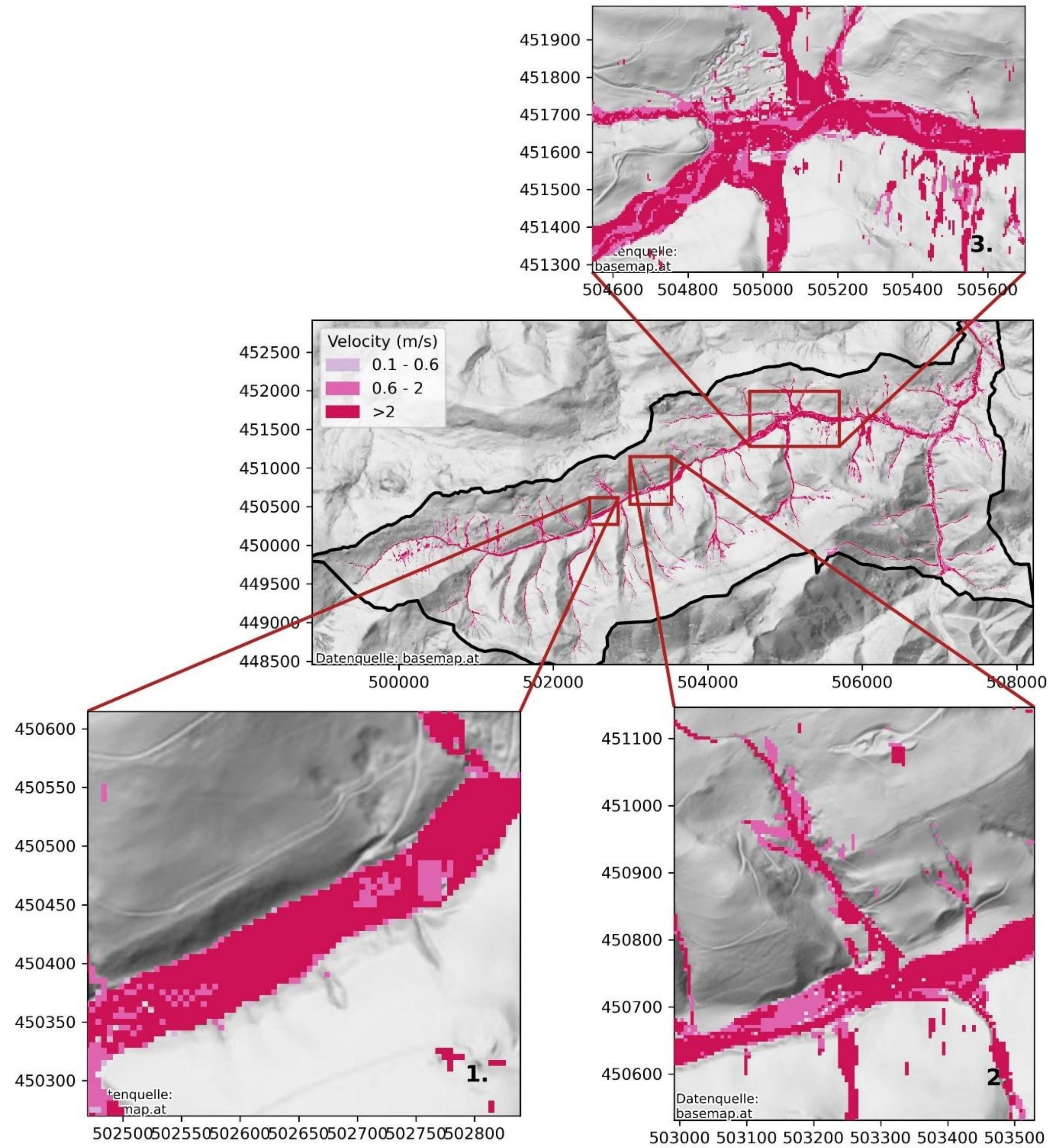


Figure A 42: Flow Velocity HQ300 1 hour landslide (Source: Created by the author).

11.4 All Scenarios Exposure

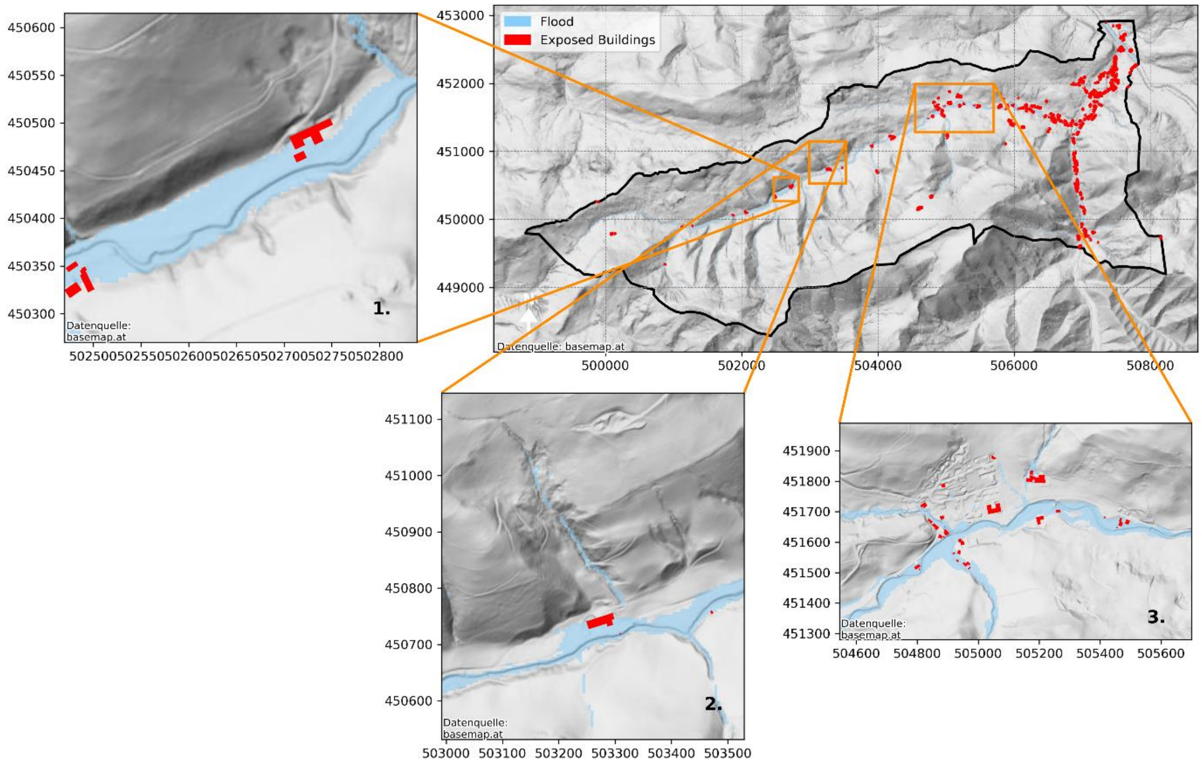


Figure A 43: Exposure HQ30 6 hours base (Source: Created by the author).

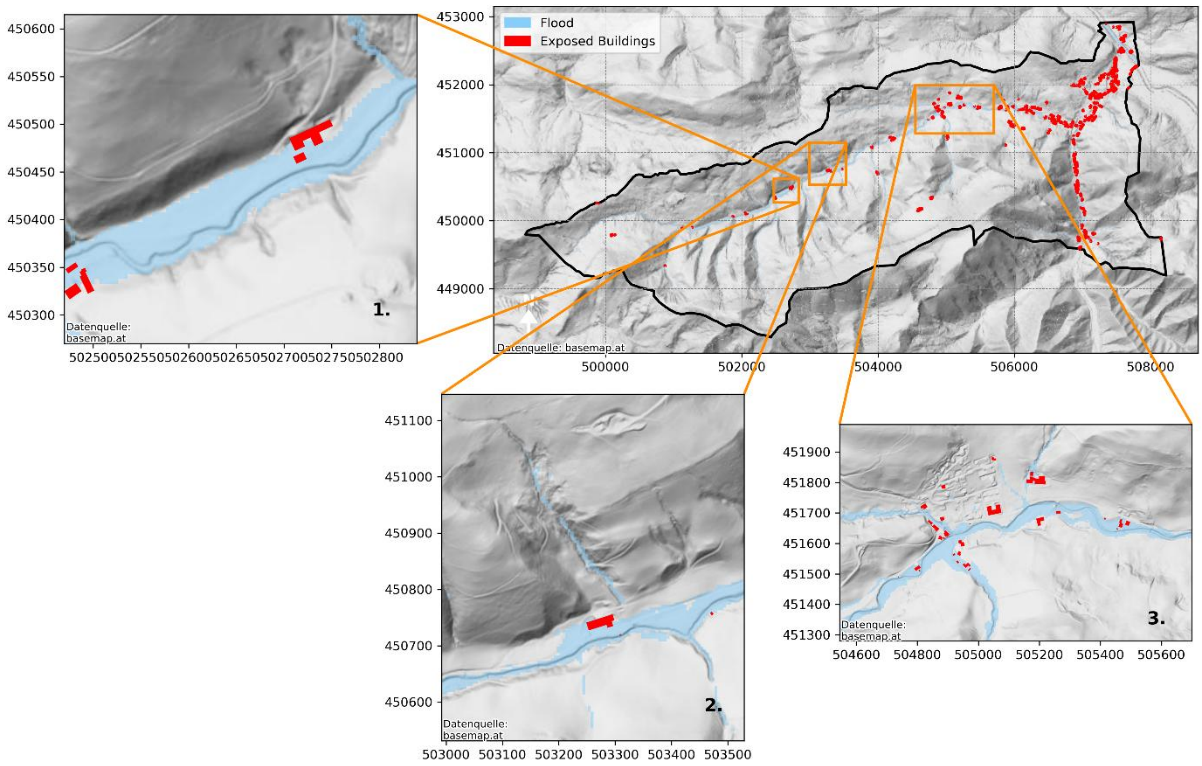


Figure A 44: Exposure HQ30 6 hours landslide (Source: Created by the author).

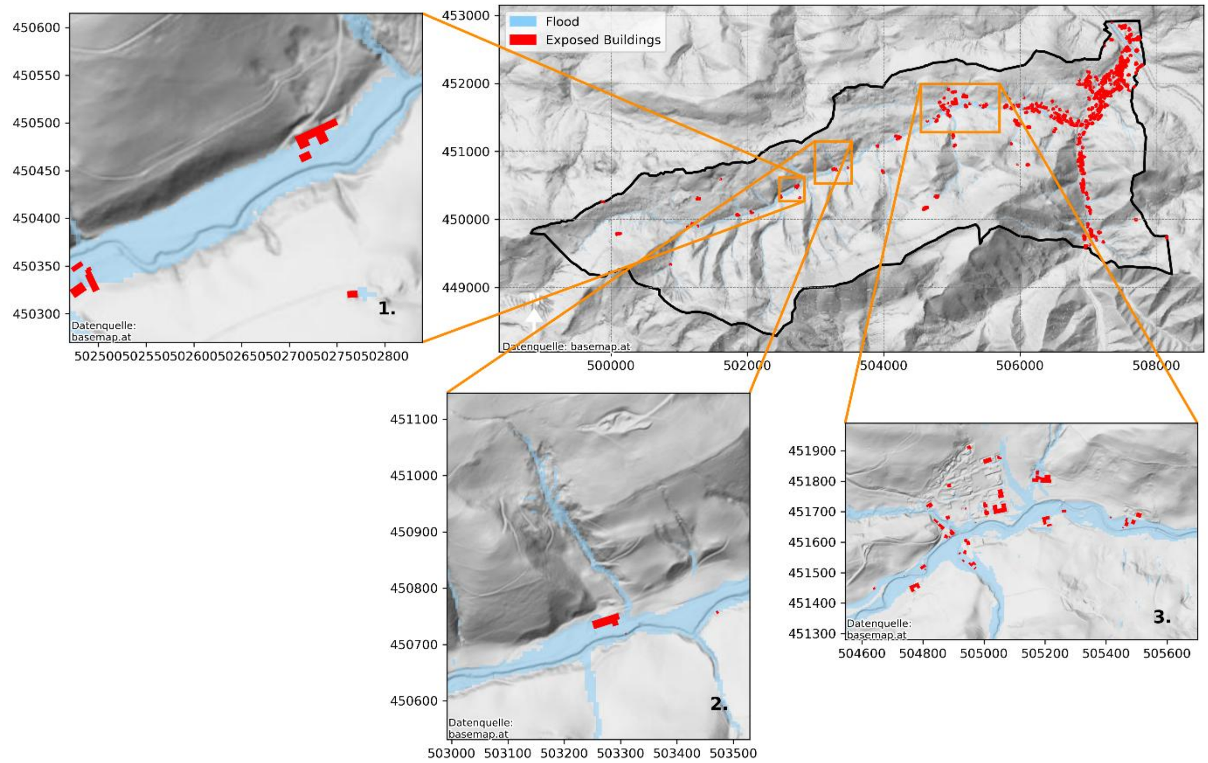


Figure A 45: Exposure HQ30 2 hours base (Source: Created by the author).

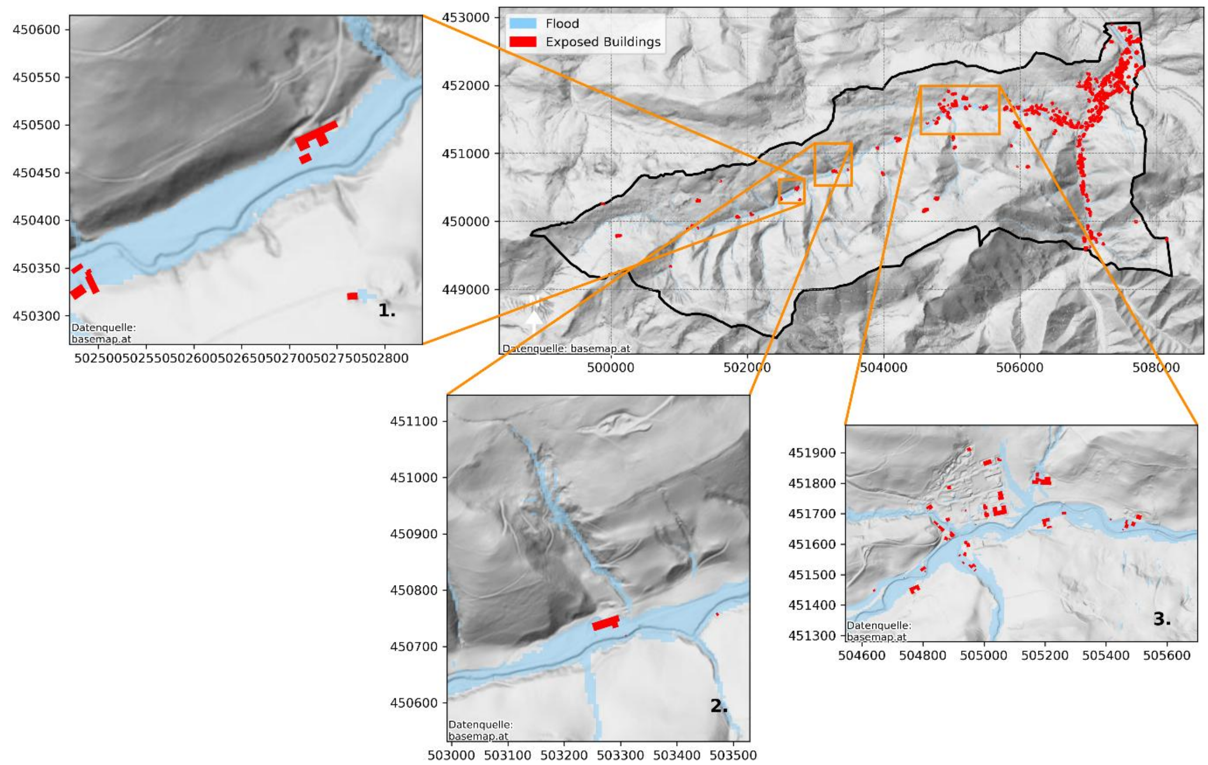


Figure A 46: Exposure HQ30 2 hours landslide (Source: Created by the author).

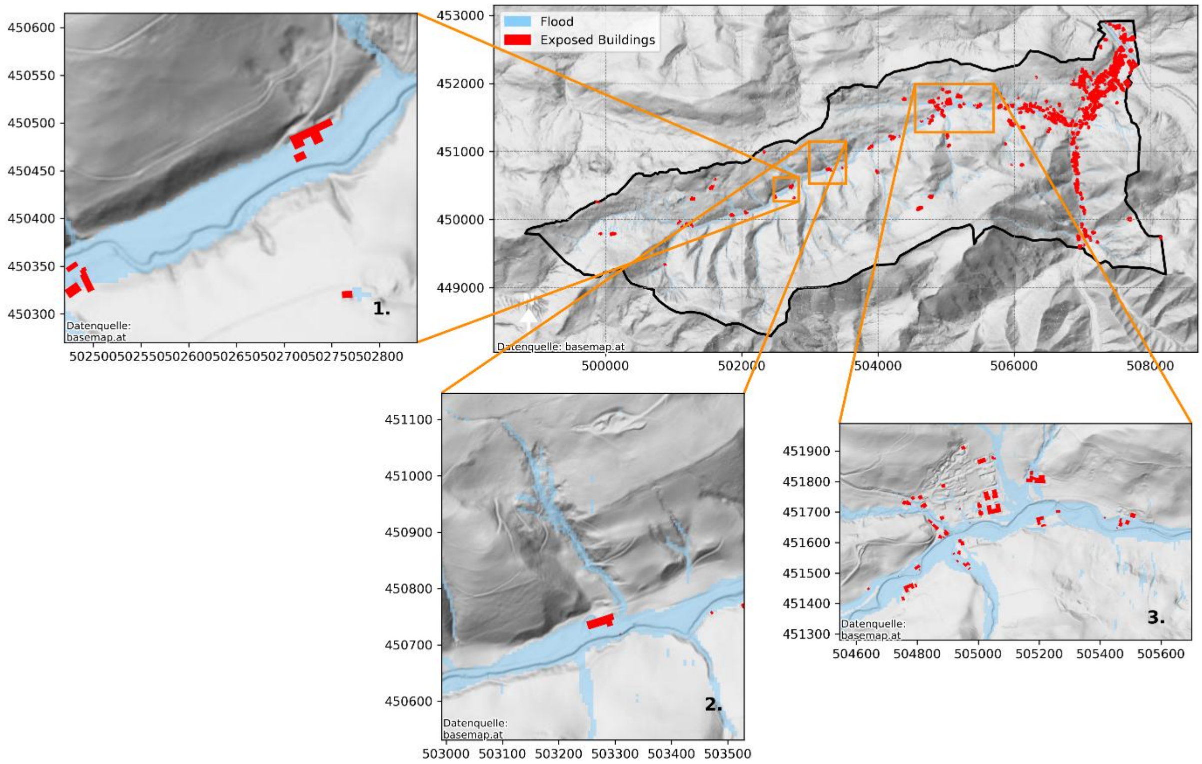


Figure A 47: Exposure HQ30 1 hour base (Source: Created by the author).

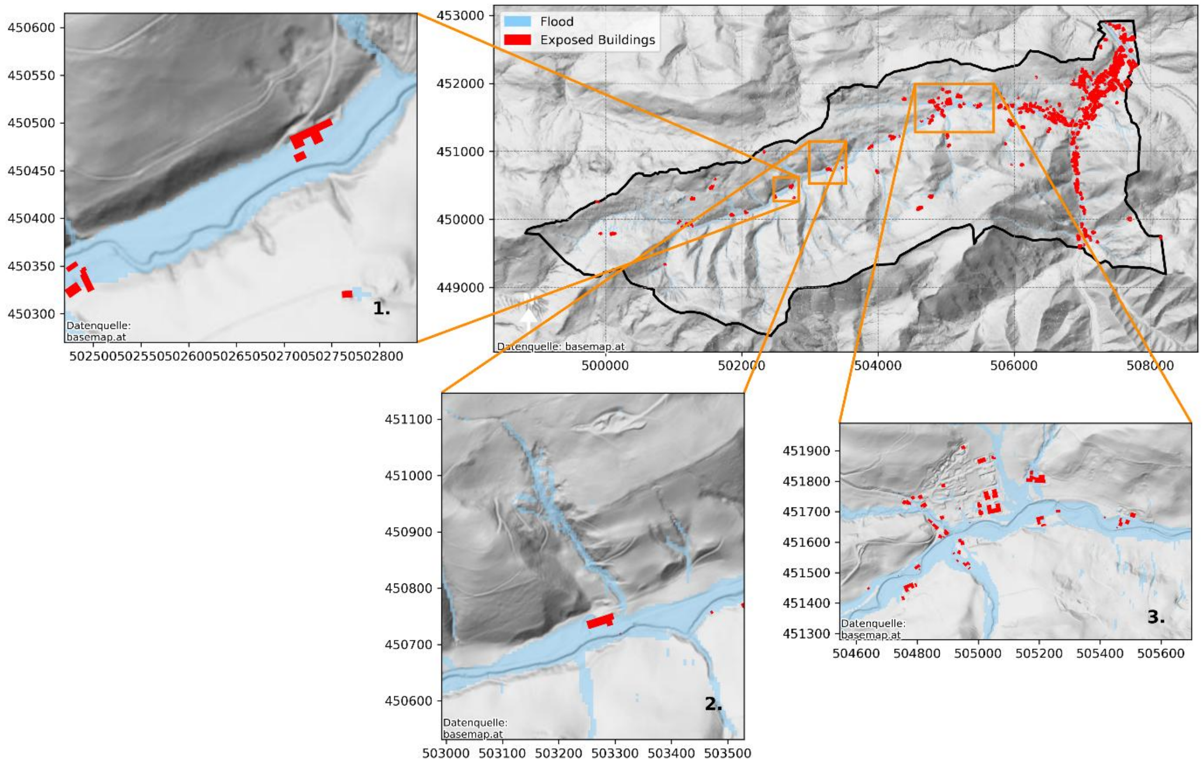


Figure A 48: Exposure HQ30 1 hour landslide (Source: Created by the author).

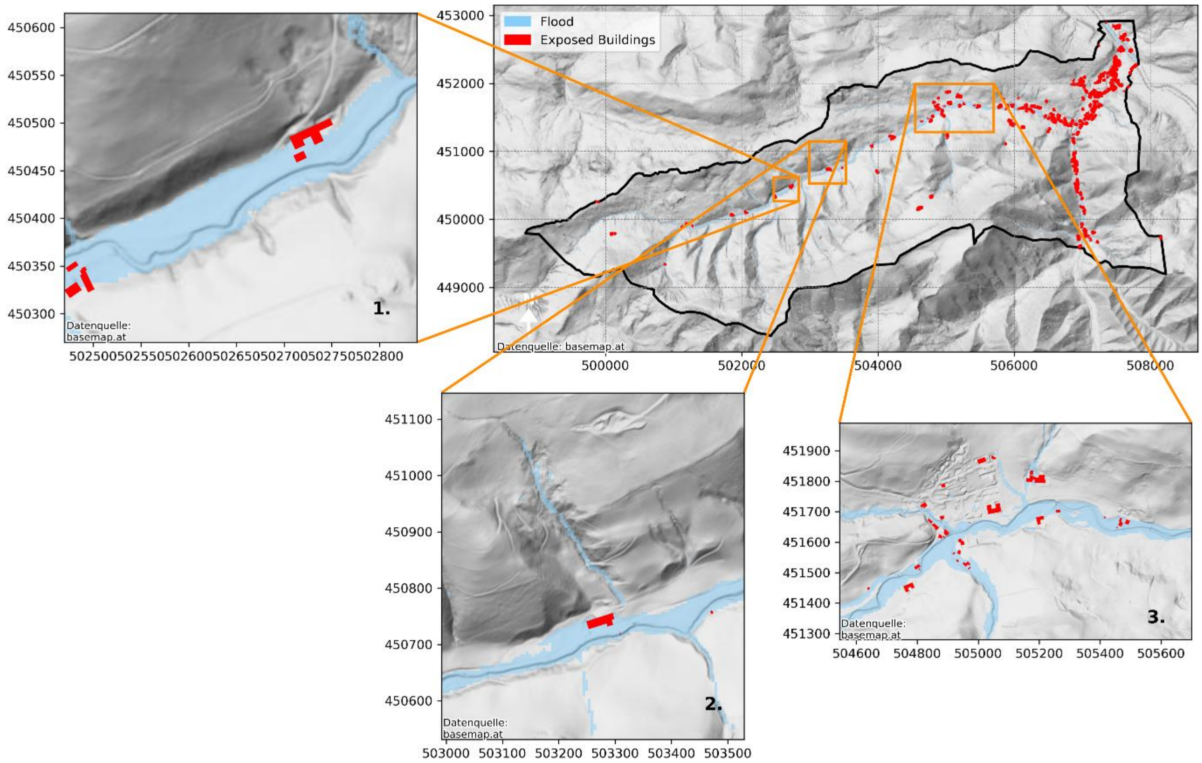


Figure A 49: Exposure HQ100 6 hours base (Source: Created by the author).

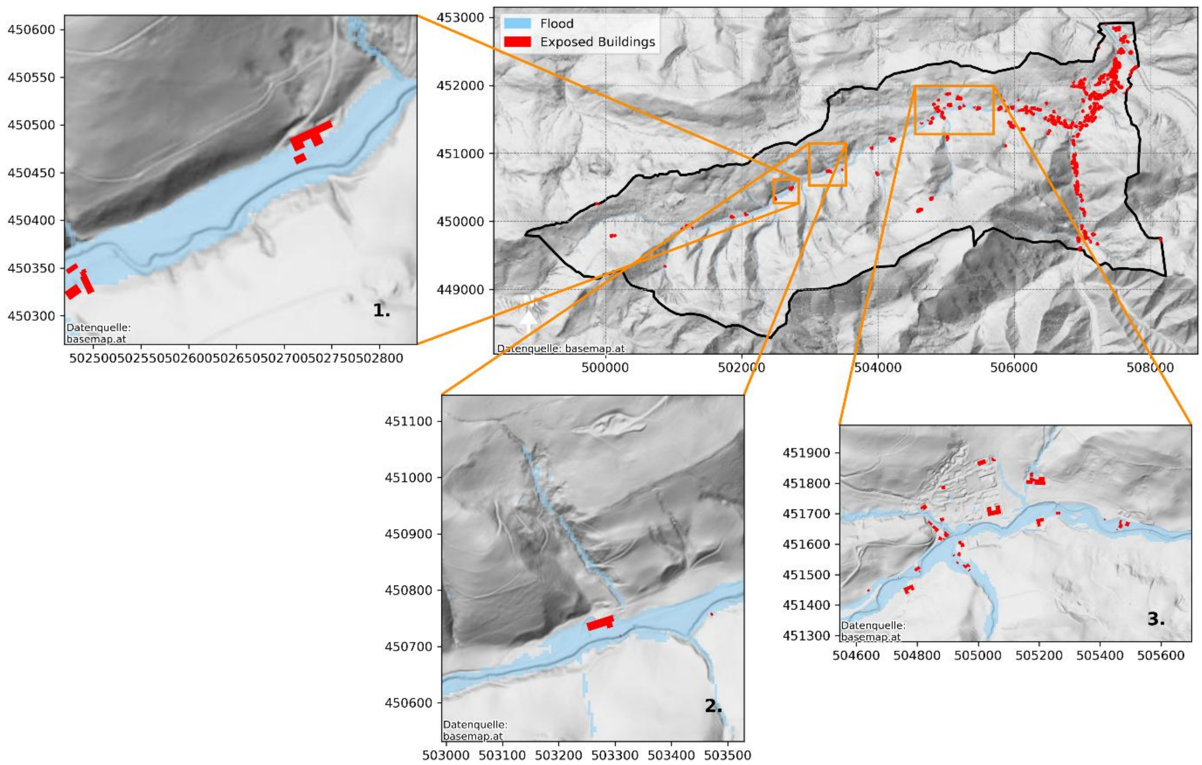


Figure A 50: Exposure HQ100 6 hours landslide (Source: Created by the author).

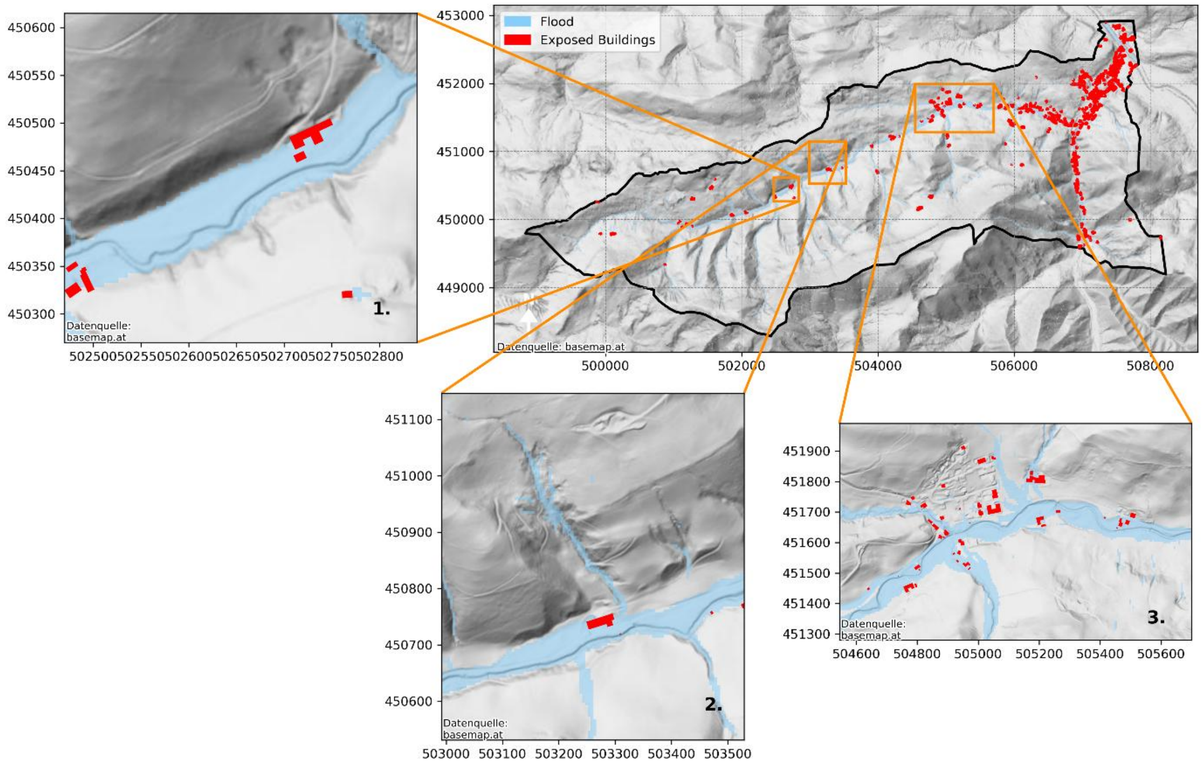


Figure A 51: Exposure HQ100 2 hours base (Source: Created by the author).

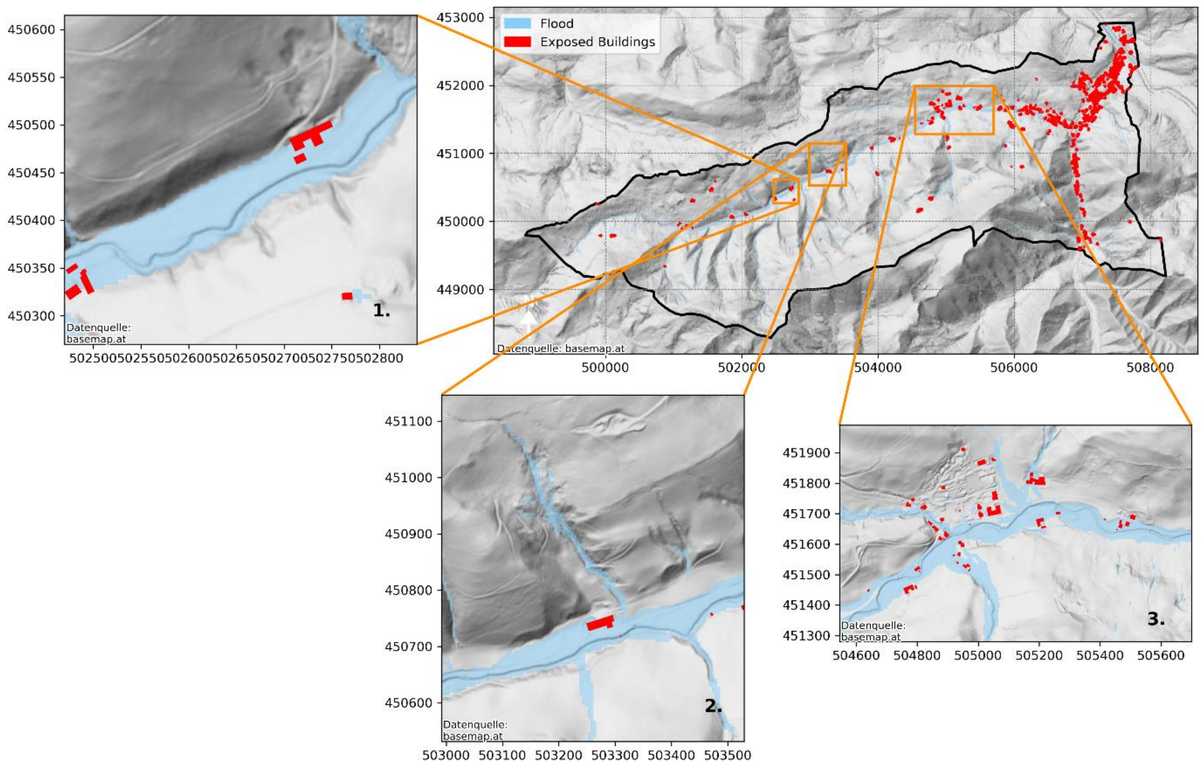


Figure A 52: Exposure HQ100 2 hours landslide (Source: Created by the author).

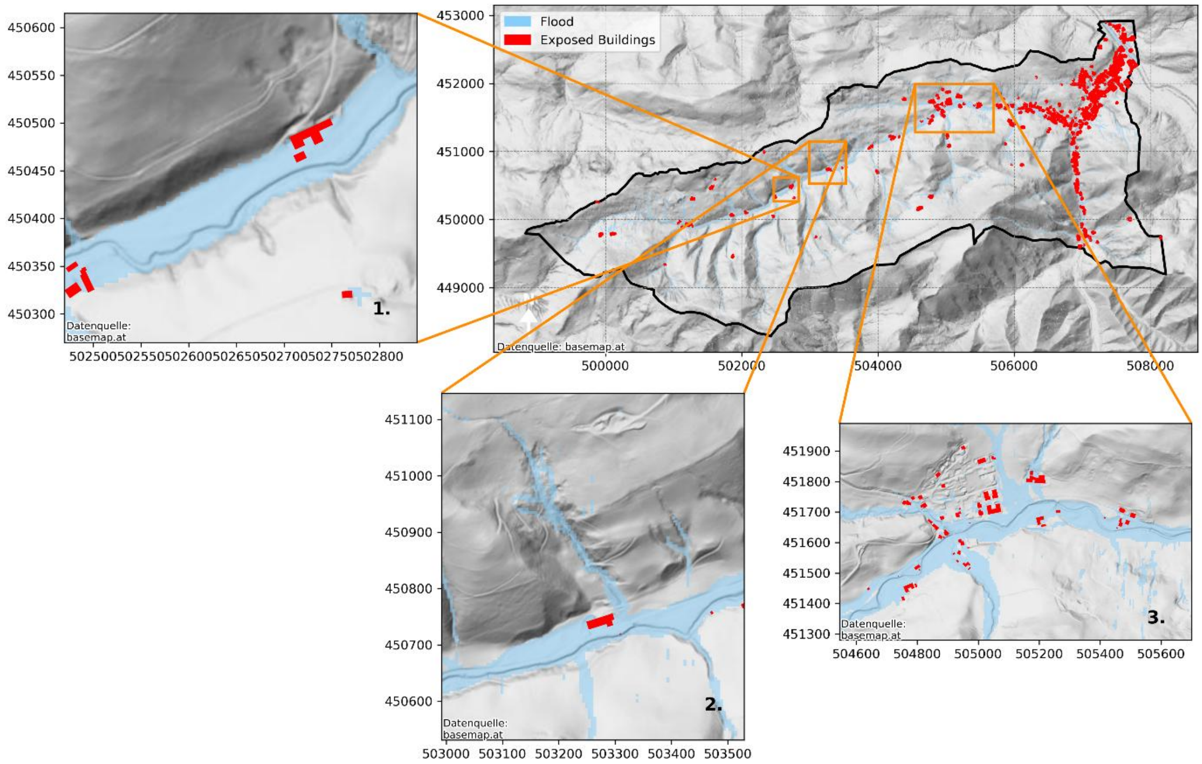


Figure A 53: Exposure HQ100 1 hour base (Source: Created by the author).

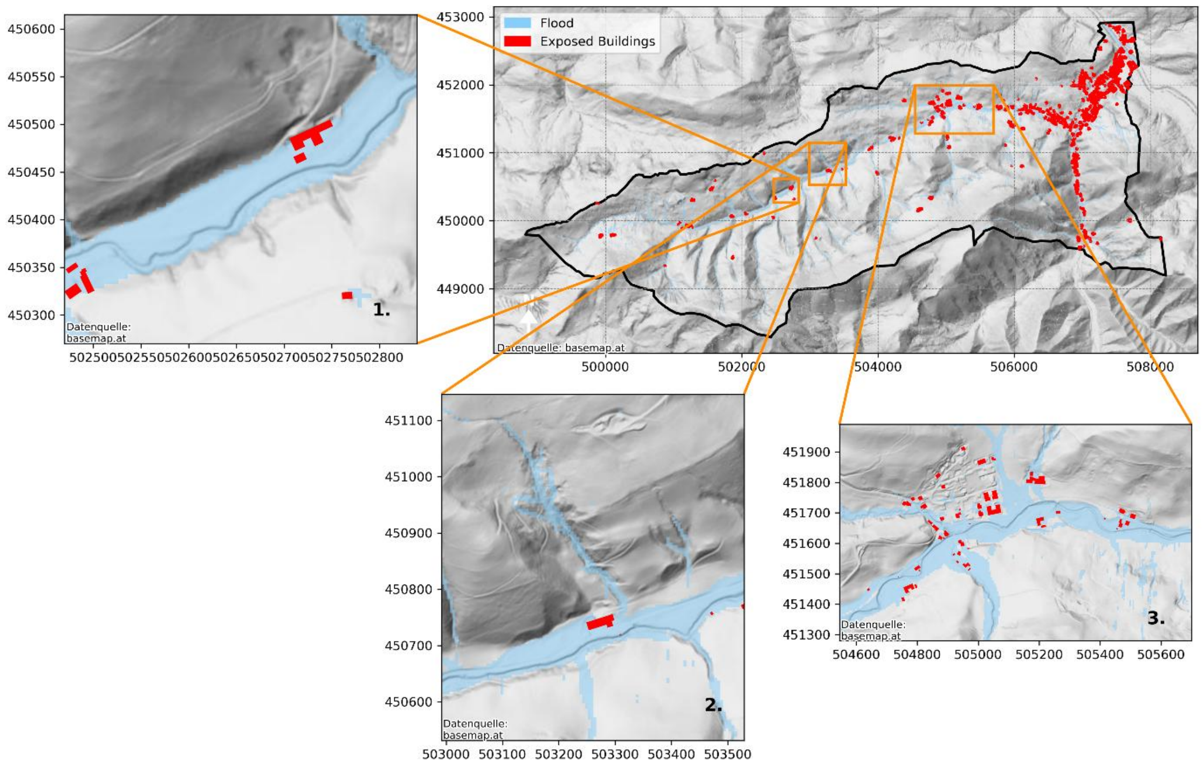


Figure A 54: Exposure HQ100 1 hour landslide (Source: Created by the author).

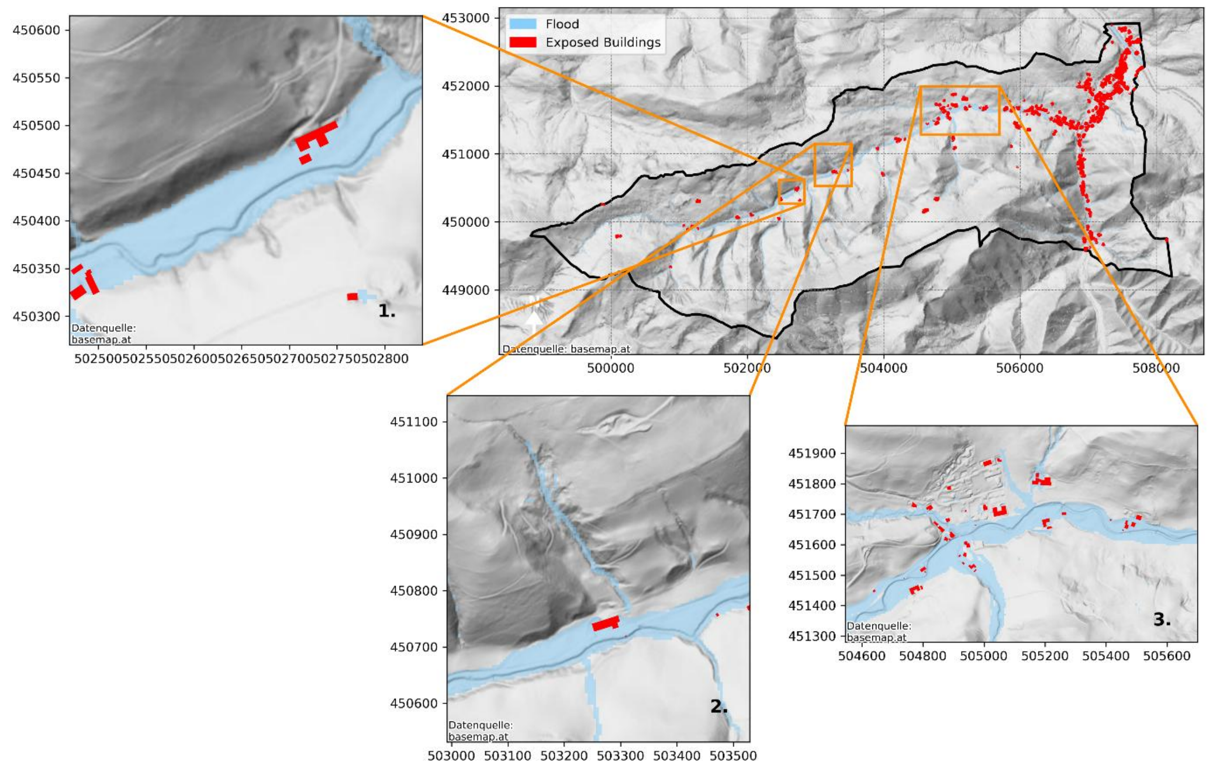


Figure A 55: Exposure HQ300 6 hours base (Source: Created by the author).

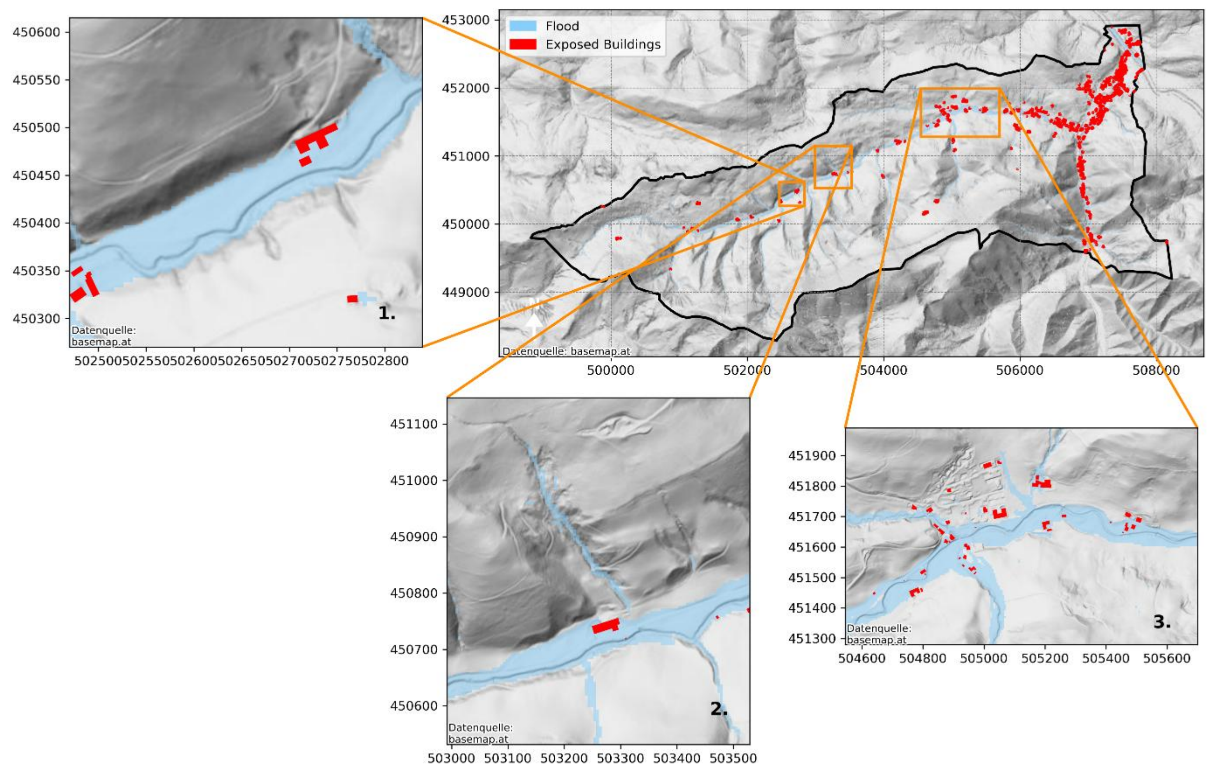


Figure A 56: Exposure HQ300 6 hours landslide (Source: Created by the author).

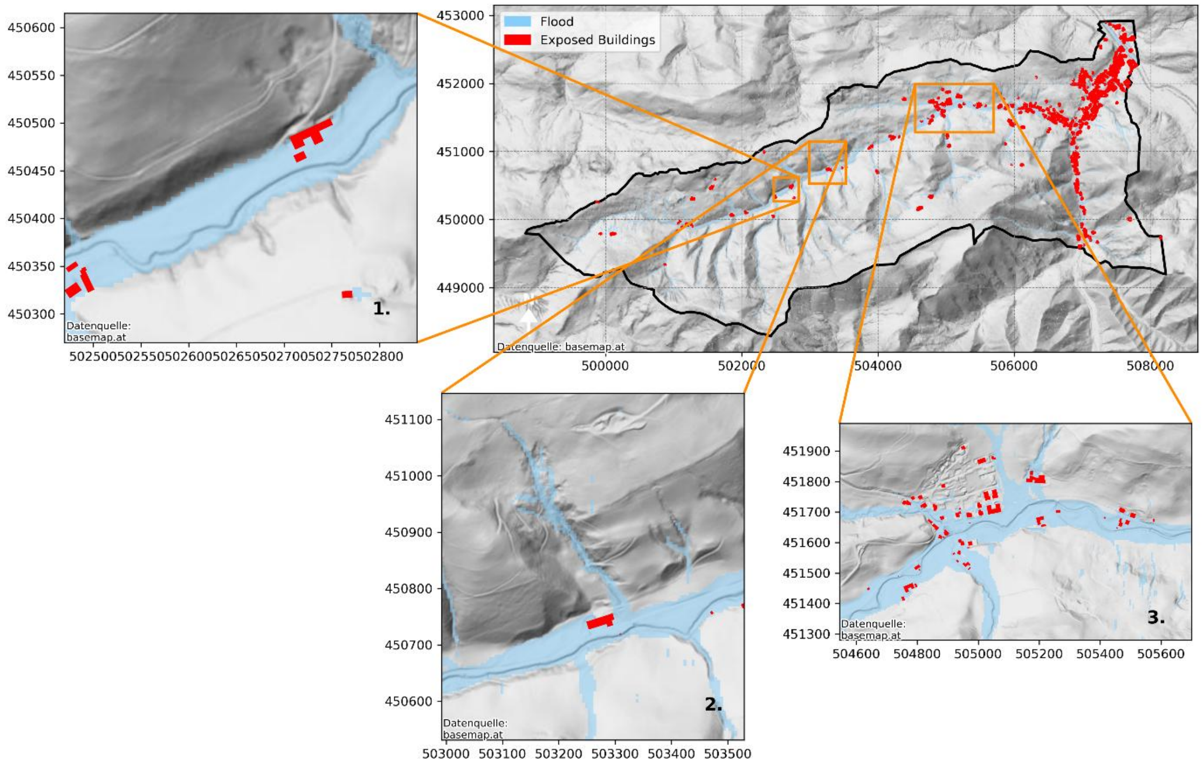


Figure A 57: Exposure HQ300 2 hours base (Source: Created by the author).

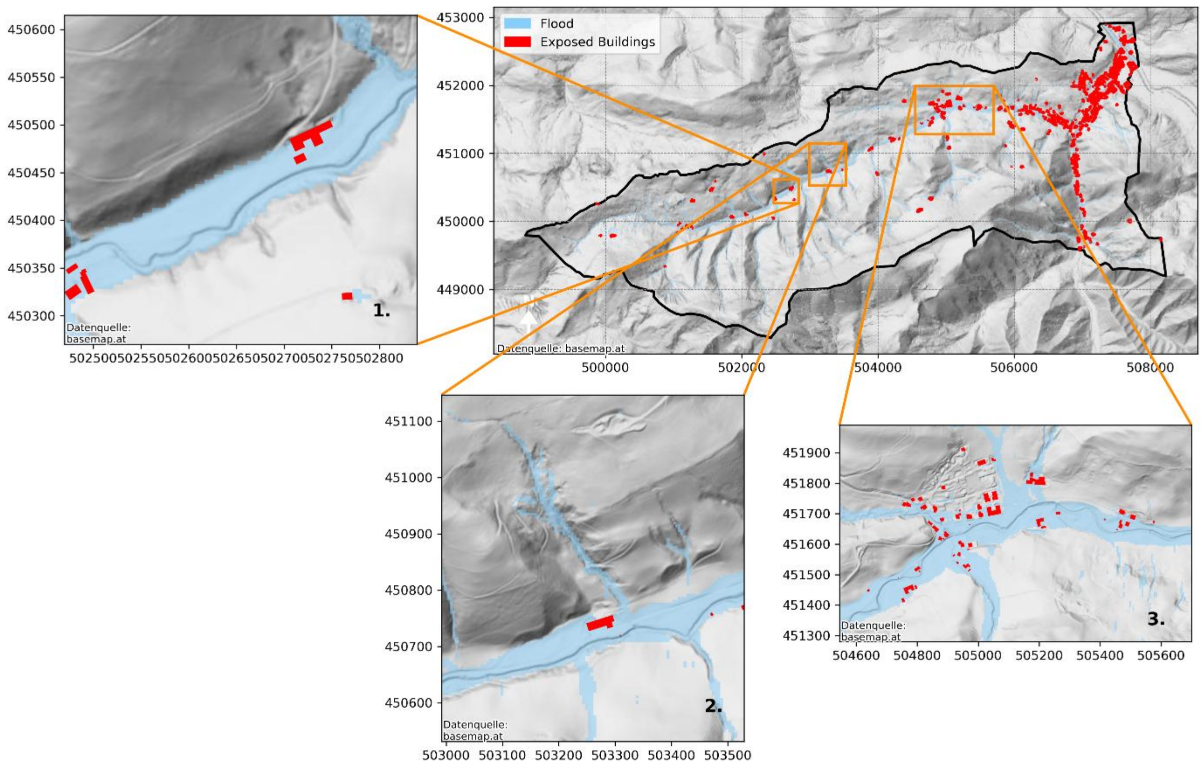


Figure A 58: Exposure HQ300 2 hours landslide (Source: Created by the author).

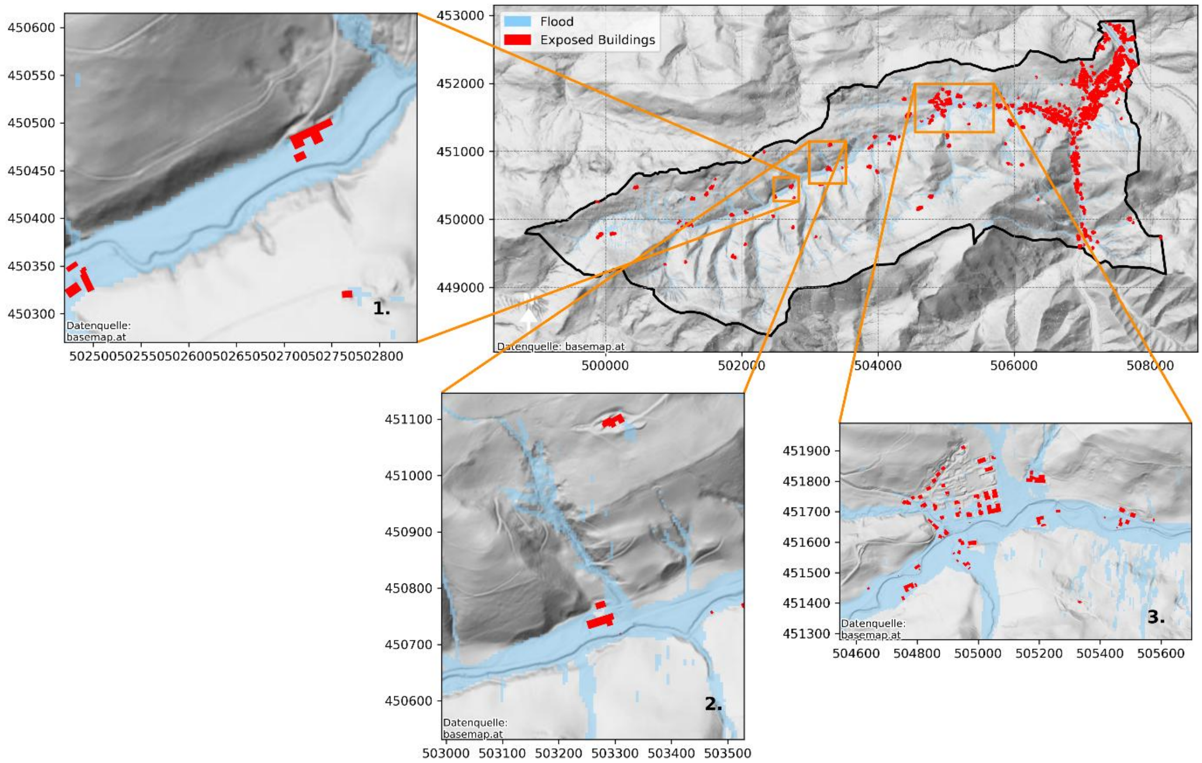


Figure A 59: Exposure HQ300 1 hour base (Source: Created by the author).

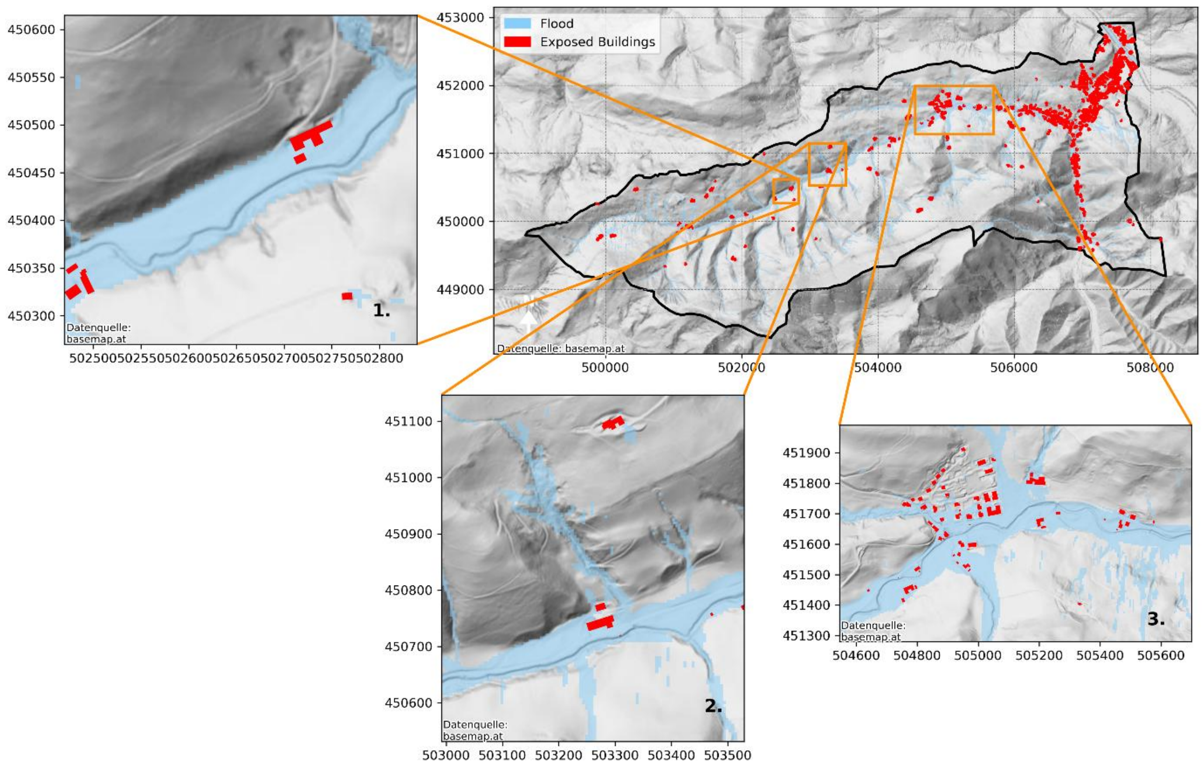


Figure A 60: Exposure HQ300 1 hour base (Source: Created by the author).