Effects of vegetation on debris flow mobility and erosion

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Abstract

Debris flows are dangerous soil mass movements which can pose a great risk for people in the downstream area of the flow. To lower the risk, hazard mitigation measures are implemented which can stabilize slopes and hinder the debris flow on its way down. Mitigation measures for slope stabilization already use vegetation, for example., by using the roots to stabilize the slope and thus preventing the debris flow from happening. At the moment however, mitigation measures against moving debris flows often consist of structures like concrete walls. The use of vegetation (either planted or naturally present in the debris flow channel) as a mitigation measures to hinder debris flow movement in channels not done.

This research looks into how vegetation in a debris flow channel influences the debris flows development and the depositional character of the flow. The results are used to understand how vegetation can alter the debris flow risk. To investigate this, debris flow experiments were executed in the small-scale debris flow-flume at Utrecht University using varying forest densities (low to high forest density) and forest clustering (random distribution to few local forests; with the same amount of trees) set ups. Also, the effect of entrained vegetation in the debris flow was investigated to see how this influences the debris flow development and its depositional character.

It became apparent that the implementation of a forest on an erodible bed lowers the debris flows velocity and increases the deposition of material transported in the flow. Obstructions (e.g., dams), formed on the erodible bed, due to the capturing of gravel and entrained vegetation (in the debris flow) in between narrow passages (e.g., closely spaced trees). These obstructions lead to localised spots of relatively high deposition and the formation of preferential flow paths. Unlike previously thought, the addition of (more) entrained vegetation to the debris flow does not necessarily result in a lower debris flow velocity.

These results demonstrate that vegetation in the debris flow channel can be used as hazard mitigation measures by lowering flow velocity and promoting deposition. This will lower the debris flow volume and runout distance which will in turn decreases the risk posed to humans. This is, for example, important for areas at risk from debris flows, which also suffer from deforestation or forest fires, because a removal of the forest could lead to a dangerous increase in the risk posted by the hazard.

<u>Key words:</u> Debris flows, debris flow development, channel bed change, protection forest, vegetation entrainment, hazard mitigation, debris flow-flume experiments

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1. Introduction

Debris flow are dangerous fast moving mountain hazards consisting of solid material (rocks, sand and clay), water and, if the debris flow moves through a forested area, organic material like entrained wood (Lancaster et al., 2003). They grow in volume when they erode the bed beneath them as they move over it. As a result, their destructive power increases and subsequently their hazard potential to people increases as well (Roelofs et al., 2022).

At the moment a lot of debris flow hazard management is done with, for example, concrete check dams, which prevent slope destruction (Clark & Howell, 1992) and thus erosion. However, these dams may lead to more serious hazardous events when they are not managed well (Haiyan et al., 2010 in Wang et al., 2017). This is one of the reasons why debris flow hazard management is starting to look into other mitigation methods like nature based solutions (Michelini et al., 2017; Moos et al., 2018; Wang et al., 2017). One way of debris flow mitigation and slope protection, using the concept of nature based solutions and bioengineering, is by the use of so called protection forest, as done in the European Alps (Dorren, Berger, et al., 2004). These forests lead to direct slope stabilisation due to their roots which reinforce the material on the slope (Cheung & Giardino, 2023; Preti, 2013; Wang et al., 2017). The use of vegetation in debris flow channels is uncommon even though the forest could potentially limit debris flow hazards due to its ability to form obstruction for the debris flow promoting deposition by limiting the amount of debris passing through the obstruction and because the forest increases channel roughness probably influencing the velocity, similar to the effects of forests on debris flow fans described by Bettella et al., (2018).

Forests may lose their mitigation function if they are damaged or removed, for example due to forest fires or deforestation. Due to climate change, wild fires happen more often and become more severe. These fires destroy the organic material in the soil and harm its internal structure, weakening the soil. As a result, the burned areas become more susceptible to debris flow events which can also result in a larger sediment loss compared to areas which did not suffer from forest fires (Cheung & Giardino, 2023; Lancaster et al., 2003). Tree stems are also influenced by the fire, and depending on the fire severity they can die or they are damaged but they can be left standing (Bär et al., 2019; Lancaster et al., 2003). This means that, even though the soil and roots might have lost their function in hazard mitigation, the tree stems might still be important.

As mentioned above deforestation is another way forests can lose their mitigation function. Deforestation can potentially increase the frequency of the mass movements, when the forest is located on an unstable slope, because of the reduced root reinforcement (Lehmann et al., 2019). It is also expected that when trees are (partly) removed from debris flow channels e.g., due to harvesting, debris flows can reach faster velocities, similar to the how less dense forests lead to faster velocities in the case of rock falls as described by Dorren, Maier, et al., (2004). A potential second effect of deforestation is that the left over woody material can be entrained in the debris flow, which could alter the flow behaviour of the debris flow do to potential clogging of the channel by the logs (Michelini et al., 2017).

Because of these forest risks it is important to understand what the effect is of the tree stems and entrained vegetation in the debris flow, on debris flow development and what the influence is of the stems and entrained vegetation on bed change. In other words, it is necessary to determine to what extent forests are useful as protection measures in channels based on how they influence the debris flow development and the subsequent bed change. Such understanding may lead to improvements in forest management and better debris flow control.

This thesis focusses on discovering how the vegetation alters the debris flow development in terms of its mobility (flow path, velocity and acceleration), how this subsequently alters the bed change and how this influences the hazard potential caused by the debris flow. This is done by using the debris flow-flume set up at Utrecht University. Three types of experiments were executed: forest density experiments, forest clustering experiments and vegetation entrainment experiments. A fake forest is placed on an erodible bed in varying layouts considering forest density and forest clustering (random distribution or small forest clusters). The forest density and forest clustering experiments are done with and without entrained vegetation in the debris flow to determine its influence on debris flow development and bed change. For the last experiment group, a varying amounts of entrained vegetation was added to the debris flow to see how it effects the debris flow development and bed change.

2. Background

In the following chapter literature research is presented about debris flows in general, the forces created by the debris flow and the forces exerted by a debris flow on the vegetation and on the erodible bed, and on debris flow regime and scaling. In addition, information about current protection forests characteristics is presented together with the potential effects of vegetation on debris flows when considering standing trees in the channel and vegetation entrained in the debris flow. This chapter concludes with knowledge gaps, based on the found literature, which lead to the research question.

2.1 Debris flows in general

2.1.1 Debris flow initiation, growth and mitigation

Debris flows are soil mass movements that happen varying mountain environments with different lithology's and geomorphologies (Bettella et al., 2018; Iverson et al., 2010; J. C. Thouret et al., 2020). The triggering mechanisms are controlled by climatic and susceptibility components. Climatic components can be separated into primary and secondary factors. Primary factors include weather situations like intense rainstorms which can create extreme erosion events or landslides which further develop into debris flows. Secondary factors, are more a control on the environment (before the debris flow trigger event) like the soil saturation and pore pressure which influence the change of failure. The susceptibility provides an indication of how much soil volume can be entrained in the debris flow (Bel et al., 2017; Iverson et al., 2010).

Debris flows grow due to the entrainment of material. This can either happen through stream bank collapse or by the scour of the bed of the debris flow channel. The amount of sediment that is entrained partly controls the maximum discharge of the debris flow as well as the debris flows runout length (Hungr, 2005; Iverson et al., 2010). This runout length is an important factor in determining the risk posed by a debris flow event, because it gives an indication of the affected area (Bettella et al., 2018). The velocity of a debris flow is also important to determining the risk. A debris flow's velocity is not equally spread out over the flow. The velocity in the middle of the flow is fast compared to the velocity at the sides and faster than the average debris flow velocity (Han et al., 2014).

Moving debris flows are often controlled using structures like check-dams (*Fig. 1a, 1b* and *1c*) which reduce the energy of the flow and capture the solid material and reduces downstream deposits (Wang et al., 2017; Zanuttigh & Lamberti, 2006). Due to multiple problems (e.g., maintenance and building costs) with these types of mitigation measures, people start to look into hazard mitigation using nature based solutions (*Fig. 1d* and *1e)*. These nature based solutions could be installed on their own or in combination with the traditional mitigation measures (like the check-dams) (EC, 2015 in Moos et al., 2018; Spalding et al., 2014). In some mountain areas like the European Alps, protection forests are used as nature based solutions. Their goal is to protect people and infrastructure against mass movements (see also section 2.4.1) (Fidej et al., 2015; Moos et al., 2018; Sakals et al., 2006). Even though nature based solutions show potential for risk reduction, structural mitigations measures (like check-dams) are preferred. This is because these structures are deemed more effective in risk reduction and faster to construct and because the amount of risk reduction as a result of nature based solutions is difficult to measure (Sudmeier-Rieux and Ash, 2009 in Moos et al., 2018; Renaud et al., 2013 in Moos et al., 2018).

Furthermore, according to multiple papers in Moos et al., (2018), most of the current risk analysis approaches do not include protection forest on risk mitigation.

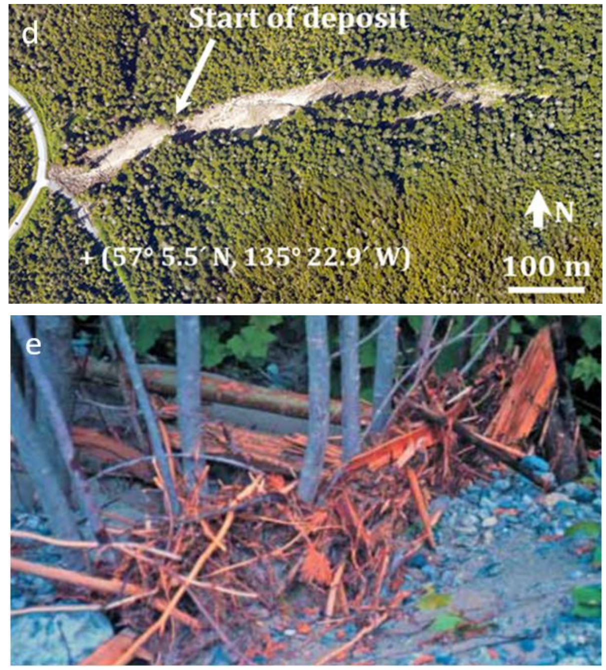

Figure 1 Fig. 1a t/m 1c, check dam collecting sediment over time in the Bourdous torrent in France. 1d (southeast Alaska) shows a forest in which a debris flow occurred (flowed from right to left) and 1e shows the formation of a woody obstruction due to the capture of (woody) debris by trees.
Figure 1a t/m 1c adaption of figure 11 in Piton et al., (2017). Photos belong to K.Royer-ONF-service RTM 06.
Figure 1d adaption of figure 3a in Booth et al., (2020).
Figure 1e adaption of figure 8 in Wilford et al., (2005).

2.1.2 Debris flow composition and structure

Debris flows are poorly sorted water-saturated mass movements (Iverson, 1997). Their composition consists of two phases: a fluid phase and a solid phase. The fluid phase is a slurry like material consisting of water and the finer particles, like clay and sand. The solid phase (80 wt% of the total mass) consist of the courser material (smaller and larger stones and boulders) which make up the suspended and/or bed load (Cui et al., 2015; J. C. Thouret et al., 2020). A third phase is possible when vegetation becomes entrained in the debris flow (see section 2.4.3) (Lancaster et al., 2003).

When a debris flow mass comes down it can be separated into a head, a body and a tail (*Fig. 2)*. The head is made up of the larger boulders in the debris flow and as a result the flow depth rises slightly in the head and just behind it. The body consists of the finer material and the tail is a remnant consisting of mainly water but still with a heavy sediment load (Hungr, 2005).

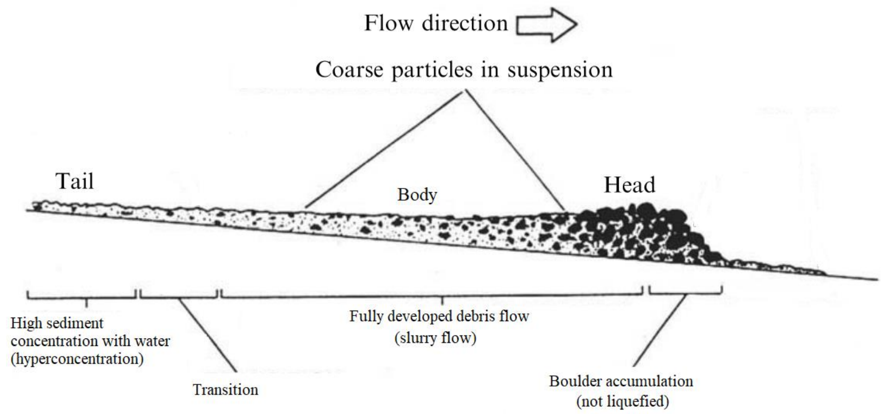

Figure 2 Schematic illustration of debris flow parts with a description of the type of material found in each part of the flow.
Adaption of figure 2.6 from Pierson, (1986), in Hungr, (2005).

2.2 Debris flow forces on vegetation and the erodible bed

Debris flows impose forces on the bed causing erosion. Two of the most important forces responsible for channel bed erosion are flow forces and impact forces (Roelofs et al., 2022). Zanuttigh & Lamberti, (2006) have argued that these forces also influence the vegetation in the debris flow channel.

2.2.1 Flow forces created by a debris flow

The flow forces are relevant for the gliding processes of the debris flow on the channel bed and can be separated into two components: the (basal) shear forces and the momentum forces. Both forces can provide an indication on the amount of expected bed erosion created by the debris flow, which subsequently gives information on the volume growth and the runout distance (Bettella et al., 2018; Roelofs et al., 2022).

2.2.2 Impact forces created by a debris flow

Impact forces are the forces resulting from the collision of a debris flow on the bed (Roelofs et al., 2022), and on the potential vegetation present in the flow channel. The impact forces are divided into forces connected to the fluid phase and forces connected to the solid phase (see section 2.1). It is important to separate the two phases because of their difference in impact forces as a result of the grain size distribution which needs to be considered when designing mitigation measures against debris flows (Cui et al., 2015).

When considering impact forces, the debris flow has to be separated into the head, the body and the tail (*Fig. 2*). This is because the three parts result in different impact forces (Cui et al., 2015; J. C. Thouret et al., 2020). Impact forces on structures (like potential vegetation in the channel) cause damage as follows: first the bottom of the structure is hit with a maximum impact pressure in the head leading to structural damage. Then the body of the debris flow makes contact subjecting the structure to a constant dynamic pressure leading to deformation. In the tail velocity decreases and this may lead to damage as a result of burying. This difference in cause of the damage is due to a changing position of the location of the maximum stress exerted on the structures (e.g., stems) as the debris flow moves by (Cui et al., 2015; J. C. Thouret et al., 2020).

Both the flow and impact forces may vary in magnitude over time, because the flow may come in multiple waves. This leads to variations in flow properties over time (Berti et al., 1999; J. C. Thouret et al., 2020; Zanuttigh & Lamberti, 2006).

2.2.3 Effects of debris flow forces on vegetation

The flow and impact forces act on vegetation (Zanuttigh & Lamberti, 2006), deforming and scraping it as the debris flow moves past. To assess the damage done by these two forces, it is important to consider the vulnerability and the conditions of the vegetation prior to the debris flow (e.g., were the trees damaged before the debris flow hit them) (Cui et al., 2015).

It is worth mentioning that the vegetation influences these forces, just as the forces influence the vegetation. Denser vegetation patches increase the intensity of the forces in the debris flow. This is because the vegetation alters parameters controlling the shear stress and momentum of the flow (Gurnell et al., 2016; J. C. Thouret et al., 2020).

For this thesis fake metal trees were used as vegetation. Therefore, damage due to the impact forces is probably less significant and the focusses lies on the development of the velocity and acceleration of the flow when it moves through a forest.

2.3 Flow regime and scaling

To describe the flow dynamics of debris flows, three motion resisting forces in debris flows can be described: collisional forces, frictional forces and viscous forces. The relation between these forces can be described by dimensional numbers: the Bagnold number, the Savage number and the Friction number. These numbers can be used to compare the dynamics of the debris flows (Parsons et al., 2001; Roelofs et al., 2022) and they provide information on the shear forces, momentum, interstitial fluid and pore pressure which are parameters influencing the erosion (Roelofs et al., 2022).

The Bagnold number describes the ratio between the collisional and the viscous forces in the debris flow. When the Bagnold number is larger than 200, collisional forces are larger than viscous forces (Iverson, 1997; Roelofs et al., 2022), and overall erosion dominates as long as the total solid fraction is not too large (Roelofs et al., 2022). When the Bagnold number is small, viscous forces dominate and deposition dominates erosion (Roelofs et al., 2022).

The Savage number defines the ratio between collisional and friction forces. When the Savage numbers is larger than 0.1, collisional forces dominate the frictional forces in the debris flow (Iverson, 1997; Parsons et al., 2001). Whether or not the flow is collisional dominated or not is an indicator for the erosion caused by the debris flow. Larger Savage number, and thus a collisional regime, link to more erosion, as long as the debris flow does not contain a large fraction of clay (Roelofs et al., 2022).

The last number is the ratio of the frictional to viscous forces, the Friction number. When the Friction number is larger than 100 (for the debris flow body) and larger than 250 (for the debris flow head) (De Haas et al., 2015; Parsons et al., 2001), frictional forces and frictional shear stresses are stronger than viscous forces and viscous shear stresses (Iverson, 1997; Parsons et al., 2001; Roelofs et al., 2022). Parsons et al., (2001), also state that an increase in the Friction number corresponds to a decrease in debris flow velocity. It is expected that this subsequently will lead to more deposition.

2.4. Debris flow interaction with vegetation

Vegetation can have a protective function against debris flow and is increasingly used for slope protection (Michelini et al., 2017; Wang et al., 2017). Since these measures intervene directly with the debris flow, vegetation is considered an active mitigation measure (Guthrie et al., 2010; Hübl et al., 2009; Michelini et al., 2017; Wang et al., 2017). One method on how forests can be used to prevent landslides, which may develop into debris flows, is through root reinforcement and by influencing the moisture regime of the soil through e.g., evaporation (Stokes et al., 2009). Apart from this direct stabilization of the soil, there are two other main ways vegetation can influence debris flow movement which are the effect discussed in this thesis. The first way vegetation can influence a debris flow is as a standing forest, growing in the path of the debris flow (e.g., taking on the function of a filter dam). The second way when vegetation is entrained in the flow itself (Bettella et al., 2018; Lancaster et al., 2003; Zanuttigh & Lamberti, 2006).

First, a general description is given on forests currently used for hazard mitigation to create a general picture on the characteristics of these protection forests. Next the effects of a standing forest in a debris flow path are discussed followed by the effects of entrained vegetation.

2.4.1 Forest types in debris flow susceptible areas

The implementation of protection forests, as a nature-based hazard mitigation is already done in several countries located around the European Alps, like France, Austria and Switzerland (Dorren, Berger, et al., 2004; Fidej et al., 2015; Moos et al., 2018). Their main function is to, (ideally) continuously, protect humans and infrastructure against natural hazards on a relatively local scale (Dorren, Berger, et al., 2004; Moos et al., 2018; Schönenberger, 2000). Michelini et al., (2017) state that only well managed forests can be an alternative for traditional mitigation measures, like check-dams, and they also believe that the protective function of the forest should be the outcome of the multidisciplinary knowledge because this combines accurate forest regeneration data after a disturbance with traditional hazard mitigation measures. It should be noted that, Michelini et al., (2017) also state that if a debris flow is likely to uproot vegetation, protection forest might actually increase the risk due to the formation of obstructions against, for example, bridges. Indicating that in such situation careful re-evaluation of the mitigation measure is needed (Michelini et al., 2017)

2.4.1.1 Types of protection forest in the European Alps

Overall description of protection forests in the European Alps

Protection forests are not stable but rotate between different phases with varying levels of protection (*Fig. 3*) (Dorren, Berger, et al., 2004). The time it takes to move from one phase to another depends on natural ageing but also on disturbances, like mass movements, which effect the ecosystem (Attiwill, 1994; Moos et al., 2018; Peterson et al., 1991). Due to this dynamic character, the protection against natural hazard is not constant in space and time, making it harder to quantify the protection when considering longer periods of time (Ammann et al., 2002 in Moos et al., 2018; Bebi et al., 2004 in Moos et al., 2018; Wehrli et al., 2007). As a result, the protection provided by a forest depends on its resilience and resistance which is related to the amount of times a forest is disturbed (Moos et al., 2018). Resilience indicates how fast a forest can execute its protective function again after a disturbance has passed (Moos et al., 2018; Motta & Haudemand, 2000). Resistance indicates in what measure a forest is changed due to disturbances (Grimm & Wissel, 1997; Moos et al., 2018). By using forest management resilience might be increased allowing for longer time periods of risk reduction (Moos et al., 2018). The dynamics of the forest ecosystem can also be an advantage because they allow for faster regeneration. However, often vegetation is damaged so badly by disturbances, that regeneration is not possible (Moos et al., 2018).

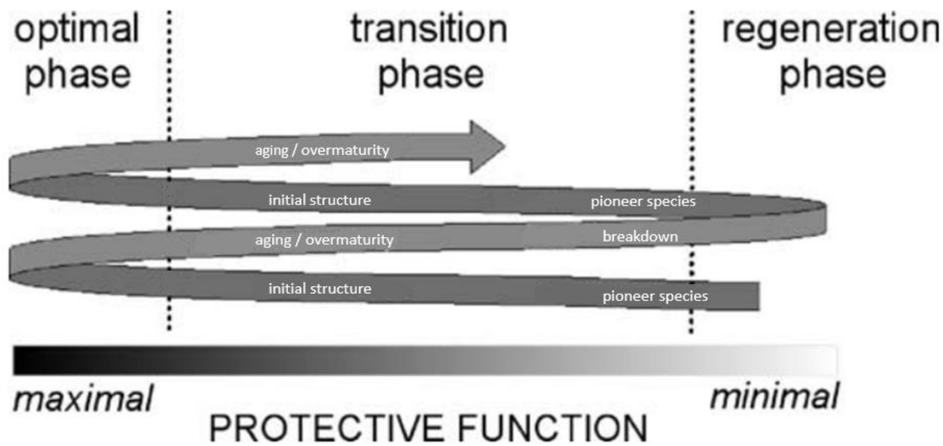

Figure 3 Different phases of protection forests, also indicating the amount of protection provided by the specific phases.
Adaption form figure 1 in Dorren, Berger, et al., (2004).

The amount of influence a disturbance, like a mass movement, has on the ecosystem depends on the magnitude of the hazard but also on the ecological stability of the forest (Moos et al., 2018). A stable forest is needed to prevent a forest from becoming less protective against hazards (Dorren, Berger, et al., 2004). Apart from stability, forests need a certain amount of integrity to keep a healthy structure and to maintain its ecosystem functions after a disturbance (Dorren, Berger, et al., 2004). Forest structure is a term describing the arrangement of vegetation together with other elements like the soil and hydrology in the forest (Seidler, 2023). For a protection forest to be functional over a longer period of time, it is necessary that the integrity and stability are relatively high (Dorren, Berger, et al., 2004).

The evolution of forests is a continuous process and to keep the necessary protection level, forest maintenance is needed to keep the integrity and stability at a certain level. Three conditions are used to help increase the stability and integrity (Dorren, Berger, et al., 2004). The first condition has to do with the species composition, which consists of both the trees and the ground vegetation (Dorren, Berger, et al., 2004), and can be used to determine the magnitude and frequency of disturbances (Michelini et al., 2017). Michelini et al., (2017) looked into forests on debris flow fans and found that pioneer species, which have a high density distribution and relatively small diameters, are common more upstream. If older forests were present at the upstream boundary of the fan, it means that disturbances (debris flows in their case) are not very common. The second condition considers the regeneration of the forest. This controls on how fast forest can regrow after a disturbance, and depends on the growing conditions (e.g., is the amount of light received enough) (Dorren, Berger, et al., 2004). The last condition, stated by Dorren et al., (2004) has to do with the forest structure which controls the amount of energy, caused by a disturbance, a forest can absorb. They found that as soon as a few trees were implement, rock fall hazards became less severe because rocks were stopped by the trees.

Examples of protection forest in the European Alps

The first example described is the Ausserbacher forest in the Montafon region in Austria, which is susceptible to rock falls and snow avalanches. The forest in this area consists of deciduous and spruce trees, in combination with shrubs. In 1988 the forest consisted of various protection phases (*according to Table 1 in* Dorren et al., 2004). The first phase is the late aging phase (max 31% of the forest). This phase has a low forest density (299 trees/ha or 0.0299 trees/m^2) and regeneration is to low, influencing the forest resilience. The trees in this phase do show some form of a structure with high and low canopy layers (called a multi-layered structure) (Dorren, Berger, et al., 2004; McElhinny et al., 2005). The second phase is the optimal phase (26%) which has a forest density of 560 trees/ha (0.056 trees/m^2) and the forest consists mainly of spruce trees, which form a single layer (Dorren, Berger, et al., 2004). The trees are relatively thin and have short crown lengths (length form point were branches start toward the top of the tree) (Dorren, Berger, et al., 2004; Z. Zhu et al., 2021). However, a large part of the trees are damaged, making the forest susceptible to e.g., falling rock. The third phase is a selection forest (28%) which consists of multi layered structure. Furthermore, this phase shows a mosaic layout consisting of regenerating parts and parts of forest that are breaking down. The last two phases consist of the regeneration phase (1% of the forest) and the phase consisting of shrubs (15%). To increase the protection a patch work forest was created by separating the optimal and ageing forest parts into smaller pieces (Dorren, Berger, et al., 2004).

The second forest is located in Sainte-Foy, Tarentaise (France) and protects against rock falls. In 1986 the top of the slope possessed a dense forest structure with a basal area larger than 25 m^2/ha (Dorren, Berger, et al., 2004). The basal area is a measure of tree density calculated by dividing the sum of all the cross-sectional tree surfaces with the total area of the forest (Bettinger et al., 2017). More downstream parts of the forest also consist of less dense forest structure which have a mosaic pattern but are still useful for protection but the distance needed to stop falling rocks is a bit longer. If no forest is placed at the top, but a dense forests was present at the bottom almost no rocks are stopped (Dorren, Berger, et al., 2004).

The third forest, locate in the Soteska gorge in Northwest Slovenia, is susceptible to debris flows. This forest is mainly beech dominated and keeping a sustainable structure can be hard, depending on species specific traits (e.g., amount of light needed for regeneration). To give an example of the diameters in protection forest, the trees in this forest have multiple diameters ranging from 10 to 50 cm (Fidej et al., 2015).

The last example are forests on fans in North Italy which show that trees in areas susceptible to debris flow impacts, have a maximum diameter of 92 m. Furthermore, disturbed areas seem to have a higher forest density compared to the unaffected areas, as long as debris flows are not to destructive (Michelini et al., 2017).

2.4.1.2 Optimal conditions for protection forest

The ideal protection forest consist of a well-structured (multiple layers), uneven aged forest, where the forest stand (the overall forest structure and composition (Lindenmayer and Franklin, 2022 in McElhinny et al., 2005)) provides enough protection and its ability to regenerate is capable of replacing damaged trees, to assure long term protection (Dorren, Berger, et al., 2004; Fidej et al., 2015; Moos et al., 2018; O'Hara, 2006).

As stated above management is needed to make sure protection forest can be used for long term hazard medications, by making the forest as resistant and resilient as possible (Dorren, Berger, et al., 2004). The forest stand needs to be managed in such a way that the protection provided by the forest can be ensured (Brang, 2001). The needed forest stand differs per area (Fidej et al., 2015). In the source area it is recommended that trees with diameters smaller or equal to 30 cm are placed in a relatively dens network to create a strong root network which prevents landslide onsets. Trees with diameters larger than or equal to 40 cm should be removed. In the deposition area trees with small diameters (< 40 cm) should be dominant, and there is a need for specifically assigned regeneration areas to allow for the formation of an uneven aged forest (Fidej et al., 2015).

Other ideas for optimizing the forest protection are mentioned in several papers (e.g., Dorren et al., 2004; Fidej et al., 2015; Michelini et al., 2017). However, the methods mentioned in the papers differ (probably because these methods are location specific and mass movement type (e.g., rock fall or debris flow) specific) but there is also some form of overlap. For example, Fidej et al., (2015) suggest that for the Slovenian debris flow gorge removing some trees from forests and also implementing specific regeneration patches creates the best protection. Michelini et al., (2017) also implies that a lower tree density helps the protective function as long as the trees present on the deposition sites have large diameters. In contrast, against rock falls, a protection forest with a high forest density and thick trees would provide better protection, as long as it is placed near the rock fall source (Wasser and Ferhner, 1996, in Dorren et al., 2004)

2.4.2. Standing vegetation in the debris flow path

2.4.2.1 Effects of vegetation on debris flows

When forests are placed on alluvial fans, in the path of the debris flows, they create a protective function because they increase the terrain roughness. This obstructs the flow and promotes deposition (Michelini et al., 2017). Michelini et al., (2017) imply that the tree density and tree diameter are important parameters in controlling the deposit thickness. They found that for the upper part of the deposit, the deposit is thicker when the trees have a relatively large diameter but a low density, while at the more downstream part of the deposit, the deposits are generally thicker when trees show a high density and a small diameter.

The effect of reduced debris flow mobility and thus shorter runout lengths on fans, in connection to forest characteristics, has been studied by Bettella et al., (2018). They examined the effect of vegetation on debris flow fans in a laboratory set-up using two types of forest: a coppice forest which consisted of trees with multiple flexible stems (originating from one trunk) and a high-forest which consisted of trees with only one inflexible stem. They found that vegetation lowers the kinematic load of the debris flow, indicating a lower mean debris flow velocity. Furthermore, their research shows that different forest types have a different effect on debris flow movement. They show that the coppice forest trees create a larger flow resistance leading to more deposition and shorter runout distances on a debris flow fan. This deposited material is partly placed at the upstream side of the vegetation, creating ramps which increase the surface roughness of the bed further, influencing the debris flow (Bettella et al., 2018).

How vegetation alters the debris flow also depends on the sediment concentration used in the experiments. When the sediment concentration in debris flows is large, high forest become less effective in reducing the debris flow motion, while for coppice forest a high sediment concentration results in a twice as large debris flow motion reduction. It is argued that a possible reason is that coppice forest is more efficient in trapping debris flows, since the multiple stems act as a filter blocking the solid parts (coarse and fine material) more efficiently, while the high-forest captures mainly larger particles. Similar effects can be seen in *Fig. 4a* (high-forest, with one stem) and *4b* (multiple stems, potentially acting as a filter) for a real debris flow setting which are found in Wilford et al., (2005). At lower concentrations this effect is much less since the larger water concentration leads to more washout (Bettella et al., 2018). Based on these results Bettella et al., (2018) argue that a high density coppice forest has a larger protective function compared to the high-forest.

Other researchers also found that a forest limits the debris flow volume and this in turn limits the run-out zone or even stops the movement of the debris flow (Fidej et al., 2015; Guthrie et al., 2010). Forests can also reduce the debris flow width, indicating that a forest act as a friction boundary when the debris flow is not to large in volume (Guthrie et al., 2010). Johnson et al., (2000) show that the debris flow width together with the forest type are important parameters in the control of the runout length.

2.4.2.2 Effects of forests in combination with different debris flow regimes

The interaction of forests and debris flows depends on different debris flow regimes. If the debris flow has collisional flow resistance posed by the forest is mainly caused by the collision of particles and trunks. The energy dissipation due to collisional resistance is more important in the upstream part of the fan area, where flow velocities are higher. Deposition in collisional regimes is mainly due to individual trees which capture boulders (Michelini et al., 2017).

When the debris flow has a viscous-frictional regime resistance is the result of the contact with soil surface and the tree surface. Energy dissipation due to viscous-friction resistance is more important downstream areas where flow velocities are lower. In this regime deposition leads to an increase in skin-friction resistance forces (Michelini et al., 2017).

2.4.3. Vegetation entrained in debris flows

The second way vegetation can influence the debris flow is when logs become entrained (*Fig. 4c* and *4d*) (Lancaster et al., 2003). Most debris flows have some amount of organic material (e.g., logs) in their composition and the amount can be as much as 60% of the total volume, especially when the debris flow moves through a forest. The volume of the woody material in debris flows is the result of the in and out flow of woody debris, the potential recruitment of the material and the possible recruitment processes. The woody debris can increase the intensity of processes in the debris flow when it becomes trapped and blocks the channel, obstructing the debris flow movement, which may subsequently result in inundation of the surrounding area (see for an example *Fig. 4c*). It is therefore important to know about the possible wood transport in debris flows to make a trustworthy risk assessment (Mazzorana et al., 2009).

Figure 4 Fig. 4a shows photo of a deposit left after the debris flow has passed and it shows how debris is captured behind a tree. The arrow (lower right corner) in 4a shows the flow direction of the debris flow. Fig. 4b shows how a trees and entrained logs are able to stop the flow and collect sediments behind the obstruction (upstream of the trees). Fig. 4c and Fig. 4d are snapshots of debris flow movies on YouTube showing entrained vegetation in debris flows. 4c gives an impression of how entrained vegetation looks in debris flows. 4d shows how a trunk became stuck in between a tree and the side, collecting smaller woody debris behind it. Fig 4a is an adaption of figure 3 in Booth et al. (2020).
Fig. 4b is an adaption of figure 10 in Wilford et al., (2005)

Fig. 4c is a YouTube video snapshot of a flash flood in the Johnson Canyon in the Canadian Rocky Mountains
Timmers, R. (2018, July, 17). Monstrous Flash Flood & Debris Flow l Johnson Canyon, UT 7/16/2018 [video]. YouTube. *https://www.youtube.com/watch?v=ORJtxkuD62E*
Fig. 4d is a YouTube video snapshot of a flash flood formed in forest fire scare in Colorado)
Timmers, R. (2021, August 1). DANGEROUS DEBRIS FLOW with trees and tractor tires in flash flood off Pine Gulch Fire scar Colorado [video]. YouTube. *https://www.youtube.com/watch?v=XAA3O2LNBSE*

Logs become entrained due to multiple processes: *(1)* trees may be uprooted through debris flow induced bank erosion or they may just snap off and become entrained, *(2)* logs may be remobilized by the debris flow or *(3)* they can be entrained when wooden constructions are destroyed by the flow (Koyanagi et al., 2023; Lancaster et al., 2003). When logs are transported by the debris flow they form a third phase in the debris flow which now consists of water, solids (gravel, sand and clay) and wood (Lancaster et al., 2003). For entrainment it is important that the flow depth is larger than twice the diameter of the wood element (Braudrick et al., 1997 in Mazzorana et al., 2009). Furthermore, if the length of the logs is less than the channel width, entrainment is controlled by the orientation of the wooden debris in respect to the flow direction, the wood density, the ratio between the wood diameter and the flow depth, the roughness of the bed and the roughness of the wood element. When the channel is smaller than the log length, wood transport by a debris flow typically involves pivoting of logs and jamming by logs (Mazzorana et al., 2009). A major control on the log length is the channel width in the upstream part of part of the debris flow catchment because this controls the destructive power of the debris flow (Koyanagi et al., 2023).

When there is sufficient bed load transport, entrainment and transport processes are facilitated by the action of hydrodynamics and mobile bed dynamics. When wood is entrained there are two mechanisms that lead to the deceleration of debris flows, which subsequently alters the deposition of both the wood and the sediment. Firstly, if the debris flow is not strong enough to entrain the wood, in other words lacks momentum, the debris flow can be stopped by the logs. This is because of the conservation of momentum: the entrainment of wood reduces the velocity, because it has to compensate for the extra mass of the debris flow (Iverson et al., 2010; Koyanagi et al., 2023; Lancaster et al., 2003). Hence, if the debris flow is not strong enough it stops. The second mechanism is the influence of the flow direction in combination with the woody debris in the debris flow. When the flow changes direction the entrained logs lead to a change of the character of the debris flow, from a more fluid like character that flows in a channel to a more collision like character in which objects collide with the channel walls. A consequence of this change in character is that the velocity of the debris flow is reduced (Lancaster et al., 2003). An external parameter which influences the deposition of the debris flow when wood is entrained is an obstruction in the channel which leads to flow retention. This effect is more important in the upstream part of the debris flow channel, while the effects of wood entrainment on the stream power (velocity) are more important downstream (Koyanagi et al., 2023).

Due to the way velocity is distributed in debris flows, logs are mainly transported in the debris flow head (*Fig. 2*). Together with the coarser sediment in the head this allows for the formation of flow obstructions which influence the deposit extent (Booth et al., 2020; Koyanagi et al., 2023). The material form the body and the tail are collected behind the woody-coarse sediment deposits while water can still drain from the flow (Lancaster et al., 2003). Entrained wood can thus result in a decreased runout length and a more widely distributed deposits (Guthrie et al., 2010; Lancaster et al., 2003).

In natural settings, wooden debris is classified in large wood debris and small wood debris. The classification boundaries do vary in between research but generally large wood debris has a diameter larger than 0.1 m and a length larger than 1m (Tang et al., 2018). When wood is entrained in the debris flow mix, three scenarios can occur. The logs can be partially broken up, they can become jammed when obstacles are present, or they are transported toward the depositional area (Mazzorana et al., 2009). When the woody debris becomes jammed, entrapment of the solid phase (larger boulders) of the debris flow becomes more likely (Lancaster et al., 2003). Furthermore, these jams can result in channel avulsions, they can reduce the cross-section of the channel which alters the volume that can pass through the channel, and lastly they can result in an increase in scour (erosion) processes. All of these effect can lead to an increase hazard conditions (Michelini et al., 2017).

2.5 Knowledge gaps and research questions

Based on the above described information some gaps in the research on the effect of forests on debris flows are found. Firstly, a lot of research is done on debris flow fans and how deposition is influenced by vegetation there (e.g., by Bettella et al., (2018)) while research on the effect of forests on the debris flow development in the channels and the influence thereof on bed change is much less abundant.

Lancaster et al., (2003) investigated the effect of vegetation in the channel on debris flow movement (also including the effect of entrained wooden debris) and the caused bed change by the debris flow. However, they do not make a correlation between the found bed change and the hazard potential of the debris flow e.g., due to changes in the volume of the debris flow as a result of more or less erosion.

Lastly, the effects of different forest layouts (like forest densities and forest clustering set ups) are not really addressed in the found papers, at least not for forests present in debris flow channels in the case of forest densities; and forest clustering is hardly ever addressed.

To fill in these gaps, the following question is formulated:

What are the effects of vegetation in the flow channel on debris flow development in terms of velocity and acceleration and how does this influence channel bed change (in terms of volume and depositional patterns), and the hazardous potential of the debris flow?

This leads to the following sub-questions:

1. *How do forest density and forest clustering influence debris flow velocity, acceleration and overall bed change?*
2. *How do forest density and forest clustering influence the flow path of the debris flow and how does this effect the bed profile?*
3. *How does the amount of entrained logs in the debris flow influence the debris flow velocity, acceleration and overall bed change?*
4. *How does the amount of entrained logs influence the flow path of the debris flow and how does this effect the bed profile?*
5. *What is the implication of different forest set ups (forest density and forest clustering) and the related changes in velocity, acceleration and flow bed for the hazardous potential of the debris flow?*
6. *What is the implication of the different amount of entrained logs and the related changes in velocity, acceleration and flow bed for the hazard potential?*

To investigate this, debris flows were simulated in a flume set up at Utrecht University using different forest set ups: high to low forest density, and high forest clustering (few places with many trees) to low forest clustering (random distribution). To determine the effect of the number of entrained logs in the debris flow, the high density forest set up was used, with a variable number of entrained logs.

For the first sub-question it is expected that the forest on the bed will lead to an increase in the channel roughness. This will alter the debris flow motion, probably leading to a decrease in the velocity and a change in the acceleration profile, based on research done by Bettella et al., (2018) and Liu et al., (2021). It is expected that for the forest density experiments the decrease in velocity will be strongest when the forest density is highest because this is the set up with the most trees. A similar effect is expected in the case of the high clustering experiments. Since more trees are located at a few locations in the flume, these forest have a larger roughness compared to low clustering experiments.

For the second sub-question it is expected that the high density forest experiments and the high clustering experiments, will influence the flow path of the debris flow more compared to the low forest density and low clustering experiments. This is again because of the increased roughness, both from the trees themselves and possible obstruction formation, making it harder for the debris flow to take certain paths and hence it will probably form preferential flow paths, creating erosion-prone areas while other parts of the erodible bed will be more depositional because of the weaker flow in the non-preferential flow paths.

For the experiments with a changing amount of entrained logs (sub-questions 3 and 4), it is expected that a larger amount of logs will result in a stronger influence on the debris flow motion (lower velocity and more deceleration), because of the larger opportunity to form obstructions (e.g., dams) between the standing vegetation which obstruct the flow, which subsequently would increase the roughness more, also leading to the formation of preferential flow paths as described above.

For sub-questions 5 and 6 it is expected that for a high density forest, a high clustering forest, or a large number of logs in the debris flow the flow movement is decreased and hence deposition is larger than when the forest is less dense, more random or when fewer trees are entrained. As a result, the debris flow loses volume, decreasing its hazardous potential.

3. Method

3.1 Flume set up, debris flow composition and bed composition

3.1.1 Flume set up

To understand the effect of above ground vegetation on the debris flow development, the subsequent erosion of the bed and what this means for the hazard potential of the debris flow, experiments have been conducted in the debris flow flume at Utrecht University in The Netherlands (*Fig. 5a* and *5b*).

The flume set up is similar to the flume experiments used in (Roelofs et al., 2022, 2023). The total flume is 5.4 m long and the upper part, before the erodible bed, is 0.3 m wide (Roelofs et al., 2023). The erodible bed, starting at 2.9 m below the debris flow entrance point, is 2.5 m long. At the erodible bed, the width changes to 0.285 m, because of technical/constructional reasons. The erodible bed can be taken in and out of the flume and is level with the upstream floor because the bed rests in a 7 cm depression in the lower part of flume (*Fig. 5a*). The floor, and sides of the flume upstream of the erodible bed are covered in sandpaper to account for the roughness of natural debris flow channels. For the erodible bed, the sloping parts at the beginning and at the end of the bed are lined with the sandpaper (*Fig. 5a*). The middle (horizontal) part is either covered with fibered felt or not, depending on the experiment type (see section 3.1.3). For the experiments the flume is placed at an angle of 30°, which is one of the angles used by Roelofs et al., (2022). They explain that this does reduce the velocity of the

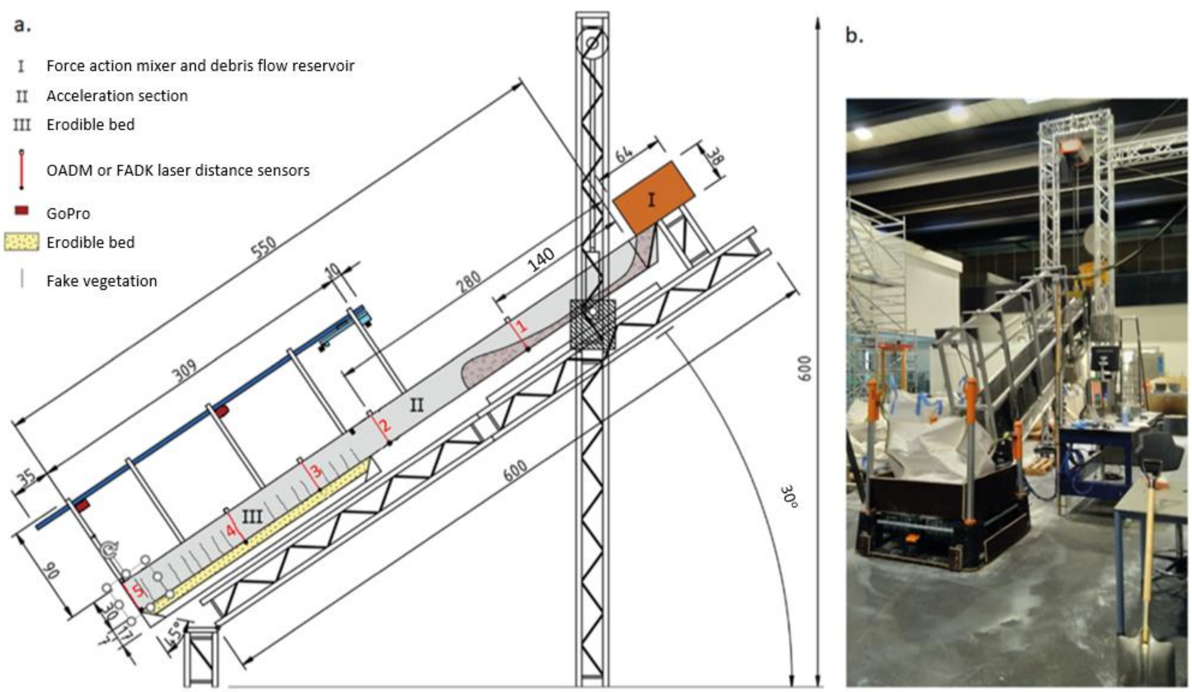

Figure 5 Flume layout (5a) and overview of the set up (5b). For Fig. 5a: The roman numbers indicate specific sections of the flume. The red numbers next to the laser sensors correspond to the referenced sensors in the text (e.g., the second sensor in the texts refers to the senor next to the red two). The sensors are placed at (starting with sensor 1) at 143.5, 279.7, 346, 418, 543.5 cm from the debris flow reservoir. Sensors 1, 2, 4 and 5 are the Baumer OADM laser sensors (type: 20U2480/S14C), and sensor 3 is the Baumer FADK laser sensor (type: 14U4470/S14/IO). The black numbers indicate distances (centimeters) and angles (degrees).
Adaption of figures form Roelofs et al., (2022, 2023).

debris flow somewhat compared to larger angles but, based on pilot experiments done for this thesis, this angle should allow for enough erosion to see (small) bed change patterns.

3.1.2 Debris flow composition

The debris flow composition is based on the reference mixture used by Roelofs et al., (2022). The mixture had a total mass of 60 kg or 0.03 m^3. The mix consisted of solids (gravel, clay and sand), and water. The components are also stated in *Table 1* specifying their grainsize and mass (Roelofs et al., 2022). The grainsize distribution of the sand is displayed in *Fig. 6.* For some of the experiments plastic sticks, representing entrained trees ("logs" in the context of this thesis}, are included in the debris flow mix (see below section 3.2.2). The debris flow mix is placed in a forced-action mixer (Baron E12) on top of the flume from which it is released (Roelofs et al., 2023). During the lifting of the flume to the used angle, the mixer is activated and it stops turning 0.8 s before it is opened (Roelofs et al., 2022).

Table 1 Debris flow composition based on Roelofs et al., 2022.

Debris flow component	**Weight of component in debris flow mix**
Sand (0.09-2 mm)	36 kg
Clay (kaolin; ~2µm)	2.4 kg
Gravel (Ardenner Split; 2-16 mm)	9.6 kg
Water	12 kg
Total debris flow weight (without logs)	60 kg

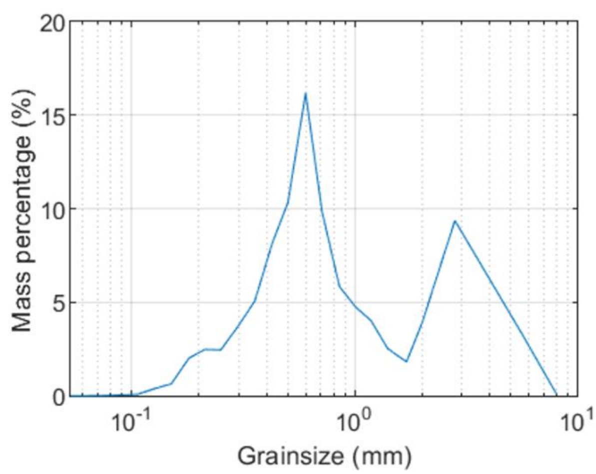

Figure 6 Grain size distribution of the sand used in the debris flow and in the bed. The figure shows the weight percentage of grainsizes in a sand sample.

3.1.3 Bed composition and layout

The bed consists of a mixture of 98 wt% sand, 2 wt% clay and 11 wt% (of the total solid weight) water. This is the bed composition also used by Roelofs et al., (2022). It creates a balance between a complete loss of the erodible bed and allowing enough erosion. The bed is mixed with a hand-held mortar mixer and is subsequently placed in the erodible bed channel (Roelofs et al., 2022, 2023). The bed differs in thickness between the experiments with vegetation and the reference (without vegetation) experiments. This is because the reference experiments have a layer of rough fibered felt at the bottom. This felt layer is not placed in the boxes for the experiments with vegetation to allow metal rods, which represent a fake forest, to be screwed into the bed. As a result, the "vegetated" channels have a bed of 6.5 cm deep while the reference experiments (with no forest) have a bed of 6.0 cm deep. Roelofs et al., (2022) used a trowel to flatten the bed to create a constant height and packing. This method is also applied for bed-flattening in the reference experiments, but was not possible in the experiments with vegetation because of the fake trees. In the vegetated experiments the bed was therefore flattened out by hand. This leads to a more irregular bed surface and sediment packing of the bed compared to the reference experiments.

The water content of the bed is an important parameter for controlling the bed change caused by the debris flow: a larger water content of the bed results in more erosion (Roelofs et al., 2023). To have some control on the amount of water in the bed a calibration curve was used which was created using HH2 Moisture Meters Delta-T devices (Theta Probe ML3) of 2 and 4 cm. The water content of the bed was measured (with the HH2 Moisture Meters) just before the debris flow was released, to assess whether or not the bed moisture content differed between the various experiments.

3.2 Forest and experiment set up

The experiments can be divided into four groups (including the reference experiment), presented in *Table 2*. The initial idea was to repeat the experiments twice, to account for natural variability and to ensure repeatability of the experiments as done by Roelofs et al., (2022, 2023). However, due to a delivery problem with the sand this became impossible.

Table 2 Overview of experiments. Reference experiments did not include a forest. Two types of forest layout experiments were done: the forest density and forest clustering experiments. Both the forest density and forest clustering experiments were executed with and without the inclusion of logs in the debris flow. The last experiment group looked into the effect of vegetation entrainment in the debris flow, using the high forest density layout.

Experiment main group	**Sub experiments**
Reference experiments Executed with and without the inclusion of 207 logs in the debris flow	No forest on the erodible bed
Forest density experiments Executed with and without the inclusion of 207 logs in the debris flow	High forest density (112.3 trees/m^2)
	Medium forest density (84.2 trees/m^2)
	Low forest density (57.5 trees/m^2)
Forest clustering experiments Executed with and without the inclusion of 207 logs in the debris flow	High forest clustering
	Medium forest clustering
	Low forest clustering
Vegetation entrainment experiments Executed with a high forest density (112.3 trees/m^2) cover on the erodible bed	642 logs in debris flow (maximum entrainment)
	435 logs in debris flow
	207 logs in debris flow (obtained from the high forest density experiment with 207 logs in the debris flow; default in other experiments)
	104 logs in debris flow (minimum entrainment)

3.2.1 Building a fake forest

The fake forest in the experiments with vegetation is simulated by 20 cm long stainless steel, threaded end rods (6 mm in diameter) which are screwed into the bottom of the erodible bed channels (*Fig 7)*. This results in permanent trees which are around 19 cm long. Metal rods are used for trees, because pilot experiments for this thesis showed that real vegetation (Alfalfa, Mung Bean, Oats and Sorghum Bicolor), is pushed over by the impact of the debris flow. As a result, their influence on the flow is altered or removed since they do no longer form an obstacle in the channel. Furthermore, the flattened plants formed a layer on top of the erodible bed and as a result the debris flow interaction with the bed probably changed (e.g., due to a change in the bed roughness), which might influence the bed changes in erosion and deposition. To circumvent these problems, fixed metal rods were used similar to the method used in Bettella et al., (2018) who used rods and wooden sticks to investigate the influence of vegetation on debris flows in fan areas. For simplicity other forest parameters like a canopy, different tree diameters or other forest characters are not included.

Figure 7 Impression of the flume layout (for the high forest density) before the erodible bed mix is put into the flume.

3.2.2 Experiment set up description

Three kinds of forested experiments where done: forest density experiments, forest clustering experiments and varying vegetation entrainment experiments (*Table 2*). All the experiments and their conditions, before the debris flows are released, (debris flow composition, bed conditions, bed wetness) are listed in a logbook shown in *Appendix B. Fig. B. 1.*

3.2.2.1 Forest layout experiments

Two types of forest layout experiments were done: forest density experiments and forest clustering experiments; to see how the various forest layouts influence the capture of coarse material and entrained vegetation and to provide an indication of the most efficient way of altering the debris flow movement (e.g., changing its velocity) and altering erosion and deposition caused by debris flows.

Based on literature discussed in section 2.4.1, forest density seems to be an important parameter in the protective function created by forests. For the forest density experiments different amounts of trees (metal rods) were screwed into the bed according to an evenly distributed pattern (see *Appendix A. Fig. A. 1*) for the forest layouts for the forest density experiments). The high forest density set up consisted of 80 trees (112.3 trees/m^2). The medium density and the low density set up consisted of 60 (84.2 trees/m^2) and 41 trees (57.5 trees/m^2) respectively. The high forest density experiments corresponds best to the optimal phase of forest protection which has the highest forest density as described by Dorren, Berger, et al., (2004), see section 2.4.1. The low density experiments matches the late ageing phase described by Dorren, Berger, et al., (2004). For the experiments in this research the forest density in the high forest density experiments is 1.95 times larger than for the low forest density experiments. For the forest described by Dorren, Berger, et al., (2004) the densities differ a factor 1.87 for the optimal (their high forest density) and late ageing phases (their low forest density)

Effects of forest clustering are not really discussed in the found literature (see section 2.4.1). The papers found do imply the usefulness of a gaps or a mosaic pattern in the forest, for example alternating between a regeneration forest and more broken down forest (Dorren, Berger, et al., 2004). The clustering experiments are done with the same number of trees (60; as in the medium density experiment) per experiment but they are placed in different ways. A high clustering means that there are a few places covered with a lot of trees which could simulate a mosaic of a healthy forest with bare ground patches relatively similar to a mosaic forest described by (Dorren, Berger, et al., 2004). Low clustering means a random placement of trees all over the channel. The patterns of the different forest clustering experiments (high, medium and low clustering) are shown in *Appendix A. Fig. A. 2.*

The forest density and forest clustering experiments are also conducted when the debris flow mixture contains entrained vegetation, referred to as logs in this thesis. The entrained vegetation consists of solid PVC tubes with diameters ranging from 2.8 to 5.1 mm, with an average of 3.78 mm and a density of 1.38 gr/cm^3. Thick and thin logs are randomly distributed among all groups of logs of different length. The composition of the log lengths of the entrained vegetation in the forest density and forest clustering experiments is shown in *Table 3*. The 207 logs added a mass of around 291.15 gr to the debris flow mix (based on the average diameter).

3.2.2.2 Vegetation entrainment experiments

For the wood entrainment experiments the high forest density set up was used and the number of logs in the debris flow was altered. The entrainment experiments were executed with 642 logs (maximum number possible), 435 logs, 311 logs and a minimum of 104 logs. A minimum of 104 logs was used because, trial and error in pilot experiments showed that lower amounts of logs showed little potential in creating obstructions. The composition of the various length pieces remained the same, according to the percentages in *Table 3* over the entrainment experiments (e.g., the experiment with 642 logs contained 62 logs of 14 cm, which is 9.7% of the total amount of entrained vegetation). Again thin and thick logs are randomly distributed among the different log lengths. The experiment of the high forest density with 207 logs added to the debris flow (described in section 3.2.2.1) was also included in the wood entrainment dataset.

Table 3 Composition of various log lengths in the debris flow, by amount and percentage for the standard mix of 207 logs used in the forest density and forest clustering experiments. The percentages indicate how much logs of a certain length contributed to the total amount of entrained vegetation. These percentages are used to determine how many logs are needed per length classes in the different entrainment experiments.

Length of logs	**Amount of logs added to the debris flow** (Default the forest density and forest clustering experiments)	**Percentage of logs lengths of total amount of logs in debris flow mix**
14 cm	20	9.7 %
12 cm	35	16.9 %
10 cm	42	20.3 %
8 cm	50	24.2 %
60cm	60	29.0 %
Total number of logs by number and percentage	207	100 %

3.3 Data collection

3.3.1 Data obtained with laser sensors

To analyse the effect of the presence of trees and logs on the debris flow development five laser distance sensors are used. Four are Baumer OADM laser sensors (type: 20U2480/S14C), with a resolution of 0.015 to 0.067 mm (sensors 1, 2, 4, 5 in *Fig 5a)*. The last is a Baumer FADK laser sensor (type: 14U4470/S14/IO) with a resolution of 0.1 to 1 mm (sensor 3 in *Fig 5a)*. The FADK sensor has to be manually adjusted each run to ascertain that is it level and always has the same distance to the bed. The OADM sensors always have the same distance to the bed due to the way they are mounted in the construction of the flume. Two of the OADM sensors (sensors 1 and 2 in *Fig. 5a)* are placed before the erodible bed and the others, together with the FADK sensor, are placed above of the erodible bed (sensors 3, 4, 5 in *Fig 5a*). The lasers register the flow depth of the debris flow using TracerDAQ software. With the flow depth, the arrival time of the flow at each sensor can be determined using a MATLAB script personally provided by Tjalling de Haas from Utrecht University. The arrival time is determined as the time step just before the laser registers a debris flow depth of 0.005 m.

3.3.2 Data obtained with a 3D scanner

To determine the erosion and deposition caused by the debris flow, a Vialux z-snapper 3-D scanner is used. It creates a point cloud, in millimetre accuracy, using a fringe pattern projector and a camera. By creating a scan before and after the debris flow it is possible to determine the bed change. This is done using MATLAB scripts, provided personally by Tjalling de Haas and Lonneke Roelofs both from Utrecht University. First the scans are denoised by removing outliers. Secondly, a “before- and after- “Digital Elevation Model (DEM) with a 3 mm resolution is created, using natural neighbour interpolation. The DEM from before and after the experiments are subsequently used to create a DEM of Difference (DoD), which visualises the erosion and deposition patterns and quantitatively defines the volumes of the bed changes. The above described method for bed change is the same as used by Roelofs et al., (2022, 2023). The only difference is the setting of the vertical limit in the script for the calculation of the DoD’s. The original scripts form Tjalling de Haas and Lonneke Roelofs had a vertical limit of 100 mm. This is changed to 140 mm because some of the obstructions formed in the experiments in this thesis resulted in higher values, leading to NaN values in the DoD and a wrong bed change volume since the NaN values are not included in the bed change volume calculation. A limit of 140 mm prevented this problem.

3.3.3 Data obtained with GoPro's

Two HERO6 GoPro cameras are installed above the erodible bed (*Fig. 5a)*. The first is placed halfway of the erodible bed, looking upstream covering the upper half of the erodible bed and a part upstream of the erodible bed. The second one is installed at the end of the bed, also looking upstream covering the end of the flume up to about halfway the erodible bed. The videos are captured at a 1080 progressive scan resolution and 240 fps and are used to discover flow patterns and to match these to the bed patterns found in the DoD. Furthermore, they are also used to fill in gaps in arrival time in case of laser sensor malfunction due to e.g., a large amount of splashing of the debris flow against the forest in the bed, subsequently obscuring the sensor. If a laser sensor malfunctioned the arrival time at that sensor is estimated by using the arrival time found in the GoPro videos or if the sensors malfunction outside the GoPro view it is interpolated using the velocity calculated form the arrival time at, and the distance between the other sensors.

3.3.4 Data for entrainment experiments

To determine the amount of logs trapped on the bed they have been dug out and counted afterward. The same is done with the logs left upstream and the logs that are not deposited. These numbers are than compared to the total added number of logs in the debris flow.

3.4 Flow characteristics

To determine the debris flow height before the erodible bed the flow depth obtained by the second OADM senor is plotted over time to create a hydrograph. The pre-erodible bed velocity of the debris flow is determined by taking the derivatives between the arrival time at the first and second sensor (see *Fig. 5a* for the sensor locations).

To determine the development of the debris flow velocity and the acceleration, the arrival time of the debris flow at the sensor is plotted against the sensors location in the flume (which also resembles the debris flow front position at that arrival time), as done by Iverson et al., (2010). This allows for the visualisation of the changes in acceleration and velocity of the debris flow by showing the alterations of the created curve (referred to as Flow Front Time-curves in this thesis).

3.5 Experiment scaling

Roelofs et al., (2022) explain that multiple researchers have shown that scaled experiments on debris flow suffer from effects on the flow dynamics. Nevertheless, experiments done in the debris flow flume at Utrecht University have shown that the dimensionless numbers (Savage, Bagnold and friction number) and flow patterns are in line with natural debris flows (De Haas et al., 2015; Haas & Woerkom, 2016; Roelofs et al., 2022).

The scaling for the vegetation (both of the trees and the entrained logs) in this thesis is done by purely altering the dimensions (length and diameter) of the vegetation so they can be used in the experiments. Scaling of other vegetation parameters, like its resistance against breaking, are not taken into account and therefore a perfect scale situation is not possible because the metal rods and PVC tubes, used as vegetation and entrained vegetation respectively, are not representative for real life vegetation (e.g., they lack branches and are probably too rigid).

The dimensions of the vegetation, both the standing trees and the entrained vegetation, are based on a few on considerations. A practical consideration is that the tree diameter used had to fit into the holes in the bottom of the erodible bed leading to the diameter of 6 mm. Booth et al., (2020) found a quadratic mean tree diameter (diameter based on the basal tree area, (Curtis & Marshall, 2000)) of 604 mm which is 100.66 times larger than the trees used in the experiments. The trees by Booth et al., (2020) might be relatively large in diameter, and tree diameters probably differ between different debris flow areas. For example, tree diameters in a forest in Northwest Slovenia had an average diameter larger or equal to 10 cm (Fidej et al., 2015). Meaning that the trees in the experiments in this thesis are only 16.67 times smaller than the trees in Slovenia.

A second consideration had to do with the tree length. The trees almost reach the top of the erodible channel. This was done on purpose because this research is focussing on non-submerged vegetation. Therefore the total tree length needed to be larger than the maximum debris flow height which is about 0.04 m based on Roelofs et al., (2022). The tree length of 19 cm is a practical outcome because 1 cm was needed for the screws underneath the channel

A third consideration is that the logs which represent the entrained vegetation are not allowed to break, as breaking will influence the formation of obstructions which is an important part of this thesis. As mentioned in section 2.4.2, an important boundary condition, for entrainment of vegetation, is that the flow depth of the debris flow is larger than twice the diameter of the entrained vegetation (Mazzorana et al., 2009). Experiments (with the same debris flow composition as in the experiments in this thesis) by Roelofs et al., (2022), have a flow depth around 0.04 m. The maximum log diameter in this thesis is 0.0051 m making the logs 7.8 times smaller than the flow depth. Hence, the log diameter complies with the boundary condition mentioned by Mazzorana et al., (2009). When considering the entrained vegetation, logs in real debris flows have a diameters about 26.45 times larger than the logs used in the experiments when comparing them to the classification boundary diameter of large wooden debris (0.1 m) mentioned by Tang et al., (2018). When comparing the diameter of the entrained logs to the gravels (representing the large solid particles in debris flows), the gravel is a maximum of 4.23 times larger in diameter. In real debris flows boulders can have diameters larger than 1 m (Jean Claude Thouret et al., 2007; Zanchetta et al., 2004). In the case of the large woody debris diameter (larger than 0.1 m) from Tang et al., (2018), this would mean that in real debris flows entrained vegetation can have diameters which are a minimum of factor 10 smaller compared to the diameters of the larger boulders. Which implies that the logs in the experiment have a diameter that is to wide.

A last consideration had to do with the length of the entrained logs. The log length mentioned by Tang et al., (2018) of 1 m (for large wooden debris) is around 11.01 times larger than the average log length (0.091 m), taken over the 207 logs, in the experiments. The length of the logs was kept at a maximum of 14 cm which is about half the width of the erodible channel. The small log length compared to the channel width indicates that the entrainment of logs depends on the relation of orientation of the log and multiple parameters, like the flow direction (Mazzorana et al., 2009), see also section 2.4.2. However, since logs are added to the debris flow before it is released this is not important in the experiments in this thesis. It should be noted, based on photo's in the paper form Booth et al., (2020) that entrained vegetation can potentially be larger than half the channel width. The decision for a maximum length of 14 cm was made because it was feared that longer logs would create large obstructions, blocking the channel and leading to an overflow of the flume. For debris flows systems the small log length compared to channel width, and the flow depth larger than twice the log diameter (mentioned above) indicate a low longitudinal (lengthwise) slope profile simulation for the debris flows in these experiments (Braudrick et al., 1997 in Mazzorana et al., 2009).

It is clear that the dimensions of the trees and the entrained vegetation are scaled with multiple factors which also depends on the forest and trees used for comparison (see the stem diameter, mentioned above, for example). This is not a really a big problem as these experiments are used to determine the interaction between vegetation and debris flow in a more general way and how this alters erosion and deposition, as also noted by Roelofs et al., (2022). They are not intended to provide a 1:1 representation of the real world.

4. Results

The results obtained with the debris flow flume experiments are reported below as follows: first, an overall description of the debris flow development before the erodible bed is given, after which the experiments with different forest set ups (forest density and forest clustering) and the experiments with different log entrainments are discussed. The results are described for the two extreme experiment cases (e.g., low and high forest density) and for the forest density and forest clustering experiments the results are further separated into the results of the debris flows without logs and the debris flows with logs. Lastly, a short analysis is given on the capturing efficiency of the logs on the bed.

4.1 Debris flow behaviour upstream of the erodible bed

4.1.1 Hydrograph analysis for all the experiment set ups

The behaviour of the debris flows before the erodible bed is shown using the hydrographs of the experiments. The hydrograph in *Fig. 8a* is based on the average debris flow height at the location of the second sensor (see *Fig. 5a*) calculated from the debris flow heights in the reference, density and clustering experiments. This is defensible, since for all these experiments, the upstream part of the debris flow is not yet affected by the forest set up of the erodible bed. A differentiation has been made for debris flows with and without log entrainment. *Fig. 8a* shows that the peak of the debris flows with logs is a bit wider than in the case of no logs and that when logs are included the maximum average debris flow height becomes less (difference of 0.0016 m) and the peak arrives later. The start (rising side of the hydrograph) and the tail are relatively similar when comparing the experiments with and without logs. However, from *Fig. 8a* it also becomes clear that the differences between the average hydrographs of the experiments with and without logs are relatively small.

When looking at the (individual) entrainment experiments (*Fig. 8b*), it can be seen that an increase in amount of logs in the debris flow does not directly translate to an increase or decrease in peak discharge. The timing and width of the individual peaks does seem to be influenced by the amount of logs in the debris flow, even though a direct relationship does not seem to be present. This is in contrast with the averaged hydrographs (*Fig. 8a)* described above in which the arrival time and width are relatively equal between the debris flows with and without logs. Important to note are the two cases of 0 logs in *Fig. 8b*. These experiments both have the same debris flow composition and yet they return a different maximum debris flow height. Hence, it might be that the difference in debris flow height seen in the entrainment experiments is actually caused by experimental variability instead of a different amount of logs.

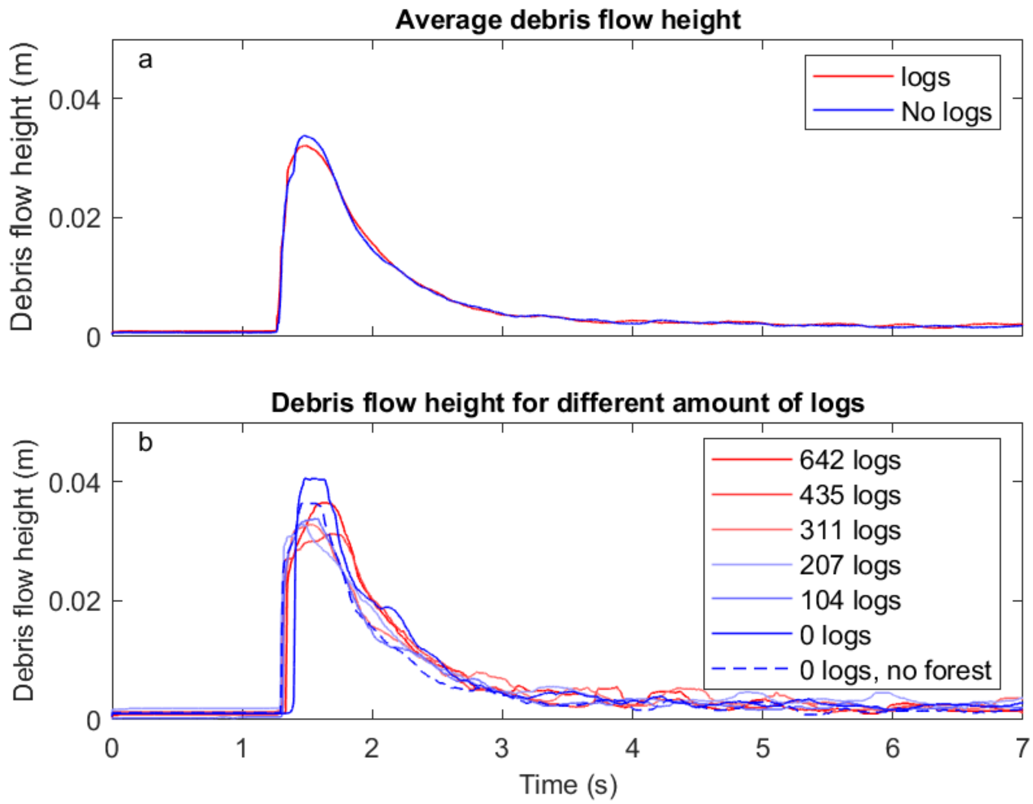

Figure 8 Hydrographs for the experiments. Fig. 8a shows the average debris flow height based on the height of the debris flows at the second sensor (see Fig. 5a). The average is taken from the reference, forest density and forest clustering experiments (6 to 8 experiments), since these debris flows are the same in composition (separating the with and without log cases), and the erodible bed is not reached yet. The individual entrainment experiments are shown in Fig. 8b. The number of logs in Fig. 8b corresponds to the total number of added logs to the debris flow. These debris flow heights are not averaged since the debris flows differ in composition. The experiment with 0 logs in Fig. 8b has a second run since this also includes the reference experiment, again since the hydrograph is based on the laser before the erodible bed it can be used as the forest on the erodible bed is not important yet.

4.1.2 Velocity analysis for the experiment set ups upstream of the erodible bed

The velocity of the different debris flows before the erodible bed is determined between the first and second OADM sensor (see *Fig. 5a* for their locations). Again, differentiation is made between flows with and without logs. *Fig. 9a* shows that the median of the velocity of the runs with logs is 0.1241 m/s lower than the velocity of the runs without logs. The spread in the velocity data for the experiments without logs is a bit larger, based on the size of the boxes for the experiments with and without logs. When looking at the velocities of the reference, forest density and forest clustering experiments individually, the debris flows without logs both have the maximum and minimum debris flow velocity over all the experiments. The maximum velocity for the debris flow without logs is 4.04 m/s (end of the upper whisker for the debris flow with no logs) and the minimum velocity is 2.95 m/s (red cross for the debris flow with no logs) (*Fig. 9a*). These velocities have a factor of difference of 1.37. In contrast the difference between the minimum velocity for the debris flow with logs (3.36 m/s; lower whisker for the debris flow with logs) and maximum velocity for the debris flow with logs (3.99 m/s; upper whisker for debris flow with logs), is a factor 1.19 (*Fig. 9a*).

The experiments with a different amount of entrained logs (*Fig. 9b*) show a relatively smaller range of velocities when compared to the maximum and minimum velocities for the reference, forest density and forest clustering experiments without logs in *Fig. 9a.* The entrainment experiments have a minimum velocity of 2.95 m/s (for one of the 0 logs experiments) and a maximum velocity of 3.70 m/s (for the debris flow with 642 total added logs) (*Fig. 9b*). This is a maximum difference factor of 1.25 between the individual experiments. Lastly, *Fig. 9b* shows no clear trend and an increase in the amount of logs does not directly translate into a higher or lower debris flow velocities before the erodible bed.

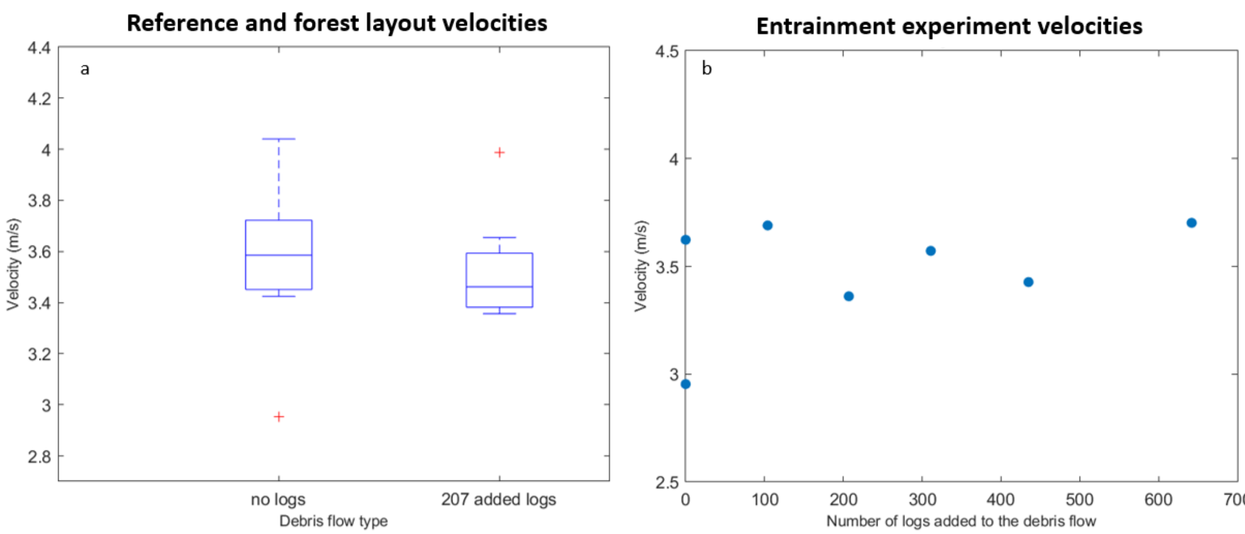

Figure 9 Velocity (m/s) (9a) measured between the first and second sensor just before the erodible bed (see for location Fig. 5a). for the reference, forest density and forest clustering experiments (6 to 8 experiments), since these debris flows are the same in composition (separating the with and without log cases) and the erodible bed is not reached yet. Figure 9b shows the velocity of the individual entrainment experiments. The number of logs on the x-axis in 9b corresponds to the total number of logs added to the debris flow. The 0 logs experiment in 9b has a second run because apart from the reference experiment, the 0 log experiment with a forest can also be used because the velocity is determined before the erodible bed and thus the forest is not yet important.

The small differences in the debris flow velocities (*Fig. 9*) can also be inferred from *Fig. 10a, 10b* and *10c*, which show that the overall arrival time at the second sensor (just before erodible bed) is virtually the same for all runs. In all of the experiments, the debris flow displays roughly the same acceleration pattern (roughly the same slope) upstream of the erodible bed. Because of this, the impact of the debris flows on the erodible bed in the experiments described in the next sections is expected to be independent of the energy contents of the debris flows since, all the debris flows have approximately the same mass (maximum increase of 2.5% due to the maximum entrainment of 642 logs) and roughly the same velocity at the moment it arrives at the erodible bed.

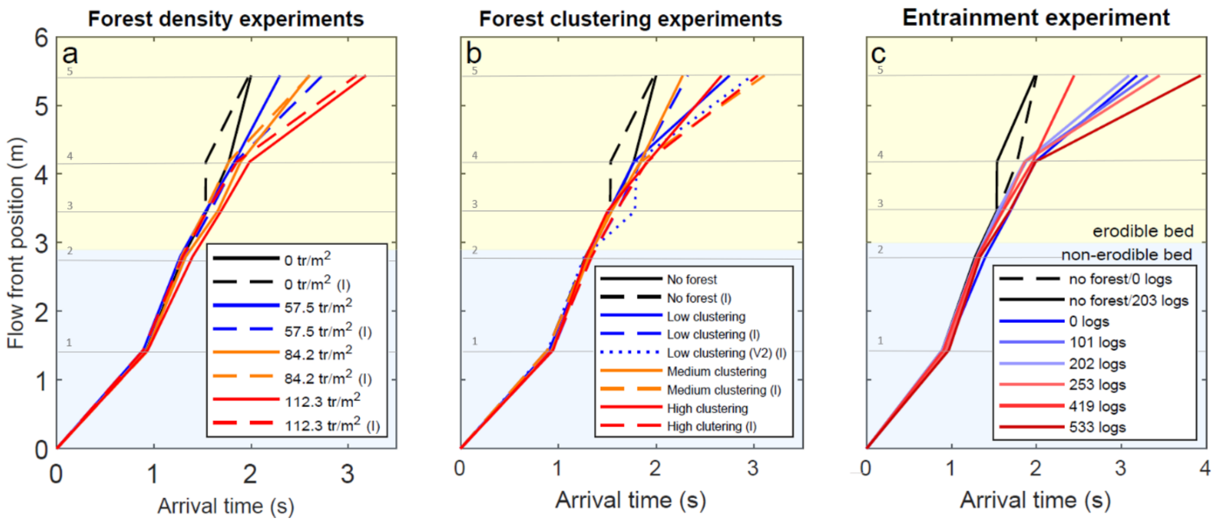

Figure 10 Arrival time of the debris flow front at the locations of the laser sensors (at 1.4, 2.8, 3.5, 4.2, 5.4 m; see the horizontal grey lines with the indication of the sensor number). The lines in the plots are called FFT-curves, which stands for Flow Front Time-curves. Figure 10a and 10b show the development for the forest density experiments and the forest clustering experiments respectively. In the legend, the experiments with a "(l)" are runs including 207 log in the debris flows and the experiments with 0 tr/m2 (tr= trees) or "no forest" are the reference experiments. The low forest clustering (10b) experiment with logs has a second run (V2). A second run of the low forest clustering experiment without logs was also executed. However this FFT-curve was almost equal to the first run and it was therefore decided to only plot the first run to keep a cleaner plot (plotting the two lines resulted in one thick curve obscuring other FFT-curves). Fig. 10c shows the development for the experiments with varying amounts of entrained logs in the debris flow. The amount of logs mentioned in the legend are the amount of logs that reached the erodible bed (total amount of logs added – logs left upstream of the erodible bed).
Based on the difference of the FFT-curve in between sensors, debris flow velocity and acceleration can be determined. A gentler slope compared to the slope more upstream indicates a decrease in velocity and a deceleration of the flow. For some of the experiments (reference experiment with logs (is the same experiment with no forest and 203 recovered logs in 10c) and the low clustering with logs (V2)) a sensor did not work properly and the arrival time had to be determined with the GoPro's resulting in the outlier points in in these FFT-curves.

4.1.3 Material distribution in the debris flow before the erodible bed

The components of the debris flow do not seem to be evenly distributed. According to the GoPro video's, gravel is located more in the head and side of the flow while the tail consists of the finer material. When logs are included in the debris flow, they also seem to be a bit more abundant in the head.

4.2 Description of forest density experiments in terms of debris flow dynamic and bed change

4.2.1 Forest density experiments for debris flows without entrained logs

Results are presented for low and high forest density, separately. The low density forest has a tree density of 57.5 trees/m^2 and the high density forest has a density of 112.3 trees/m^2. Both forest types have an evenly distributed tree pattern (see *Appendix A. Fig.* 1).

4.2.1.1 GoPro observations on obstruction formation and flow behaviour in relationship to forest density

Low forest density

Debris flows can form (relatively small) obstructions when a forest is implemented on the bed, which are not seen in absence of a forest (in the reference experiments). In a low density forest no real obstructions formed around the central line (middle between the left and right side) of the erodible bed. However, when trees are directly at the side of the flume, gravel is captured between the side of the flume and the tree (*Fig. 11b*), forming obstructions and some ramp like features. The flow behind the gravel obstructions at the side seems to be slower than the flow around the central line, where no gravel is captured. The trees planted on this line in the erodible bed influence the movement of the flow a bit, since flow separation happens behind the trees (*Fig. 11a*), creating areas with a slower flow velocity. Large preferential flow paths do not seem to form when the main body of the debris flow is moving over the bed. After the main body has passed, next to a depositional lob, a preferential flow path seems to form, in which the flow velocity is somewhat higher than in other parts of the flume. When the debris flow hits the most upstream tree line, a part of the debris flow (mainly gravel) is splashed up. As a result, it skips part of the erodible bed and is deposited further downstream along the erodible bed before the main debris flow surge arrives.

High forest density

As with the low density forest, trees in the high density forest capture gravel when they are placed at the side, but no clear flow obstructions are present along the central line of the flume. The obstructions on the side of the bed slow down the flow or completely seem to stop it as in the case of a small gravel obstruction around 1100 mm in *Fig. 12d*. After the main surge of the debris flow has passed, the GoPro's show that two flow paths form with a slightly higher velocity (*Fig. 12d* shows such a path at the right side of the flume from 250 mm to roughly 900 mm). Again splashing occurs when the debris flow hits the upstream tree line, and the material is deposited downstream after which it is overrun by the debris flow.

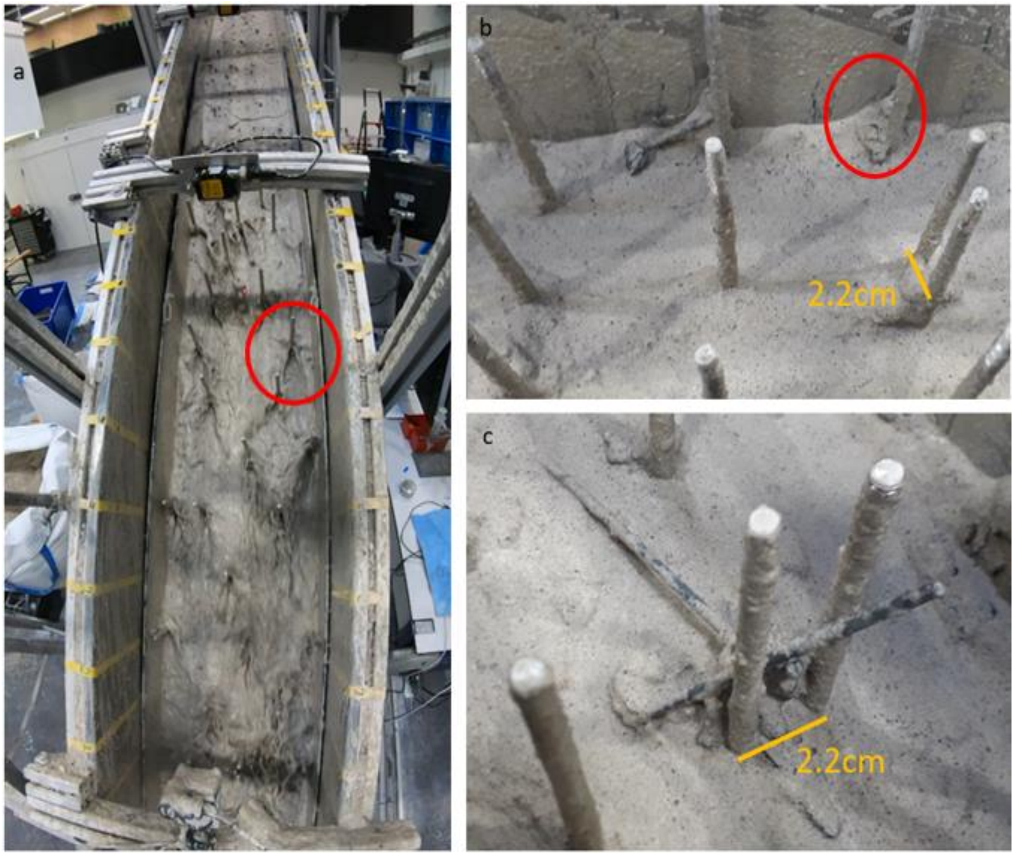

Figure 11 Flows separation and deposition features. 11a is video snapshot from a GoPro video and shows an example of the flow separation behind the trees in the red circle (for scale the trees are 6 mm in diameter). 11b shows the deposition of gravel when two trees are directly next to each other (orange line) and the capture of gravel at the flume side (red circle). 11c shows an example of how logs and gravel can be captured in an obstruction.

4.2.1.2 Sensor based frontal flow velocity in relationship to forest density

At the erodible bed, the forest density experiments show that the Flow Front Time-curves (FFT-curves), of the debris flow position compared to arrival time, become less steep when moving towards the fourth sensor (*Fig. 10a* solid lines). This indicates a deceleration of the flow when the flow enters the erodible bed.

Low forest density

The low forest density experiment (*Fig. 10a*, *blue solid line*), is relatively similar to the reference experiments (*Fig. 10a, black solid line*), and only starts to deviate just before the fourth sensor. This deviation is the result from a continued acceleration between sensor four and five (see *Fig. 10a*) in the reference experiment (without forest), whereas the flow in the experiment with the low density forest does not longer accelerate, but maintains a relative constant velocity.

High forest density

As for the low density forest velocity, the velocity of high density forest is relatively constant up to the fourth sensor. When moving to the last sensor the FFT-curve becomes less steep indicating a deceleration and a lower velocity (*Fig. 10a, red solid line)*. This deceleration in the high forest density experiment is relatively strong compared to the deceleration in the low forest density experiment. As a result, the debris flow in the high density forest arrives 0.89 seconds later at the last sensor than the debris flow in the low density forest.

4.2.1.3. Erodible bed change patterns in relationship to forest density

The DoD's (DEM's of Difference) of the forest density experiments in *Fig. 12a, 12b, 12c* and *12d* show the bed changes caused by the debris flow after it moved over the erodible bed.

Low forest density

For the low density forest (*Fig. 12b*), most of the erosion happens at the upstream part of the bed forming a scour. The rest of the erodible bed shows almost no change, with the exception of the lower part, which shows deposition (positive bed change). The scour is also present in the reference experiment (*Fig 12a*)*,* but deposition seems to occur more at the side than at the end of the erodible bed in the reference experiment. At the sides of the flume, small spots of strong deposition can be seen, for example around 750 mm (at the left side of the flume) in *Fig. 12b.* These are locations where trees are close to the side of the flume, showing the effect of the gravel capturing, as described above (see also *Fig. 11b*).

High forest density

When the forest density is increased to the high density *Fig. 12d*, the scour decreases compared to the reference and low density experiments and deposition (positive bed change) is larger and occurs both upstream and downstream. Similar to what is observed with the low density forest, small spots of strong deposition occur again at places where gravel is captured between a stem and the side of the flume (e.g., around the right side at 1200 mm in *Fig. 12d)*. In the high forest density experiments trees around the central line of the flume result in creation of small scale "crescent dune like" deposition features as the one around 1200 mm in *Fig. 12d* which are not visible in the other forest density experiments. For the upper part of the erodible bed for the high forest density experiment shows a channel like feature which matches with the flow paths described above (see section 4.2.1.1).

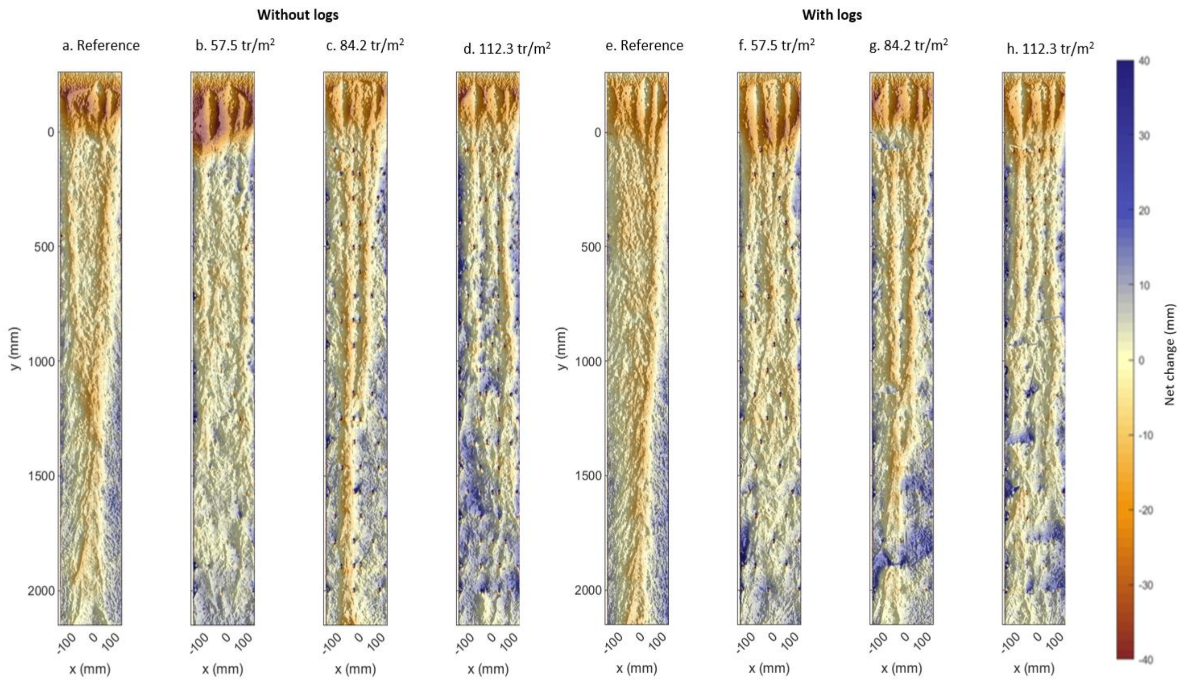

Figure 12 Dem's of Difference (DoD's) showing the erosion (negative net change, red) and deposition (positive net change, blue) patterns on the erodible bed for the reference experiments and the forest density experiments. 12a, 12b, 12c and 12d are the experiments without logs and 12e, 12f, 12g and 12h are the experiments with 207 entrained logs in the debris flow. Figure 12a and 12e are the reference experiments and thus have no forest implement on them. The DoD's with a forest show some extremely (circular) local, lined out changes of the bed. These are the fake trees implemented on the bed. The colour bar shows the net change of the bed in mm.

4.2.1.4 Volume changes of the erodible bed in relationship to forest density

A sequence of experiments (including the low and high forest density experiments described above) with various forest densities was run to study the effect of forest density on the extent of erosion and deposition. *Fig. 13a* shows the total bed change (in cm^3) in relationship to forest density and it is clear that erosion decreases (bed change becomes less negative) with an increasing forest density. If the density becomes large enough (high density forest; 112.3 trees/m^2) the bed change becomes positive, indicating net deposition. The amount of decrease in erosion between different forest density levels does not seem to be evenly distributed. For example, the decrease in erosion between the reference experiment and the low forest density is 1319.01 cm^3, while the decrease in erosion between the low density forest and medium density forest (84.2 trees/m^2) is 425.44 cm^3 (*Fig. 13a*)

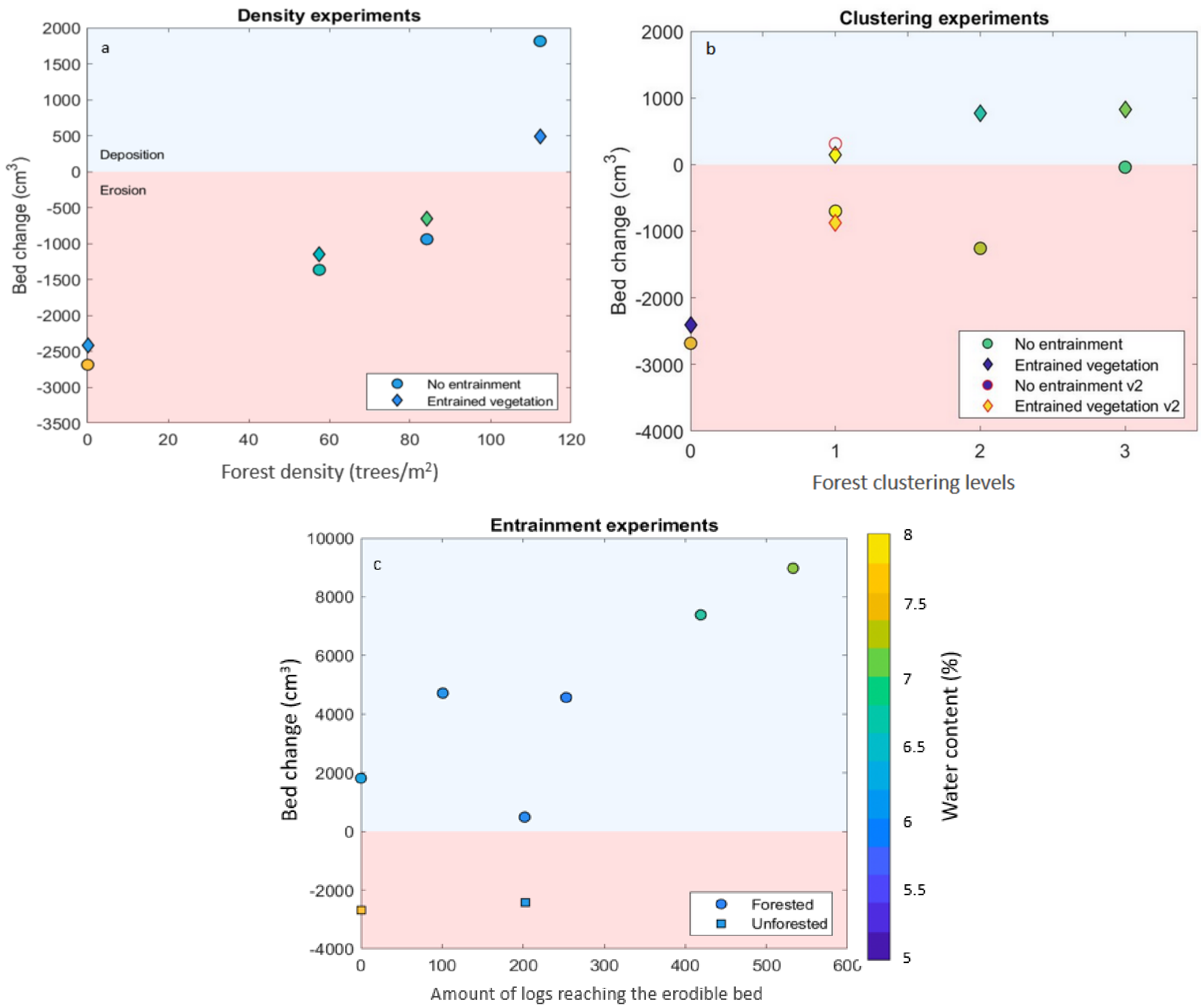

Figure 13 Bed change (cm^3) caused by the debris flow for the all the different experiment set ups. Fig. 13a shows the bed change for the forest density experiments (low: 57.5 trees/m2; medium: 84.2 trees /m2 and high: 112.3 trees /m2). Fig. 13b. shows bed change for the forest clustering experiment (level 1 is low forest clustering, level 2 is medium forest clustering and level 3 is high forest clustering). The second run for the low clustering experiments is also shown, with a red outlined circle and red outlined diamond. The circles represent the experiments without logs in the debris flow, and the diamonds represent the experiments with logs in the debris flow. Fig. 13c shows the bed change for the entrainment experiments. The number of logs on the x-axis in 13c is the number of logs that reached the erodible bed (total added – left behind upstream). The amount of 0 logs reaching the erodible bed represents the reference experiments were no logs were added to the debris flow. The figure also visualizing the water content of the bed. The colour bar, which is the same for all subfigures, shows the percentage of the water content in the bed, measured just before the debris flow is released.

4.2.2 Forest density experiments for debris flows with 207 entrained logs

Below again results are presented for the low density forest (57.5 trees/m^2) and for the high density forests (112.3 trees/m^2), but in these experiments the debris flows contained 207 entrained logs.

4.2.2.1 GoPro observations on obstruction formation and flow behaviour in relationship to forest density

Low forest density

The GoPro videos show that in the low density forest logs can be captured between the trees (as in *Fig. 11c* but can also be remobilized later on. Gravel is still captured along the sides. Flow separation (as in

Fig. 11a) still occurs behind the trees and enhances when logs and gravel are (temporarily) trapped (as in *Fig. 11c*). As in the forest density experiment without logs, splashing occurred when the debris flow made contact with the first tree lines.

High forest density

In the high density forest, a few obstructions seem to form either when two trees are directly next to each other or when logs and gravel are captured between the side of the flume and the tree right next to it (*Fig. 11b* and *11c* orange lines). As in the low density forest, the captured logs can be remobilized. In some cases, logs are captured by the trees but they do not make contact with the bed, because they are located on a slightly elevated bed and the channel continues underneath the deposited log. At the start (just after the head of the flow has past), the central line of the flume (in the high forest density set up) has a higher debris flow velocity compared to the sides of the flume which becomes a channel-like feature. The flow velocity behind the obstructions (like gravel ramps) seems to be lower compared to the flow at the side of the obstructions. As in the experiments without logs, when the debris flow hits the first upstream tree lines, the debris flow and, in these experiments, logs are partly splashed up and deposited further downstream.

4.2.2.2 Sensor based frontal flow velocity in relationship to forest density

The experiments in *Fig. 10a* show that when the debris flow enters the erodible bed, the FFT-curves (dashed lines) becomes less steep indicating a deceleration of the different forest density experiments when logs are entrained. The reference experiment with logs (black dashed line) does not follow this pattern. The deviation is most likely caused by a malfunctioning of sensor four, which had to be corrected by hand (using the GoPro's). This most likely effected the arrival time at sensor four and the acceleration between sensor three and four is thus most likely untrue. The arrival time of the reference experiment at sensor three and five are correct. Based on this *Fig. 10a* shows that the deceleration for the forested experiments with logs in between senor three and five is much larger compared to the deceleration of the reference experiment.

Low forest density

Fig. 10a shows that up to the fourth sensor, the velocity in the low density experiment with logs (*dashed blue line* in *Fig. 10a*) is relatively similar to the other density experiments with logs, in that it experiences a deceleration compared to the velocity on the non-erodible bed. The last part of the flume toward the fifth sensor shows a further deceleration of the flow, as the FFT-curve becomes even less steep.

High forest density

Roughly the same pattern is true for the high forest density experiment with logs (*Fig. 10a, dashed red line)*. Only the final arrival time (at the last sensor) of the debris flow is later compared to the low forest density experiment (difference of 0.35 seconds) indicating a stronger deceleration in between sensor four and five for the high forest density experiment.

4.2.2.3 Erodible bed change patterns in relationship to forest density

Low density forest

The DoD, DEM of Difference, (*Fig. 12f)* shows that with entrained logs deposition mainly happens downstream and at the sides of the flume and that the channel like feature visible in the reference experiment (*Fig. 12e*) disappeared. As described above, small local spots of high deposition are visible at the sides where gravel and logs are captured between a tree and the side of the flume (e.g., around 800 mm along the right side in *Fig. 12f*).

High density forest

For the high density experiments the DoD (*Fig. 12h*) shows that a part of the deposition happens along the side of the flume but also that deposition happens along the central line of the flume when the material is deposited upstream of obstructions (visible in features like around 1750 mm in *Fig. 12h*). The number of these local depositional sites along the central line of the flume increased for the high density experiment compared to the low density experiment. Furthermore, the DoD for the high density forest experiment (*Fig. 12h*) shows a slight zigzag in the depositional pattern (the area around 0 cm^3 change moves from right to the left) between 1400 mm and the end of the flume. This pattern is not visible in the video of the flow.

4.2.2.4 Volume changes of the erodible bed in relationship to forest density

The low and high forest density experiments together with the reference and medium density (84.2 trees/m^2) experiments are plotted in *Fig 13a* to see if a relationship exist between the forest density and the bed change. *Fig. 13a* shows that erosion decreases when the forest density increases, even leading to net deposition for the high density forest (112.3 trees/m^2), when logs are included in the debris flow. The difference in bed change in between different forest densities is not equal. For example, the difference in bed change between the low and medium density forest is smaller than the difference between the medium and high density forest.

4.2.3 Comparison of debris flows with and without logs in relationship to forest density

4.2.3.1 Comparison of sensor based frontal flow velocity

When comparing the with and without log experiments for the various forest densities, a few differences are found when comparing their arrival times at the different laser sensors. For example, the low forest density experiment without logs shows a relatively constant velocity compared to the low forest density experiment with logs (*Fig. 10a solid and dashed blue lines*). The FFT-curve of the experiments with logs falls below the FFT-curve of the experiment without logs in the low forest density experiment (dashed blue line is below the solid blue line). This indicates that the debris flow in the low density experiment with logs moves slower, creating a difference in arrival time of 0.437 seconds at the fifth sensor. In contrast, in the high density case, the experiment with logs (*dashed red line*) in *Fig. 10a* is above the experiment without logs (*solid red line*) indicating that the debris flow in the experiment with logs is faster with a difference in arrival time of 0.096 seconds at the fifth sensor. This difference between the high and low density forest shows that the inclusion of logs does not directly translate to a later arrival time of the debris flow.

4.2.3.2 Comparison of bed change patterns and volume changes

When comparing the DoD's of the density experiments with and without logs (*Fig. 12*), a main difference seems to be that in the experiments with logs the deposition sites are relatively local, while the deposition in the experiments without logs is more spread out over the whole erodible bed. This difference is especially clear for the high forest density experiments.

Looking at data of the reference and all the forest density experiments in *Fig. 13a* it is clear that an increase in forest density leads to a less negative and eventually to a positive bed change, indicating an increase in deposition. This is true both in the cases with and without logs in the debris flow. However, the amount of increase in the deposition differs per experiment set up and a relationship between the changes in deposition, forest density and the presence of logs is not clear. A last note is that in the case of the high density forest, the experiments with logs returns a smaller positive bed change than the experiment without logs (*Fig. 13a*).

4.3 Description of forest clustering experiments in terms of debris flow dynamic and bed change

For the clustering experiments three different forest layouts were made (see *Appendix A. Fig. A. 2*), all consisting of 60 trees (so a density of 84.2 trees/m^2 over the whole erodible bed). The high clustering set ups means that only a few places on the erodible bed are covered with a relatively high local forest density inside the clusters, while a low clustering set up means that the 60 trees are placed randomly on the bed, resulting in a lower local tree density.

4.3.1 Forest Clustering experiments for debris flows without entrained logs

4.3.1.1 GoPro observations on obstruction formation and flow behaviour in relationship to extent of clustering

Low forest clustering

For the low clustering set up flow obstructions are formed when gravel are captured, either in between trees that are directly next to each other or in between a tree and the flume sides (similar to the ones shown in *Fig. 11b*). As a result, the obstructions are relatively small. Looking at the GoPro videos it can be seen that the flow around the central line of the flume is faster and that behind the trees flow separation occurs (as in *Fig. 11a*). When the main body of the debris flow moves over the obstructions it leads to small waterfalls or an area with a smaller flow velocity directly behind the obstruction. After the main body of the debris flow has moved passed the obstructions formed around the central line, bifurcation of the channel occur around these obstructions. In the low clustering experiments splashing of the debris flow occurs as described above in the forest density experiments.

High forest clustering

As with the low clustering experiment, gravel is the component forming the obstructions in the high clustering set up. A large obstruction formed in the first where four trees are placed directly next to each other (*Fig. 14a, 14b* and *14c*). A similar obstruction is also present in the second cluster (see the DoD in *Fig. 15d*). Smaller obstructions (as described above) are also present. The large obstruction in the first cluster creates an overflow leading to a waterfall like feature when the main body of the debris moves over it (*Fig. 14a,* red circle). The obstruction directs the flow to the opposite side of the flume toward the vegetated side of the second cluster increasing the debris flow height locally (*Fig. 14a* and *14b*) (see for the layout of the clusters in the flume *Appendix A. Fig. A. 2*). When the main body has passed, the GoPro videos show that the flow velocity decreases directly behind the obstruction. The area that is not planted with trees on the side of the flume, seems to have a relatively faster flow compared to the flow inside the clusters. This is especially clear at the location of the first, upstream cluster. In the case of the high clustering experiment splashing also occurs, mainly on the first (upstream) forest cluster but also a little bit on the second forest cluster, however this is less visible in the videos due to the splashed up material form the first cluster.

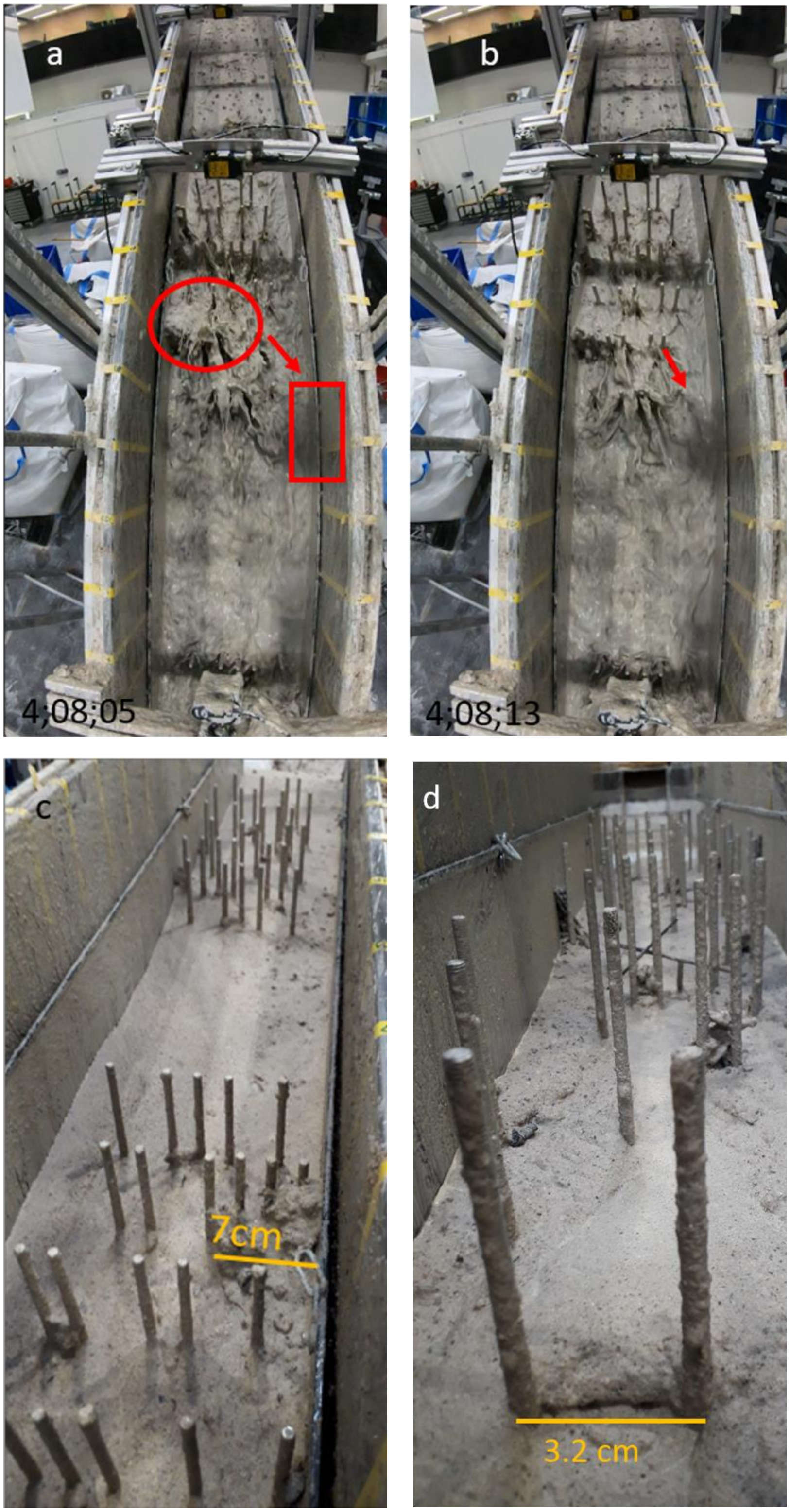

Figure 14 14a and 14b are video snapshots taken from the GoPro for the high forest clustering without logs. Their time codes (min;sec;ms) are visible in the lower left corner. The circle in 14a shows an obstruction forming at the four trees directly next to each other which redirects the flow (arrow) and leads to a rise in the debris flow height in the rectangle. 14b shows that the flow is still redirected (arrow) an that the flow behind the obstruction is very small after the main body of the debris flow has passed. 14c and 14d are photos taken after the debris flow has passed. 14c shows the ramp like feature which lead to the redirection, in 14a and 14b, in the high clustering experiment. 14d is a photo of the low clustering experiment with logs, and shows an obstruction at the orange line.

4.3.1.2 Sensor based frontal flow velocity in relationship to extent of clustering

Fig. 10b shows that, as with the forest density experiments, when the debris flows enter the erodible bed, they decelerate slightly in case of the forest clustering experiments, and the largest changes in the FFT-curves and thus the velocity are found between the fourth and fifth sensor.

Low forest clustering

The FFT-curve for the low forest clustering experiment (*Fig. 10b, solid blue line*), is relatively similar to the FFT-curve for the other forest clustering experiments up to the fourth sensor. In between the fourth and fifth sensor the FFT-curve becomes less steep indicating a deceleration. This can also be seen in the difference in arrival time between the reference experiment (*black solid line*) and the low clustering experiment. It should be noted that a second run was executed for the low forest clustering. The first and second run had a maximum difference in arrival time of 0.0107 seconds at the different laser sensors. Therefore, the choice was made to exclude the second run form *Fig. 10b*, which prevented obscuring the FFT-curves from other clustering experiments.

High forest clustering

The FFT-curve for the high forest clustering experiment (*Fig. 10b, solid red line*) is relatively similar to the other forest clustering experiments at the start of the erodible bed. However, the flow starts to deviate (deceleration) form the other forest clustering experiments at the third sensor, after which the velocity is relatively constant compared to, for example, the low forest clustering experiments (blue solid line in *Fig. 10b*), which experiences a further deceleration between the fourth and fifth sensor. For the low clustering experiment, the arrival time at the fifth sensor is 0.0809 seconds later than for the high clustering experiment.

4.3.1.3 Erodible bed change patterns in relationship to extent of clustering

Low forest clustering

The DoD for the low clustering set up (*Fig. 15b)*, shows a channel like feature around the central line of the flume and a large depositional area on the right side. Small concentrated high positive bed change (deposition) spots are placed mainly on the side of the flume. These are locations were gravel has been captured. Around 1500 mm in *Fig. 15b* the channel separates temporarily into two channels when the flow moves around such a gravel-formed obstruction. A main difference between the first and second low clustering run for their DoD's is that in the first run (*Fig. 15b*) the channel continues almost to the end of the flume, while in the second run the channel stops around 1250 mm after which mainly deposition occurs.

High forest clustering

The DoD for the high clustering (*Fig. 15d*) shows that the area next to the clusters (un-vegetated sites) have a small bed change either negative or positive and that most deposition (positive bed change) occurs inside the clusters. The dark blue spots in the clusters (around 600 mm and 1400 mm) corresponds to the (previously described) relatively large obstructions seen (see for an example *Fig. 14c)*. Behind the obstruction scour-like features (sharp change from net deposition to a small net change for example around 1450 mm at the left side of the flume, in *Fig. 15d*), are present. Furthermore, the depositional pattern in the second (downstream) cluster shows small local increases in deposition behind closely spaced trees (*Fig. 15d*, around 1550 mm).

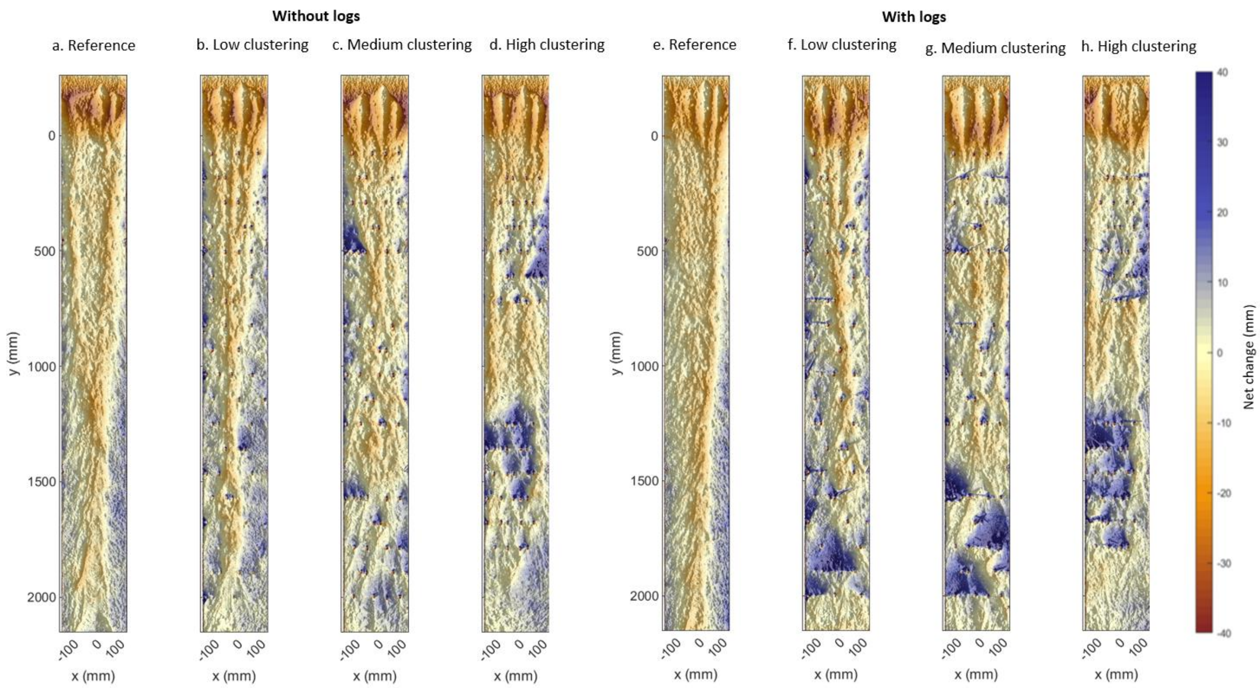

Figure 15 Dem's of Difference (DoD's) showing the erosion (negative net change, red) and deposition (positive net change, blue) patterns on the erodible bed for the reference experiments and the forest clustering experiments. 15a, 15b, 15c and 15d are the experiments without logs and 15e, 15f, 15g and 15h are the experiments with 207 entrained logs in the debris flow. The low clustering figures (15b and 15f) are the result of the first runs of both the set up with and the set up without logs. 15a and 15e are the reference experiments and thus have no forest implement on them. The DoD's with a forest show some extremely (circular) local, lined out changes of the bed. These are the fake trees implemented on the bed. The colour bar shows the net change of the bed in mm.

4.3.1.4 Volume changes of the erodible bed in relationship to extent of clustering

Fig. 13b shows the overall bed change due to the debris flow for all the clustering experiments as well as the reference experiment. The figure shows that the bed change becomes less negative when the level of forest clustering increases and the bed change almost reaches a net deposition value (bed change of -40.23 cm^3, so net erosion) for the high clustering experiment (level 3). This indicates a decrease in the erosion, when clustering levels increase. The decrease in erosion, between two clustering levels, seems to be the largest between the reference and the low clustering experiments. The difference between the first low clustering run (black circle at level 1 in *Fig. 13b*) and the second low clustering run (red circle at level 1 in *Fig. 13b*) is 1030.86 cm^3. This could be an indication of experimental variability between experiments. Hence, the more negative value for the medium clustering set up could be due to experimental variability, especially considering that the high clustering experiment again returns smaller erosion value (smaller negative bed change) compared to the other forest clustering experiments (*Fig. 13b*).

4.3.2 Forest clustering experiments for debris flows with 207 entrained logs

Below the results for the forest clustering experiments (focussing on the low and high clustering set ups) for debris flows with 207 entrained logs are discussed.

4.3.2.1 GoPro observations on obstruction formation and flow behaviour in relationship to extent of clustering

Low forest clustering

When the flow enters the erodible bed, logs and gravel are captured in between the trees in the low forest clustering set up (*Fig. 11c*) (e.g., the sharp, thin horizontal lines around 600 mm in *Fig. 15f* are captured logs visible at the surface), forming obstructions both along the central line and at the sides of the flume. As mentioned in the density experiments the logs and gravel can be remobilized later on. The obstructions formed in the low forest clustering set up are relatively small, except for the one formed downstream, which is about half the width of the flume and consist of both gravel and logs (*Fig. 14d* and *Fig. 15f* around 1800 mm). Some of the deposited logs do not touch the erodible bed and hence the flow can continue underneath (e.g., around 1450 mm in *Fig. 15f*). The small obstructions can lead to small waterfalls when the flow is still relatively strong. When the flow decreases in strength the obstructions start to separate the flow in multiple channels. The relatively large downstream obstruction (visible in *Fig. 14d*) redirects the flow to the opposite side of the flume (towards the right side). Furthermore, the flow on the sides of the flume seems to be relatively slow compared to the flow around the central line of the flume. Splashing of logs and gravel occurs when the debris flow hits the upstream tree lines as described for the forest density experiments with logs in the debris flow.

High forest clustering

For the high forest clustering experiments obstructions are only present within the two forest clusters (*Fig. 15h*). Both clusters show a relatively large obstruction (consisting of both logs and gravel) formed where four trees are directly next to each other, as in the clustering experiments with no logs. Some small obstructions form around the sides of the flume when a tree is present. Trapped logs only effect the flow when they make contact with the bed. The larger obstructions are shaped like ramps (similar to *Fig. 14c*) both in the upstream and downstream cluster, leading to a redirection of the flow (similar to the redirection described in *Fig. 14a and 14b*). Especially in the upstream cluster the flow is redirected towards the other side of the flume increasing the debris flow height. In the downstream cluster the large obstruction is flooded and this flooding reaches the end of the flume faster than the flow that moves over the un-vegetated side (right part of the flume) next to the second cluster (*Fig. 15h*). After the main body of the flow has passed it seems that the locations with an initial faster flow stay active for a longer time, no matter if the area is overgrown or not. As with the low forest clustering experiment, splashing of logs and gravel occurred at the upstream tree lines, when hit by the debris flow.

4.3.2.2 Sensor based frontal flow velocity in relationship to extent of clustering

Low forest clustering

The velocity of the low forest clustering experiments with logs is plotted for two different runs (*Fig. 10b, blue dashed and dotted lines*). When the debris flow hits the erodible bed, the low forest clustering experiments show a slight decrease in velocity and a later arrival time at the last sensor compared to the reference experiment (*black dashed line*). The first low forest clustering run (*blue dashed line*) shows a relative constant velocity after it enters the erodible bed, with a slightly less steep angle indicating a deceleration. The second experiment (*V2, blue dotted line* in *Fig. 10b*) shows a stronger deceleration in the last part of the bed and arrives 0.66 seconds later at the last sensor than the first low forest clustering run. This difference in arrival time is probably caused by experimental variability since the conditions between the two runs were equal.

High forest clustering

For the high forest clustering experiments (*red dashed line* in *Fig. 10b*) the velocity decreases after it enters the erodible bed and decelerates even further (FFT-curve becomes less steep) when moving between sensor four and five. When comparing this to the two low forest clustering experiments in *Fig. 10b*, the debris flow in the high forest clustering experiment arrives 0.717 seconds later at the last sensor than the first low forest clustering run (*blue dashed line*) but the high forest clustering arrives earlier at the last sensor (0.056 seconds) compared with the second low forest clustering run (*blue dotted line*).

4.3.2.3 Erodible bed change patterns in relationship to extent of clustering

Low forest clustering

For the low forest clustering experiments, most of the deposited material seems to be captured in the obstructions at the side of the channel and in the obstruction downstream, which form (local) cone size deposition features (*Fig. 15f*). In contrast the reference experiment shows a more spread out deposition along the right side of the erodible bed (*Fig. 15e*). The channel formed in the bed of the low forest clustering experiment seems to be closed in between areas that were able to capture some logs (e.g., around 750 mm). Behind the larger obstruction around 1900 mm (*Fig. 14d*) a relatively large scour like feature is visible in *Fig. 15f*.

High forest clustering

The cone-like shapes visible in the low clustering DoD (*Fig. 15f*), are also present in the DoD of the high forest clustering experiment (*Fig. 15h*). In the high forest clustering experiment the cones are smaller, but there are more individual deposits. Their location is relatively local since they only occur inside the tree clusters. In the more downstream cluster these cones form a sequence in the different various tree lines. The area without a forest shows relatively little bed change (*Fig. 15h*).

4.3.2.4 Volume changes of the erodible bed in relationship to extent of clustering

Fig. 13b shows the bed change of all the clustering experiments. When logs are added to the flow, the erosion becomes less when the forest clustering level increases. In the low forest clustering experiment, the erosion decreases in both of the runs when compared to the reference experiment. However, the decrease for the first run (black diamond) is larger, leading to net deposition (positive bed change values) than for the second run (red diamond), which still results in net erosion. As a result, for the first low clustering run a net deposition is already reached in the low clustering case while in the case of the second run net deposition start to occur after a medium clustering (level 2) is implemented. The volume of the bed change, between the different clustering levels, is not equal when moving from one level to another. The largest decrease in erosion (difference of 2555.37 cm^3) seems to happen between the reference (black diamond at level 0) and the first low clustering experiment (black diamond at level 1) in *Fig. 13b*.

4.3.3 Comparison of debris flows with and without logs in relationship to extent of clustering

4.3.3.1 Comparison of sensor based frontal flow velocity

When looking at the arrival time, there is difference between the with and without log clustering experiments (*Fig. 10b*). For the first low forest clustering run with logs (*dashed blue line*, in *Fig. 10b*) the arrival time is 0.427 seconds earlier compared to low forest clustering experiment without logs (*solid blue line)*, while the second low forest clustering run with logs (*V2, dotted blue* line in *Fig. 10b*) arrives 0.225 seconds later than the low forest clustering experiment without logs. In the case of high forest clustering the arrival time of the debris flow with logs (red dashed line) is 0.371 seconds later than the debris flow without logs (*Fig. 10b*).

4.3.3.2 Comparison of formed obstructions

Formed obstructions seem to be larger in the case where logs are added to the debris flow, both for the low and high forest clustering experiments. In case of the high forest clustering experiments with logs the location of the obstructions is relatively similar to the location of the obstructions in the high forest clustering experiments without logs although, the obstruction in the upstream cluster in the high forest clustering experiment with logs seems to be a bit smaller (less deposition) than in the high forest clustering experiment without logs (*Fig. 15d* and *15h*). Furthermore, the deposition in the high forest clustering is more concentrated compared to the low forest clustering experiment, both in the experiments with and without logs.

4.3.3.3 Comparison of volume changes of the bed

Net change is negative in all the forest clustering experiments without logs indicating erosion for all the experiments. For the forest clustering experiments with logs (*Fig. 13b*), erosion becomes less (the bed change becomes less negative) and eventually, with increasing clustering, net deposition occurs (positive bed change). The two low forest clustering experiments, both in the case with and without logs show that there is probably some experimental variability since both the experiments with and without logs return one run with deposition and one run with erosion.

4.4 Description of various log entrainments experiments in terms of debris flow dynamic and bed change

The entrainment experiments consider the effect of a different number of logs in the debris flow mix when it enters the evenly distributed high density forest (112.3 trees/m^2) set up. This is the same forest layout as used in the high forest density experiments (see *Appendix A. Fig. A. 1*). Not all logs reached the erodible bed because some logs were left upstream. The number of logs mentioned in the text below are the amounts of logs that reached the erodible bed. Not all of the logs that reached the erodible bed were left behind on the bed, some were also transported out of the flume (see section 4.4.6). When looking at the experiments with different entrainments, the main focus lies on the experiments with 101 logs and 533 logs, which are the minimum and maximum number of logs that reached the bed respectively.

4.4.1 GoPro observations on obstruction formation and flow behaviour in relationship to the amount of logs reaching the erodible bed

4.4.1.1 Minimum amount of logs reaching the bed

When 101 logs reached the bed some flow obstructions are formed. Upstream the logs are often remobilized, resulting mainly in obstructions due to gravel capture at the sides or in small spaces between trees in the upstream part of the flume. Downstream an obstruction is formed due to the capture of logs. The obstructions influence the flow path as they lead to a separation of channel features. The obstructions also slightly reduce the flow velocity directly behind them. When logs are captured downstream some do not touch the bed allowing flow to pass underneath, but some do also capture gravel. This creates a more solid obstruction leading to overflow. Splashing of gravel and logs also occurred as described above, only less severe.

4.4.1.2 Maximum amount of logs reaching the bed

When 533 logs reached the bed, obstructions formed both up and downstream on the erodible bed . Upstream they are formed by the capture of gravel and logs on the side and along the central line of the flume. In the upstream part of the flume the flow moves passed the areas obstructed by logs and gravel. Furthermore, the flow in the areas at the sides with captured gravel seems to almost stand still compared to the flow around the central line of the flume. These upstream obstructions are relatively small compared to the obstructions formed downstream. One such an obstruction downstream consists of both gravel and logs and covers almost the whole width of the flume (*Fig. 16a:* before the obstruction formed; and *16b*, solid red circle, during creation of obstruction). Just after this obstruction a second one is present, which is a bit smaller (*Fig. 16c, dot-dashed red circle*). These two larger obstructions lead to a pushing up and redirection of the flow (*Fig. 16b, 16c and 16d*). The flow first creates a waterfall when it meets the first large obstruction while material also passes through the less blocked side (*Fig. 16b*). This material is then redirected by the second obstruction creating a zigzag pattern of the flow while it moves over the bed (*Fig. 16c* and *16d*). In the experiment with 533 logs reaching the bed the splashing created upon impact with the treeline seems to have a larger volume and it seems to be more force full, when compared to the splashing form the previously described experiments. The splashed up material is deposited downstream in the flume, but also partly thrown out of the flume, ending up in the trash or on the floor, missing the bed.

4.4.2 Sensor based frontal flow velocity in relationship to the amount of logs reaching the erodible bed

Fig. 10c shows the development of the debris flow movement for the different entrainment experiments. When the debris flows enter the erodible bed, velocity decreases for all the entrainment experiments (coloured FFT-curves). As a result, the debris flows arrive later at the last sensor compared to the reference experiments (solid and black dashed line). For the experiment with 101 logs reaching the erodible bed in *Fig. 10c*, the velocity is relatively constant when moving from the second to the fourth sensor after which it starts to decelerate when it moves further down the bed towards the last sensor. In the case were 533 logs reached the bed, the debris flow starts to decelerate more compared to the other entrainment experiments as soon as it reaches the erodible bed, but as in the other entrainment experiments most deceleration occurs in the last part between the fourth and fifth sensor.

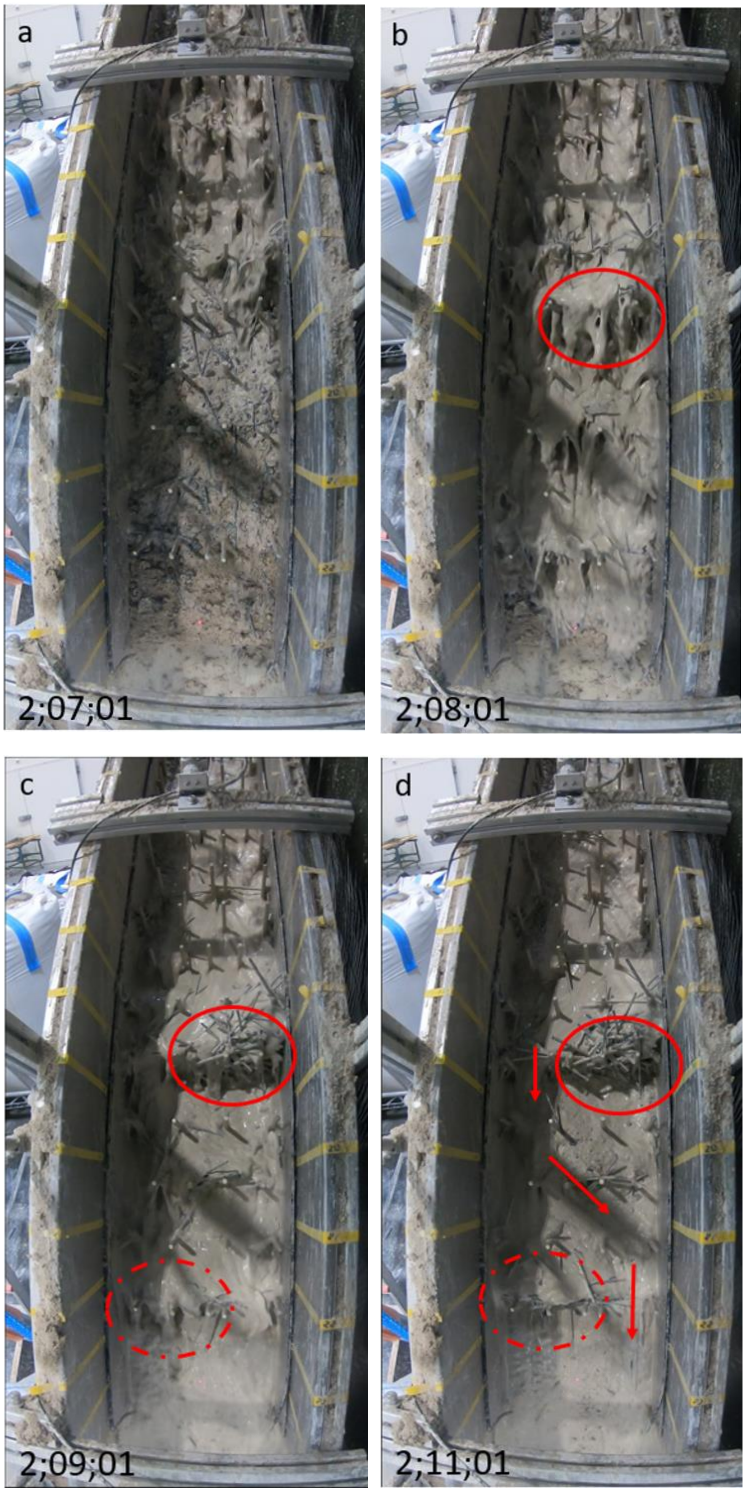

Figure 16 Video snapshots of the GoPro at the end of the flume for the experiment were 533 logs reached the erodible bed, with the time codes (min;sec;ms) in the left lower corner. 16a shows the run over of the deposited splashed material. 16b shows the development of the large dams (red circle) and the formation of the waterfall. 16c and 16d show that the dam grows in size (red circle), the formation of second dam (dashed-dotted red circle) and how these dams alters the flow direction (red arrows).

4.4.3 Erodible bed change patterns in relationship to the amount of logs reaching the erodible bed

Fig. 17b shows that for the experiment with 101 logs reaching the erodible bed most deposition occurs on the downstream half of the erodible bed, matching the obstruction mentioned above (see section 4.4.1). The overall bed pattern upstream is relatively similar to the experiment with zero logs (which serves as a reference experiment, *Fig. 17a*). In the case were 533 logs reach the erodible bed, deposition happens along the sides and in the middle of the bed, especially downstream around the large obstructions (*Fig. 17f and section 4.4.1*). These large obstructions can be seen in between 1500 and 2000 mm in *Fig. 17f*. Directly after the obstruction around 1500 mm a slightly larger depression can be seen (slightly dark orange in colour, at the right side of the flume in *Fig. 17f*). This corresponds to the area where a waterfall like feature formed when the debris flow moved over the obstruction (*Fig. 16b*, red circle).

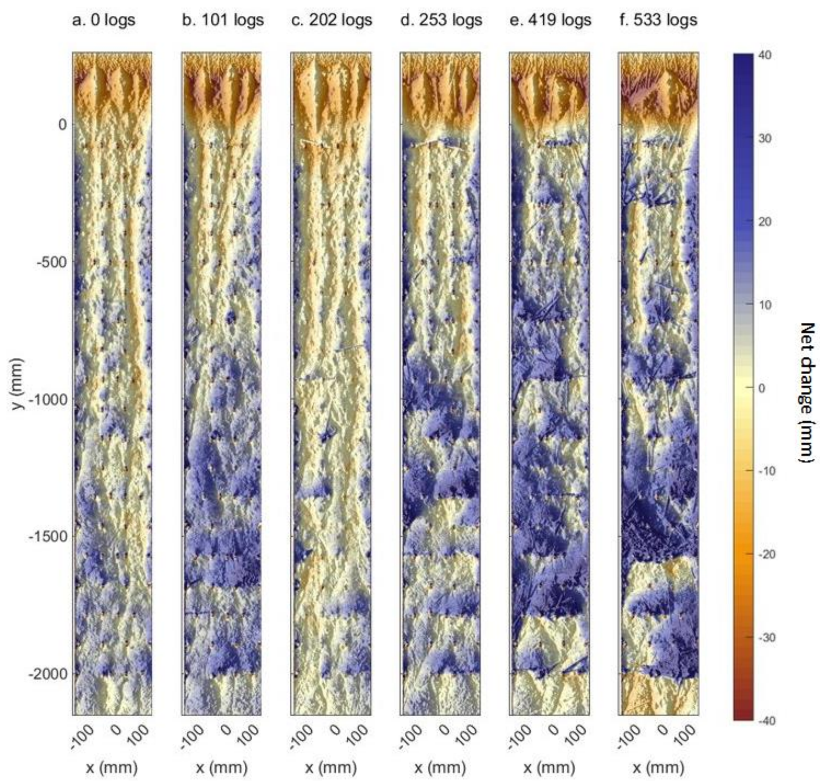

Figure 17 Dem's of Difference (DoD's) showing the erosion (negative net change, red) and deposition (positive net change, blue) patterns on the erodible bed for the entrainment experiments with an increasing number of logs reaching the erodible. The number of logs in the titles refers to the amount of logs that reached the erodible bed (total amount of logs – logs left behind upstream of the erodible bed). The 0 log experiments in this figure serves as a reference plot experiment (in this experiments no logs were added). All the DoD's have a forest on the erodible bed. The extremely (circular) local bed changes are due to the fake trees implemented on the bed. The colour bar shows the net change of the bed in mm.

4.4.4 Volume changes of the erodible bed in relationship to the amount of logs reaching the erodible bed

As mentioned above, several experiments were carried out in which the number of entrained logs was modified, but the erodible bed conditions (tree density and forest layout) were kept constant.

Fig. 13c shows that to some extent an increase in the number of logs reaching the erodible bed can be linked to an increase in deposition (positive bed change). The experiment with 101 logs reaching the erodible bed shows an increase in deposition compared to the experiment with zero logs (no logs added to the flow), both for the forested (circle) and un-forested (square) experiment (*Fig. 13c*). The largest positive bed change (8971.36 cm^3) happens for the experiment were 533 reached the erodible bed. An outlier is the forested experiment were 202 logs reach the bed. It was expected to have a bed change more along the lines of the experiments were 101 and 253 logs reached the bed. Again this may be a result of experimental variability, and might indicate a need for repeated runs to reduce the influence thereof on the interpretation of the results.

4.4.5 Comparison of minimum and maximum amount of captured logs

The FFT-curves (*Fig. 10c*) shows a large variation between the amount of logs reaching the bed and the latest arrival time. A trend between the amount of logs reaching the bed and the arrival time at sensor five is unclear. A main difference between the experiments with 533 logs reaching the bed and 101 logs reaching the bed is that the obstruction size is relatively large in the experiment with 533 logs compared to the experiment with 101 logs. There does seem to be a slight trend that an increasing number of logs reaching the bed leads to larger obstructions with the note that the experiment were 202 logs reached the bed is deviant from this trend (*Fig. 17*). A similar trend can be seen when looking at the total bed change (again with the exception of the experiment with 202 logs), where an increase in the amount of logs reaching the bed seems to translate into more deposition (a larger positive bed change) (*Fig. 13c*).

4.4.6 Log capturing efficiency

Fig. 18a shows that as the amount of logs reaching the erodible bed increases, the percentage of captured logs on the erodible bed also increases. The exception is the experiment were 202 logs reach the erodible bed, which has a relatively low capturing percentage (12.38%) compared to the experiments were 101 or 253 logs reach the bed. These experiments had a capturing percentage of 22.77% and 32.02% respectively. The fact that, for all the entrainment experiments, the amount of captured logs is lower than the amount of logs reaching the bed is not unexpected. This is because a part of the logs that reached the bed were not deposited, but were transported out of the flume.

Fig. 18b shows the percentages of logs captured on the erodible bed, differentiated according to log length. Generally, it appears that with an increasing number of logs reaching the bed the percentage of logs captured per length group increases with a few exceptions. The experiment with 101 logs reaching the bed does not really follow this trend, and the experiment with 533 logs for example shows a deviation for the 14 cm logs.

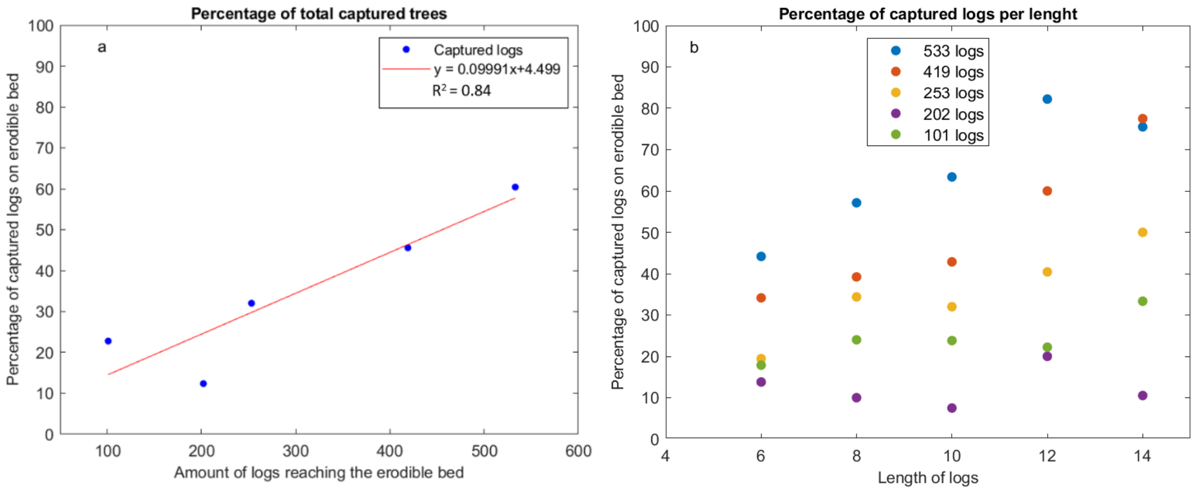

Figure 18 Efficiency of log capturing. 18a shows how the amount of logs reaching the erodible bed is linked to the percentage of captured logs on the bed after the debris flow has passed. The trend line is a poly1 fit from MATLAB. 18b shows how the amount of captured logs is linked to the length of the logs. The legend tags in 18b represent the amount of logs reaching the bed.

5. Discussion

5.1 How forest densities and forest clustering effect the debris flow development and bed change

5.1.1 Effects of forest densities on debris flow development and bed change

5.1.1.1 Effects of varying forest densities on flow velocity

In all the forest density set ups the arrival time becomes later when a forest is implemented on the erodible bed when compared to the reference experiments, both in the case with and without logs. When comparing the different density set ups, higher forest densities translate to lower velocities, and most deceleration happens at the end of the flume (*Fig. 10a*). A possible reason for the decrease in the velocity is due to an increase in channel roughness and slope friction, as a result of the trees (Bettella et al., 2018; Booth et al., 2020; He et al., 2023; Moos et al., 2018; Wilford et al., 2005; X. Zhu et al., 2020). Dorren, Maier, et al., (2004) found that in the case of rock falls in the European Alps, rocks could reach relatively large velocities when they moved through a transport channel because of the low channel roughness due to the absence of trees. According to their research a decrease of 50% of the forest density results in a slightly increased hazard potential, and a cover of 0% leads to a more significant increase in the hazard potential posted by the rock fall (Dorren, Maier, et al., 2004). Even though Dorren, Maier, et al., (2004) worked with rock falls and the this research focusses on debris flows, the results are in line with the hypothesis that velocity decreases with a denser forest.

5.1.1.2 Effects of entrained logs on flow velocity in various forest densities

The inclusion of logs does not directly translate to a later arrival time at the last sensor (*Fig. 10a*). When logs are added to the debris flow, a higher density forest does not directly mean a slower debris flow movement. This is clear when the high forest density experiment with logs is compared to its counterpart without logs (see the high density experiments in *Fig. 10a) (red FFT-curves)*, but also when it is compared to other forest density levels (e.g., see medium (orange FFT-curves) and low forest density (blue FFT-curves) in *Fig. 10a),* where a low forest density with logs returns a later arrival time when compared to both the with and without logs experiments of the medium forest density set up.

This outcome is unexpected because the logs were expected to increase the potential for formation of obstructions. This in turn should increase the channel roughness more as compared to the experiments without logs. A possible reason for this discrepancy could be that due to formed obstructions, certain flow paths became more efficient and reached the sensor sooner. Hence, only a part of the debris flow slowed down because of the obstructions while the other part moved on, resulting in a faster debris flow than expected. Another explanation could be that the amount of logs added to the flow is not enough to create large enough obstructions to alter the channel roughness. A last potential reason could be that the entrapment of the gravel particles alters the consistency of the debris flow as it moves downstream since the amount of the fluid phase (water and fine particles) in the debris flow increases relatively to the amount of gravel when it is left behind in obstructions. This could lead to a more fluid-like flow which may flow faster which could lead to the faster velocities. Results from Roelofs et al., (2022) show indeed that when the solid fraction of a debris flow decreases (less gravel and sand added to the debris flows before they were released in the experiments), the flow velocity becomes larger, supporting the last potential reason for the unexpected arrival times. Changes in flow characteristics are also found by Michelini et al., (2017) who studied debris flows in North Italy. They found that due to the deposition of coarse sediment (e.g., boulders) and woody debris, debris flows can become debris floods, which have different flow characteristics due their larger water volume compared to debris flows (Ilinca, 2021). However, Jakob et al.,(2020) state that debris floods are usually slower compared to debris flows, so more research on the effect of altered debris flow composition, in combination with obstruction formation and thus reduced solid fraction, on the arrival and thus velocity is needed.

5.1.1.3 Effects of varying forest densities on bed change, both for debris flows with and without logs

Bed changes related to velocity changes

The found bed change (*Fig. 13a*) shows a similar trend with the arrival times (*Fig. 10a*) in the case of no included logs: less erosion occurs (less negative bed change), and eventually deposition is possible when the forest density increases enough. The lower flow velocity (indicated by less steep FFT-curves and later arrival times at the last sensor) and an increase in deposition with increasing forest density is expected, because a lower velocity results in a lower transport capacity of the flow (Hovius et al., 2000; Kleinhans et al., 2012). When the sediment load in the debris flow exceeds the transport capacity, the excess sediment is consequently deposited (Huang et al., 1999). This is also mentioned by Bigelow et al., (2007), who discuss that the increase of roughness can lead to an increase of deposition of smaller sediments.

The results of the experiments with logs, roughly match with this concept (only the medium forest density with logs does not), that lower flow velocities result in more deposition. This explains why the high forest density with logs experiences less deposition than the high forest density experiment without logs, because the debris flow without logs has a lower flow velocity (arrives later at last sensor), which according to the above explanation leads to more deposition due to the lower transport capacity (*Fig. 10a* (red lines) and *Fig. 13a*).

He et al., (2023) found that for viscous debris flows (flows were the main component is the solid material, like clay and sand, make up 40 to 80% of the flow; as is the case in the debris flows in the experiments for this thesis), smaller spaces in between trees lead to a larger decrease in flow velocity. This is in line with the results for the density experiments, were higher density forest which had smaller spaces in between trees resulted in later arrival times and thus lower velocities.

Bed changes related to obstruction formation

The capture of gravel, and logs when entrained, by trees and the flume sides, is potentially the cause for the decrease in erosion (less negative bed change). This becomes clear when comparing bed change values of the unforested, reference experiment and the low density forest (57.5 trees/m^2) experiment. *Fig. 13a* shows that the implementation of a forest leads to less erosion, indicating that a few trees are already enough to alter the bed change. Furthermore, the loss of the channel (both in the experiment with and without logs), together with the captured gravel and logs, might also be a reason for the decrease in net erosion (less negative bed change) for the overall bed change for the low density forest compared to the reference experiment displayed in *Fig. 12a, 12b and 12e and 12f.*

5.1.2 Effects of forest clustering on debris flow development and bed change

5.1.2.1 Effects of varying forest cluster levels on flow velocity and bed change

The clustering experiments do not really show a trend in flow velocity, either with logs or without logs. The only relatively clear result is that the cases with logs arrive later compared to their counter parts without logs (excluding the first run of the low clustering experiment). The velocity (*Fig. 10b*) does not seem to match with the bed change data found in *Fig. 13b*: a lower velocity (later arrival time) does not always mean more deposition.

When looking at *Fig. 15* it is clear that the forest clustering experiments with logs have more and larger obstructions when compared to the forest clustering experiments without logs. Based on the above description, this increases the roughness more and thus could lead to the lower velocities for the forest clustering experiments with logs. However, this would also imply a lower transport capacity and thus more deposition (as described above), starting a positive feedback loop since the deposition would further increase the roughness and in turn lowering the velocity. However, the velocity in the clustering experiments with logs (with the exception of the first low clustering experiment (*dashed blue line in Fig. 10b*) is relatively similar. So the differences in deposition between the forest clustering experiments are probably caused by the amount of captured logs and gravel, and the forest layout. As mentioned above, it could be that the major part of the debris flow moves slower but that the arrival time at sensor five is determined by the flow in a preferential flow path, which could potentially be visible in the DoD (e.g., in the zig zag pattern downstream in *Fig. 15g* for the medium forest clustering set up). In that situation, the arrival time at the end of the flume does not accurately reflect the velocity of the entire flow, which could explain the results of the bed change data.

5.1.2.2 Effects of forest clusters on debris flows described in other papers

Research by He et al., (2023) seems to match with the clustering experiments. Apart from their research into individual tree spacing they also looked in to tree row spacing. They found that at first, with increasing row spacing the flow velocity reduction also increased, but that a too far row spacing starts to decrease the reduction again. A high clustering forest indicates a lower row spacing inside the clusters but a large gap in the tree rows in between the clusters. This gap in tree rows in between the clusters could perhaps, based on the results form He et al., (2023), be the reason that the high clustering forest (without entrained logs) does not lead to the lowest velocity, while the constant tree spacing in the low forest clustering (without entrained logs) shows a lower velocity (later arrival time in *Fig. 10b)*. Important to note is that He et al., (2023) does use fake vegetation with a canopy. This probably influences flow velocity reduction due to the larger roughness, making a comparison of their data and this research more challenging.

Using field data and aerial photography, Guthrie et al., (2010) showed the influence of a forested area on a shallow debris flow when it moves from a clear area into a forested area in coastal British Colombia. They found that, when the debris flow moves from a clear-cut area into a forested area (relatively similar to the high clustering situation used in the experiments here) the momentum and width of some debris flows decreases (28%) and some debris flows stopped completely (48%). The only cases were the debris flow did not reduce in width were the ones were the debris flow was relatively large before it made contact with the forest. Their results state that a forested area can thus provide a protective measure against shallow landslides due to their constraining influence on debris flow mobility. This matches the results described above where forests lead to later arrival times compared to the un-forested reference experiments. It also matches with results discussed by Booth et al., (2020), who found that a patchwork forest (similar to the clustering in this research and the forested area form Guthrie et al., (2010)) results in a relatively strong local deposit.

5.1.3 Obstructions and flow paths for forest density and forest clustering

Both the forest clustering and forest density experiments showed the potential to create obstructions, due to the capture of gravel and logs, just like real debris flows as shown by e.g., Wilford et al., (2005) (*Fig. 19*). Logs have the potential to form obstructions when trees are spaced further apart. When logs are not included, the spacing of the trees needs to be small enough (directly next to each other or the side) to allow the capture of the gravel, otherwise no obstructions seem to form. This spacing seems to also be important in real debris flow situations (*Fig. 19*). If the trees were further apart the log (*yellow arrow*) and the rock (*red arrow*) would not have become stuck and they would have travelled further downstream. Furthermore, the log would not have been able to capture sediment on its upstream side.

Figure 19 Example of obstruction formation in a real forest. The yellow arrow indicates an obstruction formed due to a captured log with gravel captured upstream of the log. The red arrow shows a captured rock. The rock was transported in the debris flow and according to Wilford et al., (2005) provides an indication of the debris flow depth.
Adaption of figure 11 from Wilford et al., (2005).

In the experiments the number and size of obstructions increased when the forest density and forest clustering level increased. This is in line with the research by Bettella et al., (2018) who found that a forest consisting of coppice sticks (which has a higher density by nature) is more efficient in capturing gravel compared to a high forest (similar to the forest used here). The capturing of gravel and logs is also described by Wilford et al., (2005), who state that trapped logs can form (woody) dykes (see *Fig. 1e* and *Fig. 4b*), similar to the obstructions formed in for example the high forest clustering experiments.

Both the forest clustering experiments and the forest density experiments showed some alteration of the flow path as a result of the formed obstructions. This effect appears to be strongest in the high clustering case where the obstructions redirected the flow towards the other side of the flume almost completely (*Fig. 14a and 14b)*. The large obstructions in the forest clustering experiments formed when the trees were spaced relatively close to each other. The flow did not stop due to the obstruction. This outcome is similar to the blocking of the flow shown in *Fig. 4d*, where the tree trunk prevents the flow on one side of the channel. Possibly the redirection of the flow into a preferential flow path as a result of obstructions (as e.g., the zig zag motion in *Fig 15g*), creates a positive feedback loop in such a way that the redirection of the flow, could lead to a less energetic environment on and around the obstruction. This favours new deposition which in turn further alters the flow path. The redirection of the debris flow motion also occurs in natural settings (Booth et al., 2020; Kattel et al., 2018). Kattel et al., (2018) found that debris flows can experience a change in flow dynamics due to the redirection, deceleration and deflection of the debris flow after it makes contact with obstructions like dams or braking mounds. Booth et al., (2020) state that large (standing) trees can lead to bifurcations of the channel. The fake trees in the research presented here are, by themselves, not large enough to replicate this, however when gravel is captured in between two trees, channels can bifurcate (see for example, *Fig. 15b* around 1500 mm).

5.2 Effects of increasing log entrainment on debris flow development and bed change

5.2.1 Influence of varying entrainment on velocity and bed change

An increase in the number of entrained logs translated, in some extent, to more deceleration and a lower flow velocity. However, there is a lot of internal variation. In the case of 533 logs reaching the erodible bed, the obstructions are largest, the velocity is lowest and most deposition occurs (most positive bed change). This matches with the before mentioned explanation in which obstructions increase the roughness of the channel decreasing the velocity. The found arrival times and their linked velocities match with the found bed change (for the above described transport capacity idea) in all the experiments except in the case were 419 logs reach the bed. This debris flows is relatively fast and still returns a relatively high deposition value compared to the other entrainment experiments which have later arrival times (hence lower velocities) at the last sensor. This deposition might again be the result of preferential flow paths as mentioned above (see sections 5.1.1.2 and 5.1.2.1). The measured arrival time might not be a true representative of the actual flow velocity. However, in the case of 419 logs, no clear paths are found in *Fig. 17e* or in the GoPro video's. The experiment does show a waterfall over the obstruction which might be the preferential flow path used.

The places with very little deposition or erosion directly behind the obstructions and the trees (also for the forest density and forest clustering experiments) could be formed as a result of counteracting forces in the transport capacity. A sudden increase in transport capacity could occur because the material is deposited on the obstruction and then the debris flow sediment load is less, meaning that material behind the obstructions can be picked up. However, the GoPro's show that the flow velocities behind the obstructions are relatively small which may in turn result in a smaller transport capacity (as described by Hovius et al., (2000) and Kleinhans et al., (2012)), which then counteracts the loss of sediment, leading to the relatively small bed changes behind the obstructions.

5.2.2 Influence of varying entrainment on obstruction formation and bed change

With an increase in the number of logs reaching the bed there is an increase in the formation of depositional features (with the exception of the experiment were 202 logs enter the bed), which both grow in width, length and height. It is suspected that, based on the reference experiments, first a small obstruction has to form before the flow path is altered in such a way that it starts to influence the flow conditions around the deposit. This would initiate the before mentioned positive feedback loop in section 5.1.3 where less energetic environments lead to more deposition. The reason for the lack of obstructions formed in the experiment with 202 logs is probably due to the difference in the amount of logs captured on the bed. *Fig. 18a* shows that in the experiment with 202 logs reaching the bed, not many trees were captured in the 202 log experiments and most logs were transported out of the flume compared to the other entrainment experiments, most likely lowering the potential for obstruction formation.

When comparing the bed change data in *Fig. 13c* with *Fig. 18a*, the lower deposition (lower positive bed change) in the experiment with 202 logs reaching the bed corresponds with a lower amount of logs found back in the erodible bed. The other experiments show that a larger amount of captured logs (larger percentage in *Fig. 18a*) leads to more deposition (more positive bed change), which is also expected since this implies that more obstructions can be formed since more logs are captured. However, this explanation does not hold for the experiment were 101 logs reached the erodible bed. Less logs (23 logs in total) were captured for the experiment with 101 logs reaching the bed and still this experiment had a larger deposition compared to the experiment with 202 logs reaching the bed in which 25 logs were captured. The experiment with 202 logs reaching the bed has a relatively high velocity compared to the other entrainment experiments (*Fig. 10c*), which could also be an (additional) explanation for the lower deposition value.

From these experiments it seems that especially the longer logs are able to form obstructions while the smaller logs are not able to form obstructions. A likely explanation is that the longer logs are captured more easily than the smaller logs because they can also be captured when trees are spaced further apart.

Notable is that in the experiments in this research only the amount of logs was altered in the debris flow. However, Koyanagi et al., (2023) found a positive relationship with the sediment yield of debris flow: a larger sediment yield in the debris flow also leads to more logs. Therefore, it might be that some of the results found in this research are not proper representatives of natural situations since the relative amount of logs in the debris flow might not represent a natural situation as the amount of sediment also differs in natural debris flows.

5.3 Potential of forests for hazard reduction

5.3.1 Effectiveness of different forests on debris flow risk reduction

To limit the risk posted by debris flows, it is important to limit their travel length and inundated area. To achieve this, debris flow volume has to be brought down (Bettella et al., 2018; Booth et al., 2020). This can be done by increasing the deposition potential for the debris flow. Based on the experiments executed in this research a high forest density forest, a high forest clustering and a relatively large amount of entrained vegetation should result in more deposition (larger positive bed change) indicating a high volume loss of the debris flow. As a result, the runout and inundation area should decrease and lower the debris flow risk.

This outcome for the high forest density experiments is in line with the ideas for optimizing protection forest presented by Dorren, Berger, et al., (2004). The optimal phase protection forest in their research has the highest forest density, and in the experiments presented here the high forest densities also lead to the most deposition (in the forest density experiments), hence a lower risk. However, Fidej et al., (2015) and Michelini et al., (2017) advocate for a less dense forest to increase protection, with the condition that other measures (e.g., larger tree diameters, and more regeneration places) are implemented. This difference between Dorren, Berger, et al., (2004), Fidej et al., (2015) and Michelini et al., (2017) could be the result of different, site-specific, factors. Michelini et al., (2017) do point out that high forest densities can lead to potential problems because these forests are more susceptible to obstruction formation as also seen in the forest density experiments in this research. The obstructions formed could lead to unwanted channel avulsions (Michelini et al., 2017). In such cases a lower forest density could lead to safer situations because the low forest density experiments show that obstruction formation is less common.

The high clustering experiment are most similar to mosaic like forests as for example described by Dorren, Berger, et al., (2004). They state that a forest with a lower density but a mosaic layout is still capable of functioning as a protective forest. In contrast to the research by Dorren, Berger, et al., (2004), the forest density in the clusters in the experiments here, is relatively high, in the high clustering experiments. This is because the same number of trees is used in the different forest clustering set ups. Based on the combination of the forest density and forest clustering experiments and the statement by Dorren, Berger, et al., (2004), an increase in forest density inside the forest clusters could lead to more protection.

The effects of forest as a barrier is also shown by Guthrie et al., (2010). Their analysis of shallow debris flows show that a forest (on an open slope) hinders debris flow mobility, leading to a decrease in the debris flow volume and runout distance. The effectiveness of the deposition does depend on the amount of gravel and the logs. More logs resulted in more deposition and thus volume loss. Since gravel is the only captured material when logs were not included this also possess an important parameter which needs to be considered when using forests for risk reduction. Michelini et al., (2017) does state that the formation of obstructions (e.g., against bridges) does lead to problems like increased local scouring and less area for the debris flow to move, increasing the hazard posed by the debris flow.

Apart from the placing of the trees, the tree type used for the forest is also an important control in the risk reduction. Bettella et al., (2018) used a coppice forest (multiple small stems from one trunk) and a high-forest (same type of trees as in this experiment). They did not investigate the effect of logs but found that coppice forests are better in capturing gravel and thus form a better protection. This matches with the results in this research that gravel could be captured only when the trees were directly next to each other or next to the sides of the flume.

5.3.2 Forest management problems and debris flow risk reduction

The results described above imply that forest management for forested areas at risk of debris flows should take into account threats like forest fires and deforestation, because a loss of the tree cover will increase the risk posted by debris flows for example because debris flows moving over unforested beds move faster.

In the case of forest fires, vegetation is either damaged or it dies off, depending on the intensity of the fire and the ability of the bark to insulate the tree (Bär et al., 2019). In both cases tree stems are still important since they are often left standing (Lancaster et al., 2003). As a result, they still increase the roughness of debris flow channels and are able to fulfil (some of) their role in decreasing the hazard potential (e.g., lower the velocity) as described above. It is expected that the stems (and branches), due to the weakening of the plant tissue, will become more fragile and as a result they are more likely to break off. The parts that breaks off will probably be transported in the debris flow as entrained vegetation, but the left over tree trunk will perhaps be able to form a flow obstruction e.g., by capturing rocks and logs.

In the case of deforestation, the protective function of the forest is, partly or fully lost. When trunks are left in the channel they can still disperse the flow and lower the velocity because of they increase the channel roughness (Wilford et al., 2005). The same goes for logs and thus the organic material left behind could perhaps still serve a protective function because this left-over woody debris could become entrained in a debris flow, leading to jamming's further downstream increasing the channel roughness and potentially slow down the debris flow motion. Guthrie et al., (2010) also advised to leave some forest in between areas of deforestation to still keep the protective function. Wilford et al., (2005) however advise that forest that interact with events like debris flows should not be harvested at all, because of the ways forest influence the hydro-geomorphic processes, like sediment transport.

5.3.3 Current use of, and problems with protection forest

In the European Alps forests are already used for debris flow risk mitigation. The direct function of these "protection forests" is to protect people and infrastructure against mass movements (Dorren, Berger, et al., 2004). One way these forest work is by directly stabilizing the slopes using the roots, which limits the slope destabilization effects caused by trigger events like high intensity rainfalls. As a result, the risk of a mass movement initiation is decreased or completely eliminated (Preti, 2013).

The second use of protection forest is discussed by Dorren, Maier, et al., (2004), who describe the potential of the use of the above ground biomass (e.g., stems) to influence rock fall events, on slopes in general but also in transport channels, similar to the research for debris flows done here. A problem with this use of protection forest is that the forest cover suffers from the impact of the rocks (or in the case of this research of debris flows) (Dorren, Berger, et al., 2004; Dorren, Maier, et al., 2004). The severity of the impact is related to the forest density. Fewer trees allow for a larger velocities of the rocks moving through the channel, thereby increasing the impact. As a result, younger trees are less likely to survive (are destroyed by the impact) further decreasing the amount of trees, implementing a positive feedback loop (Dorren, Maier, et al., 2004). Proper management is needed to prevent such problems. Management is done by controlling the flow using protective wooden barriers which allow rock falls but in a more controlled matter and by increasing the regeneration rate of the forest (Dorren, Maier, et al., 2004). With proper management, the above described feedback is flipped: a denser forest allows for less movement in the rock falls which in turn allows younger trees to survive providing more protection.

Debris flows, just like rock falls, damage the trees when they make contact (Zanuttigh & Lamberti, 2006). The amount of damaged to trees and to the whole forest due to debris flows depends on the tree diameter. A thicker tree suffers less damage than a thinner tree (Michelini et al., 2017). It is expected that the material stopped by the trees (e.g., the obstructions in this thesis) continues to exert some form of pressure on the trees until deposited material is brought back into motion. Unlike rock falls it is expected that, as debris flows are composed of water and solids, the impact does not end when the large rocks make contact with the tree (as in the case of rock falls) but that due to the flow of the water with fines the debris flow continue to pull on the trees, as also described by Zanchetta et al., (2004). This probably leads to a longer disturbance time on the tree, potentially increasing the deformation of the tree or leads to parts of it breaking of.

As can be seen form the experiments a debris flow motion becomes less fast (later arrival times, *Fig. 10a*) when the forest density increases, just as in the case with rock falls described above. It is therefore expected that impact by debris flows on trees will decrease due to the lower velocities as described above by Dorren, Maier, et al., (2004).

5.3.4 Protection forest recommendations

Based on the found literature it is advised that first an analysis of the area at risk is made to determine whether a high forest density (as in Dorren, Berger, et al., (2004)) or low forest density (as in Fidej et al., 2015 and Michelini et al., 2017) is more appropriate for a protection forest. Based on this research it is advised to at least implement a medium density forest, if not enough site-specific information can be acquired. This is because the medium density forest does lead to more deposition and a lower velocity, and thus a lower risk compared to debris flows without vegetation in the channel but the negative effects from high density forest (e.g., the potential for channel avulsions due to the larger possibility for obstruction formation as mentioned by (Michelini et al., 2017)) are most likely less severe or not present in the medium density forest. If the medium density forest turns out to be an incorrect solution it is “relatively” easy to upgrade or downgrade the forest density to a more appropriate setting because the forest density is not in either of the extremes (low or high forest density). Starting off with a low density forest is not advised because tree diameters need to be large enough to withstand mass movements, and if the forest density is to low the trees are damaged and killed (as described by (Dorren, Maier, et al., 2004)) before they can reach the needed diameter.

For the clustering set ups, it is recommended to implement some regeneration patches in between well grown patches (which can create a protective barrier) to allow natural regeneration of the forest. Furthermore, some form of clustering allows for the capture of material in more clustered areas, increasing deposition and thus lowering the risk due to a loss in debris flow volume (Bettella et al., 2018; Booth et al., 2020). A too high forest clustering is not recommended because the experiments show that high clustering might lead to strong alteration of flow direction due the formation of obstructions, increasing the risk (Michelini et al., 2017). So some form of medium forest clustering seems like a good starting point after which patterns can be adapted to site-specific requirements if they are not known before the forest is planted.

The entrainment of woody debris is also recommended up to a certain degree because the obstructions formed by woody debris increases the capture of solids in the debris flow. This leads to more deposition and thus lowering volume and thus debris flow risk. Too much entrainment however, leads to alteration of the flow direction (e.g., as in the experiments with 533 logs reaching the bed) leading to new flow paths, subsequently altering the risk posed by the debris flow (Michelini et al., 2017).

This research does not focus on tree types but Bettella et al., (2018), show that multiple stems (the coppice forest set up) to allow for more capture of debris flow solids, which lowers the debris flow volume and thus the risk. However, these experiments done by Bettella et al., (2018) were executed on alluvial fans and it is possible that the coppice forest may lead to different outcomes when implemented in the debris flow channel itself. For example, Bettella et al., (2018) used thin wooden sticks to represent the coppice forest. However, these might break when the debris flow hits them in the channel, lowering their use as protection forest in the experiments.

So to summarize, it is necessary to find a balance is met between the amount of trees, the clustering level and the amount of wood allowed to be entrained. Apart from these forest layout factors and the entrainment the type of trees planted are also important as described by Bettella et al., (2018).

5.4 Research limitations

The experiments executed do suffer from uncertainties. One of such becomes clear when looking at the low clustering experiments and at the hydrograph of the entrainment experiments. The two low clustering experiments with logs differ relatively much in their arrival time and their total bed change even though their experimental set ups were equal (*Fig. 10b* and *Fig. 13b*). Similarly, the hydrograph of the entrainment experiment (*Fig.* 8b), shows that both the zero log experiments (solid and dashed blue line) return a different debris flow height even though the experiments were the same since the erodible bed is not reached yet. These two examples show that the experiments are susceptible to experimental variability. Therefore, it is recommended that in the future for all experiments a second run is executed to be able to say more about the variability in the different experimental results. The execution of a second run was initially the intention of this research but could not be done because a new batch of sand had to be ordered, which had a different particle size distribution and had such different outcomes in the measured data that they were not included in this research. Furthermore, the velocity differences (see *Fig. 10b*) and the hydrograph differences (*Fig.* 8b) are relatively small and for stronger quantification and meaningful interpretation of the results, insight is needed in the influence of natural variability on the study results.

A second uncertainty has to do with the water content. The bed change figures (*Fig. 13a, 13b and 13c*), show a relatively large spread in water content in the erodible bed. This could be caused by the evaporation of water from the sand because an equal amount of water was added each time the bed was prepared. This spread in water content has most likely influenced the outcome of the bed change data as shown by Roelofs et al., (2023). They show that for larger water percentages the erosion increases. However, their results indicate that this only becomes relevant for beds with a water content percentage larger than 13 wt%, which is larger than the maximum water content (8.00 wt%) found in the experiments executed here. Notable is that the remaining water content in the bed does not match with the added amount of 11 wt%. Possible reasons for this could be the holes in the bottom of the erodible bed, the packing density difference due to the way the bed was equalized (by hand) and/or evaporation.

A last uncertainty has to do with the splashed up material. In the forested experiments part of the debris flows splashed up when it made contact with the forest. Consequently, part of the debris flow did not make contact with the bed anymore. The splashed material is either deposited at the end of the flume or partly skips over the bed completely (ending up in the trash bag at the end of the flume). Roelofs et al., (2022) found that a larger debris flow volume should result in more erosion. Since some of the debris flow volume is lost due to the splashing it might be that a part of the increase in deposition, or decrease in erosion, is actually caused by the decrease in debris flow volume instead of the influence of the vegetation on the bed. It is most likely that the splashing of the debris flow material when it makes contact with vegetation also happens in a real debris flow events. However, the amount of material and the distance it travels (towards end of flume) is perhaps less likely. A possible reason could be the stiffness of the metal rod used for the vegetation. It is likely that the metal used are too stiff compared to vegetation present in actual debris flow catchments and that the real vegetation would bend somewhat with the flow or even break off. This bending and possible breaking would alter how the flow hits the vegetation probably making the splashing less severe.

In terms of measurement errors, a main one is the correction applied to circumvent missing arrival time data, resulting from sensor malfunctioning, using time-stamp data in the GoPro videos. *Fig. 10* shows that the points corrected for the failing sensors are not in line with the other data obtained through the working laser sensors. Hence, a better way of interpreting these gaps must be found in case of future sensor malfunctioning. It should be noted though that the malfunctioning was not a technical issue: sensor malfunctioning was caused by debris deposition on the sensor. However, since this occurred only at one sensor at the time per experiment, the other sensor data of the experiment are correct and the wrong point can be ignored for the overall picture.

A last improvement point is the amount of entrained logs. This research used 207 logs to start off with and later expanded to the experiments with other numbers of entrained logs. For further research with entrainment it is advised to increase the amount of logs to increase the potential for obstruction formation and to get clearer visuals on the influence on velocity (-development), flow paths, erosion and deposition, and bed profile patterns. The obtained data did not show much difference between the cases with and without entrained logs and also for this reason it would be necessary to repeat runs in order to get insight in the natural variability between experiments.

5.5 Recommendations for further research

Ultimately, a future goal is to expand this research to real vegetation. However, at the moment no useful vegetation species (that do not bend down at impact) are known. However, other processes and forces can be looked into in the meantime, which will help to work towards this goal. Firstly, the arrival time data can be used, in combination with the drag force, to determine the expected obstruction size formed in the channel, which can be compared to the actual obstruction size found based on (for example) the DoD's. This will provide some indication on how efficient the forest is in creating obstructions. Secondly, the metal rods could be replaced by other materials like 3D printed trees. These trees would allow us to study the influence of canopy on the debris flow and processes like drag. Furthermore, a magnet (with or without hinge) could be added to their core which might allow for the study on stem bending and breaking forces. This could then be used to find a strong enough vegetation species for experiments with real vegetation. A last point for future research, (for finding suitable real vegetation) is to determine how much damage the impact of the debris flow does to the vegetation in the channel. As Dorren, Maier, et al., (2004) mentioned, damage to the trees inhibits the regeneration of the vegetation making the forest less useful in hazard mitigation. Determining the damage done and thus the amount of management needed to restore functionality will help to make optimal use of forests as hazard mitigation measurement.

Further investigating the effect of the layout of the forest would also be interesting to look into. In the current experiments the velocity is mainly influenced in the downstream half of the flume. By altering the layout of the flume (e.g., more trees upstream compared to downstream) it might be possible to also start decreasing the flow's velocity more upstream (maybe at the expense of creating more splashing, though). The effects of such forest layouts are discussed for rock falls by Dorren, Berger, et al., (2004), who state that a dense forest downstream but a bare slope uphill still lead to rocks reaching infrastructure in the downstream area. So it would be interesting to see how this type of layout influences the debris flows.

Lastly, it would be interesting to investigate how an increase of the debris flow volume would influence the formed obstructions and, if they occur, how the break-through of such an obstruction would alter the bed change.

6. Conclusions

The aim of this research was to discover the effect of vegetation on debris flow mobility, how this influences the bed change and to discuss what this means for the hazard potential created by the debris flow. To examine this, laboratory flume experiments with various forest density covers, clustering set ups and a varying amount of entrained vegetation were done using the debris flow flume at Utrecht University.

In all experiments it is clear that when a forest is planted on the erodible bed the velocity, and acceleration decreases, and that the bed change shows less erosion or even deposition when compared to the experiments without a forest implemented on the erodible bed. When looking at the different forest set ups (forest density and forest clustering) trends became less clear and only the forest density experiments without entrained vegetation in the debris flow returned a clear delay in arrival time at the end of the bed when the forest density increased. The inclusion of logs in the debris flow, in the forest density and forest clustering experiments, does not necessarily lead to a lower velocity and a lower acceleration, even though this was expected because of the increase in amount and size of obstructions in the channel. The inclusion of logs seems to result in more deposition compared to the experiments without entrained logs

The forest influences the morphology of the bed profile, due to the formation of obstructions and potential preferential flow paths. The amount and size of obstructions seems to increase with an increase in the forest density and with a stronger forest clustering. For the formation of these obstructions it is however important that the trees on the bed are not spaced to far from each other, since this allows for the best capturing of gravel and logs.

Increasing the amount of entrained logs in the debris flow does not directly translate into a larger deceleration of the flow and a lower flow velocity. An increase in the entrainment does appear to lead to a larger potential for the formation of obstructions which can alter the flow path and the bed profile subsequently. The increase in the total amount of logs in the debris flow roughly translates into an increase in deposition. However, the deposition also seems to depend on the amount of logs that actually become captured in the forest.

So concluding, a forest cover in the debris flow channel stimulates a lower velocity and more deposition on the erodible bed and deposition seems to increase even more when logs are entrained in the debris flow. As a result, the volume of the debris flow will decrease during its voyage through the flow channel and this will eventually lead to a smaller runout, thus decreasing the hazard potential of the debris flow. However, literature does state that proper forest management is needed to keep the forest useful as a mitigation measure.

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Statement of Originality

<u>I declare that:</u>

1. This is an original report and is entirely my own work
2. Where I have made use of the ideas of other writers, I have acknowledged the source in every instance
3. Where I have used any diagram or visuals I have acknowledged the source in every instance
4. This report has not and will not be submitted elsewhere for academic assessment in any other academic course.

Student data:

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Appendix A. Forest layouts

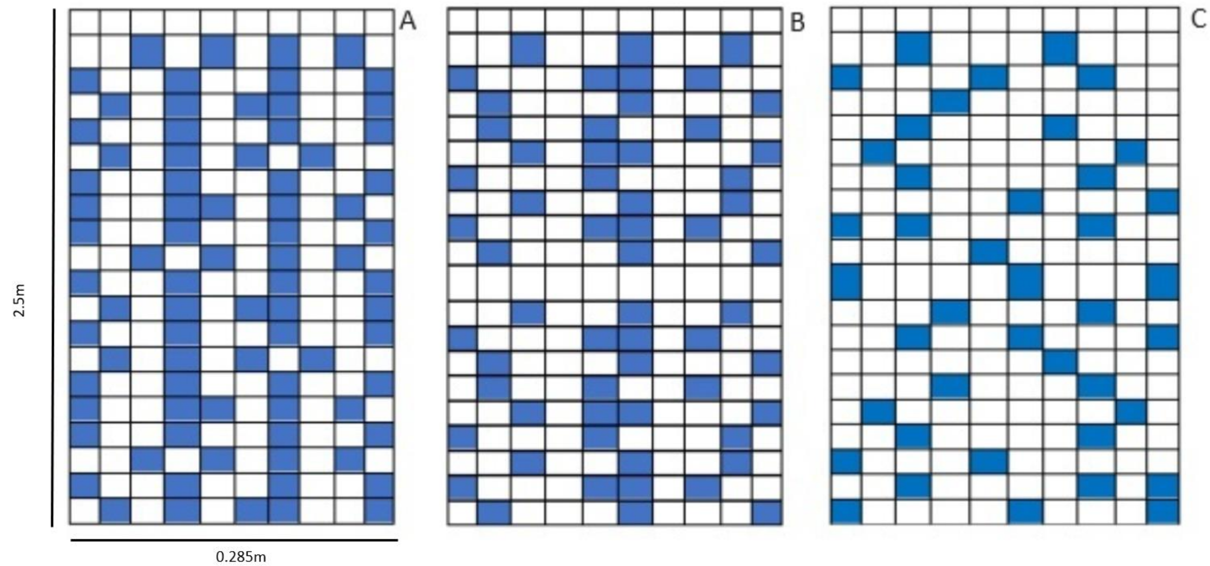

Figure A. 1 Forest density set up of the erodible bed. The blue boxes are representing the location of the "trees" (metal rods). (A) is the high forest density set up, (B) the medium forest density and (C) the low forest density set up. The top of the figure corresponds to the upstream boundary. The first row is kept empty to prevent direct clogging of the flume and preventing the debris flow from entering the bed.

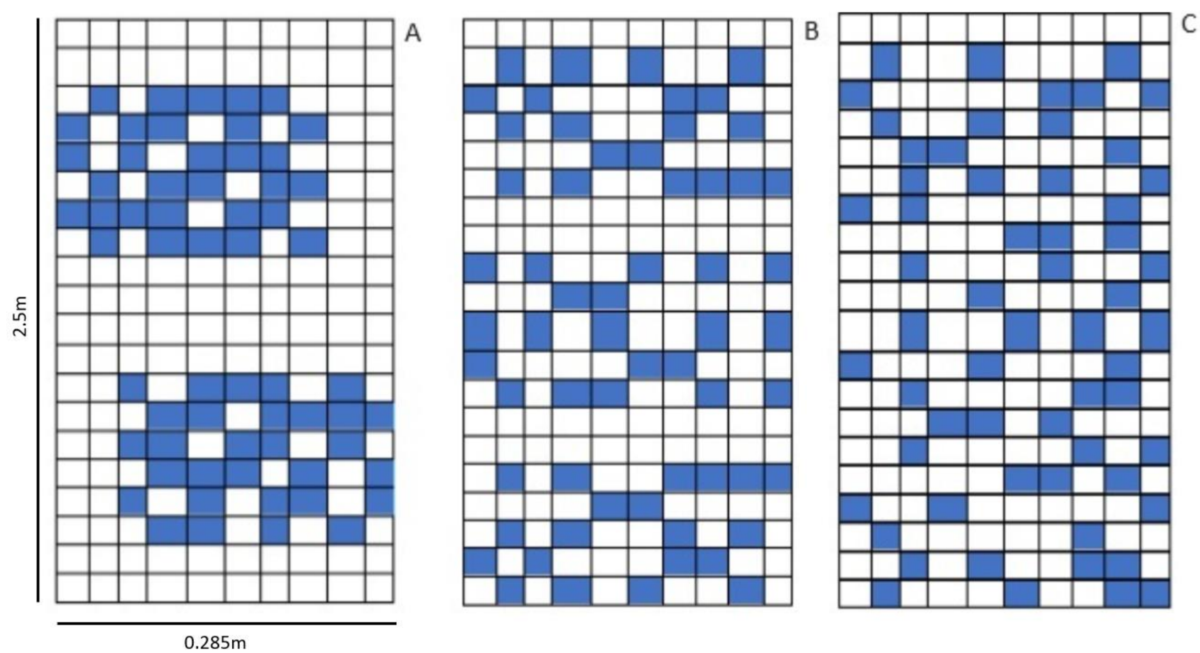

Figure A. 2 Forest clustering set up of erodible bed. The blue boxes are representing the location of the "trees (metal rods). (A) is the high forest clustering set up, (B) the medium forest clustering and (C) the low forest clustering set up. The top of the figure corresponds to the upstream boundary. The first row is kept empty to prevent direct clogging of the flume and preventing the debris flow from entering the bed.

Appendix B. Experiment log

	Boundary conditions							Bed conditions						Bed wetness measurements (mV) 2cm device					Particularities/Remarks
	Channel slope (°)	Gravel (kg)	Sand (kg)	Clay (kg)	Water (kg)	Total mass (kg)	Total volume (m3)	total weight (kg)	Gravel (kg)	Sand (kg)	Clay (kg)	Water (kg)	Clay fraction (wt%)	1 (Wing-side)	2 (middle)	3 (Straight-side)	Average	bet wetness (%) based on calibration curve	

Reference experiments																		
without sticks	30	9.60	36.00	2.40	12.00	60	0.0301	62485	0.00	55166.94	1125.86	6192.21	2.00	119.3333	118.25	148	128.5278	7.53
With logs in the debris flow	30	9.60	36.00	2.40	12.00	60	0.0301	61011.00	0.00	53865.57	1099.30	6046.14	2.00	88	94.66667	103.6667	95.44444	6.03

Forest density experiments																			
High density																			
without sticks	30	9.60	36.00	2.40	12.00	60	0.0301	67959.00		59999.84	1224.49	6734.68	2	86	107.3333	100.3333	97.88889	6.15	
With logs in the debris flow	30	9.60	36.00	2.40	12.00	60	0.0301	67281.00	0.00	59401.24	1212.27	6667.49	2	90.66667	89.66667	98.75	93.0277778	5.92	
Medium density																			
without sticks	30	9.60	36.00	2.40	12.00	60	0.0301		0.00	0.00	0.00	0.00	2	101.333333	93.25	94.5	96.3611111	6.08	
With logs in the debris flow	30	9.60	36.00	2.40	12.00	60	0.0301	66826	0.00	58999.53	1204.07	6622.40	2	108	120.6667	109.6667	112.777778	6.82	
Low density																			
without sticks	30	9.60	36.00	2.40	12.00	60	0.0301	66342.00	0.00	58572.22	1195.35	6574.43	2	118	108.6667	91.8	106.155556	6.52	Bit of water leaked form the mixing tank. May influence the depth of the scour and thus erosion calculations
With logs in the debris flow	30	9.60	36.00	2.40	12.00	60	0.0301	67962.00		60002.49	1224.54	6734.97	2	101	89	122.3333	104.111111	6.43	

Figure B. 1 Screenshots of the experiment logbook showing the boundary conditions (flume angle, and debris flow composition), the bed conditions, the bed wetness and specific remarks on the experiment if they occurred) for the reference (upper table) and forest density (lower table) experiments. The next page shows the experiments logbooks for the forest clustering (upper table) and vegetation entrainment experiments (lower table).

	Boundary conditions							Bed conditions						Bed wetness measurements (mV) 2cm device					Particularities/Remarks
	Channel slope (°)	Gravel (kg)	Sand (kg)	Clay (kg)	Water (kg)	Total mass (kg)	Total volume (m3)	total weight (kg)	Gravel (kg)	Sand (kg)	Clay (kg)	Water (kg)	Clay fraction (wt%)	1 (Wing-side)	2 (middle)	3 (Straight-side)	Average	bet wetness (%) based on calibration curve	
Forest clustering experiments																			
High clustering																			
without sticks	30	9.60	36.00	2.40	12.00	60	0.0301	66260	0.00	58499.82	1193.87	6566.31	2	115	116.6667	128.6667	120.111111	7.16	
With logs in the debris flow	30	9.60	36.00	2.40	12.00	60	0.0301	67181.00	0.00	59312.95	1210.47	6657.58	2	123	115.3333	130.3333	122.888889	7.28	
Medium clustering																			
without sticks	30	9.60	36.00	2.40	12.00	60	0.0301	64561.00	0.00	56999.80	1163.26	6397.94	2	126	122	128.3333	125.444444	7.4	Scan before was taken at an angle since flume was not lowered completelly
With logs in the debris flow	30	9.60	36.00	2.40	12.00	60	0.0301		0.00	0.00	0.00	0.00	2	111.6667	107.6667	132.3333	117.222222	7.03	
Low clustering																			
without sticks	30	9.60	36.00	2.40	12.00	60	0.0301	63429.00	0.00	56000.38	1142.86	6285.76	2	141	125.67	142	136.2222	7.89	
without sticks (v2)	30	9.60	36.00	2.40	12.00	60	0.0301	62659.00	0.00	55320.56	1128.99	6209.45	2	NaN	NaN	NaN	NaN	NaN	No moisture meters
With logs in the debris flow	30	9.60	36.00	2.40	12.00	60	0.0301	64654.00	0.00	57081.91	1164.94	6407.15	2	136	137	137	136.6667	7.91	Obstructed lasers at end by phone (last 10 seconds of measurement)
With logs in the debris flow (v2)	30	9.60	36.00	2.40	12.00	60	0.0301	63472.00	0.00	56038.34	1143.64	6290.02	2	138	149.6667	113.25	133.6389	7.77	
Entrainment experiments																			
642 logs	30	9.60	36.00	2.40	12.00	60	0.0301		NaN	NaN	NaN	NaN	2	128.6667	112.6667	112	117.7778	7.05	sand from ripped bag which is probably wetter because it had less time to dry
435 logs	30	9.60	36.00	2.40	12.00	60	0.0301		NaN	NaN	NaN	NaN	2	111	106	108.6667	108.5556	6.63	sand from ripped bag which is probably wetter because it had less time to dry
311 logs	30	9.60	36.00	2.40	12.00	60	0.0301		NaN	NaN	NaN	NaN	2	79.66667	95.33333	99	91.33333	5.85	sand from ripped bag which is probably wetter because it had less time to dry
104 logs	30	9.60	36.00	2.40	12.00	60	0.0301		NaN	NaN	NaN	NaN	2	95.33333	88	100	94.44444	5.99	sand from ripped bag which is probably wetter because it had less time to dry