We would like to thank Referee #1 for this thorough review. You will find in this comment the complete reply with our answers in italic type. I am also attaching a pdf of the same answers, this time in blue, if it makes it easier to read.

The authors present a preliminary study on the routing of a viscous solid-liquid flow including boulders at the purpose of simulating the observed debris flows in the field. The study is interesting but unfortunately is not yet ready for publication. Main deficiencies are:

- The title should reflect the content of the paper: viscous debris flows or debris flow in viscous regime rather than debris flows.

Thank you for pointing this out, it will be added to the revised manuscript.

- At subsection 2.5 it is introduced a collision algorithm. Authors should provide some explanation about its role. In other words, it is missing some sentence where it is stated that SPH code models the viscous flow and the collision algorithm models ……..? Moreover, another observation is raised about the term collision because another debris-flow rheology is the collision one (Bagnold, 1954, Takahashi, 2014).

The collision algorithm is modelling the collisions of the boulders explicitly for section 3.2 and 3.3, but is not used in section 3.1. There are no macroscopic computations representing collision through rheology. This will be clarified in the updated document.

- Therefore, some other explanation for explaining the difference from a collisional-rheology dominated debris flows are required.

The debris flows of interest of this paper fall under the viscous debris flow category, as determined in Takahashi (2014), where the main driving stress in the viscous one. This will be explicitly written both in text in the introduction and the abstract.

- About velocity profiles, it seems missing the plug, typical of cohesive rheology. Some explanation about that, it is required.

Since we have made the assumption to use a Newtonian fluid as a first stepping stone of a more complete model, we know we are lacking the precision of the plug flow description in the pure fluid models. The investigation presented here knowingly simplifies the interstitial fluid in order to investigate the feasibility of such a numerical method to represent the complexity of a debris flow. We completely agree that using a non-Newtonian rheology would yield more accurate results in terms of velocity profile, specifically when looking at pure fluid simulations of section 3.1. We think however, that the absence of a true plug in the pure fluid models is not detrimental to the accuracy of the macroscopic behaviour of the flow, although we do acknowledge that the boulder mobility is reliant on the velocity profile. We will mention this inaccuracy in the discussion section 4.3 by adding the following paragraph :

"The lack of representation of cohesive rheology via a non-Newtonian constitutive model in the SPH resolution leads to an underestimation of the plug. In Figure 7c-f, the effect of boulders on the velocity profile can be seen, with flows with a higher boulder concentration (7c-e) having a larger section with an almost constant velocity. This effectively leads to a

pseudo-plug that is driven by the presence of granular matter. However, the viscous matrix should also drive a plug zone. This plug influences the shear profile in the flow and affects the relative motion of the boulders in the flowing material, impacting both boulder mobility and spatial distribution.This assumption, combined with the 2D assumption, are acknowledged as intrinsic limitations of the model. Nonetheless, the objective of this paper is to capture macroscopic features comparable to those observed in the field for which the model remains satisfactory. "

In general, some specification and explanations are missing (see the comments below)

Some other comments as follows

Line 8 "Surges are composed of a viscous Newtonian fluid and poly-disperse boulders" This is not true at all: surges can be partially saturated and therefore dominated by friction or turbulent (Simoni et al., 2020). Authors should specify that the want to simulate a debris flow dominated by a viscous rheology. In a such a case they should introduce the dominant rheology of debris flows (see the mechanical-based classification for debris flows of Takahshi, 2014)

We agree that we need to clarify that we are modelling debris flow which have characteristics common among european alpine streams. Both in text and in the abstract, we will add this information. In the introduction we will add "Debris flows considered in this paper fall under the viscous debris flow category (Takahashi 2014), common in the French Alps."

Lines 11-14 "Debris flows are rapid flows saturated with non-plastic debris in a steep channel (Hungr, 2005). These fast flows yield suddenly, behaving as so-called surges, creating a granular front which has the potential to be very destructive. Debris flows evolve naturally in steep, erosion-prone catchments under intense rain as well as ice and snow melts (Recking et al., 2013)…"

The authors state that debris flows create a front without specifying anything else. After that, they mean that rain snowmelt and …. trigger debris flows. The writer suggests to specify at the beginning the cause of debris flows, in order of quantity, abundant runoff (Bernard et al., 2025); landslide (Iverson et al., 1997), snow melt and ice (Recking, 2013). After that it could added, that, after the formation of a front, it routes downstream volumetrically growing due to the entrainment of large quantity of debris material (Reid et al., 2016; Simoni et al., 2020). Finally, it is worth to specify which type of debris flow is dominated by viscous rheology (landslide-induced debris flow for sure).

Thank you for this comment. We will add the following precisions :

"Debris flows are rapid flows saturated with non-plastic debris in a steep channel (Hungr, 2005). These fast flows yield suddenly, behaving as so-called surges, creating a granular front which has the potential to be very destructive, followed by a viscous matrix engulfing granular material. Debris flows evolve naturally in steep, erosion-prone catchments and can be triggered by abundant runoff (Bernard et al., 2025), landslides (Iverson 1997; Recking, Richard, and Degoutte 2013)*, or snow and ice melt* (Recking, Richard, and Degoutte 2013)*.*

Once initiated, the flow propagates downstream, often recruiting material from the channel through entrainment (Simoni et al. 2020)*,* (Reid, Coe, and Brien 2016)*). In the European Alps, the material transported by the flow usually comes from the naturally occurring weathering processes of mountain hill-slopes, either constant or due to glaciation/ deglaciation phases* (Recking, Richard, and Degoutte 2013)*. This leads to the presence of viscous dominated debris flow, with high clay content in the interstitial fluid and granular materials of a wide verity of sizes, from sand to boulders* (Coussot et al. 1998)*."*

Line 34 "However, because the models….." it should be specified these models, or the models above.

OK, thank you, done.

Lines 40-42 "However, depth-averaged models are only adapted to large scale representation of the flow. When dealing with the mechanical changes inside the debris flow material during the flow, they become limited as they are not designed to represent the material in depth. In addition, the large boulders that are transported by debris flows cannot be described in such models. Surge-scale-or small-scale- models aim at representing the physics of debris flow dynamics at a mesoscopic scale to better understand internal motion of the material and its interaction with infrastructures" This period is ill-posed. The depth-averaged models are 2D models and, therefore, they are approximated because they neglect the vertical exchange of momentum. For these reasons they cannot accurately simulate the transport of large boulders, the surge routing or the interaction with obstacles and structures.

We are not completely certain we understand your comment, we offer this alternative text, which explains more explicitly the limits of the 2D assumption we wanted to stress in the context of depth average modelling:

"However, depth-averaged models, by nature, are only adapted to large scale representation of the flow. As they represent the flow in 2D, they intrinsically neglect the momentum changes in depth, and thus, when dealing with the mechanical changes inside the debris flow material during the flow, they become limited. Consequently to their 2D nature, the large boulders that are transported by debris flows cannot be explicitly described in such models.

Conversely, surge-scale-or models with smaller spatial domains aim at representing the physics of debris flow dynamics at a mesoscopic and microscopic scale to better understand internal motion of the material and its interaction with infrastructures."

We hope this formulation is clearer and that is in line with the review vision that we share.

Line 130 "Finally, we present the initial results to model a surge scale 2D debris-flow, investigating three different solid concentrations and their influence on the macroscopic behaviour of the surge" This sentence, it seems to contradict what written at lines 40-45 and 97-100.

Here, the 2D dimension refers as 2D in width, i.e. we do not take into account movements that are neither longitudinal or in the depth of the flow. Here we use 'initial" to mean the first model with this method. The sentence will be changed to "Finally, we present exploratory validated results to model a surge scale 2D debris-flow with an SPH based hybrid model, investigating three different solid concentrations and their influence on the macroscopic behaviour of the surge"

Line 420 insert the reference Johnson et al. (2012)

OK, thank you, done.

Subsection 3.3.2 Authors should explain what they are modeling. The writer does not understand what panels 7c-f represent. The reproduction of a surge routing toward the right on an horizontal plane? The vertical black bar on the left what is it (the wall upstream of the channel)? What does it mean the white arrow? (the conveyor belt?).

Figure 7c-f represents the experiments described in section 3.3.1 and Table 3. We understand the title and graphical representation in the figure make it hard to relate to the description. We will add a tilted gravity vector to show the tilted experiment better.The title of Figure 7 will be changed to :

2D debris flow model : Boxplot of a) the Froude numbers and b) the ratio of equivalent viscosity over fluid viscosity : whiskers represent the upper and lower quartiles, orange bar represents the mean value, gray vertical line on b) highlights $\mu/\mu_0=1$. Velocity fields and general view of the different simulations for c) $\phi=0.53$ d) $\phi = 0.29$, e) $\phi=0.13$ and f) $\phi = 0$. The white arrow represents the movement of the conveyor belt. Views have been tilted back to the horizontal plane in order to ease the reading of the comparison : the tilted gravity vector is shown.}

Line 451-452 "The accuracy of the results at different points in the flow are promising in terms of possible applications, especially close to the toe of the front." The writer does not agree: in figure 7c-f there is not any front composed of boulders.

This does not refer to the results of Figure 7 but of the results of section 3.1 named the same way. We will try to clarify by a short sentence which discussion section refers to which results section. We are sorry for the misunderstanding.

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Bernard, M., Barbini, M., Berti, M., Simoni, A., Boreggio, M., Gregoretti, C. (2025) Rainfall-runoff modelling in rocky headwater catchments for the prediction of debris flow occurrence. Water Resources Research Water Resources Research, 61(1), doi: 10.1029/2023WR036887

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Simoni A., Bernard, M., Berti M., Boreggio M., Lanzoni S., Stancanelli L., Gregoretti C (2020) Runoff-generated debris flows: observation of initiation conditions and erosion-deposition dynamics along the channel at Cancia (eastern Italian Alps). Earth Surface Processes and Landforms - 45, 3556 – 3571 doi:10.1002/esp.4981

Added references

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