SIMULATING SNOW PROCESS CHAINS: AVALANCHE-RIVER INTERACTIONS WITH R.AVAFLOW

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ABSTRACT: r.avaflow is an open source tool for the simulation of gravitational mass flows and related complex process chains. Simulations can be performed using a classical single phase or a general two phase mixture flow model. The applicability of the tool has been evaluated with several back calculations of different natural hazard events. In this work we focus on snow avalanches. We first back calculated the 2009 Costa della Madonna snow avalanche event (north-east Italy) with the single phase model. With multiple simulations we optimized the material parameters that successfully minimized the difference between simulated and observed runout distances. Going beyond classical avalanche simulations, a complex process chain has been reconstructed, using the two phase model with entrainment applied in r.avaflow. The test case referred to the Damalanche that took place in January 2014 in Alaska, near the city of Valdez, and involved multiple avalanches, river flow and their interactions. The impacted river was completely dammed by a series of wet avalanches that entrained debris along their travel paths. A first simulation representing the steady state of the river was obtained whereas three successively released avalanches were discharged in the final simulation. We were able to reconstruct the cascade of effects including the different processes and could reconstruct similar affected areas as observed. Challenges included density differences of the involved materials or the initial conditions. In total, the single and multiphase test cases were well represented by r.avaflow, underlining its applicability to real complex events.

KEYWORDS: process chains, Damalanche, snow river interaction, avalanche simulation, open source, r.avaflow.

1. INTRODUCTION

r.avaflow is an open source tool designed to simulate the propagation of natural gravitational events over a defined basal topography (Mergili et al., 2017). Effectively the tool is a GRASS (Neteler and Mitasova, 2007) raster module and it is completely open source and freely available (www.avaflow.org). r.avaflow includes two different models for mass flow simulations: a single-phase shallow water model with Voellmy friction relation (Christen et al., 2010 and Fischer et al., 2012) and the Pudasaini (2012) two-phase model with ambient drag. Together with these two kind of models, six optional complementary functions are implemented in r.avaflow: conversion of release heights into release depths, diffusion control, conservation of volume, surface control, entrainment (based on a user defined erosion coefficient) and stopping.

To run a simulation in r.avaflow, essentially three inputs are required: the DEM (representing the pre-event conditions), the solid and fluid release heights or/and hydrographs and a set of values representing the flow parameters.

Once the simulation is completed, it is possible to run the validation and visualization functions. They are implemented in the R programming language and the visualization produces for every time step an image of the solid and fluid flow height, pressure, kinetic energy and change in basal topography due to entrainment and stopping of the flow. Indeed, the validation module relies on the availability of a raster map representing the impact or the deposition area of the observed event and on a user-defined line along the main flow path. The latter is useful to compare the difference in the runout distance of the observed and simulated flow in order to calculate the excess travel distance and the related ratio.

The main objective of this study is to further test the applicability of r.avaflow on avalanches and related process chain events (Mergili et al., 2018). For this purpose, two different snow avalanche events were chosen: the Costa della Madonna and the Damalanche event.

The first one occurred in the north east of Italy, within the province of Belluno, on the 23rd January of 2009. It consisted an avalanche triggered by the weight of the snow compacted by the wind and the rise in temperatures. The upper part of the site is represented by a regular open side with a mean slope of 35°, while downward the slope divides in two main channels; however only one was impacted by the event.

Technicians from the avalanche Veneto region agency surveyed the site the day after the event. The type of snow detected was classified as wet snow, with an estimated density of 300 kg/m^3. The type of avalanche is described as wet snow avalanche, with a sliding surface on the ground, confined in a channel. The impacted area was estimated by 100,000 m^2 with a travel distance of 1700 m and a vertical drop of 880 m (between 1910 and 1030 m a.s.l.). The total snow height at that date was 2.5 m, while the height of the disconnected layer was measured as approximately 2 m.

The second investigated, process chain event is the Damalanche, which occurred in Alaska, 25 km east from the city of Valdez. The event was given this name for the series of wet avalanches that stopped the flow of the Lowe river and led to the inundation of the upstream area (Carter and Carter 2014). The Lowe river comes from a 300 - 400 m wide valley and successively it flows through the Keyston canyon (30 – 40 m wide); just at the entrance of the canyon the series of avalanches blocked the river.

The Damalanche was not a single event but the accumulation of many avalanches between January 14th and 30th, both natural and triggered by artillery. The entire deposit of multiple avalanches in the river valley was estimated to be 600 m long, 150 m wide and 23 m deep; the total volume accumulated in the dam consisted in 2,070,000 m^3 of snow mixed with debris at an estimated density of 500 kg/m^3. At its maximum, the lake behind the dam inundated an area of 560,000 m^2.

2. MATERIALS AND METHODS

2.1 Costa della Madonna

Regarding the Costa della Madonna avalanche the simulation set up includes the identification of the boundary of the released snow mass. The upper border is defined with a map of the impacted area obtained by the avalanche control office of the Veneto Region (ARPAV), while the thickness of the mass was fixed to 2 meters as reported in the post event avalanche documentation. The lower border is defined through terrain morphology analysis using different layers (ortophoto, hillshade, slope, and curvature maps).

The single-phase model with entrainment was used for this event; the set of flow parameters are 7 in total and 2 of them were optimized (basal friction angle and turbulent friction coefficient). To optimize these values the multiple model runs function of r.avaflow was used. This function allows the user to fix the extreme values of a given flow parameter and then single simulations are launched one after the other. At every simulation, the parameter value is progressively increased until the given range is completed. To evaluate the accuracy of every single simulations, and consequently to optimize the set of flow parameters, the excess travel distance ratio (ETDR) is used, automatically computed at the end of every single simulation as function of the validation procedure (Mergili et al., 2017):

$$ETDR = \frac{length\ simulated\ impact\ area - length\ observed\ impact\ area}{length\ observed\ impact\ area}$$

2.2 Damalanche

To simulate this event, it was necessary to reconstruct the pre-event conditions, to identify the released areas representing the avalanches and to set up the final simulation.

Firstly, it was necessary to fill the path of the Lowe river with water for the interested area. To obtain this result, a r.avaflow simulation was run, giving as input a constant hydrograph with a discharge value of 60 m^3/s. The historical daily mean discharge data (USGS, Water Resources Department) was analyzed for the “Horsetail Falls” station obtaining a mean value of 4.1 m^3/s for the month of January (calculation period: 2013-10-01 -> 2017-09-30). However, this value is not acceptable for the analyzed period because rainfall was very intense and moreover it was associated with an unusually low snow limit that reached an altitude of 800 - 1000 m a.s.l. (Carter and Carter 2014), and so the discharge value was fixed to 60 m^3/s.

Furthermore, before launching the simulation to fill the river, the DEM was modified to represent the river bed. At a spatial resolution of 10 m the path was not present on the DEM and also some artifacts were observed in the canyon. Then, first the artificial peaks were manually corrected producing a gentle slope through the keystone canyon. Second, to reproduce the U cross section of the river path a series of 4 buffers were generated one after the other and every time the DEM values are decreased by 1 m inside the buffer zone. The buffers have values respectively of 50, 40, 30, 20 m starting from the major stream line computed with the grass algorithm r.watershed. So, a simulation with the river-hydrograph was performed until the steady state of the river was reached. The final water map was used as input to represent the initial conditions of the Damalanche event.

Then, three release areas were identified from the hillshade and the slope maps. They cover an area of 460,000 m^2 for a total volume of 1,386,609 m^3; the height of the disconnected layer was fixed to 3 m in order to obtain the same amount of deposit for the series of observed avalanches.

In the end, a final simulation of the damalanche event was performed with all input data. At the same time, a constant input hydrograph was released for the whole time of the simulation always representing a discharge of 60 m^3/s. The model simulated the event for 10,000 s (2.7 hours); in this way it was possible to capture the effect of the snow dam on the river and, consequently the generation of the upstream lake.

3. RESULTS

3.1 Costa della Madonna

In total, 143 simulations were performed. The excess travel distance ratio of every single simulation is summarized in Figure 1. Every pixel of the figure represents the validation value (ETDR) of a single simulation. Red squares show simulations in which the simulated travel distance is less than the measured one (non-conservative), in blue the contrary (conservative), while in green when they match.

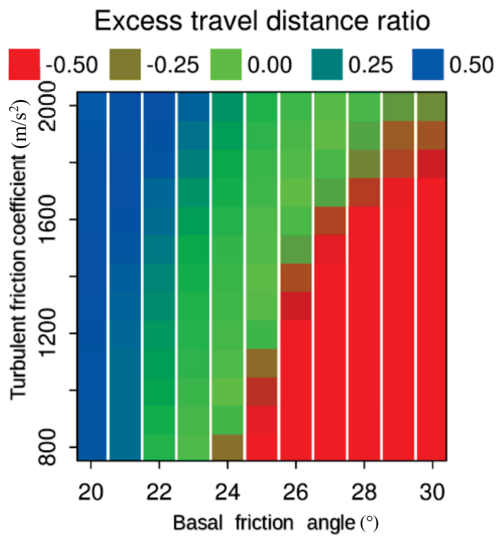

Figure 1: ETDR derived with the various models runs for the Costa della Madonna avalanche.

The chosen values used for the final simulation of the Costa della Madonna event are 26° for the basal friction angle and 1700 m/s for the turbulent friction coefficient. The validation algorithm calculated an excess of travel distance equal to 0 m; the deposition snow mass was approx. 42,000 m^3 at a maximum in which approx. 180 m^3 were entrained along the avalanche path. The simulated deposition is shown in Figure 2; the maximum snow depth in the deposition area is simulated in 2.70 m. Although it is known that additional optimization variables could allow for a more detailed parameter estimation (Fischer et al., 2015), no such measurements were available and therefore could not be utilized.

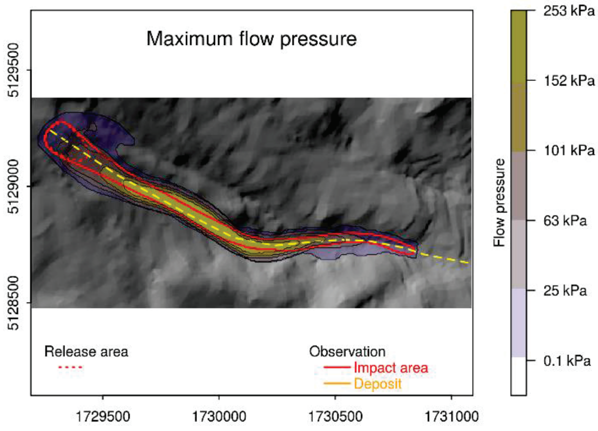

Figure 2: Map representing the maximum flow pressure. for the Costa della Madonna avalanche.

3.2 Damalanche

Once all the inputs were set up, the final simulation including the release of the solid (snow avalanches) and fluid (water) material and the input hydrograph (river) was launched for a duration of 10,000 s (2,7 hours).

surface of 194,000 m^2. Figure 3 shows the comparison between the simulated and the observed area regarding the snow dam and the flooded valley*.

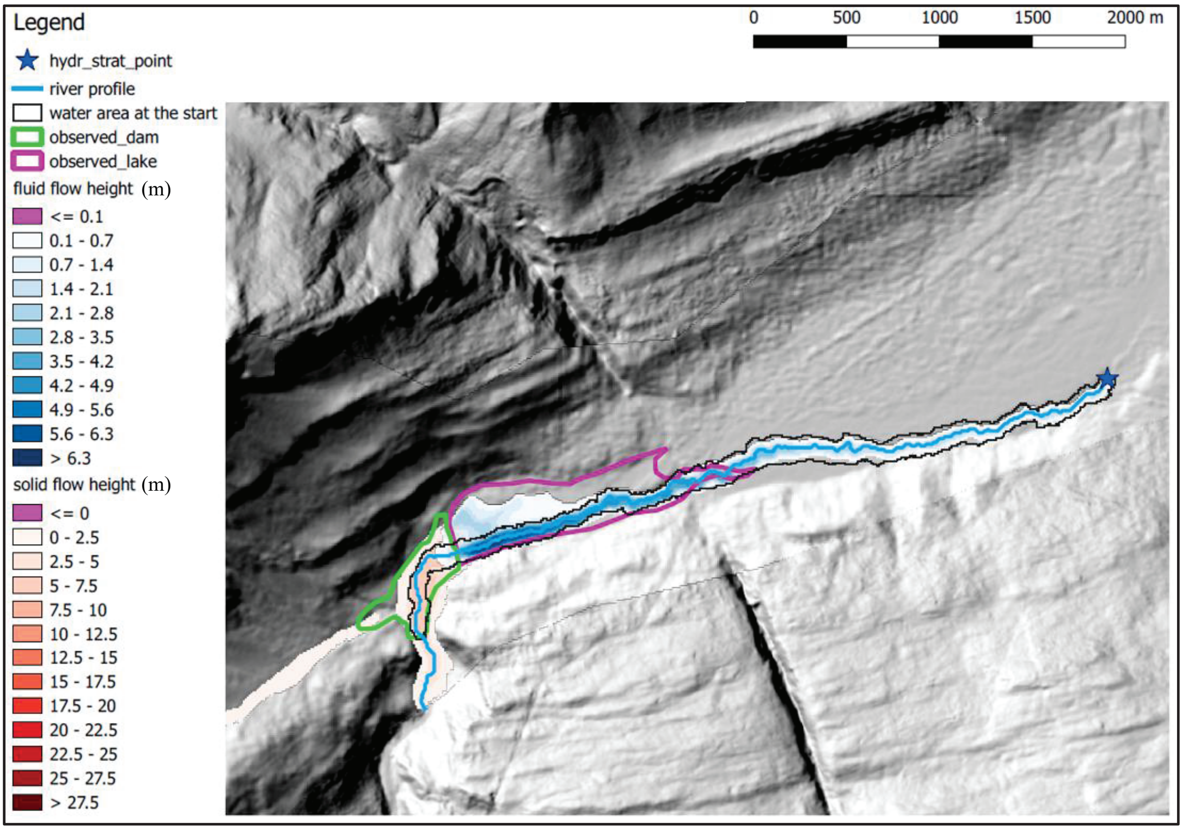

Figure 3: Fluid and solid flow height at the last time step of the simulation and comparison with the observed dam and lake.

Regarding the mass a total volume of snow equal to 1.4 million m^3 was released from three different areas. Furthermore, the complementary function for entrainment was activated and at the end of the simulation the mobilized volume consisted in 2.2 million m^3, in which 0.8 million m^3 were entrained. The total simulated snow volume that reached the main valley clogging the river consisted of 0.6 million m^3 with a maximum height at the last time step of 8 m. The snow mass completely stopped the flow of the Lowe river and no water is detected flowing through the Keystone canyon. In the end of the Damalanche simulation the inundated area has a

4. DISCUSSION AND CONCLUSIONS

The two case, studied and analyzed, were well simulated and represented by r.avaflow. Regarding the Costa della Madonna event, the multiple simulation runs were used to optimize the two main flow parameters of the single-phase model. This allows a quick calibration of the flow parameters thanks to the validation process that is performed at the end of each simulation. The single phase model is easier to apply due to the smaller amount of flow parameters to determine. However, comparing the observed and the simulated deposit, we notice a much smaller height of the simulated snow mass, with a maximum value of 2.7 m, against the 4.5 m

** Additional animations and simulation results are available at: https://drive.google.com/open?id=19dG071UvP5lGriJ3dGfzw_PkPBX3So6Z* of the observed deposit, and a higher degree of lateral spreading.

To simulate the Damalanche event we used the two phase model, allowing to simulate the interaction of two different types of masses as water and snow. The Pudasaini (2012) model was previously implemented to simulate debris flows and so the calibration process was challenging, especially because it was required to adapt the model parameters for snow. One of the concerns of the model implementation is related to the material densities. Introducing a solid (in the present case snow) with lower density than the fluid (water), may lead to numerical instabilities. Therefore, for simplicity, we assume snow density larger than the fluid density (1500 kg/m^3 for snow and 1000 kg/m^3 for the fluid component). With this assumption the initial snow volume remains the same, but the snow mass is largely over estimated. To circumvent this ad hoc approach, we would require to properly treat the buoyancy reduced normal load of the particles that effects, e.g., the drag, and Coulomb friction. Nevertheless, the main objective of the simulation is to reproduce the observed snow dam and the inundation of the valley. The simulated snow dam completely stopped the flow of the river; no fluid discharge is detected at the end of the Canyon meaning that the solid mass is completely impermeable. However, the height of the simulated snow dam resulted minor than the observed one. This is most likely the results of a non-perfect optimization of the solid mass parameters. The simulated lake has an extension of 19.4 ha which is 2.5 less than the observed one. Although the flooded area increases with every time-step, it did not fully reach the observed area, which this is probably due to the relatively short time span covered by the simulation: the final simulation (10,000 seconds).

Besides the reported adaptations, this work produced a valuable representation of the complex process chains, involving multiple materials and their interaction, utilizing r.avaflow.

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