**UNIVERSITY OF CALIFORNIA,
SANTA BARBARA**

SENIOR THESIS

Simulations of the 2018 Montecito Mudflow and Debris flow

Author:
Alejandro STAWSKY

Supervisor:
Bjorn BIRNIR

June 12, 2018

Acknowledgements

A huge thank you to Professor Birnir for mentoring me and making this Senior Thesis possible. This paper is dedicated to my father, Leonardo Stawsky.

Abstract

This thesis deals with simulating the Mudflow and Debris flow of the event in Montecito, January 2018, in order to provide visual aid for the destructive phenomena that caused the event and give a general framework to model mudflows over Discrete Elevation Maps of any mountain range where data is available. The Mathematical model is discussed, as well as the few changes made to the original MATLAB code and a brief description of how the animations were created. Then the data gathering and manipulating procedure is explained, followed by a presentation of the results and what they tell us about the different flows. Finally, suggestions for improving the model are given and possible applications for the use of this model are proposed.

Contents

1 Introduction

On January 9, 2018, a month after Santa Barbara and Ventura counties were scorched by the Thomas Fire, heavy rains in Montecito, California produced mudflow and debris flow which engulfed certain areas of the town, and left other areas unscathed. There are many factors that cause a mud/debris flow event to occur. The conceptual model used in (Staley et al., 2017), which is to date the most robust model to anticipate the probability of a post-fire debris-flow event and its magnitude, reduces these factors to an essential four: terrain steepness, the intensity of the wildfire, surface properties that influence sediment availability or erodibility, and the intensity of rainfall.

Firstly, the terrain steepness influences the rate of erosion and, more importantly for us, the stability of the rock and sediment on a mountain which, if eroded away by gravity or water, can be transported by runoff rainfall and create debris flow (Gabet, 2003a, 2003b, 2003c; Kean et al., 2011, 2013; Lamb et al., 2011, 2013; Nyman et al., 2011; Schmidt et al., 2011; Smith et al., 2012; Prancevic et al., 2014; Staley et al., 2014). It should be noted that the sediment transport rates from gravitational processes have been shown to significantly increase after wildfire (Florsheim et al., 1991, 2016; Gabet, 2003c; Lamb et al., 2011, 2013, Staley et al., 2017). Greater steepness also results in greater speed of a debris flow, which in the event of a mudflow results in more destructive force and a greater area of impact.

Secondly, the intensity of the wildfire defines how much vegetation on the mountain has been burned and how drastic the chemical changes to the soil were. As the vegetation burns (in the case of Montecito, the vegetation is chaparral), the resulting fine ash fills pores in the soil column, reducing how much rain the soil can absorb (Balfour et al., 2014; Bod et al., 2014). This fine ash also provides more available sediment for runoff rainfall to transport and convert to debris flow (Moody et al., 2013). The burning of both the vegetation and soil increases hydrophobicity in the soil by, among other processes, volatilizing water-repellent organic compounds which may bond with mineral particles in the top few centimeters of soil (DeBano, 2000; Letey, 2001, Staley et al., 2017). Intense runoff, steep terrain, and loose sediment have long been considered the main components to initiating post-fire debris flow (Cannon, 2001; Cannon et al., 2003; Santi et al., 2008; Schmidt et al., 2011; Parise and Cannon, 2012; Smith et al., 2012; Staley et al., 2014, Staley et al., 2017). Not only that, but it may also take several years before the debris flow susceptibility of a recently burned region returns to stable, prewildfire levels (Cannon and DeGraff, 2009; Cannon et al., 2010; DeGraff et al., 2015).

Thirdly, surface properties are simply the inherent characteristics that a soil has with respect to infiltration capacity, erodibility, and sediment availability. For example, the lower the infiltration capacity, the more susceptible it is to runoff and debris flow (Noske et al., 2016). Finally, it should come as no surprise that higher intensity rainfall results in a higher chance of debris-flow initiation. It should be noted that on a recently burned terrain, studies show that debris-flow initiation occurs even with short, low intensity rainfall (e.g. the example of the San Gabriel Mountains in (Kean and Staley, 2011; Kean et al., 2011; Schmidt et al., 2011; Staley et al., 2013)).

The Thomas fire, being the largest wildfire in modern California history, supplied more than enough loose sediment and chemical changes to the soil to initiate a debris flow. Adding to this the intense, four-inch rainfall that took place the 8th and 9th of January, and it is clear that the conditions in Montecito and Santa Barbara County were extremely susceptible to post-fire debris flow. So much so, that it is from the accumulation of so much debris and excess sediment that the mudflow eventually took place.

1.1 Underlying Model and Numerical Techniques

The model at the base of this thesis comes from (Cattan and Birnir, 2017), where it was originally used to study how the choice of numerical techniques affects the erosion on a mountain surface. The theory underneath the model can be found in (Birnir and Rowlett, 2013; Birnir, 2001; Cattan, 2017):

$$\eta^2 \frac{\partial h}{\partial t} = \nabla \cdot \left[\frac{\nabla H}{|\nabla H|} h^{\frac{5}{3}} |\nabla H|^{\frac{1}{2}} \right] + R, \tag{1}$$

$$\frac{\partial H}{\partial t} = \nabla \cdot \left[\frac{\nabla H}{|\nabla H|} h^{\frac{5}{3}\gamma} |\nabla H|^{\frac{1}{2}\gamma+\delta} \right] \tag{2}$$

Here, if we let the initial mountain surface be $z = z(x, y, t)$, $h = h(x, y, t)$ is the height of the dilute mixture of water and debris varying over the mountain surface, $H = H(x, y, t) = h(x, y, t) + z(x, y, t)$ is the height of the free water surface over the mountain, R is a constant rainfall rate, γ and δ erosion constants, and $\eta \equiv [h]/[H]$ a "landscape" parameter.

The dimensionless equation (1) is used to model the flow of the debris down the mountain surface, while equation (2) models the mudflow. The debris flow was solved numerically using the upwind scheme (Cattan and Birnir, 4.2), while the mudflow used the Crank-Nicolson scheme (Cattan and Birnir, 4.3).

The Matlab code for equation (2) was altered to prohibit the rainfall and mudflow from eroding the surface of the mountain lower than sea level, so as to accurately represent what happened in Montecito.

The final simulations were stop-frame animations utilizing the frames of variables H and h. Since erosion is a highly non-linear process, equations (1) and (2) required very small time-steps. Therefore the model was ran through several hundred thousand time-steps to create the animations.

2 Data Gathering and Manipulating Procedure

The contour elevation data for the Montecito and Santa Barbara mountains came from the US Geological Survey's National Map Viewer. In order to manipulate the contour data and discretize the region that got hit the hardest, the geographical computer program QGIS was used. A 101x101 vector grid was made over these areas, whose boxes were given the value of the highest contour line that crossed them.

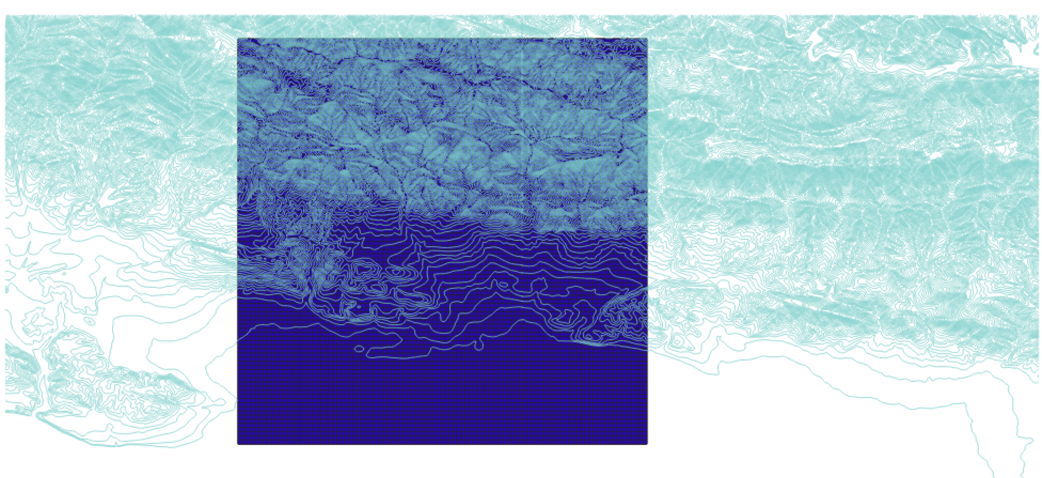

Fig. 1: Area of Montecito/Santa Barbara mountains used for the simulations

In some of the more level areas of the mountain, there were boxes that received a NULL value because the mountain slope was too small for a contour line to indicate a new height and cross the box. To get a cohesive Digital Elevation Model (DEM), these NULL values were approximated by assigning the value of the box on top of them, i.e. the elevation points were rounded up. This was done by exporting the vector grid as a single vector in a .csv file, importing it to MATLAB, running a for loop to approximate each NULL value and then reshaping the vector into a matrix that would later serve as the initial mountain surface on which the code would run. Once the mountain surface was normalized, transposed and smoothed to run the code, animations were made to show the mud and debris flow, along with the water/debris dilute mixture height and surface change.

3 Results

This model replicated two different types of flows: debris and mudflow. The debris flow is created from a dilute mixture of water from the rainfall and ash left from the burnt chaparral. Though the debris flow does not significantly alter the mountain surface, the fine, dense ash gives it greater carrying capacity than water, causing it to move heavy boulders and other sort of debris. All this happened within a span of hours. The mudflow however took two to three days to stabilize. Unlike the debris flow, the mudflow has significant erosion power over a longer time-span, although it may erode the surface of the mountain faster if it is sufficiently large. Generally, debris flow occurs first, followed by an extended mudflow if conditions permit.

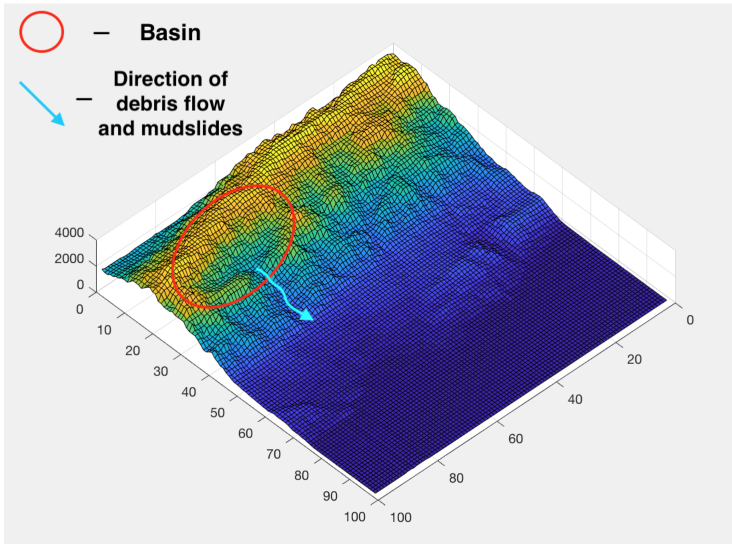

Fig. 2: Aerial view of a basis and canyon on the Montecito/Santa Barbara mountains

The mudflow is caused by the transportation of ash from the debris flow into the pockets of the basins on the side of the mountains, which has already been accumulating loose ash in the weeks prior to the rainfall. The debris flow then dilutes a lot more ash with water, creating a denser non-Newtonian fluid, i.e. flowing mud. This mudflow leaves the basin through the canyons but, unlike the debris flow, is slower and has its own inertia, causing it to create its own paths once the basin and the creeks have been filled. Though it does not travel as far as the debris flow, the force of this mudflow is so powerful that it is enough to destroy houses, break trees and carry cars.

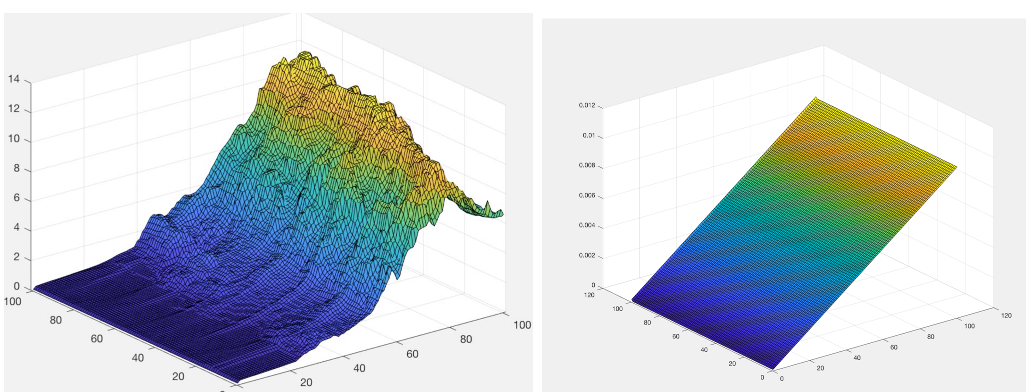

Fig. 3: The initial surface and rainfall used for the simulation

3.1 Debris/Water dilute mixture height

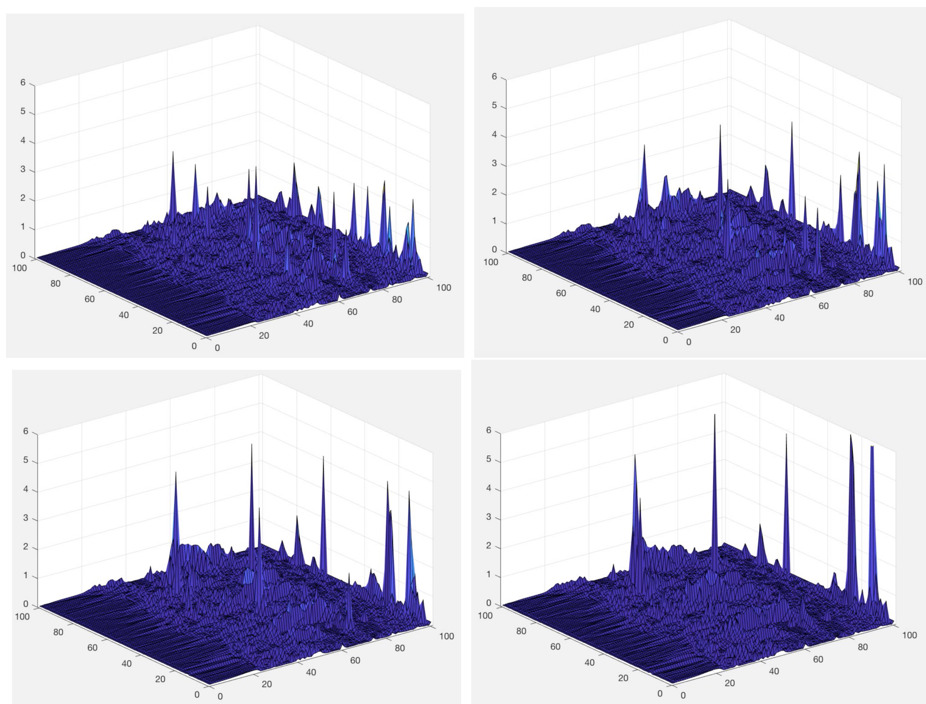

Fig. 4: Stop-frames of the variable h ordered from top left to bottom right

The image above contains selected and chronologically ordered frames of the debris and water dilute mixture height animation, corresponding to the variable h in the model. Notice the clear accumulation of the mixture in the pockets of the basins until, around the third frame, the mixture is seen traveling down very specific paths, which are the creeks and canyons. The results of the simulation therefore coincide with the current geological explanation of how and where the diluted mixture accumulated into mud, as well as what path it takes downhill. Comparing these paths to Figure 5, which shows which houses were hit the worst, the correlation between the simulation and what actually happened is made clear.

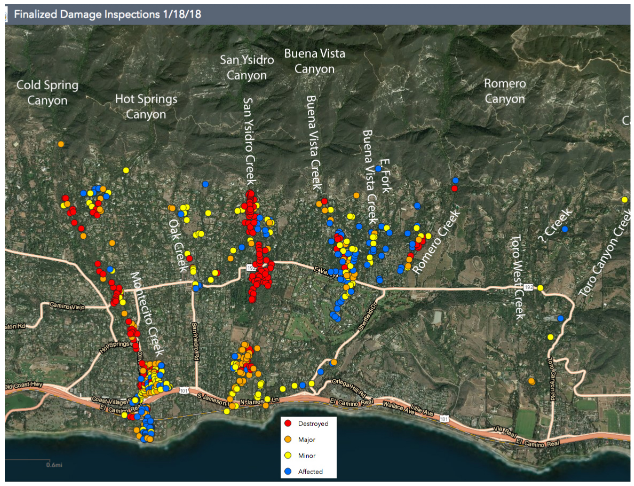

Fig. 5: Areas worst hit [36]

3.2 Debris Flow

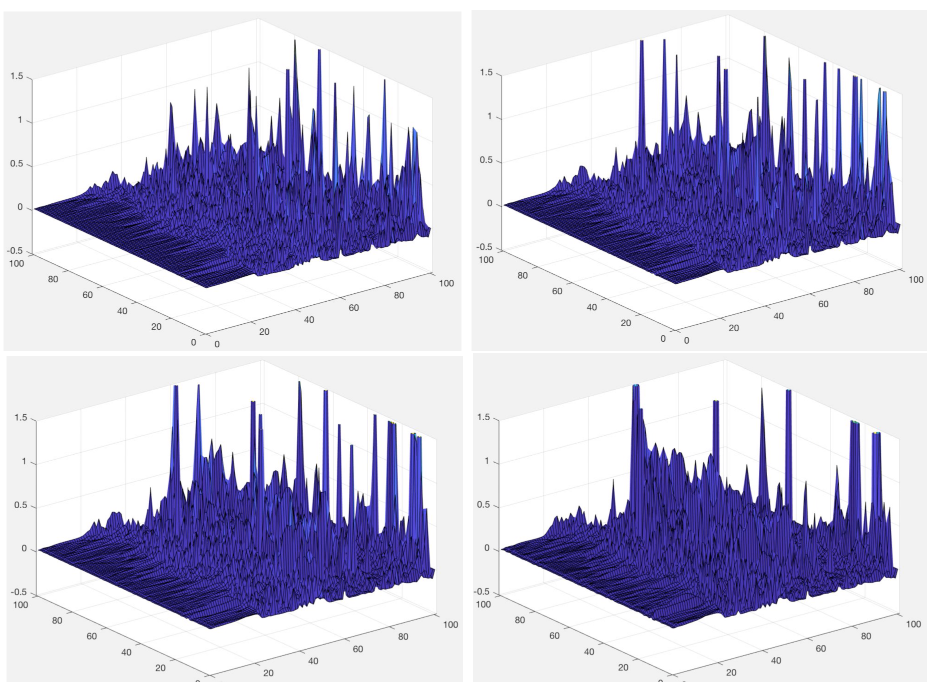

Fig. 6: Stop-frames of the debris flow ordered from top left to bottom right

The image above contains selected and chronologically ordered frames of the debris flow animation, which are the difference of the current and initial dilute mixture depth frames, i.e. $h(i) - h(1)$ for $i \in T$ where T is the discretization set of the total length of time the code was left to run. This difference takes into account the water that was in the basin to start with. Again the animation shows that the trend of the flow goes down the mountain in relatively straight lines, agreeing with the path the flow actually took, as seen by Figure 5. This concurs with the theory that the debris flow follows the canyons downhill and does so in a relatively fast pace compared to the mudflow, which will be shown in the following subsection.

3.3 Surface height

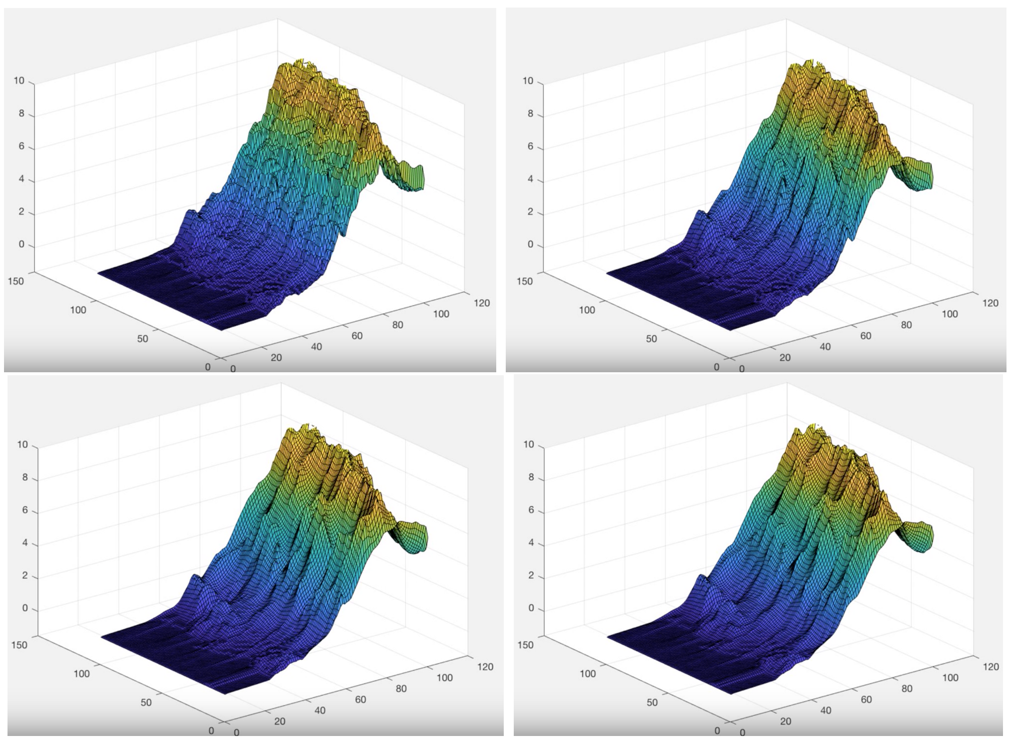

Fig. 7: Stop-frames of the variable H ordered from top left to bottom right

Above are the selected and chronologically ordered frames of the mountain surface animation, corresponding to the variable H in the model. Though it is not suspected that the mountain surface has changed to this extent – the US Geological Survey has yet to release the new topological maps taken after the mudflows – this animation is helpful to look at because it gives an idea and prediction as to how the mudflows would have eroded the surface, given enough time to do so. Hence, this animation was created in a much longer simulation than the debris flow simulations above. Notice how the the mud slides smooth the surface by filling in the basins.

3.4 Mudflow

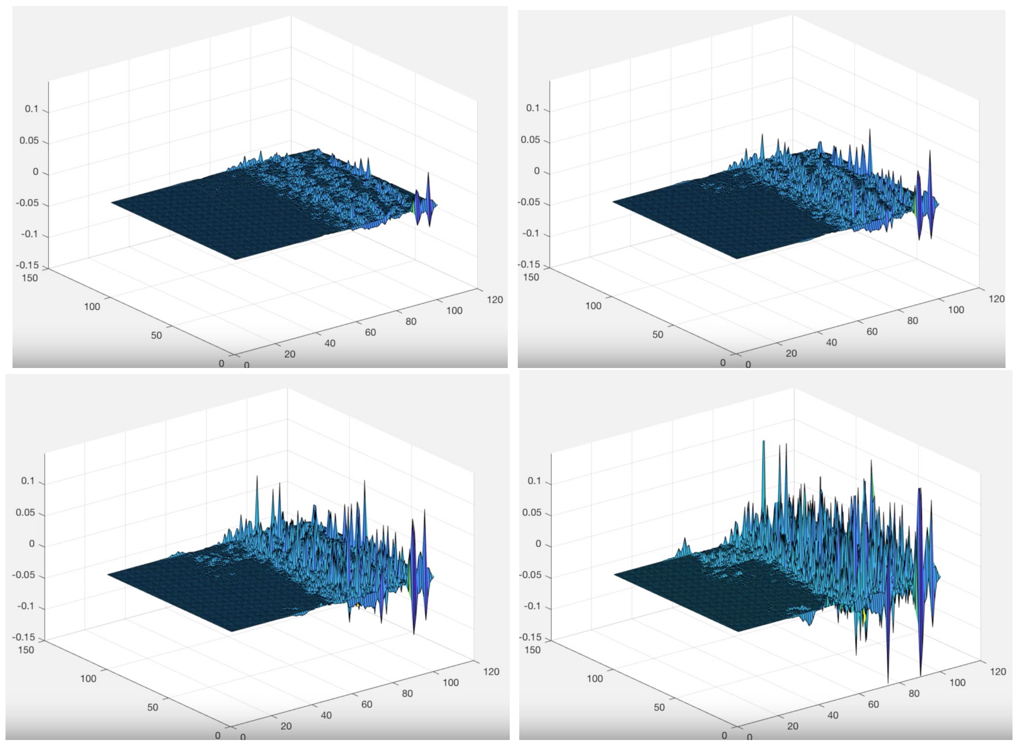

Fig. 8: Stop-frames of the mudflow ordered from top left to bottom right

Above are the selected and chronologically ordered frames of the mudflow animation, which are the difference of the current and initial surface frames, i.e. $H(i) - H(1)$ for $i \in T$ where T is the discretization set of the total length of time the code was left to run. In the first frame, it is clearly visible that the mud initially accumulates in the basin and, by the third frame, starts forming its own paths to go down the mountain. Comparing this to the debris flow animation, the difference in how mud and debris flow down the mountain is clearly shown: debris flow follows, more or less, the same trajectory as the natural canyons and creeks that were there before the fire, while the mud behaves like a non-Newtonian fluid and flows in a much more cohesive way. This does not mean that mudflow does not follow the paths of creeks and canyons but that it is much more likely to make its own paths as well. Also, notice how slowly the mud moves down the mountain – by the last frame, most of the mud is still in the basins and on the higher part of the mountain. Comparing the last frame of the debris and mudflow animations, the difference in speed is better seen. This model therefore coincides with what we know about mudflow and its differences and similarities with debris flow.

4 Conclusion

What do these simulations and animations bring to the scientific community? Firstly, it is a rough but robust model of a mudflow down a mountain. As explained in the paper, while not perfect, this model correctly reproduces several of the results expected from the geological understanding of how mud and debris flow downhill. The magnitude and destructive power of what happened in Montecito and Santa Barbara County on January 9th took most by surprise. Furthermore, the amount and duration of wildfires have been increasing gradually (Westerling et al. 2006), meaning areas with little to no history of wildfires or debris/mudflow could soon find themselves in a situation similar to the one in Montecito (Cannon and DeGraff, 2009). If further improved, this model holds the potential to one day be the basis of a preemptive simulation, a prediction of sorts, of how powerful a mudflow would be and in which areas it would hit the hardest. Secondly, these animations can be used as educational resources to demonstrate some of the phenomena talked about earlier. The framework of these animations already coded and the procedure of obtaining a DEM from contour plots on QGIS explained, one need only download the desired countour plots of, say a local mountain, from the US Geological Survey National Map to create animations of a mudflow down said mountain and make a lecture more relatable for students by using a familiar sight as an example.

A suggestion to further improve the model is to experiment with the different exponents in equations (1) and (2) to achieve a more accurate level of viscosity for the dilute mixture and the mud. However, the goal of this thesis was to obtain a basic framework for modeling mudflows down mountains, so such details were not accounted for.

References

[1] Balfour, V.N., Doerr, S.H., Robichaud, P.R., 2014. *The temporal evolution of wildfire ash and implications for post-fire infiltration.* Int. J. Wildland Fire 23, 733745.

[2] Birnir, B., Rowlett, J. (2013). *Mathematical Models for Erosion and the Optimal Transportation of Sediment*. International Journal of Nonlinear Sciences and Numerical Simulation, 14(6).

[3] Birnir, B., Smith, T. R., Merchant, G. E. (2001). *The scaling of fluvial landscapes*. Computers Geosciences, 27(10), 1189-1216.

[4] Bod, M.B., Martin, D.A., Balfour, V.N., Santn, C., Doerr, S.H., Pereira, P., Cerd, A., Mataix- Solera, J., 2014. *Wildland fire ash: production, composition and eco-hydro- geomorphic effects.* Earth Sci. Rev. 130, 103127.

[5] Cannon, S.H., 2001. *Debris-flow generation from recently burned watersheds.* Environ. Eng. Geosci. 7, 321341.

[6] Cannon, S.H., DeGraff, J., 2009. *The Increasing Wildfire and Post-Fire Debris-Flow Threat in Western USA, and Implications for Consequences of Climate Change.* Sassa, K., Canuti, P. (Eds.), Landslides Disaster Risk Reduction. Springer, Berlin Heidelberg (177-190 pp.).

[7] Cannon, S.H., Gartner, J.E., Parrett, C., Parise, M., 2003. *Wildfire-related debris-flow gener- ation through episodic progressive sediment-bulking processes, western USA.* Rickenmann, D., Chen, C.L. (Eds.), Debris-Flow Hazards Mitigation - Mechanics, Pre- diction, and Assessment, Proceedings of the Third International Conference on Debris-Flow Hazards Mitigation, Davos, Switzerland, 1012 September 2003. A.A. Balkema, Rotterdam (71-82 pp.).

[8] Cannon, S.H., Gartner, J.E., Rupert, M.G., Michael, J.A., Rea, A.H., Parrett, C., 2010. *Predicting the probability and volume of postwildfire debris flows in the intermountain western United States.* Geol. Soc. Am. Bull. 122, 127144.

[9] Cattan, D., Birnir, B., 2017. *Numerical Analysis of Fluvial Landscapes.* Mathematical Geosciences 49.7 (2017), pp. 913942. doi: 10.1007/s11004-0179698-6.

[10] Cattan, D., 2017. *On the Numerics, Generation, and Scaling of Fluvial Landscapes* (Unpublished doctoral dissertation) University of California, Santa Barbara.

[11] DeBano, L.F., 2000. *The role of fire and soil heating on water repellency in wildland environments: a review.* J. Hydrol. 231232, 195206.

[12] DeGraff, J.V., Cannon, S., Gartner, J.E., 2015. *The timing of susceptibility to post-fire debris flows in the western USA.* Environ. Eng. Geosci. 21, 277292.

[13] Florsheim, J.L., Keller, E.A., Best, D.W., 1991. *Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California.* Geol. Soc. Am. Bull. 103, 504511.

[14] Florsheim, J.L., Chin, A., O'Hirok, L.S., Storesund, R., 2016. *Short-term post-wildfire dry-ravel processes in a chaparral fluvial system.* Geomorphology 252, 3239.

[15] Gabet, E.J., 2003a. *Post-fire thin debris flows: sediment transport and numerical modelling.* Earth Surf. Process. Landf. 28, 13411348.

[16] Gabet, E.J., 2003b. *Sediment detachment by rain power.* Water Resour. Res. 39, ESG 1-1ESG 1-12.

[17] Gabet, E.J., 2003c. *Sediment transport by dry ravel.* J. Geophys. Res. 108, 2049.

[18] Kean, J.W., Staley, D.M., 2011. *Direct Measurements of the Hydrologic Conditions Leading up to and During Post-fire Debris Flow in Southern California, USA.* Genevois, R., Hamilton, D.L., Prestininzi, A. (Eds.), Proceedings of the Fifth International Conference on Debris Flow Hazards Mitigation/Mechanics, Prediction, and Assessment, Padua, Italy, June 711, 2011. Italian Journal of Engineering Geology and Environment Book: Casa Editrice Universita La Sapienza, Rome, Italy, pp. 685694.

[19] Kean, J.W., Staley, D.M., Cannon, S.H., 2011. *In situ measurements of post-fire debris flows in southern California: comparisons of the timing and magnitude of 24 debris-flow events with rainfall and soil moisture conditions.* J. Geophys. Res. 116, F04019.

[20] Kean, J.W., McCoy, S.W., Tucker, G.E., Staley, D.M., Coe, J.A., 2013. *Runoff-generated debris flows: observations and modeling of surge initiation, magnitude, and frequency.* J. Geophys. Res. Earth Surf. 2013JF002796.

[21] Lamb, M.P., Scheingross, J.S., Amidon, W.H., Swanson, E., Limaye, A., 2011. *A model for fire-induced sediment yield by dry ravel in steep landscapes.* J. Geophys. Res. 116, F03006.

[22] Lamb, M.P., Levina, M., DiBiase, R.A., Fuller, B.M., 2013. *Sediment storage by vegetation in steep bedrock landscapes: theory, experiments, and implications for postfire sedi- ment yield.* J. Geophys. Res. Earth Surf. 118, 11471160.

[23] Letey, J., 2001. *Causes and consequences of fire-induced soil water repellency.* Hydrol. Process. 15, 28672875.

[24] Moody, J.A., Shakesby, R.A., Robichaud, P.R., Cannon, S.H., Martin, D.A., 2013. *Current research issues related to post-wildfire runoff and erosion processes.* Earth Sci. Rev. 122, 1037.

[25] Noske, P.J., Lane, P.N.J., Nyman, P., Sheridan, G.J., 2016. *Effects of aridity in controlling the magnitude of runoff and erosion after wildfire.* Water Resour. Res. 2015WR017611.

[26] Nyman, P., Sheridan, G.J., Smith, H.G., Lane, P.N.J., 2011. *Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia.* Geomorphology 125, 383401.

[27] Parise, M., Cannon, S., 2012. *Wildfire impacts on the processes that generate debris flows in burned watersheds.* Nat. Hazards 61, 217227.

[28] Prancevic, J.P., Lamb, M.P., Fuller, B.M., 2014. *Incipient sediment motion across the river to debris-flow transition.* Geology 42 (3), 191194.

[29] Santi, P., Dewolfe, V., Higgins, J., Cannon, S., Gartner, J., 2008. *Sources of debris flow mate- rial in burned areas.* Geomorphology 96, 310321.

[30] Schmidt, K.M., Hanshaw, M.N., Howle, J.F., Kean, J.W., Staley, D.M., Stock, J.D., Bawden, G.W., 2011. *Hydrologic Conditions and Terrestrial Laser Scanning of Post-fire Debris Flows in the San Gabriel Mountains, CA, USA.* Genevois, R., Hamilton, D.L., Prestininzi, A. (Eds.), Proceedings of the Fifth International Conference on Debris Flow Hazards Mitigation/Mechanics, Prediction, and Assessment, Padua, Italy, June 711, 2011. Italian Journal of Engineering Geology and Environment-Book: Casa Editrice Universita La Sapienza, Rome, Italy, pp. 583593.

[31] Smith, H.G., Sheridan, G.J., Nyman, P., Child, D.P., Lane, P.N.J., Hotchkis, M.A.C., Jacobsen, G.E., 2012. *Quantifying sources of fine sediment supplied to post-fire debris flows using fallout radionuclide tracers.* Geomorphology 139-140, 403415.

[32] Staley, Dennis M., Negri, Jacquelyn A., Kean, Jason W., Laber, Jayme L., Tillery, Anne C., Youberg, Ann M. *Prediction of Spatially Explicit Rainfall IntensityDuration Thresholds for Post-Fire Debris-Flow Generation in the Western United States.* Geomorphology, vol. 278, 2017, pp. 149162., doi:10.1016/j.geomorph.2016.10.019.

[33] Staley, D.M., 2014. *Emergency Assessment of Post-fire Debris-flow Hazards for the 2013 Springs Fire, Ventura County, California.* U.S. Geological Survey Open-File Report 20141001 (10 pp.)

[34] Staley, D.M., Kean, J.W., Cannon, S.H., Schmidt, K.M., Laber, J.L., 2013. *Objective definition of rainfall intensityduration thresholds for the initiation of post-fire debris flows in southern California.* Landslides 10, 547562.

[35] Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. *Warming and earlier spring increase Western U.S. forest wildfire activity.* Science 313, 40943.

[36] Source of photo from figure 5, from the The County Office of Emergency Management's interactive map of the damage assessment data *https://sbc-gis.maps.arcgis.com/apps/webappviewer/index.html?id=ee848a57d8b24* 16eb2802da300df5b6e.