Comments from Anonymous Referee #1

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I think that the manuscript is excellent. I only suggest insert these further references, concerning the statistical models, at page 4 line 67-69:

Baum, R.L., and Godt, J.W. Early warning of rainfall-induced shallow landslides and debris flows in the USA, Landslides, 7(3), 259-272. DOI: 10.1007/s10346-009-0177-0, 2010.

Berti, M., Martina, M.L.V., Franceschini, S., Pignone, S., Simoni, A., and Pizziolo, M. Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach, Journal of Geophysical Research: Earth Surface, 117 (4), doi:10.1029/2012JF002367, 2012.

Cannon, S.H., Gartner, J.E., Wilson, R., Bowers, J., and Laber, J. Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California, Geomorphology, 96(3–4), 250–269, DOI: 10.1016/j.geomorph.2007.03.019, 2008.

De Luca D.L.; Versace P. A comprehensive framework for empirical modeling of landslides induced by rainfall: the Generalized FLaIR Model (GFM). Landslides, 14(3): 1009-1030, ISSN: 1612-5118, DOI: 10.1007/s10346-016-0768-5, 2017.

Godt, J.W., Baum, R.L., and Chleborad, A.F. Rainfall characteristics for shallow landsliding in Seattle, Washington, USA. Earth Surface Processes and Landforms, 31, 97-110, DOI: 10.1002/esp.1237, 2006.

Guzzetti, F., Peruccacci, S., Rossi, M. and Stark, C.P. The rainfall intensity–duration control of shallow landslides and debris flows: An update, Landslides, 5, 3–17, DOI: 10.1007/s10346-007-0112-1, 2008.

Staley, D.M., Kean, J.W., Cannon, S.H., Schmidt, K.M., and Laber, J.L. Objective definition of rainfall intensity–duration thresholds for the initiation of post-fire debris flows in southern California, Landslides, 10(5), 547-562 DOI:10.1007/s10346-012-0341-9, 2013.

After addition of these references, in my opinion the manuscript is ready for publication**.**

Authors’ Response

Thank you so much for the comments. Your suggestion is well taken and helpful to make the manuscript more informative and comprehensive. We have added the references you suggested.

Author's changes in manuscript

Lines 66-72: Statistical models have also been proposed to relate debris-flow initiation to rainfall (e.g. Caine, 1980; Wieczorek, 1987; Chen et al., 2005; Godt et al., 2006; Cannon et al., 2008; Coe et al., 2008; Guzzetti, et al., 2008; Baum and Godt, 2010; Berti et al., 2012; Staley et al., 2013; Zhou and Tang, 2014; De Luca and Versace, 2017a; De Luca and Versace, 2017b; Gao et al., 2017) and other parameters such as surface runoff discharge (Berti and Simoni, 2005) or clay content (Chen et al., 2010).

Comments from Anonymous Referee #2

Received and published: 20 March 2018

Version 2.0 of the EDDA model features improvements over the previous version. However, its process representation is still deterministically-derived, and it rests on assumptions that limit the veracity of the physics-based representations of key processes. Some examples: Line 189 - the assumption here is that surface runoff is generated solely by Hortonian Overland Flow - that is the rainfall intensity exceeds the infiltration capacity. In fact, surface runoff is often associated with other situations and locations. Saturation Overland Flow (SOF) is another likely driver of surface erosion that may trigger a debris flow, for example. The spatial distribution of SOF is largely, topographically controlled and could be predicted based on the DEM and application of appropriate topographic analyses. Line 197 - Richards equation is outmoded. We know it doesn't work. It should be replaced in EDDA 3.0 by a current approach to simulating through flow. Line 214 - Terrain places an important role in determining the initiation point and pathway for a debris flow. This is not well represented by the infinite slope model. Line 245 - the du Boys shear stress equation is old and outmoded. There are better methods based on, for example, specific stream power (stream power per unit bed area). Goodness of fit - describing model and observed results as agreeing 'reasonably well' is insufficient. Quantitative criteria for agreement should be derived and applied to test 'goodness of fit'. Notwithstanding these criticisms, the model and paper have merit and can be used for broad scale forecasting of debris flows triggered by rainfall that is heavy and/or prolonged.

Authors' Response

Thank you so much for the constructive and helpful comments. The response to your comments is as follow.

1. "Line 189 - the assumption here is that surface runoff is generated solely by Hortonian Overland Flow - that is the rainfall intensity exceeds the infiltration capacity. In fact, surface runoff is often associated with other situations and locations. Saturation Overland Flow (SOF) is another likely driver of surface erosion that may trigger a debris flow, for example. The spatial distribution of SOF is largely, topographically controlled and could be predicted based on the DEM and application of appropriate topographic analyses."

Indeed the Hortonian runoff concept cannot explain storm runoff in many of the humid regions where the infiltration capacity of the ground is typically much greater than average rainfall intensities. Steenhuis and Muck (1988) found that soils of the Ithaca NY, especially the shallow hillside soils maintained in grass and pasture, have infiltration rates that are rarely exceeded by the rainfall rate. This has been confirmed in other studies (Merwin et al., 1994; Dunne and Black, 1970). For example, over 90% of the soils in Delaware County, NY (in the Catskill Mountains) have permeabilities above 3 cm/hr. However, rainfall intensities greater than 3 cm/hr are rare. In contrast, storm responses in streams reflect runoff processes occurring upstream almost every time it rains, which means that there must be some mechanisms other than Hortonian Flow that generate runoff. Since then, researchers have found other runoff-generating mechanisms, such as saturation overland flow (SOF).

The SOF has two sources, Direct Precipitation onto Saturated Areas (DPSA) and Return Flow (RF). Rain falling on already-saturated soil has no option but to run off. This case is termed direct precipitation on saturated areas (DPSA). The return flow (RF) occurs if the rate of interflow entering a saturated area from upslope exceeds the capacity for interflow to leave the area by flowing downhill through the soil. The excess interflow thus "returns" to the surface as runoff. The combination of RF and DPS is called saturation overland flow.

This mechanism derives a concept called Variable Source Area (VSA) which recognizes that the extent of saturated areas in a watershed will vary temporally. Before a storm, saturated areas are limited to the close vicinity of the stream. They expand during the storm, resulting in a larger rate of runoff generation. The application of this concept utilizes the information including bedrock, impermeable soil layers, and/or the depth to the water table. Thus, both hydrologic and soil-water concepts are combined to evaluate potential runoff areas in the landscape.

In this paper, the debris flow case being simulated occurred in the Wenchuan earthquake zone. A large part of the study area remained uncovered by vegetation before the debris flow event, because the Wenchuan earthquake triggered many landslides and the previous vegetation cover was wiped out. Also considering that the fresh landslide deposits had a relative fine-grained surface, which is due to an inverse segregation mechanism, infiltration capacity becomes a limiting factor in this study and Hortonian overland flow is thus a dominant process.

Your suggestion is very good and appreciated. We will revise/expand the runoff mechanisms in the model in the future version to make the model more comprehensive.

References

[1] Dunne T and Black RD (1970) Partial area contributions to storm runoff in a small New England watershed. Water Resources Research 6(5): 1296-1311.

[2] Merwin IA, Stiles WC and van Es HM (1994) Orchard groundcover management impacts on soil physical properties. Journal of the American Society for Horticultural Science 119(2): 216-222.

[3] Steenhuis TS and Muck RE (1988) Preferred movement of nonadsorbed chemicals on wet, shallow, sloping soils. Journal of Environmental Quality 17(3): 376-384.

2. “Line 197 - Richards equation is outmoded. we know it doesn’t work. It should be replaced in EDDA 3.0 by a current approach to simulating through flow.”

Zhang et al. (2011) made a comprehensive review of existing research on infiltration analysis. Based on this review, there are two main types of infiltration analysis methods.

(1) Conceptual infiltration models. Infiltration models have been proposed based on a wetting front concept (Green and Ampt, 1911; Lumb, 1962; Mein and Larson, 1973; Sun et al., 1998). However, serious limitations impose restrictions on the use of the conceptual infiltration models, because they usually do not consider sloping ground conditions, down-slope flows, variation of rainfall intensity or, most importantly, the dependence of soil permeability on moisture content (Ng and Shi, 1998b). In addition, there may not be a distinct difference between the infiltration zone and the unsaturated zone.

(2) Analytical and numerical solutions. A combination of Darcy’s law as applied to unsaturated flow and the equation of continuity is considered the most robust method available for computing infiltration and soil moisture profiles in saturated–unsaturated soil systems. Based on Darcy’s law and the mass conservation for water flow, the three-dimensional water flow in unsaturated soil is described by the Richards equation (Richards, 1931; Fredlund and Rahardjo, 1993). Many analytical solutions (e.g., Srivastava and Yeh, 1991; Iverson, 2000; Chen et al.,

2001; Yuan and Lu, 2005), numerical solutions (e.g., Ng and Shi, 1998a; Gasmo et al., 2000; Tsaparas et al., 2002; Blatz et al., 2004; Zhang et al., 2004; Rahardjo et al., 2007; Rahimi et al., 2010) and computer programs (e.g., Seep/W (Geo-slope Ltd, 2001); SVflux (SoilVision System Ltd, 2001); Flow3D (Gerscovich, 1994); and FEMWATER (Lin et al., 1997)) have been proposed for solving the Richards equation. However, analytical solutions for the infiltration problem can be obtained only by making some assumptions, and under some given initial and boundary conditions because of the natural spatial variability in the field, uncertain initial conditions and boundary conditions, and complex soil layering in practical applications.

Another theory for modeling the seepage process is the computational fluid dynamics/discrete element method (CFD-DEM model). However, this method is computationally demanding and may not be applicable to catchment-scale studies.

We are very interested in latest methods for simulating through flow and will study and adopt one in the future version of EDDA.

Reference

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[2] Chen JM, Tan YC and Chen CH (2001) Multidimensional infiltration with arbitrary surface fluxes. Journal of Irrigation and Drainage Engineering, ASCE 127(6): 370-377.

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[5] Geo-slope Ltd (2001) Seep/W for Finite Element Seepage Analysis: User’s Guide. Geo-Slope Ltd, Calgary, Canada.

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3. “Line 214 - Terrain places an important role in determining the initiation point and pathway for a debris flow. This is not well represented by the infinite slope model.”

In this study, rain-induced landslide is one of the initiation mechanisms. These landslides are normally shallow, with a depth of failure less than 3 m, and generally of small volume on steep soil slopes of 30-50° (Dai et al., 2003; Johnson and Sitar, 1990). Considering that these rain-induced landslides are shallow-seated, the thickness of the sliding mass is small compared to the large plan dimensions of these slopes. Therefore, an infinite slope model for two-layer soil slopes is a reasonable option to evaluate the slope stability. The terrain is not treated as an infinitely straight surface. In fact, the terrain is discretized into cells based on the real topographic conditions. Each cell has different sloping gradient and is evaluated using the infinite model. The infinite slope model is a simplified method to achieve a balance between accuracy and computational time for catchment scale studies.

The traveling process of debris flow is simulated using mass conservation and momentum equations. The effects of terrain are involved in the equations. So, the debris flow is simulated to march along an optimal (the steepest) pathway automatically, based on the given terrain data.

4. "Line 245 - the du Boys shear stress equation is old and outmoded. There are better methods based on, for example, specific stream power (stream power per unit bed area)."

Thank you very much for your suggestions. There are erosion models based on the perspective of energy, which is widely used in hydrological studies. As Bagnold (1977) commented, since stream power and sediment transport rate are different values of the same physical quantity, it is rationale to relate one to the other. This is a heuristic enlightenment for us to consider interdisciplinary research in the future. The method of stream power is mainly used for sediment entrainment and transportation in a river system where clear water flow dominates the process. Before adopting relevant models, it is critical to evaluate whether and how these models can be used to describe the material entrainment by earth-surface mass flows that have very high solid-phase concentration. Besides, there is limited research on calibrating the threshold specific stream power of the ravines like the study area in this paper. Considering all of these issues, we regard them as good potential areas to be tacked, perhaps in EDDA3.0 as mentioned in your comments. We are interested in these problems and will work on them when developing the future version of the proposed model.

Reference

[1] Bagnold RA (1977) Bed Load Transport by Natural Rivers. Water Resource Research 13(2): 303-312.

5. "Goodness of fit - describing model and observed results as agreeing 'reasonably well' is insufficient. Quantitative criteria for agreement should be derived and applied to test 'goodness of fit'."

(1) Line 366 - "It is found that the results of the two separate analyses are very similar. The computed total scar area is 4.42×10^5 m^2, comparing well with 5.20×10^5 m^2 from the satellite image. It is concluded that the proposed slope stability module performs reasonably well."

The distribution of the computed unstable cell has been verified by Chen and Zhang (2014) using the confusing matrix method, shown in Figure 1. The results indicate that the proposed model is capable of predicting the locations of rainfall-induced landslides reasonably well. For brevity, we omitted the presentation of the quantitative analysis of the degree of coincidence.

The computed total area of landslides is 4.42 × 10^5 m^2 and the observed value is 5.20 × 10^5 m^2. The difference is about 15%, which may be acceptable for large-scale numerical simulations. We will add this to the revised manuscript.

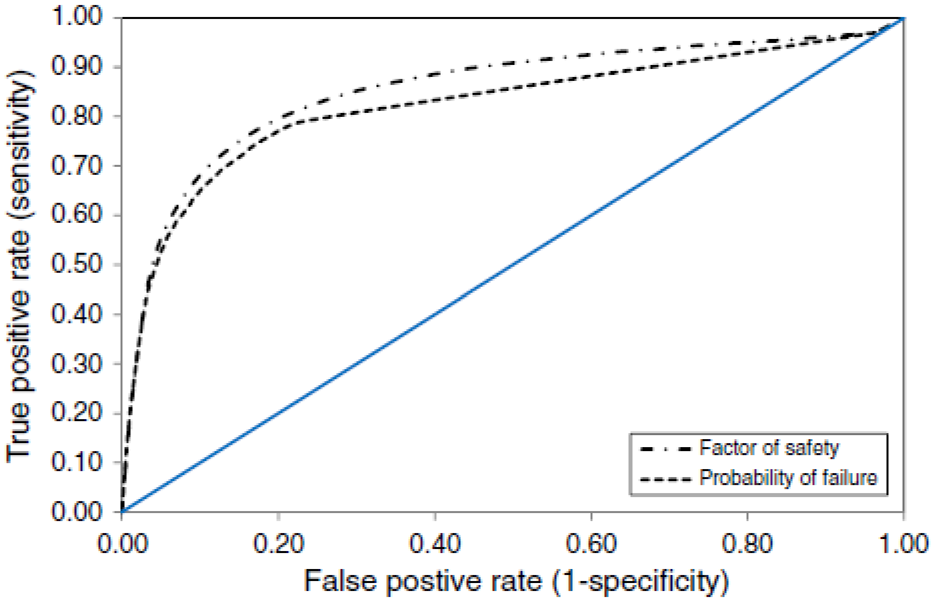

Figure 1. Receiver Operating Characteristic (ROC) curves in the form of factor of safety and probability of failure at the end of storm. The true positive rate (TPR) is the ratio of TP to (TP + FN); the false positive rate is the ratio of FP to (FP + TN).

(2) Line 414 - "The simulated and observed deposition areas are compared in Fig. 11. It is seen that the simulation results (Fig. 11a) match the observation (Fig. 11b) reasonably well. The simulated deposition depth is approximately 20 m, very close to that of the observed thickness of the deposit fan during the field investigations. The total volume of the observed deposition fan is about 1.17 × 10^6 m^3, while the simulated deposition volume of the debris flow is 0.9 × 10^6 m^3. The integrated model evaluates a smaller debris flow volume. The main uncertainty arises from the slope failure module and surface erosion module."

The simulated deposition volume (0.9×10^6 m^3) and the observed volume (1.17×10^6 m^3) differ by about 23%, which is also acceptable for numerical simulations, considering inevitable uncertainties such as spatial variability along a large distance. We will add this to the revised manuscript. However, such comparison is still rather qualitative. Numerical simulation of large-scale debris flows is still a challenge.

Author's changes in manuscript

1. Lines 362-366: Moreover, the results are compared with those by Chen and Zhang (2014), which have been verified using the confusing matrix method (e.g. Van Den Eeckhaut et al., 2006). It is found that the results of the two separate analyses are very similar. The computed total scar area is 4.42×10^5 m^2, comparing well with 5.20×10^5 m^2 from the satellite image. The difference is 15%. It is concluded that the proposed slope stability module performs reasonably well.

2. Lines 413-419: The simulated and observed deposition areas are compared in Fig. 11. It is seen that the simulation results (Fig. 11a) match the observations (Fig. 11b) reasonably well. The simulated deposition depth is approximately 20 m, very close to that of the observed thickness of the deposit fan during the field investigations. The total volume of the observed deposition fan is about 1.17×10^6 m^3, while the simulated deposition volume of the debris flow is 0.9×10^6 m^3. The integrated model evaluates a smaller debris flow volume and the difference is 23%. The main uncertainty arises from errors in the slope failure module and the surface erosion module.