Response to Reviewer 1

May 28, 2019

Manuscript title: Reconstructing the Salgar 2015 Flash Flood Using Radar Retrievals and a Conceptual Modeling Framework: A Basis for a Better Flood Generating Mechanisms Discrimination

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General Concept:

I appreciate the revision of the manuscript that makes the paper to be more concise and better structured. Specially the rewriting of the introduction, the study site and data description and part of the methodology appears in a clearer way. I would however still suggest several rewording of the section 3.2 and 3.3. The theoretical background of the latter one must be clarified to be maintained in the manuscript, either by referring to the related literature, or by explaining the hypotheses behind the floodplain sub-model.

We sincerely thank the anonymous reviewer #1 for the careful, detailed and thoughtful review. The first and the second round of reviews were key to improve the manuscript. We have followed the detailed suggestions and have rewritten some of the paragraphs in sections 3.2 and 3.3. We also have expanded the description of the floodplain submodel, adding an schematic diagram explaining step-by-step the flash flood submodel methodology. The explanation is included in the section: HydroFlash. Below, the reviewer comments are in black and our comments are in "blue".

Finally concerning the methodology, I have one main doubt about the actual connection between the hydrological model set up and the landslide model one. The strength of the overall paper methodology is to use the soil storage dynamic simulated by the hydrological model to deduce landslide occurrence. However, it does not appear clear any more if the soil storage set up (Z) is the same for both simulations. This assumption has to be clearly clarified.

The connection is given by Equation 9 in the manuscript, where the saturated soil thickness is defined as a function of the gravitational storage simulated by the hydrological model. The saturated soil thickness is then compared to the critical value, which in turns depends on Z.

The results and the discussion appear in a clearer way as well in that second version, specially when describing the results of the hydrological model, explaining the different flow processes during the two distinct events. I think that the results could even be better inserted within the current literature, showing standardize figures or adjusting the discussion. My comments below support this point.

We have taken in consideration all the detail suggestions, and we have modified the manuscript accordingly.

The discussion about the limitation of the landslide model might be more more detailed. I think, the authors should be able to settle on the reasons of the result limitations: does it come from the lack of spatial information about soil and land cover properties, or from too strong assumptions of the landslide model? Ruling on the reasons of the limitation would bring a direct outlook of the study.

We believe it is related mostly to the data limitations, as discussed in the new version of the manuscript.

Finally, I found really interesting that the soil storage capacity available before flood event impacted not only the flood magnitude but also the response time of the catchment. From my point of view, it could be appear as one of the main incomes of the paper.

We agree with the reviewer. This point has been highlighted in the conclusions.

1 Comments on the sections

1.1 Comments on the methodology description

Description of the shallow landslides sub-model

• From my point of view, the description of the sub-model could be clearer expressed. It doesn't emphasize the crucial definition of the model. The stability state of the cells, which is presented on the first part of the section, depends on the stability criteria which is presented later. I suggest here a draft, but please feel free to adapt it :

The shallow landslides sub-model coupled to the hydrological model is proposed by Aristizabal et al. 2016. The stability of each cell is calculated through the assessment of the different stresses applied to the soil. The stability of the soil decreases with the pore water pressure (Graham, 1984). The slope failure occurs when the saturated soil thickness above the slip surface (Zw, here related to the gravitationnal storage S3, eq. 9) is greater than a critical saturated depth (Zc), which depends on the soil cohesion (C), the hillslope (beta), [...] (eq. 10).

Eq 9 : Zw = S3 / (Wc - Wfc); with Wc and Wfc the soil saturation depth and the field capacity respectively, S3 the gravitationnal storage.

Eq 10 : [...]

We sincerely thank the reviewer for the helpful suggestion. We adopted most of the suggestion by the reviewer, and also changed the order of the text and the equations, trying to present a better explanation of the submodel. The modified text appears in the manuscript as follows:

The shallow landslide submodel coupled to the hydrologic model is proposed by (author?) [1]. The stability of each cell is calculated through the assessment of the different stresses applied to the soil. The stability of the soil decreases with the pore water pressure [?]. The slope failure occurs when the saturated soil thickness above the slip surface $Z_{i,w}$ (equation (1)), which depends on the gravitational storage $S_{3,i}(t)$, the soil wilting point $W_{i,pwp}$, and the soil field capacity $W_{i,fc}$, is greater than a critical saturated depth $Z_{i,c}$ (equation (2)). The critical saturated depth depends on the shallow soil depth Z_i , the soil bulk density γ_i , the water density γ_w , the gradient of the slope $\beta_{i,0}$, the soil stability angle ϕ_i , and the soil cohesion C'_i . Figure 7 [in the manuscript] describes the variables of the model and the balance of forces considered, and Table 1 presents the parameters for this model.

$$Z_{i,w}(t) = \frac{S_{3,i}(t)}{W_{i,cfc} - W_{i,pmp}}$$
(1)

| Parameter Name | Symbol | Scalar | Mean Value | Spatial distribution |
|----------------------|---------------------------|-------------------------|------------|----------------------|
| | | Parame- | | |
| | | ter | | |
| Soil depth | $Z_i [\mathrm{mm}]$ | 0.3 | 300 | As a function of the |
| | | | | slope |
| Topography slope | $\beta_{i,0}$ [adim] | 1 | 0.01 - 5.3 | Taken from the DEM |
| Soil bulk density | $\gamma_i [KNm^{-3}]$ | 1 | 18 | Assumed constant |
| Water density | $\gamma_w [KNm^{-3}]$ | 1 | 9.8 | Constant |
| Soil stability angle | ϕ_i [⁰] | 1 | 30^{0} | Assumed constant |
| Soil cohesion | C'_i [KN] | 1 | 4 | Assumed constant |

Table 1: Shallow landslides model parameters.

$$Z_{i,c} = \frac{\gamma}{\gamma_w} Z_i \left(1 - \frac{tan\beta_i}{tan\phi_i} \right) + \frac{C'}{\gamma_w cos^2 \beta_{i,0} tan\phi_i}$$
(2)

According to the soil stability definition, the topography and the soil properties, all cells are classified into three: unconditionally stable, conditionally stable and unconditionally unstable. In particular, three parameters determine the stability of each cell: (i) residual soil thickness water table $Z_{i,min}$ (equation (3)), (ii) the maximum soil depth at which a particular soil remains stable $Z_{i,max}$ (equation (4)), and (iii) the maximum slope at which the soil remains stable $\beta_{i,0}$ (equation 5)).

$$Z_{i,min} = \frac{C'_i}{\gamma_w \cos^2\beta_{i,0} tan\phi_i + \gamma_i \cos^2\beta_{i,0} (tan\beta_{i,0} - tan\phi_i)}$$
(3)

$$Z_{i,max} = \frac{C'}{\gamma_i cos^2 \beta_i, 0(tan\beta_i, 0 - tan\phi_i)}$$
(4)

$$\beta_{i,0} = \tan^{-1} \left[\tan \phi_i \left(1 - \frac{\gamma_w}{\gamma_i} \right) \right] \tag{5}$$

A cell is unconditionally stable when Z_i is smaller than $Z_{i,min}$ or when the cell slope is smaller than $\beta_{i,0}$. On the other hand, a cell is unconditionally unstable when Z_i is greater than $Z_{i,max}$, and finally, a cell is conditionally stable when Z_i is between $Z_m in$ and $Z_{i,max}$. Shallow landslides are calculated at each time step of the hydrological simulation, based on the latter cell class, where the soil stability depends of the storm event, becoming unstable when $Z_{i,w}(t)$ is greater than $Z_{i,c}$.

• In addition, I suggest to summarize the specific parameters to the landslide sub-model in a table as done for the hydrological model. I suggest as well to indicate the references used to set up the parameter values.

We adopted the good suggestion by the reviewer and included a table with the description of the landslide submodel parameters and their values. Table 1 corresponds to the new table in the manuscript:

• Finally, the lines 563 – 566, page 19, correspond to the landslide sub-model description; they should be inserted in that section.

We included the parameters of the land slide model in Table 4 in the new version of the manuscript. For this reason, we deleted the lines corresponding to 563 to 566 in the previous version of the document.

1.1.1 Description of the flood plain model

• I still have some difficulties to understand the theory behind the calculation of the flood plain. I'm ok with the assessment of the water depth (eq. 11), the friction velocity (eq. 12) and the sediment concentration (eq. 13). Then, I have some trouble to follow the method. Could you please define what is a constitutive coefficient (r) and add a reference for the eq. 14 ?.

We agree with the reviewer; the original explanation of the submodel was confusing. For this reason we edited the corresponding subsection, and added a new schematic figure explaining the steps followed by HydroFlash as follows:

The model requires hydraulic parameters for all network cells to determine flash-flooding spots. The channel width is estimated using the [4] approach $W_i = 3.26\overline{Q_i}^{0.469}$. The channel slope $(S_{i,0})$ is obtained as the mean value of the slopes that correspond to the cells of a hydrological reach. The characteristic diameter $D_{i,50}$ is assumed equal to 0.138 m and constant [?]. The cross-section $(F_{sec,i})$ is obtained from the DEM for every network cell, perpendicular to the flow direction of the cell, $D8_i$, (see step 1 in Figure 1).

For each time step t and for each stream cell, equation 6 determines the height of the water table $Y_i(t)$ using the simulated streamflow $Q_{i,sim}(t)$ and flow velocity $v_{i,sim}(t)$ (step 2 in Figure 1). The model calculates the friction velocity $(v_{fr,i}(t))$ using $Y_i(t)$ as in equation (7) derived from Keulegan and Rouse equations [6?]. Equations 8 and 9 allow the estimation of the concentration $(c_i(t))$ and constitutive coefficients $(r_i(t))$, respectively. The constitutive coefficient summarizes the dynamics associated with flows containing colliding particles, such as a flash flood [6]. In general, the characteristics of an apparent fluid are determined by the relationship between the operating shear stress and the rate of strain, known as the constitutive law. In equation 8, C_{max} represents the maximum sediment concentration; according to ?] C_{max} is near 0.75 during flash floods. The streamflow plus estimated sediments and rubble are estimated according to equation 10.

$$Y_i(t) = \frac{Q_{i,sim}(t)}{v_{i,sim}(t)w_i} \tag{6}$$

$$v_{fr,i}(t) = \frac{v_{i,sim}(t)}{5.75 \log\left(\frac{Y_i(t)}{D_{i,50}}\right) + 6.25}$$
(7)

$$c_i(t) = C_{max}(0.06Y_i(t))^{\frac{0.2}{v_{fr,i}(t)}}$$
(8)

$$r_i(t) = \frac{1}{D_{i,50}} \left[\frac{g}{0.0128} \left(c_i + (1 - c_i) \frac{\gamma_w}{\gamma_{sed}} \right) \right]^{1/2} \cdot \left[\left(\frac{C_{max}}{c_i} \right)^{1/3} - 1 \right]$$
(9)

$$Q_{i,sed}(t) = \frac{Q_{i,sim}(t)}{1 - c_i(t)}$$
(10)

Assuming an infinite sediment and rubble supply, $Q_{i,sed}(t)$ corresponds to the maximum streamflow for each section. The flood depth $F_{d,i}(t)$ is computed following



Figure 1: HydroFlash submodel scheme. 1. The model **wmf** extracts the cross-profile from the network. 2. With equation (13), the model obtains a first approximation to the flash flood streamflow; then, the flood depth and area are obtained with equations (11) to (13). 3. The model obtains the flooded portion of the cross section. 4. Erosion post-process. 5. Filling post-process. 6. The final result is acquired for a time step t.

equation (11), iteratively, such that the difference between the estimated stream flow $(\hat{Q}i, sed(t))$ (equation 13) and the simulated streamflow Qi, sed(t) is less than a predetermined admissible error σ (step 2 in Figure 1). In the process, the model obtains the flooded area $A_{i,sed}$ (equation (12)), the flooded cells for each; section $F_{f,i}$ and the flood depth (step 3 in Figure 1).

λT

$$F_{d,i,j} = b_i + \Delta y \cdot j \tag{11}$$

$$\hat{A}_{i,sed} = \Delta x \sum_{j=1}^{N} F_{d,i} - F_{sec,i}$$

$$\tag{12}$$

$$\hat{Q}_{i,sed}(t) = \left(\frac{2}{5}\right) r_i(t) (j\Delta y)^{\frac{3}{2}} S_{0,i} \hat{A}_{i,sed}(t) \cdot 0.5$$
(13)

The resulting flood maps might include the presence of small isolated flood spots and discontinuities where the flow direction changes from orthogonal to diagonal or vice versa. We included two post-processing steps to correct these issues by (i) using an image processing erosion algorithm [?] to remove the small isolated flood spots (step 4 in Figure 1); the image erosion is performed once with a 3 by 3 kernel. To solve the flow direction discontinuities, (ii) each flooded cell seeks to inundate its eight neighboring cells. A neighbor cell is also flooded if the altitude of the original flooded cell, plus the flood depth, is higher than its elevation (step 5 in Figure 1). An example of the final result for a time step t is shown in the step 6 in Figure 1.

Regarding the constitutive coefficient, we expanded the HydroFlash description including a definition of constitutive coefficient, as shown in the previous paragraphs. Also, in the text we mention that equation (14) is derived form the Keulegan and Rouse equations.

• The main trouble I had, is that you're going into sediment fluxes assessment to calculate flood plain area. What the gain of that method compared to a direct assessment of the flood plain area through the simulated discharge, the simulated velocity and the DEM?.

We could apply the proposed method using only the simulated streamflow. However, there is evidence that suggests that a significant portion of the total discharge corresponds to a concentration of sediments during the event (Qtotal= Qliquid + Qsediments). In the Colombian Andean region, flash flood events tend to have high sediment loads, and we wanted to develop a low-cost model that represents the different processes involved in the flood.

Comments on the results and the discussion

L451 The simulation shows that Event 1 generates a hydrograph with a peak flow of Qmax = 160 m3s1. It is important to note that during precipitation Event 1 there were no damage nor flooding reports by local authorities." Can you link the simulated peak flow value to a flooding / no flooding status ? I mean, could we consider the simulated peak flow as consistent with the fact that they were no flooding reports, or is that assessment to high ?.

Days after the event we talked with the community and the authorities of the region, and they reported high levels in the river the day before the flash flood event, with no inundation or affected people/infrastructure. According to our estimations, a discharge close $200m^3s^{-1}$ is required for an inundation to occur in the area.

L483 "Although some of the surface speed values used in the analysis are unrealistically low". It would be better to directly limit the sensitivity analysis over a range of realistic speed values. The assessment of such a range might be done choosing a range of realistic roughness coefficient (Manning, Strickler, ...), and using the relation between runoff speed (v), and water level (h) under cinematic wave hypotheses ($v = S^{1/2}n^{-1}h^{2/3}$), with S the slope, and n the Manning coefficient. As you mentioned somewhere in the manuscript, this range of observed speed values finally has to be rescaled to be adapted to the model resolution: the transit time along the water paths must be maintain although the DEM data processing can have modified the simulated water path lengths (*Lnum*). In other terms, the ratio *Lobs/vobs = Lnum/vnum* must be kept when rescaling the surface speed range.

We followed the suggestion by the reviewer and only used realistic speeds.

P16 Comments on Figure 10: To describe the sub-catchment I would suggest to indicate as well the surface area [km2] in addition to the percentage of the basin. I also think it could be really interesting to describe the flow peaks in terms of m3.s-1.km2 which can be compared to flash flood features found in the literature (for example, see figure 6, Page 8 in Gaume et al, 2016).

We had included the size of each sub-cachment in the figure, however, the text was very small. We have modified the figure to increase the text. In the same image we include the relation between the peak flow and the area.

P17 Page 17, comments on Figure 12: a) The transit times of the events 1 and 2 are really interesting, because the catchment response is slightly shorter in event 2, while the rainfall storm was located really in the upstream and remote part of the catchment. In contrast the first event was located closer to the outlet, and therefore we might have expected faster response. It's mean that the storage capacity before the event has not only an impact on the magnitude of the flood but also on it timing. The result is not straight forward, and could be mentioned here or in the discussion. b) It's also really interesting to see that the runoff and the subsurface flow start at the same in the event 2, while in the first one, we can see a delay of around 2 hours between the start of those two processes.

Figure 5 shows the temporal evolution of the rainfall over the watershed. According to this figure, the convective (and more intense) portion of the rainfall during Event 1 occurred near the end of the event, explaining the delayed peak discharge time. Additionally, Figure 13 presents the spatio-temporal evolution of the gravitational storage. According to the model, this storage responds quickly to the rainfall, and also, the more relevant increments ocurred at the end of event 1. The described behavior is coherent with Figure 15, in which the elapsed time between the streamflow and the rainfall is shorter near the end of the event. We added a comment in the manuscript.

L528 In event 2, the convective rainfall and the runoff show a similar evolution, denoting a strong influence of the convective portion (figure 12b). From my point of view, it rather means that the stream network (as there are mainly runoff) does not temporize, convert and attenuate the rainfall input signal.

According to former Figure 12b, streamflow runoff accumulation is similar but not equal to the convective accumulation. There is a time lag between both lines, denoting that there are conversions and temporizations due to the stream network. However, we find it very interesting how this relation changes among both events, and we think that this could be related to other factors such as the soil moisture and the spatiotemporal structure of the rainfall. Also, we believe that more work is required in this direction, exploring how rainfall-runoff relations evolve in different events. We included the following text in the document: According to [new] Figure 15b, the accumulations of streamflow runoff and convective rainfall become similar with the increase in time. Additionally, the runoff has a lag and shows signs of attenuation of the convective signal. However, this description only applies for the runoff portion, since the evolution is different when we consider the total simulated streamflow.

P18 Figure 13: I'm still not convinced by the interest of this figure, but it remains your paper.

We erased the Figure from the manuscript.

L578 About the landslide model set up. Do you mean that you have two different calibrations of Z (i.e. S 3) for the landslide model and for the hydrological model? If so, that makes the connection between both model simulations inconsistency.

The parameter S_3 of the model refers to the gravitational water storage. On the other hand, Z is the soil depth. Although both variables are related, they correspond to two different characteristics of the soil.

P19 About the landslide results: First, I would suggest no to insist so much to the difference between the observed and the simulated number of unstable cells. The way to observe landslide are quite qualitative, as – I assumed – it was certainly based on color differentiation between aerial views. The successive soil transport to the landslides and the soil spread through the runoff might have lead to detect unstable cells where there were only sediment charged overflow occurring over it. Second, I would suggest to rather focus on the spatial distribution. I slightly disagree with 'considerably well spatial distribution representation'. I agree that the upstream landslide were really well detected. However the false positive detection in the south part of the catchment should be discussed. Where are the limitations of the landslide model? Is it the fact that the same cohesion or other soil parameter are choose uniform over the catchment ? In that case, different land cover, soil textures, at the good positive and the false positive cells could support this hypothesis. Or is that the landslide model it self that is to simplified ? improvement taking rainfall intensities.

We fully agree with this reviewer's take on the results. Considering both reviewer's suggestions, which do not necessarily coincide in this case, we change the manuscript as follows: The model represents the spatial distribution of the areas that are prone to trigger shallow landslides during Event 2 reasonably well, especially in the upper part of the basin, showing a significant density of unstable cells in the hills where slides took place. This result is important because in that sense, it serves to verify the capability of the model to estimate risk areas only considering topography and rainfall data. On the other hand, there are some false positives in the middle of the basin, which could be related to the poor description of the soils. The landslide model has been used in a nearby watershed with similar characteristics, but with high-quality distributed information [1]. In that case, the model shows a better performance, which highlights the relevance of the input data. A pinpoint localization of the unstable cells is still considered a hard task, in part due to the small temporal and spatial scale at which landslide processes take place [1, 2, 8]. Notwithstanding the difficulties, the results suggest that the model simulations could have been used and should be used in the future for early detection and warning to improve both short- and long-term risk reduction strategies.

L609 It would be interesting to add the proportion of the river length for the different orders.

We agree with the reviewer. We now include a table with a summary of the hills and streams slopes, stream lengths, flooded percentage by order, and relative flooded percentage respect to the total order length.

Table 2: Channels and flooded cells percentages summary. Sh_0 and Ss_0 correspond to the mean hill and stream slope respectively. L corresponds to the total channel length. F Spots and S spots correspond to the flooded and slides percentages respectively.

| Order | Sh_0 [%] | Ss_0 [%] | $L \ [km]$ | F Spots | Ss Spots |
|------------|------------|------------|------------|---------|----------|
| 1 | 60 | 37 | 59 | 5 | 64.5 |
| 2 | 57 | 27 | 26 | 6 | 26.3 |
| 3 | 49 | 13 | 16 | 18.5 | 5.5 |
| 4 | 43 | 9 | 10 | 38.5 | 3.6 |
| 5 | 42 | 6 | 6 | 32 | 0.05 |
| Mean/total | 50 | 18 | 117 | 100 | 100 |

L654 I would suggest to refer to the importance of the rainfall spatial distribution in connection / interaction with the soil storage capacity ones (Zocatelli et al,2010, and to Douinot et al, 2016). Those are exactly the two main differences between the two events.

We agree with the reviewer and have included the reference to both papers. Additionally, we expanded the discussion including the following paragraph in the document: Additionally, when we compare Events 1 and 2, there is an interplay between the rain spatial structure and the soil storage capacity. During Event 1, there is almost no saturation, hence runoff production is low, while Event 2 is influenced by the pre-event water and the occurrence of multiple convective systems over the same region. The structure of the rainfall associated with the La Liboriana event and its interaction with the soils highlights the need to consider in more detail the role of

orographic rainfall intensification in practical applications such as early warning systems. Evidence suggests the spatial structure of the rainfall is at least as important as the geomorphological features of the basin in regulating the generation of flash flood events.

L674 The description of the different order are interesting but I don't see the link with the results present in section 4. Could you specify how did you deduce those assessments?

The reviewer is right, we didn't include support for this conclusion. We added a table containing a geomorphological summary by orders, and also we expanded the discussion based on this Table. The new version of the document contains a text stating the following: Due to geomorphological characteristics (see Table 2), water tends to reach faster the channels in hills of order 1 and 2, and, at the same time, the sediment production and transport in these hills tend to be larger. Order 3 subbasins most likely act as transport elements, with no important energy losses (Table 2), and floods tend to occur at order 4 and 5 subbasins due to the widening of the channel and slope attenuation.

Technical comments

L121 when introducing the 3 models. Similarly to the short description of the hydrological model done between the lines 123 – 126, I suggest to keep the short description of both sub-model initially given in the first version of the manuscript.

We agree with the reviewer. We changed the text as follows: The methodology followed in this study includes a hydrological model [7, 3], a shallow landslides model and a flash flood model. The landslide sub-model follows the formulation described in [1]. The hydraulic sub-model corresponds to a low-cost 1D model (hereafter referred to as HydroFlash) that [assumes infinite sediment supply and] estimates the cross-sectional filled area at all time step.

L123, 137, 390 the sub-model simulated flood plain inundation is alternatively called : "hydraulic sub-model", "inundation sub-model", "flash flood submodel", and "HydroFlash". For a sake of consistency, and clarity, I suggest to choose only one of those terms and use it everywhere in the manuscript when calling that sub-model.

We agree with the reviewer. We have changed the document to just use "HydroFlash", except in the introduction, before calling the model HydroFlash.

- L161 please put bracket around "HAND" We included the brackets following the reviewer's suggestion.
- L190 By soil properties map, I was thinking to spatial distribution of the soil properties, as used to define the hydrological model. It would give an overview of the spatial distribution of the soil classes. I'm still thinking it is of interest. If you don't want to add another map, I would suggest just to adapt the color scale of the slope map to the soil classification. In that way, the reader could guess the spatial distribution and the proportion of each soil class. Another option, might be to add a column in table 1, with those proportions.

We added another column to Table 1 in which we include the total percentage of each soil type in the basin. We also included the spatial distribution map by adapting the Figure 2,

however, it is important to note that this is just an extrapolation of the soil properties based on the slope and it is not a detailed soil map. See the following table and Figure.

...

| Table 3: Description of the soils in the region [5]. | | | | | | | | | |
|--|---------|--------------------|-----------|--------------|------------|--|--|--|--|
| Type | Slope | Depth $[m]$ | Retention | Permeability | Percentage | | | | |
| Class III | < 12 | 0.6 | Low | High | 3.2 | | | | |
| Class IV | 12 - 25 | 0.6 | Mean | Mean | 8.3 | | | | |
| Class VI | 25 - 30 | 1.0 | Mean | Mean | 2.1 | | | | |
| Class VII | 30 - 50 | 0.3 | Too Low | Low | 25.5 | | | | |
| Class VIII | > 50 | 0.2 | Too Low | Low | 60.0 | | | | |

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L196 "Unfortunately [...]." I would suggest to remove this sentence for a sake of conciseness.

We removed the sentence following the reviewer's suggestion..

76.00°W

593

76.05°W

L211 the range of value of the stream discharge [185 - 222] m 3 .s -1 does not correspond to the range of value of the velocities [5 - 7] m.s -1 . A maximum discharge of 259 m 3 .s -1 is expected. Please change either the velocity of the discharge stream range.

The range 5-7 corresponds to observations for another watershed in the region with similar characteristics. However, our estimations were based on a range between 5 and 6, which gives the values of 185 and 222 respectively. We now indicate this explicitly in the document.

Soils map

L213 the sentence "The timing of peak flow is also [an] important information" can be removed.

We removed the phrase following the reviewer's suggestion.

L216 Please refer to the figure 16. Some details of how the contrast between both images are calculated would be welcomed.

We included the following explanation in the document: We empirically performed a detailed contrast between both products by using a geographic information system (QGIS), which provided us with information about flooded areas and landslide locations.

L230 the optimal distance for radar rainfall observation is described twice. Please remove "optimum" line 233 in "optimal optimum" and the sentence line 236 : "The results of the radar QPE methodology indicate that the rainfall estimation works well within a radius of 120 km."

We edited the document following the reviewer's suggestion.

L256 the sentence "Chocó is the [...]" can be removed.

We remove the word following the reviewer's suggestiond.

L296 add a space between "Figure" and 6.

We added a space following the reviewer's suggestion.

Table 3 are the capillarity and the gravitational storage really in mm? Or rather in cm?.

They are in mm. The values appear to be low, but they are consistent with the soils description. However, H_u varies between 27 and 137 mm.

Table 3 table 3: write "capillarity" instead of "capilary".

We changed the word following the reviewer's suggestion.

L358 write "10 parameters" instead of "ten parameters".

We changed the word following the reviewer's suggestion.

L363 please specify here the objective of the calibration. Here a suggestion: "The model simulation is calibrated to reach a base flow of 3 m 3 .s 1 . The calibration consists in scaling each physical parameter by a constant value in the entire basin (Francés et al. (2007b)). Table 3 includes the mean value for all the parameters used in the model and the scalar value adjusted during the model calibration."

We included the reviewer's suggestion. The manuscript now states: The model simulation is set to reach a base flow of 3 m³s⁻¹, a value that corresponds to the discharge measurements during field campaigns days and weeks after the flash flood event and during dry spells. To set the soil wetness initial conditions realistically, the model runs start two days prior to Event 1. Before this period, there were only a couple of small rainfall events; for this reason, the overall wetness was set to represent to dry conditions at the start of the simulation. Table 3 includes the mean value for all of the parameters used in the model, and the scalar value is adjusted during the model calibration. In this implementation of the model, we left uncalibrated the channel speed, the subsurface speed, the aquifer losses, and the capillary and gravitational storages (see Table 3). The values for these parameters are inherited from a local watershed with similar characteristics. L367 the reference date is missing for "Aristizabal et al. ..."

We included the year following the reviewer's suggestion.

Eq 6 to 10 equation 6, 7, 8, 9, 10 : In the equation, the index "i" referring to the cell "i" of the catchment is specified in the left side of the equation but not in the right one. Please either specify the "i" index to any or no one of the parameter with cell dependent value.

We edited the equations in order to specify the index according to the revierwer's suggestion

Eq 16 the index "j" should be added to the parameter Fd,i which depends on it.

We added the "j" following the reviewer's suggestion.

L449 please remove the sentence "The model simulation is set up [...]". It refers to the method and therefore should be inserted in the section 3.

We removed the sentence following the reviewer's suggestion.

L470 the observed timing could be indicated in brackets, as a remember.

We followed the reviewer's suggestion.

L482 "particularly in the low end values", do you mean the discharge recession?.

The reviewer is right, the manuscript was not clear in this section, we change the text to: **particularly during the peak flow and early recession.**

L496 those lines correspond to the method description and should be inserted in section 3.2.

We moved the lines to the end of the **Hydrological modeling framework** subsection, which is inside the **Modeling** section.

L516 The first sentence "It is well known [...]" is not relevant and could be remove for a sake of conciseness.

We agree with the reviewer and we removed the phrase: "It is well known [...]".

Figure 2 unit of the slopes is [-] and not [mm. -1].

We corrected the error following the reviewer's suggestion.

Figure 5 plot a) y-axis: please confirm the rainfall unit : [mm / 5 min] ?.

The original units were in fact mm/5min, however that is an odd unit to present rainfall. In the new manuscript we changed the units to mm/hour.

All Within all the manuscript : choose between "sub-model" or "submodel" and maintain the same spelling.

We changed the monuscript to use the word submodel.

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Response to Reviewer 2 (Dr. Eric Gaume)

May 28, 2019

Manuscript title: Reconstructing the Salgar 2015 Flash Flood Using Radar Retrievals and a Conceptual Modeling Framework: A Basis for a Better Flood Generating Mechanisms Discrimination

Authors: Nicolás Velásquez, Carlos D. Hoyos, Jaime I. Vélez, and Esneider Zapata

General Concept:

The manuscript has been substantially modified after the first reviews. This new version deserves nevertheless some major improvements before a publication in HESS can be considered to my point of view. An annotated manuscript is joined to this review. Six major points need especially improvement.

We sincerely thank Dr. Eric Gaume for his reviews and suggestions. We find most of them very useful, however, we disagree in some of the points he raised during this round of reviews. In particular, we would like to stress, as it is mentioned in the paper, that the information available for La Liboriana basin is limited, hence there could not be a perfect validation of the model. The conditions for La Liboriana basin, and the lack of data, are not unique of this region, but we must strive to develop strategies to provide risk management tools for these areas. We believe we do that in our work, based, as much as possible, on a conceptualization of the physical processes leading to the triggering of the flash flood. As we did during the first round of reviews, we have taken in serious considerations all the issues raised by Dr. Gaume, and have responded to his concerns both in the paragraphs below and within the manuscript. We feel the current manuscript is an improvement thanks to the reviewer comments. Below, the reviewer comments are in black and our comments are in "blue". Event though we do not agree 100% with Dr. Gaume, we acknowledge that his comments were constructive. In the cases we do not agree with the reviewer, we try to state it clearly.

1) The manuscript is based on a very limited amount of inaccurate observations: a single peak discharge, estimated at a cross-section located downstream the considered watershed, radar quantitative precipitation estimates from a radar located 90 km far away from the considered mountainous area with no ground raingauge or even amateur measurements confirming the estimated amounts and two aerial photographs for the location of landslides. This is very little to support the implementation, calibration and validation of a physically based distributed model.

This is perhaps the main difference we have with Dr. Gaume. We certainly agree that, in general, the information available to reconstruct La Liboriana flash flood is very limited. However, that is precisely the point. If there was enough information perhaps the point of the study would be very different. The goal of the study, which takes into account the fact that the information is scarce, is to test a low-cost methodology to reconstruct the main features of the Salgar flash flood. As mentioned before, the conditions for La Liboriana basin, and the lack of data, are not unique of this region, but we must strive to develop strategies to provide risk management tools for these areas. We believe we do that in our work, based, as much as possible, on a conceptualization of the physical processes

leading to the triggering of the flash flood, and the observational evidence available. Information from a C-band radar 90 km away is considered, in general, very good information, especially considering the high-resolution scanning strategy used at SIATA. In the original revision, we provided evidence of the quality of the QPE, and we provide more evidence of the spatial scale of the radar information in this revision.



Figure 1: In situ water stage sensor installation after the flash flood.

Additionally, we have included a new analysis of the model based on water stage data, using measurements from an in situ radar sensor (see Figure 1) installed at the same time as the rain gauges used to validate the QPE technique (the rain gauge information was included in the first review, and it is included in the work by Hoyos et al. (2019)). We include the rainfall information in this response, once again:

About rainfall estimates The radar QPE methodology uses rainfall gauges and disdrometers within the radar domain. The results indicate that the rainfall estimation works well within a radius of 120km (La Liboriana is located at 90km). Despite the distance between the radar and the basin, and the mountains between them, there are no blind spots in this region for the radar. Figure 2 shows a comparison between the radar QPE and two rain gauges stations installed 3 days after the event The correlation among the hourly precipitation records is 0.65.





After the flash flood event, SIATA installed a stream gauge level station near the outlet of the basin (see Figure ??). We use these records to validate the model results without further calibration.



Figure 3: Comparison between hydrological model simulations and streamflow estimations. The events were observed by a level station installed by SIATA days after Event 2 on a bridge at the outlet of the basin (see Figure ??)

Since the observed series correspond to level values, the streamflow estimation is performed following two different approaches. The first approach, the empirical one, consists of subtracting the 10th percentile of the observed stage time series from the observational record, and the 10th percentile of the simulated streamflow, from the same series. On the other hand, the second method uses the Manning formula. For this, we consider the geometry of the section in Figure ??, and the slope from the DEM. Additionally, due to the potential uncertainties, we consider three different Manning values (0.015, 0.02, 0.03). Figure 3 shows the estimated streamflow using the two methods for four different hydrographs during July, August (2 events) and December 2015. The simulated magnitudes appear relatively close to the observations, and the peak discharge time is captured skillfylly in three of the four cases presented. The discharge values using the "high" Manning number estimation (0.015) are similar to the empirical method. The performance of the model is acceptable (Figure 3), considering the lack of calibration, the size of the basin, and the magnitude of the recorded events. The results shown include cases where the peak flow was over-estimated (panels c and d), and under-estimated (panel b).

The evidence in the previous paragraphs, together with the sensitivity tests, in our opinion, are sound enough to consider the main conclusions of the paper robust.

2) Some additional data are mentioned in the manuscript a) direct discharge measurements in nearby watershed supporting the proposed average cross-sectional velocities between 5 and 7 m/s at line 220 and b) comparisons between radar QPE and measurements of two raingauges installed after the event at line 240. But, this important information to assess the accuracy of the estimated values is not provided in the manuscript. There is neither reference to any publication the readers could refer to. All information necessary for the analysis should be either provided or accessible.

In the first round of reviews, we included all the information mentioned by Dr. Gaume in the response. We are now including the information in this response, again, and some of it has been

included within the paper (See previous response, and the response to the detailed issues), within the main manuscript, or as an appendix.

3) The presentation of the models remains partial and confused. The model contains numerous parameters or variables that are not all defined in the text or which units are not given (see annotated manuscript). All the parameters defined in table 3 do not appear in the presented equations. The article is not clear on how the model is implemented: which parameters are calibrated, why and how, how is the value of the other parameters fixed and how are the initial conditions determined. Initial conditions are crucial for the considered rainfall events with limited rainfall amounts (less than 50 mm on average for both events).

We have improved the description of the models, and we have made sure all the parameters are properly included. The comments from both reviewers were very helpful. We now believe the calibration procedure is clear, and we included a clear description on the soil wetness initial conditions used in the simulation. We would like to stress that the rainfall appears modest only if it is considered as the average of the basin, but the intensity in the upper part of the basin is approximately 3.5-4 times the value mentioned by Dr. Gaume.

4) The article contains some obvious major errors. The flood volumes given at line 490 do obviously not correspond to the presented results (see annotated manuscript)! By the way, the simulated runoff rates for both events exceed largely 50%. This is extremely surprising, considering the limited total rainfall amount of both events and the experience of other extreme flash floods over the world (see Marchi et al., 2010 for instance). This of course is a modelling result, but is it realistic? I have some doubts.

We had made a mistake (a typo) in the units used to describe the volumes. We thank Dr. Gaume for pointing it out. We have corrected our mistake. Again, the rainfall appears modest only if it is considered as the average of the basin, but the intensity in the upper part of the basin is approximately 3.5-4 times the value mentioned by Dr. Gaume. We are convinced the results are robust, despite the lack of data. The paper includes evidence supporting the discussion and conclusions.

5) The authors are not critical enough about their own results. The landslide mapping result illustrates this particularly well. The results presented in figure 15 are considered as excellent by the authors. But, first it seems quite obvious that landslides will predominantly affect the upstream areas that have the steepest slopes and have been affected by the most intense rainfall. Moreover, a detailed look at figure 15b shows that the simulated landslides are by far less concentrated and localized on the watershed than the observed ones. Likewise, the maximum simulated number of unstable cells at the very beginning of the rainfall event (figure 15c, is a surprising and probably unrealistic results that would deserve some comments...

We acknowledge the potential limitations of the landslide and flash flood submodels in different parts of the paper, including, explicitly, in the conclusions. We also mention the limitations due to the DEM and the lack of detail soil information. During Event 2, the soils were saturated, and the intensities during the fist part of the event were extreme in the upper part of the basin (as shown in this document), and as it was mentioned in the manuscript. Intense rainfall during the fist part of the event appears responsible for the unstable cells during the beginning of Event 2. In our view, and considering the overall evidence, it is a realistic result. That is precisely why we are considering both events in order to reconstruct the flash flood event. Without Event 1, there wouldn't be flash flood. See the answers to the detailed comments below for more information.

6) Most of the paper analyses and comments the results of the proposed poorly calibrated and not validated models. This is moderately interesting and does not support, as I did mention in my previous review, the conclusions drawn by the authors about the dominant hydrological processes during this flood event. Neither the title of the manuscript, nor the conclusions correspond to the real content of the paper. The proposed procedure, based on very little real information about the flood and moreover inaccurate information, can by no way help discriminating flood generating mechanisms.

We have addressed most of the issues raised by the reviewer. Considering the comments by Dr. Gaume, we modified the title of the paper to "Reconstructing the Salgar 2015 Flash Flood Using Radar Retrievals and a Conceptual Modeling Framework in an Ungauged Basin". We do believe that the conclusions mention clearly enough, in different places, that the results come from a modeling framework and could be flawed given the data scarcity, for example: The limitations of the methodology presented in this work do not allow representing all the detailed small-scale preferential pathways of the water in the watershed, but rather focus on the first-order processes to study the partitioning between runoff vs. subsurface flow. Additionally, the model results are used to obtain a conceptual idea about the general processes, but it must be taken into account that the simulations are subject to a calibration process that could lead to erroneous conclusions about the mentioned processes. This consideration could be true even when different steps were taken trying to avoid this situation.

Marchi, L., Borga, M., Preciso, E., and E. Gaume, 2010: Characterisation of selected extreme flash floods in Europe and implications for flood risk management. Journal of Hydrology, 394 (1-2), 118-133. doi:10.1016/j.jhydrol.2010.07.017.

Several changes were made to the manuscript to improve the description of the methods and to correct problems with the structure of the document.

Detailed comments

FIGURE 1 on the left bank of the river more precisely. The houses on the right bank remain.

All the houses shown in the image are on the before-and-after images are on the right bank. Additionally, all of the houses shown standing in the 2015 image had to be either demolished or structurally repaired. We added this comment to the figure caption.

L104 This sentence maintains the ambiguity about the aim of the work raised by the editor : is it focussed on modelling or on event analysis ? The aim, to my point of view is event analysis.

We rewrote the beginning of the paragraph: La Liboriana basin is a typical case of an ungauged basin (Sivapalan et al., 2016; Seibert and Beven, 2009; Beven, 2007; Bonell et al., 2006; Yamanaka and Ma, 2017), with non-existing detailed records of soils or land use, topographic maps or digital elevation models, and scarce hydro-meteorological data, certainly not available in real time. Due to the lack of data, the reconstructing of La Liboriana flash flood is a challenge...

L149 Relatively rough resolution considering the size of the river bed (cf. figure 4).

Here we agree with Dr. Gaume. The resolution is indeed far from ideal. Unfortunately 12.7m is the highest resolution freely available for the region. Additionally, we want to express and to stress that this lack of information is usual at several regions in developing countries. We wanted to develop and to test a methodology applicable for this type of regions, with scarce information. This is mentioned in a few places in the document, and it has been stressed even more in the current version.

L172 areal



Figure 4: Scatter plot of water level (depth) (cm) and surface speed (ms^{-1}) for Doña Maria basin, located in the Aburrá Valley.

We have corrected the word to **aerial** in several places in the document.

TABLE 1 Change word **Slow** to **Low** at Table 1.

We changed the word following the reviewer's suggestion.

L200 How has the speed been measured during a post-event campaign. It has certainly been estimated...

We measured the surface water speed at the time of the visit, at different points of the streamflow, using a hand-held Stalker Pro II surface velocity radar. We have included the latter information in the manuscript. For detail technical information on the sensor we provide the link to their web site: .

203 The considered cross-section is located immediately upstream a bridge. Is the cross-section not reduced under the bridge. What about the possible effect of the overflow of the bridge which seems to have occurred ?

The cross-section is located downstream the bridge. We added that comment to the Figure caption.

L209 For which discharge value and water level. Some direct measurements have been performed. Please provide these measurements at least in an appendice.

We change the sentence to: During the campaign, we measured surface speeds in the channel oscillating between 2 and 3 ms^{-1} , for a $3 \text{ m}^3 \text{s}^{-1}$ discharge.

L212 Please be more accurate. Do the author speak about maximum measured velocities, average cross-sectional velocities. Are the river bed slope comparable. Provide also these data.

We recorded surface velocities in a watershed with similar characteristics. This watershed has an area of $73km^2$ and a slope of 34%. In the Figure below we present the surface velocities versus the flow depth. We included the figure as an appendix.

L215 Cite the sources in each case.

We modified the text as follows, including a footnote with the URL:

Local authorities reported that the peak streamflow reached the urban perimeter after 2:10 a.m. on May 18th (personal communication during the field visit).

Some reports state that the peak flow in the most affected community occurred at approximately 2:40 a.m¹.

L220 Google is not the provider of the image. What is the source of the images ?

The reviewer is right. The source of the image is **Digital Globe CNES** / **Airbus**. We changed the manuscript accordingly.

L241 Not totally convincing in the absence of direct local ground rainfall measurements.

The methodology relies on the reflectivity measured by the radar, and not on the QPE technique. The text was modified as follows:

In addition to the rainfall quantification, radar retrievals, before feeding the hydrologic model, are classified in convective and stratiform areas following a methodology proposed by ? and Steiner et al. (1995), based on the intensity and sharpness of the reflectivity peaks. The methodology has been widely used in tropical regions as reported in the review by Houze et al. (2015).

L250 Could a return period be proposed for these values in the area?

One of the goals of the Hoyos et al. (2019) work is to assess the likelihood of occurrence of extreme events similar to the one, or to the ones, triggering La Liboriana flash flood. Hoyos et al. (2019) state that is important to evaluate whether or not the characteristics of the May 18, 2015 flood were exceptional, and ideally, estimate their recurrence rate. In a traditional sense, it would be desirable to estimate a return period of the conditions that led to the la Liboriana flash flood. While the length of the historical radar QPE record is not enough for a robust estimation of the mentioned return period, the Hoyos et al. (2019) allows to conduct a preliminary assessment of the exceptionality of the precipitation conditions associated with the event. Hoyos et al. (2019) show that the individual event on May 18 was not exceptional, the climatological anomalies were negative-to-normal, and the synoptic patterns around the extreme event were similar to the expected ones for the region, but the combination of high rainfall accumulation in a 96-hour period as a result of successive precipitation events over the basin, followed by a moderate extreme event is unique in the available observational record, in particular for the upper part of the basin. We added a short comment in the manuscript.

L252 According to the estimated rainfall amounts based on the radar measurements... These are estimated values.

We changed the sentence to: Event 2 accumulated, on average over the basin, approximately 38 mm; however, over the upper watershed, the accumulation exceeded 180 mm according to the estimated rainfall amounts based on the radar measurements. Figure ??a presents the temporal evolution of the estimated convective-stratiform rainfall partitioning during both Events 1 and 2.

L258 Please provide the mean annual precipitation to support this statement.

We removed the sentence following a suggestion by the other reviewer. In any event, here is the fact: Chocó is the rainiest department in Colombia, and one of the wettest places on Earth, due to the inflow of moisture from the Pacific Ocean and the orientation of the Andes mountain range (Poveda and Mesa, 2000; Mapes et al., 2003), with several municipalities experiencing average annual precipitation between 8,000 to 13,000 mm.

FIGURE 5 the unit is probably mm/5min. If so, the intensities may be considered as modest if compared to other areas in the world (maximum 5 min intensity of 40 mm/h).

¹As reported by the media and the national government: http://www.elcolombiano.com/antioquia/ tragedia-en-antioquia-salgar-un-ano-despues-XX4145514, https://caracol.com.co/emisora/2015/12/ 25/medellin/1451076926_792470.html, http://portal.gestiondelriesgo.gov.co/Paginas/Noticias/2015/ Antecion-Emergencia-Salgar-Antioquia.aspx

The figure has been modified following the reviewer's suggestion. We agree, the intensities were modest if one considers the average of the precipitation over the entire basin, which is one of the points we make in the paper. The intensities in the upper part of the basin during the triggering rainfall event are, however, 4-5 times that of the entire basin.

FIGURE 5 The unit of the axis could have been better chosen (3 hours rater than 2h55).

The figure has been modified following the reviewer's suggestion.

L285 What is the size of a cell?

We have now included the spatial resolution of the model. The text now reads as follows: The model distributes processes by cells with a spatial resolution of 12.7 m (same as the DEM used); in each cell, five tanks represent the hydrological processes including capillary (tank 1), gravitational (tank 2), runoff (tank 3), baseflow (tank 4) and channel storage (tank 5).

L305 The generic equation 1 is not really useful since the detailed equations used for each "tank" are given in eq 2 and 3 (v4 is missing). The presentation of the model is improved but still not totally accurate. All variables and their units are not described (such as v for instance which is certainly a discharge divided by a cross-section).

We made several changes regarding the reviewer's comments from L305 to L330:

- L304 We included the area units (that are m^2).
- L305 We included a description for the v_{tank} variable as follows: Finally, v_{tank} correspond to the estimated velocity in m/s.
- L320 We included the equation for v_4 , which in this case is constant for each cell.
- L321 We included the following text in the paper: On the other hand, equation (4) corresponds to a linear approximation. In this case, the model assumes the speed as a constant value over time, and the total outflow from the tank is estimated through a linear tank approximation (equation (7)). Under this approximation, L[m] corresponds to the length of the cell, which is Δx when the downstream connection is orthogonal and $\Delta x \sqrt{2}$ when it is diagonal.
- L326 According to the equations, the numerical scheme seems to be explicit. The computation time step must be carefully selected for the scheme to be stable and limit numerical diffusion. How is this done in the proposed model ?

The solution for v_i is obtained by using the successive substitution method described by ?. In the model we use a 5-minute time step which ensures the stability of the computations. This comment was added to the manuscript.

L328 To be consistent vtank should be replaced by vi)

We changed v_{tank} for v_i as suggested by the reviewer. We also changed it for other variables, to be consistent.

L329 Etank : please provide units again).

 $E_{tank}(t)$, now $E_i(t)$ is in mm. This is now clear in the manuscript: Finally, the total outflow from the tank is calculated using equation ??, in which $E_i(t)[mm]$ represents the outflow from an storage at time step t.

L343 There is a priori no possible direct latteral flow from the subsurface to the river system. If I understand well, return flow from subsurface to the surface is necessary. This may limit the relative contribution of subsurface flow to the flood flow in the proposed model... This should be acknowledged by the authors.

We are not sure we totally follow this comment. The model, in its current conceptualization, does include the possibility for lateral flow to the river system. If a cell has a direct connection with a channel, there is lateral flow to the river (See Figure 6 in the manuscript). In the model, there are two mechanisms to produce runoff: The model generates runoff as a response to high precipitation intensity (Hortonian), and runoff produced by saturation (return flow). These considerations imply that the return flow is not necessary for runoff generation. We know that subsurface supply is limited during a flash flood, however, there is a significant amount of subsurface water over the hills which likely will reach the streamflow.

L355 Such a spatial resolution for radar products appear relatively unreasonnable to me. Typically, C-band reflectivities and intensities are provided at a kilometric scale.

Usually weather services operate radars focusing only on the main meteorological aspects of the storms, without considering in depth hydrological and risk management applications. Also, there radars are operated using a standard protocols developed to easily develop national (NEXRAD in US) or continental (OPERA in Europe) mosaics, loosing information in the local scale. The reviewer is right, most met services provide a kilometric resolution. It all really depends on the angular velocity of the scans. NEXRAD and OPERA scans are usually pretty fast to be able to complete many sweeps, with different tilts, in a period of 4-6 minutes. We, at SIATA, given our risk management goal, operate the radar to obtain higher spatial resolution retrievals (with the burden of hard-drive space), scanning fewer vertical levels. The 1° tilt PPI is performed at 5 deg/s, with a 0.5 μ s pulsewidth, and a 1180 Hz PRF.

Figures 5 and 6 show examples of instantaneous radar retrievals (precipitation), and cumulative rainfall during events 1 and 2, at two different moments. The images show evidence of the spatial resolution of the retrievals.

L364 The parameters were fixed. If they have been calibrated, please explain the procedure and the criterion used.

The parameters of the model were obtained from a modeling exercise for a gauged watershed in the region. The parameter associated with the base flow as fixed as a function of the streamflow recorded during the field visit a few days after the event. In the manuscript, the following text has been added/modified: The model simulation is set to reach a base flow of 3 m³s⁻¹, a value that corresponds to the discharge measurements during field campaigns days and weeks after the flash flood event and during dry spells. To set the soil wetness initial conditions realistically, the model runs start two days prior to Event 1. Before this period, there were only a couple of small rainfall events; for this reason, the overall wetness was set to represent to dry conditions at the start of the simulation. Table ?? includes the mean value for all of the parameters used in the model, and the scalar value is adjusted during the model calibration. In this implementation of the model, we left uncalibrated the channel speed, the subsurface speed, the aquifer losses, and the capillary and gravitational storages (see Table ??). The values for these parameters are inherited from a local watershed with similar characteristics.

TABLA 3 This is a low value (about 5 mm/h) for soils that are described as permeable (see table 1)

The value (5mm/h) was obtained using the description of the soils given by Osorio (2008). However, we share the same concern about the value being relatively low, and this is somewhat confirmed by the need to use scalar calibration parameter of 2.7, as shown in table 3, effectively increasing the infiltration rate.

TABLA 3 This value seems high.

First, the value represents the average magnitude of the coefficient corresponding in equation (1), and not directly to surface velocity. Similar to the previous comment, we use a scalar value of 0.5, effectively reducing the overall magnitude. This is now clear in Table 3.





Figure 5: Instantaneous radar retrievals (precipitation), and cumulative rainfall during event 1 at two different moments.

TABLA 3 All parameters are not described in the previously presented equation. The velocities appear here as fixed whereas they seem to result from a computation in equations 2 and 3. The presentation of the model is still confused.

The model has ten scalar parameters that could be modified during the calibration process. In this implementation of the model, we left uncalibrated the channel speed, the subsurface speed, the aquifer losses, and the capillary and gravitational storages. As mentioned in the manuscript, The values of these parameters were adopted from a near similar watershed.

L376 Again the description of the model is partial. C' is not described.

We have included the description of C' in a better place in the manuscript: ...and the soil cohesion C'_i .

L385 $S_{3,t}$ rather than $S_{3,i}$

We changed $S_{3,t}$ for $S_{3,i}(t)$ in the text description and in the equation.



Figure 6: Instantaneous radar retrievals (precipitation), and cumulative rainfall during event 2 at two different moments.

L389 What is the usefulness of equations 6 to 8 ? The text only refers to equations 9 and 10 for the stability computation...

We changed the description of former equations 6 to 10 as follows (now equations 9 to 13): The slope failure occurs when the saturated soil thickness above the slip surface $Z_{i,w}$ (equation (??)), which depends on the gravitational storage $S_{3,i}(t)$, the soil wilting point $W_{i,pwp}$, and the soil field capacity $W_{i,fc}$, is greater than a critical saturated depth $Z_{i,c}$ (equation (??)). The critical saturated depth depends on the shallow soil depth Z_i , the soil bulk density γ_i , the water density γ_w , the gradient of the slope $\beta_{i,0}$, the soil stability angle ϕ_i , and the soil cohesion C'_i According to the soil stability definition, the topography and the soil properties, all cells are classified into three: unconditionally stable, conditionally stable and unconditionally unstable. In particular, three parameters determine the stability of each cell: (i) residual soil thickness water table $Z_{i,min}$ (equation (11)), (ii) the maximum soil depth at which a particular soil remains stable $Z_{i,max}$ (equation (12)), and (iii) the maximum slope at which the soil remains stable $\beta_{i,0}$ (equation (13)).

L397 Why is the channel width fixed and not directly obtained from the DTM ?



Figure 7: HydroFlash submodel scheme. 1. The model **wmf** extracts the cross-profile from the network. 2. With equation (19), the model obtains a first approximation to the flash flood streamflow; then, the flood depth and area are obtained with equations (??) to (??). 3. The model obtains the flooded portion of the cross section. 4. Erosion postprocess. 5. Filling postprocess. 6. The final result is acquired for a time step t.

As the reviewer mentioned, the spatial resolution of the DEM doesn't allow us to obtain an approximation of the channel width.

L399 The Manning roughness value could be directly provided...

The original model conceptualization does not make direct use of the Manning roughness. It rather uses an approximation of the characteristic diameter or the mass-median diameter D_{50} .

L400 The last sentence is unclear. A depth is needed to compute a cross-section or wetted area. How is this depth evaluated. How can the computation be conducted in each cell separately ?

The cross-section $(F_{sec,i})$ is extracted from the DEM at each cell that belongs to the network. For the extraction of the cross-section, the distance from the network cell is measured perpendicularly if the cell direction zonal or meridional, and diagonal otherwise. We have included a new schematic diagram that explains the overall methodology followed in the flash flood submodel.

L429 Not clear at all.

We rewrote the paragraph: Assuming an infinite sediment and rubble supply, $Q_{i,sed}(t)$ corresponds to the maximum streamflow for each section. The flood depth $F_{d,i}(t)$ is computed following equation (??), iteratively, such that the difference between the estimated stream flow $(\hat{Q}i, sed(t))$ (equation ??) and the simulated streamflow Qi, sed(t) is less than a predetermined admissible error σ (step 2 in Figure 7). In the process, the model obtains the flooded area $A_{i,sed}$ (equation (??)), the flooded cells for each; section $F_{f,i}$ and the flood depth (step 3 in Figure 7).

L439 This approach appears uncommon to me. It is possibly interesting but not clearly enough prensented to be really understood. If it has been already presented in previous papers, refer to these publications and skip the details. If not, it would deserve a separate publication providing more details and some validation results.

We included an schematic diagram explainin step-by-step the flash flood submodel methodology. The explanation is included in the section: HydroFlash

L449 1 value for the calibration of 10 different parameters. This is clearly insufficient. Please explain how, and which parameters exactly were adjusted.

We agree that one value for a calibration is not sufficient. However, our study is not a model calibration exercise. Our main goal is to provide a comprehensive idea of what happened during the flash flood event. That is precisely why we stressed in the document that this is an ungauged basin. In the current version of the manuscript we have expanded the explanation about the calibration procedure followed in this exercise.

L453 yes, but would the 160 m3/s have generated inundations according to the proposed model ? This value is not very far from the simulated value for the second peak (220 m3/s) which induced catastrophic damages. I would therefore say, that the first simulated peak discharge is probably over-estimated by the model.

We respectfully disagree. According to our estimations, a discharge close $200m^3s^{-1}$ is required for an inundation to occur in the area. People from the town did report that the day before the flood the river level was considerably high, but there was no flooding.

L463 This of course is according to the proposed model, which could not really be calibrated... By the way, how where the initial soil wetness conditions set ? They may play an important role for event 1.

The sentence was changed to: [The Figure] presents the capillary storage (purple), as well as the runoff (continuous blue) and the gravitational (dashed blue) storage temporal variability as represented by the proposed model.

To set the initial conditions realistically, we started the model runs two days before Event 1. Before this period, there were only a couple of small rainfall events; for this reason, the overall wetness conditions were set to dry. This comment was added to the text.

L486 A legend is missing for this figure (significance of each line). Te lack of sensitivity to the infiltration rate parameter is quite strange and deserves some additional explanation.

We have changed the figure to add legends, and we also changed the figure caption and the description: Hydrological simulation sensitivity analysis. Hydrological simulation sensitivity analysis. Similarly as in Figure 9, all panels show the simulated streamflow, and the runoff and subsurface flow separation. Total streamflow is purple, runoff is green and subsurface dashed purple. The left panel shows sensitivity to changes in the infiltration rate parameter, the middle panel to changes in surface speed, and the right panel to changes in subsurface speed.

We do vary the infiltration parameter. We included a better explanation of the sensitivity analysis: In the sensitivity analysis, we vary the infiltration parameter between 0.02 and 20, the surface speed parameter between 0.01 and 20, and the subsurface speed parameter between 0.1 and 10.

L487 These results raise some questions. The flood has been predominantly generated on the upper part of the watershed (8.9 km2). The flood hydrograph has been transferred with some added volumes to the outlet, but the timing of the peak discharge is the same everywhere along the stream as if the transfer times were negligible.

There is actually a difference of about 35min between the hydrograph of the upper portion of the watershed and the hydrograph of the outlet. This is plausible with a travel speed between 5 and $7 m s^{-1}$ for an effective distance of 14km. A comment has been included in the manuscript.

L490 There is a problem here with the computation of volumes. The upstream hydrograph volume is about 138 (m3/s) *3 (hours) * 3600 /2 =745000 m3.(rough triangular approximation). This is consistent with the rainfall amount and is equivalent to 84 mm of runoff for the 8.9 km2 of watershed.

The reviewer is right; we made typo in the magnitude/units used in the text. We have corrected the text: In terms of volume, approximately 737,000 m³ of the total 1,438,000 m³ simulated at the outlet of the basin are generated on the 15% upstream part of the watershed, corresponding to about half of the total mass. In terms of peak flow, due to the slope and velocity changes, the simulated discharge at the 15% upstream part of the watershed corresponds to 50% of the peak discharge at the outlet of the basin.

L513 Interesting figure, but too small to be read and understood.

The reviewer is right. We modified former Figure 11, and included Figures 12 and 13.

L523 The higher value of elapse time for event 1 may be surprising taking into account that this event has predominantly affected the downstream part of the watershed. I suppose that the elapse time is computed based on the downstream hydrograph.

Figure 5 shows the temporal evolution of the rainfall over the watershed. According to this figure, the convective (and more intense) portion of the rainfall during Event 1 occurred near the end of the event, explaining the delayed peak discharge time. Additionally, Figure 12 presents the spatio-temporal evolution of the gravitational storage. According to the model, this storage responds quickly to the rainfall, and also, its more relevant increments occurred at the end of event 1. The described behavior is coherent with Figure 14, in which the elapsed time between the streamflow and the rainfall is shorter near the end of the event. We added a comment in the manuscript.

L524 Please provide a clearer explanation on how this elapse time is computed (equation maybe). Of course the difference is a modelling result.

We have added the following sentence.: We compute the elapsed time between the rainfall and the simulated streamflow by measuring the time differences between the lines for the cumulative rainfall and streamflow in Figure 14.

L532 The simulated runoff values about 1120000 m3 for event 2 according to the hydrograph, which means about 21 mm for the 57 km2 are extremly high for such moderate rainfall volumes especially for a vegetated watershed...

We also think that it is high. However, our hypothesis is that this high value was triggered by the antecedent conditions of the watershed, and the structure of the rainfall, with very large cumulative values in the upper part of the basin, over the steepest hills. Event 1 preconditioned the soil wetness over the entire basin. Additionally, during the event, there were two convective systems that occurred sequentially, and over the same region of the basin. We have deleted former Figures 13 and 14 following the suggestions by reviewer 1. Some of the analysis from these figures was moved to the discussion section..

L537 This is probably true

The overall evidence seem to suggests that the spatio-temporal distribution of precipitation, enhanced by orography, and the training convective elements, are in fact one of the most important discriminating factor between both events, and for the occurrence of the flash flood event.

L560 These figures are not easy to understand. Moreover, they provide interpretations of the output of the model. The real question is : is the model faithful ?

We have deleted former Figures 13 and 14 following the suggestions by reviewer 1 and the comments by Dr. Gaume.

L572 As for the rainfall-runoff model, the authors do not describe the calibration procedure : which parameter has been calibrated and how ?

The text does in fact include a description of the calibration of the landslide model: Calibration of the landslide model was performed by finding the maximum overlap between simulated and observed unstable and stable cells, and at the same time reducing the overall number of false positives and false negatives. It is important to note that the calibration strategy is not a cell-by-cell modification of the parameters involved but rather a basin-wide modification of soil properties. A sensitivity analysis of soil parameters is carried out by making small variations of the variables within specified intervals: ϕ between 25 and 32, γ between 17 and 19, C' between 3.5 and 4.2, and Z between 0.1 and 3 m. The sensitivity analysis suggests that slight variations in the parameter in Z produce significant changes in the results, with overestimation of the number of unstable cells or no unstable cells at all.

Also, table 4 includes a description of the parameters of the landslide model, and a summary of the scalar calibration factors.

L581 We understand that the average soil depth is the calibrated parameter. The calibrated value appears unrealistic. What is the conclusion bout the model.

Correct. The depth of the first layer oscillates between 0.1 and 3m; this according to the soils descriptions of the region (Osorio, 2008). Most of the landslides occur in category VII soils (30 cm depth), and the best results were obtained assuming the depth was around 10 cm. The latter value is actually not that unrealistic given the magnitude of the slopes. Similar values are also reported by other authors (Bordoni et al., 2015; Bui et al., 2018).

L583 What is done is not clearly explained here but does not seem to be scientifically rigorous.

We disagree. We have less than perfect information about the soils in the basin. In the model we use a single calibration factor for the entire basin, maintaining the soil depth dependence on slope, as suggested by (Osorio, 2008). Yes, all calibrations lack robustness, however, models require it due to simplified conceptual framework and the limited or non-existing observations errors. The calibration of this parameter is also suggested by the original author of the land slide model (Aristizabal, 2016).

L590 The right location is a relatively obvious results : they are located in the area with the larger slopes which, by chance, have been affected by the most intense rainfall rates during event 2... No surprise there.

We agree with the reviewer, no surprises. But it is important that the model represents fairly well the observations. It shows the model output could be use for risk management guidance. In the literature, several authors recognize it is difficult to simulate accurately the location of shallow land slides (e.g. Wu and Sidle, 1995). On other topic, the spatial distribution of precipitation is not a result of chance, but that is not the topic of the present study.

FIGURE 15 A detailed look at the results gives a less satisfactory impression of the results. If the authors had tried to reach the same amount of affected cells as observed, their spatial repartition would have been much less satisfactory (light blue cells on figure 15b).

We agree with the reviewer on this point. Either the model or the soil information need to be improved to achieve a better spatial structure. We acknowledge this fact in the conclusions. Current results are, to our opinion, satisfactory (the model achieves a good representation of the regions with high probability of slide occurrence), but there is room for a lot of improvement.

FIGURE 15 The number of unstable cells does not appear to be correlated with rainfall intensities surprisingly. Is this due to the high spatial heterogeneities of rainfall rates during event 2 (i.e. the average value does not reflect the variation of local maximum values). Or are there some other explanations. The peak number at the start of the event is also very surprising.

The results are not just a direct function of instantaneous precipitation, but rather a nonlinear combination of the slope, and the weight of water in the soil column, which is a function of precipitation, but it is also modulated by the spatio-temporal evolution of surface and subsurface processes. In addition, during Event 2, the soils were already saturated, and the intensities during the fist part of the event were extreme in the upper part of the basin (as shown in this document), and as it was mentioned in the manuscript. Intense rainfall during the fist part of the event appears responsible for the unstable cells during the beginning of Event 2. In our view, and considering the overall evidence, it is a realistic result. That is precisely why we are considering both events in order to reconstruct the flash flood event. Without Event 1, there wouldn't be flash flood.

FIGURE 16 The match is far from perfect probably due to the limitations of the DTM.

We believe so. We acknowledge this fact in the conclusions.

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Reconstructing the Salgar 2015 Flash Flood Using Radar Retrievals and a Conceptual Modeling Framework: A Basis for a Better Flood Generating Mechanisms Discrimination

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Abstract. Flash floods associated with severe precipitation events are highly destructive, often resulting in significant human and economic losses. Due to their nature, flash floods tend to occur in medium to small basins located within complex high mountainous regions. In the Colombian Andean region these basins are common, with the aggravating factor that the vulnerability is considerably high

- 5 due to the presence of important human settlements frequently occupying floodplains and other flash-flood prone areas. During May 18 of 2015, severe rainfall generated-triggered a flash flood in the municipality of Salgar, in La Liboriana basin located in the northwestern Colombian Andes, resulting in more than 100 human casualties and significant economic losses. This work aims to reconstruct the 2015 La Liboriana main features of the flash flood to understand better the hydrological
- 10 processes that took place during the event and to serve as a proof of concept for the development of a flash flood guidance low-cost tool when information is scarce. Radar QPEmodulating the event occurrence. Radar quantitative precipitation estimates (QPE), satellite data, and post-event field visits are used to reconstruct the Salgar flash flood addressing the relationship between rainfall spatiotemporal structure, soil moisture, and runoff generation during successive rainfall events, using a
- 15 conceptual modeling framework including land-slide and hydraulic sub-models. The hydrological model includes the addition of hydrologic model includes virtual tracers to explore the role of runoff and subsurface flow, as well as the relative importance of convective and stratiform precipitation in flash flood generation. The In spite of potential shortcomings, the modeling results allow an assessment of the impact of the interactions between runoff, subsurface flow, and convective-stratiform
- 20 rainfall allows a better understanding of on the short-term hydrological mechanisms leading to the flash flood event. The overall methodology reproduces considerably well the magnitude and timing

of La Liboriana flash flood discharge peak, as well as the areas of regional land-slide landslide occurrence and flood spotslocation, with some limitations due to the available spatial scale of the digital elevation model spatial resolution. Simulation results indicate that the flash-flood and the regional

- 25 land-slide features were strongly influenced by the antecedent rainfall associated with a northeasterly stratiform event that recharged the gravitational and capillary storages . The hydrologic within the model. The simulation shows that the antecedent event set wet conditions in rainfall event moistens the entire basin before the occurrence of the flash flood event, governing modulating as well the streamflow during the flash flood event. Evidence suggests that the spatial structure of the rainfall
- 30 is at least as important as the geomorphological features of the basin regulating the generation in regulating the occurrence of flash flood events. Results also suggest that the described model-based tool is useful for policy-makers not only for short-term decisions in the context of an early warning system but also as a planning resource for long-term risk management.

1 Introduction

- Flash floods are regarded as one of the most destructive hydrological hazards resulting in considerable loss of human life and high costs due to infrastructure damages (Roux et al., 2011; Gruntfest and Handmer, 2001)
 - damage (Roux et al., 2011; Gruntfest and Handmer, 2001). Among all different types of floods, Jonkman (2005) shows that flash floods result in the highest average mortality rate per event (3.62%), almost ten times larger than the mortality rate for river floods. Flash floods are usually described as
- 40 rapidly rising water level events happening in steep streams and rivers, associated with short-term, very intense convective precipitation systems, or orographically forced rainfall events over highly saturated land surfaces and steep terrains (Šálek et al., 2006; Llasat et al., 2016; Douinot et al., 2016). Convective precipitation episodes often feature high intensities, short durationsintensity, short duration, and relatively reduced spatial coverage (Houze, 2004). Jonkman (2005), based on information
- 45 from the International Disaster Database, maintained by the United States Office for Foreign Disaster Assistance and the Center for Research on the Epidemiology of Disasters in Brussels, shows that between 1975 and 2001 a total of 1816 worldwide freshwater flood events killed over 175, 000 persons and affected more than 2.2 billion people. These events not only caused human and economic losses but also damages to ecosystems and loss of historical and cultural values. Among all different
- 50 types of floods, Jonkman (2005) shows that flash floods result in the highest average mortality rate per event (3.62%), almost ten times larger than the mortality rate for river floods.

Several studies assess the role of rainfall, geomorphological features and soil conditions on flash floods occurrence from different points of view. Wu and Sidle (1995) highlight Several authors have

55 assessed the role of the geological and geomorphological features of the catchment, soil type, soil moisture conditions, and the spatio-temporal structure of rainfall on flash flood occurrence, trying to

identify the leading causative mechanisms of this hazard (Merz and Blöschl, 2003). Adamovic et al. (2016) and Vannier et al. (2016) tried to understand the governing processes of flash floods from the geological formation of the basin with mixed results. Wu and Sidle (1995) emphasize the role of the topogra-

- 60 phy, ground cover, and groundwater in the occurrence of shallow landslides and associated debris flows. Merz and Blöschl (2003) highlighted the importance of understanding the physical processes giving rise to floods of a certain probability of occurrence and proposed a framework, from a catchment perspective, for identifying causative mechanisms of inundations and the viability for a large number of episodes and basinsDue to their rapid nature, flash floods are more likely to occur
- 65 in small and steep basins (Younis et al., 2008); many authors have assessed the influence of hills and stream slopes suggesting the slopes of the hills are significantly more important for flash floods occurrence and magnitude than the slope of the stream (Šálek et al., 2006; Roux et al., 2011; Yatheendradas et al., 2008). Rodriguez-Blanco et al. (2012) analyzed fifty-four flash flood episodes in Spain and determined that antecedent soil moisture conditions play a vital role in runoff production. Castillo et al. (2003)
- 70 , using a modeling approach, also suggested an important flash flood occurrence dependence on antecedent moisture conditions. Aronica et al. (2012) used spatial and statistical analysis to reconstruct landslides and deposits, finding a connection between flash flood occurrence and soil moisture antecedent conditions.
- 75 The fact that small basins are more prone to flash floods increases their intrinsic physical and measurement uncertainty (Wagener et al., 2007), difficulting their prediction (Hardy et al., 2016; Ruiz-Villanueva et al., 2013; Yama , and underlining the need for high spatio-temporal resolution precipitation data (Norbiato et al., 2008) . Given the critical role of precipitation, some authors follow a climatological approximation to as-

sess the recurrence of flash floods in particular regionsand study the different, focusing on the atmospheric causative mechanisms. These studies have evidenced the need to incorporate global and

regional elimatological conditions and variability in local risk reduction. For example, Kahana et al. (2002) examined the extent to which floods in the Negev Desert are the outcome of distinct climatological synoptic-scale features finding that about 80% of the events can be linked to distinct synoptic types characterized by the prevailing atmospheric conditions days prior the flood events. Schumacher

80

- 85 and Johnson (2005) studied extreme rain events associated with flash flooding in the United States over a 3-yr period using the national radar reflectivity composite data are to examine the structure and evolution of each extreme rain events. The use of radar data to study flash flood generating storms is vital for understanding and forecasting these events (National Research Council 1996). Schumacher and Johnson (2005) found that 65% of the total number of episodes are associated with
- 90 mesoscale convective systems (MCSs), with two recurrent patterns of organization: the existence of training convective elements and the generation of quasi-stationary areas of convection with stratiform rainfall downstream. Fragoso et al. (2012) analyzed storm characteristics and required rainfall conditions for flash flood occurrence at Madeira (Portugal), and their results suggest an essential role

of global climate patterns (North Atlantic Oscillation -NAO- forcing) and also local forcing (oro-

- 95 graphic features) in the triggering of such events. Piper et al. (2016) examined the critical elements of flash flood triggering storms following a statistical approach, finding an essential role of stationary convective cores. Gochis et al. (2015) studied the great Colorado flood of 2013, documenting not only the meteorological conditions but also the climatological ones responsible for producing the observed widespread destruction, associating them with the potential for sustaining a blocking ridge
- 100 over the Canadian Rockies and a slow-moving, cutoff, upper-level cyclonic circulation to its south over the western United States. Implicitly, all the studies mentioned Implicitly, these studies and all the others available in the peer-reviewed literature point to the need for local and regional quality high-quality spatio-temporal rainfall data. Berne and Krajewski (2013) highlight the need to incorporate high-resolution weather radar information, even with some limitations, in flash flood hydrology.
- 105

Different authors have shown that antecedent soil moisture significantly influences the occurrence and behavior of flash floods. Rodriguez-Blanco et al. (2012) analyzed fifty-four flash flood episodes in Spain and determined that antecedent conditions are a vital point in runoff production. Castillo et al. (2003) , using a modeling approach, highlighted the role of antecedent moisture conditions in flash flood

- 110 occurrence associating them with different kinds of storm events. Aronica et al. (2012) used spatial and statistical analysis to reconstruct landslides and deposits, finding a connection between flash flood occurrence and soil moisture antecedent conditions. Tramblay et al. (2012) showed better flash flood model performance when using remotely sensed soil moisture data as initial conditions in a hydrological modeling study. Other authors have tried to understand the governing processes of flash
- 115 floods from the geological formation of the basin (Adamovic et al., 2016; Vannier et al., 2016). Due to the rapid nature of flash floods, they are more likely to occur in small and steep basins (Younis et al., 2008), highlighting the need for the availability of detailed temporal scale precipitation data (Norbiato et al., 2008) and high-resolution terrain information. Watersheds prone to these events are usually located in rural mountainous areas with poor gauge information (rain and level). The
- 120 utilization of radar data to study flash flood generating storms is vital for understanding and forecasting these events (National Research Council 1996). One of the most critical challenges associated with flash floods is their simulation and prediction (Yamanaka and Ma, 2017; Borga et al., 2011; Marra et al., 2017)
 . The fact that flash floods are more prone in small basins increases their intrinsic physical and measurement uncertainty (Wagener et al., 2007), difficulting their prediction (Hardy et al., 2016; Ruiz-Villanueva et al., 2013)
- 125 . Many authors have assessed the influence of hills and stream slopes and evidence suggest the slopes of the hills are significantly more important for flash floods occurrence and magnitude than the stream slope (, eds.; Šálek et al., 2006; Roux et al., 2011; Yatheendradas et al., 2008).

Arguably one of the most meaningful applications of quantitative precipitation estimation (QPE) from a societal point of view is its use to improve flash flood forecasting. The use of weather

130 radar QPE products in flash flood applications could potentially offset, in part, the lack of in-situ

precipitation products in small poorly gauged basins and become an important stepping stone for improving the state-of-the-art understanding of flash flood processes such as orographically enhanced extreme rainfall events and runoff generation (Creutin and Borga, 2003a). However, in some cases, there still exist limitations associated with the spatial resolution of radar retrievals (Šálek et al., 2006; Hardy et al., 2016)

135 . Nevertheless, several modern approaches involving radar information, in-situ precipitation data, model approximations and merging algorithms are promising (Braud et al., 2016).

The topography of Colombia is characterized by three branches of the Andes crossing the country south-to-north, generating a mixture of landscapes from high snow-capped mountains, vast highland plateaus, deep canyons to wide valleys, making some regions highly prone to flash flood occurrence.

- 140 The likelihood of flash flood occurrence in Colombia is also high due to the spatio-temporal behavior of the Intertropical Convergence Zone, and the direction of the near-surface moist air flow leading to orographic enhancement of convective cores (Poveda et al., 2007). In the last decade, there have been several widespread and localized flash flood events in Colombia associated with climatological features and with the local intensification of rainfall events. The 2010-2011 La Niña event alone
- 145 triggered 1233 flooding events and 778 mass removal processes in Colombia, with more than 3 million people affected and damages estimated by the "Comisión Económica para América Latina y el Caribe" in more than 6.5 billion US dollars. After this-

After the 2010-2011 widespread disaster, several localized isolated events have occurred in the 150 country with devastating consequences.

Between May 15th and May 18th, 2015, several storms took place over La Liboriana basin located in the municipality of Salgar, in the department of Antioquia (Colombia). By 2015, the population of Salgar was estimated at 17400 persons, 8800 residing in the urban area. La Liboriana is a small tropical basin(The present paper focuses on studying the processes triggering a flash flood in La

- 155 Liboriana basin, a 56 km²) km² basin located in the western range (Cordillera Occidental) of the Colombian Andes. During the night of May 17th, between 02:00 and 09:00 A.M. (local time), a precipitation event covered almost all the basin (hereafter referred to as event 1). Twenty hours later, between 23:00 P.M of , as a result of consecutive rainfall storms that took place between May 15th and May 17 and 02:00 A.M. of May 18 two successive extreme convective systems occurred over
- 160 the basin with the maximum intensity in the upper hills (event 2). Event 1 corresponds mainly to a stratiform event, covering almost all the basin area and with an average precipitation accumulation of 47 mm. Event 2 accumulated, averaging over the basin, around 38 mm, however over the upper watershed the accumulation exceeded 180 mm. The occurrence of these successive rainfall events resulted in a flash flood that took 18th, 2015. The resulting flash flood dramatically affected the
- 165 region, causing more than 100 human lives and affected casualties, affecting several buildings and critical infrastructure. The total investment for the reconstruction of Salgar's infrastructure and the psychosocial attention of the community is and resulting in a total reconstruction cost estimated



a) Aerial photograph before the event (2012).



b) Aerial photograph taken after the event (2015-05).

Figure 1. Example of infrastructure damage as a result of the La Liboriana May 18 of 2015 flash flood event. a) Aerial photograph before the event (2012) taken during a mission of the Department of Antioquia's Government, and b) satellite image after the event (2015-05). The images show the destruction of most houses in that particular community, a bridge over La Liboriana, and the main road. The images also present changes in the delineation of the main channel as well as considerable erosion in the river margins.

at 36.000 million Colombian pesos (approximately 12,5 million dollars considering 2018 exchange rate), which corresponds to three times the annual income of the municipality. Figure 1 shows an
example of infrastructure damage as a result of the flash flood event, and satellite images changes of the basin's main channel before and after the flash flood, showing considerable river margins margin and bed erosion. In spite of the data scarcity, including discharge measurements, the analysis of the successive rainfall events triggering the Salgar flash flood provide an interesting case of study for assessing the mechanisms depending on the soil moisture conditions and rainfall distribution.

175

La Liboriana basin flash flood is a typical case of prediction in ungauged basins (PUB) (Sivapalan et al., 2016; Seibert and Beven, 2009; Beven, 2007; Bonell et al., 2006; Yamanaka and Ma, 2017).
In this case, there are no local records of soils or land use and the local hydro-meteorological data is scarce or non-existent and certainly not available in real time. Due to the lack of data, La Libo-

- 180 riana case imposes a challenge for flash flood prediction and modeling. According to Blöschl et al. (2012), there are three methods for using models in <u>PUB these</u> cases. The first strategy is to obtain the required model parameters from historical basin behavior and the morphological characteristics of the basin. This strategy often leads to low model performance (Duan et al., 2006). The second approach is to inherit the hydrological calibration from a gauged neighboring watershed, which in this
- 185 case does not exist. The third method is to parameterize the model based on proxy variables, such as hydraulic information obtained during field recognitionvisits. In the case of the 2015 La Liboriana basin flash flood, there are no previous historical streamflow records, nor records from a neighboring watershed-

The present work aims to reconstruct the 2015 La Liboriana flash flood, not only to understand

- 190 better the hydrological processes that took place during the event but also to serve as a proof of concept that hopefully leads to the development of a flash flood guidance low-cost tool based on the scarce information existent. Such a tool should be useful for decision-makers not only for short-term decisions in the context of an early warning system but also as a planning resource for long-term risk management. In particular, this workuses, thus we followed the third approach. In this work,
- 195 we use precipitation information derived from radarQPE, satellite data, satellite and aereal images, and post-event field visits to reconstruct the Salgar flash flood event. Also, this This study addresses two broad hydrological issues. The first issue consists in exploring the relationship between rainfall spatio-temporal structure (Llasat et al., 2016; Fragoso et al., 2012), soil moisture and runoff generation (Penna et al., 2011; Tramblay et al., 2012; Garambois et al., 2013) during the successive rain-
- 200 fall events. The second issue consists, and the second issue in proposing a simplified hydrological hydrologic modeling scheme including land-slide and hydraulic sub-models to detect and anticipate potential assess the potential occurrence of flash flood events.

The methodology followed in this study makes use of a conceptual modeling framework that in-

205 cludes a hydrological model-hydrologic model (Vélez, 2001; Francés et al., 2007a), a shallow landslide sub-model (Aristizábal et al., 2016), and a hydraulic sub-model . The hydrological model, based on the work by Vélez (2001) and Francés et al. (2007a), simulates different hydrological processes as independent but interacting storages. The shallow landslide sub-model follows the formulation described in (Aristizábal et al., 2016). The hydraulic sub-model corresponds to a low-cost 1D model

210 (hereafter referred to as HydroFlash)that assumes infinite sediment supply and estimates the cross-sectional filled area at all time steps. The hydrological model includes the addition of . The hydrologic model includes virtual tracers to explore separately the role of runoff and subsurface flow, as well as the relative importance of convective and stratiform precipitation in flash flood generation. The convective and stratiform classification follows the methodology proposed by Houze et al. (2015)

- 215 and Steiner et al. (1995). The assessment of the interactions between runoff, subsurface flow, and convective-stratiform rainfall allows a better understanding of the short-term hydrological mechanisms leading to the flash flood event. The model is parameterized using field information from a river cross-section located at the entrance of the urban area of Salgar. A comparison between the results from both sub-models and the observed landslides scars and flooded spots helps to evaluate the overall skill of the proposed methodology.
- 220 the overall skill of the proposed methodology.

The document is structured as follows. Section 2 describes in more detail the region of study, La Liboriana basin, including geomorphological and climatological characteristics of the basin as well as the information sources used in this study. Section 3 presents a description of the overall methodol-

- 225 ogy and the model used for the reconstruction of the 2015 La Liboriana flash flood event, including flow separation, shallow landslide parameterization, and the proposed hydraulic model. Section 4 describes the main results of the study, including model parameterization and validation. Section 4 also validation and sensitivity analysis, and presents results from the land-slide and inundation sub-models. Section 5 includes a discussion on the role of the rainfall structure in the flash flood
- 230 reconstructionand presents results from the land-slide and inundation sub-models. Finally, the conclusions are presented in section 6.

2 Data and Area of Study Site and Data

2.1 Catchment description

- The urban area of Salgar municipality is located near the outlet of La Liboriana basin, a small (56 235 $\frac{km^2}{km^2}$) tropical watershed located in the westernmost range of Colombia's Andes (Figure 2). By 2015, the population of Salgar was estimated at 17400 persons, 8800 residing in the urban area. La Liboriana basin joins El Barroso river basin and both drain to Cauca river.
- The availability of the ALOS-PALSAR Digital Elevation Model (DEM) (ASF, 2011), with a resolution of about 12.7 mm, allows estimating the fundamental geomorphological features of the basin. The average slope of La Liboriana is 57.6 %, and the basin longitude and perimeter are 13.5 km km and 57.8 km km, respectively. The Strahler-Horton order of the principal main stream is 5, and the its longitude and slope of the principal stream are 18.1 km km and 8.1 %, respectively. The highest elevation of the watershed (Cerro Plateado) reaches 3609 meters above sea level (m.a.s.l), while the
- 245 outlet of the basin is at 1316 m.a.s.l.. The longitudinal profile (see Figure ??) exhibits considerable steepness in the upper basin. The 99th slope percentile of order 1 streams is 78%. For streams order 2, 3, 4, and 5, the 99th slope percentile are 61, 27, 18 y 11%, respectively. Figure 2 shows the spatial distribution of the slopes in the watershed. These features are typical of Andean mountainous basins. The hypsometric curve shows considerable elevation changes for a cumulative area below 33% (see

250 blue line in Figure ??). Geomorphologically, this kind of watershed is tends to be prone to the occurrence of flash floods (Lehmann and Or, 2012; Penna et al., 2011; Martín-Vide and Llasat, 2018; Longoni et al., 2016; Ozturk et al., 2016; Ozturk et al., 2018; Longoni et al., 2016; Ozturk et al., 2018; Longoni et al., 2016; Ozturk et al., 2018; Longoni et al., 2018; Longoni et al., 2016; Ozturk et al., 2018; Longoni et al., 2018; Longoni et al., 2016; Ozturk et al., 2018; Longoni et al., 2018; Lo

Geographical context of Liboriana basin, located in Colombia, in the Department of Antioquia. 255 The color bar represents the Height Above the Nearest Drainage (HAND). Low HAND values correspond to areas prone to flooding.

At the sub-basin scale, La Liboriana exhibits a vast range of slopes and altitude differences. Figure 2 shows the Height Above the Nearest Drainage -HAND- model (Rennó et al., 2008) for La Liboriana. The HAND calculates the relative difference between cell i and its nearest streamflow cell j.

- 260 La Liboriana HAND exhibits values between 500 and 800 mm. Near the outlet of the basin, over the banks, there are values close to 0 m. High HAND values at the upper region of the watershed often denote areas of high potential energy, with increased sediment production and frequent shallow landslides landslide occurrence. Banks with low HAND values are more susceptible to flooding and tend to correspond to areas prone to extensive damages caused by extreme events. While the
- 265 elevation differences described in Figure 2 are typical of the region, the social challenges lie in the high vulnerability of the Salgar given the location of the main urban settlement.

Vegetation and land use vary considerably within the basin. Figure 3 shows land use in different regions of the watershed from a 2012 aereal image. In the upper La Liboriana basin, there are crop

- 270 fields and tropical forests; a is dense vegetation (see Zoom 1 in Figure 3), with a high percentage of tropical forests, with the presence of grass and few crop fields. A portion of the upper water-shed is considered a national park. Hillslopes near the divide do not evidence significant anthropic intervention most likely due steepness of the slopes in this region. Down the hills and at the bottom of the valley there are coffee plantations (the primary economic activity of the region) and
- 275 pastures. Downstream (Figure 3, Zoom 2), it is evident the presence of crops among forest and grass. Near the middle of the basin (Figure 3, Zoom 3), the presence of crops is more notorious and human settlements and roads start to appear. The watershed exhibits grazing areas and urban development near the river banks. In Figure 3, Zoom 4, corresponding to the first affected urban area from upstream to downstream during the flash flood, it is also possible to see a marked presence of
- 280 crops and some forest patches. Finally, zoom 5 shows the main urban area of Salgar surrounded by crops, grass and an important loss of forest coverage.

The Andean Colombian region tends to present well-developed soils of different textures with a predominance of limes and elays.

One of the challenges for hydrological modeling and risk management in the country is that soils are not well mapped; the national soil cartography is usually available in a 1:400.000 scale. At this



Figure 2. Longitudinal profile Geographical context of Liboriana basin, located in Colombia, in the principal stream (colored line) from the upper part Department of Antioquia. The color bar represents the basin to its outlet at Height Above the entrance of Nearest Drainage (HAND). HAND values where estimated using the urban area, hypsometric curve same resolution of the drainage basin DEM (blue line12.7 m). Low HAND values correspond to areas prone to flooding.

scale, the municipality of Salgar, including La Liboriana basin, corresponds to only one category of soil texture. The only available information corresponds to descriptions by regional authorities. Osorio (2008)describe Osorio (2008), based on field campaign observations and laboratory tests,
described La Liboriana soils as a well-drained soil with poor retention capacity. Organic material is predominant in the first layer and clay loam soil within the second one. The depth of the soil is hills-lope dependent, varying between from 20cm and to 1m (Osorio, 2008). Table 1 provides a summary of soil characteristics for five different categories, all as a function of slope. Each soil category has a corresponding depth and a qualitative description of permeability and retention.

295

A field campaign

2.2 Flash flood post-event observations

We conducted a field campaign a few days after the May 18th flash flood event was instrumental in obtaining to assess cross-section geometry along the main channel in different sites, including at the



Figure 3. Land use in different regions of La Liboriana watershed from a 2012 aereal images (Source: Department of Antioquia.

| Table 1. Description of the soils in the region (Osorio, 20) | J8). |
|--|------|
|--|------|

| Туре | Slope | Depth [m] | Retention | Permeability |
|------------|-------|-----------|-----------|--------------|
| Class III | 12-25 | 0.6 | Mean | Mean |
| Class IV | <12 | 0.6 | Low | High |
| Class VI | 25-30 | 1.0 | Mean | Mean |
| Class VII | 30-50 | 0.3 | Too Low | Slow |
| Class VIII | >50 | 0.2 | Too Low | Slow |

- 300 outlet of the basin. The Unfortunately, most of the affected areas were not accessible after the event and it was not possible to obtain reliable information in other locations along the main channel other than at the outlet of the basin. During the campaign, we measured sectional distances and surface water speeds at different points of the streamflow. We also identified traditional post-event terrain, land-cover, vegetation and infrastructure markers to assess the high-water marks associated with the
- 305 peak of the flash flood. Figure 4 presents the selected cross-section used for the estimation of the maximum discharge during the flash flood given its geometrical and hydraulic regularity. The section has a rectangular shape, and it is 4.6 m wide and has m wide and a height of 5 m m for a total area of about 23 m^2 m². A visual inspection of the flooded infrastructure around this sectionhouse around the section, located 4-5 m away from the channel, reveals the presence of mud marks on the walls
- 310 with heights varying between 0.5 and 1.2 *m*. These mud stains are evident in buildings located 4-5



Figure 4. Channel cross-section shown an example of flooded infrastructure after the flash flood event. The section shows mud marks on the walls with heights varying between 0.5 and 1.2 m_{m} . These mud stains are evident in buildings located 4-5 m_{m} away from the channel. The photograph also shows the width of the channel and the total estimated depth during the flash flood.

m away from the channel m (see Figure 4). The area of the section plus the flooded area during the event was estimated to be approximately 37 m^2 . Assuming flow speeds m^2 . During the campaign we measured surface speeds in the channel oscillating between 2 and 3 ms⁻¹. In instrumented basins in the region, with similar characteristics in terms of area and slopes, we have recorded peak flow

- 315 surface water speeds oscillating between 5 and 6 m/s, the total discharge required to generate 7 ms⁻¹. By assuming an area of 37 m² and the mentioned surface speeds, we estimate that the observed flash flood vary peak flow may have been between 185 and 222 m^3/s . In this work, the soil information and the field campaign are used to parametrize a hydrological modelm³s⁻¹. The timing of the peak flow is also important information. Local authorities reported that the peak streamflow
- 320 reached the urban perimeter after 2:10 a.m. on May 18th. Some reports state that the peak flow in the most affected community occurred around 2:40 a.m.

There is also relevant aerial information before and after the occurrence of the event. During 2012, the Department of Antioquia conducted a detailed aerial survey of the Salgar municipality, and few days after the event Google displayed publically high detailed satellite images of the same

- 325 and few days after the event Google displayed publically high detailed satellite images of the same region. The contrast between both products provides information about flooded areas and landslide locations. Field campaign estimates and satellite aerial imagery are central to validate the results obtained from the proposed hydrological modelmodels.
- 330 The reconstruction

2.3 Rainfall Information

The assessment of the 2015 Salgar flash flood event following a hydrological modeling strategy uses a radar-based QPE technique developed by Sepúlveda and Hoyos (2018)-2019) using rainfall gauges and disdrometers within the radar domain to obtain spatiotemporal precipitation maps over

- 335 the basin. A detailed description of the <u>rainfall</u> estimation, as well as the overall meteorological conditions that led to the La Liboriana extreme event, are described in a companion paper (Hoyos et al. 20182019). The QPE technique uses retrievals from a C-band polarimetric Doppler weather radar operated by the Sistema de Alertas Tempranas Alerta Temprana de Medellín y del el Valle de Aburra (SIATA, is a local early warning system from a neighboring region, www.siata.gov.co)and it
- 340 is located at 100km, located around 90 km away from the basin. The radar has an optimal optimum range of 120 km radius km radius for rainfall estimation and a maximum operational range of 240 km km for weather detection. The radar operating strategy allows obtaining precipitation information every 5 min and the minutes with a spatial resolution is about 128 m. The sensor is a C-band polarimetric Doppler weather radar operated by the Sistema de Alertas Tempranas de Medellín y
- 345 del Valle de Aburra (SIATA, a local early warning system from a neighboring region, www.siata. gov.eo)m. The results of the radar QPE methodology indicate that the rainfall estimation works well within a radius of 120km. Despite the distance between the radar and the basin, and the mountains between them, there are no blind spots for the radar. A comparison between the radar QPE estimates and records from two rain gauges installed three days after the flash flood event show a correlation for
- 350 an hourly time scale of 0.65. In addition to the rainfall quantification, radar retrievals, before feeding the hydrologic model, are classified in convective and stratiform areas following a methodology proposed by Houze et al. (2015) and Steiner et al. (1995).

Between May 15th and May 18th, 2015, several storms took place over La Liboriana basin. During the night of May 17th, between 02:00 and located at 100km away from the basin09:00 a.m. (local time), a precipitation event covered almost all the basin (hereafter referred to as precipitation Event 1). Twenty hours later, between 23:00 p.m. of May 17 and 02:00 a.m. of May 18 two successive extreme convective systems occurred over the basin with the maximum intensity in the upper hills (precipitation Event 2). Event 1 corresponds mainly to a stratiform event, covering almost all the

- 360 basin area and with an average precipitation accumulation of 47 mm. Event 2 accumulated, in average over the basin, around 38 mm, however over the upper watershed the accumulation exceeded 180 mm. Figure 5a presents the temporal evolution of the convective-stratiform rainfall partitioning during both Events 1 and 2. The main difference between both events is the timing of the convective versus stratiform participation within each case. Event 1 started as a stratiform precipitation event
- 365 moving from the southwest, from the Department of Chocó to the Department of Antioquia across westernmost Andes mountain range. The radar has an optimal optimum rangeof 120 km radius and a maximum operational range of 240 km. The radar operating strategy allows obtaining precipitation information every 5min and with a spatial resolution is about 128 mChochó is the rainiest department

in Colombia, and one of the wettest places on Earth, due to the inflow of moisture from the Pacific

- 370 Ocean and the orientation of the Andes mountain range (Poveda and Mesa, 2000; Mapes et al., 2003) . After 3 hours of stratiform rainfall, training convective cores move over La Liboriana basin generating intense precipitation peaks during 2.5 hours. It is important to note that these cores did not strengthen within La Liboriana basin; these systems formed and intensified over the western hills of Farallones de Citará draining to the Department of Chocó towards the Atrato river. The latter is not a minor fact
- 375 because once the convective system moved with a northeast direction, the maximum intensity cores did not fall over the steepest hills of La Liboriana basin but rather near the basin outlet where the slopes are considerably flatter. Figure 5b shows the spatial distribution cumulative rainfall during Event 1, with the maximum precipitation located towards the bottom third of the basin. Event 2, on the other hand, started as a thunderstorm training event with two convective cores moving from
- 380 the southeast followed by remaining stratiform precipitation. Even though the average cumulative rainfall over the basin was 9 mm less than during Event 1, this event is characterized by orographic intensification within the basin leading to a more heterogeneous spatial distribution and with the highest cumulative precipitation in the steepest portion of the basin (see Figure 5b). Event 2 spatial distribution and highly localized observed intensities most likely led to the flash-flooding episode,

385 as it is explored in this work.

3 Methodology

The data requirements, and rainfall preprocessing needed for the overall methodology followed in the reconstruction of the 2015 Salgar flash flood , is presented in an illustrative are summarized in
Table 2 and are presented in a schematic diagram in Figure 6.

3 Methodology

3.1 Hydrological modeling framework

- The availability of radar-based QPE and a detailed DEM allows the use of a modeling framework based on the distributed hydrological hydrologic model described in Vélez (2001) and Francés et al. (2007a) with important modifications(left column in Figure 6). The hydrological. The hydrologic model simulates different hydrological processes as independent, but interacting storages (second row, left panel in Figure 6). The model distributes processes by cells; in each cell, five tanks represent the hydrological processes including capillary (tank 1), gravitational (tank 2), runoff (tank 3),
- 400 baseflow (tank 4) and channel storage (tank 5). The state of each tank varies in function of vertical and lateral flows as shown in the diagram, where the storage is represented by S_i , the vertical input



Figure 5. a) Temporal evolution of the convective-stratiform rainfall partitioning during both Events 1 and 2. The figure shows the total rainfall (yellow), and the convective (blue) and stratiform (green) portions integrated over La Liboriana basin. b) and c) Spatial distribution of the cumulative rainfall during Events 1 and 2 over La Liboriana basin.

to each tank by D_i , which in turns depends on the vertical flow through tanks R_i . E_i represents the downstream connection between cells, except for tank 1, where E_1 represents the evaporation rate. Vertical flows are only time dependent, while lateral flows could also depend on the actual state of the tank (kinematic approximation).

405

Illustrative diagram of the methodology followed in the present study. The left column represents the availability of radar-based QPE and a detailed DEM as the basis of the modeling framework and the mains aspects of the distributed hydrological model used. In each cell five tanks represent the

- 410 hydrological processes including capillary (tank 1), gravitational (tank 2), runoff (tank 3), baseflow (tank 4) and channel storage (tank 5). The state of each tank varies in function of vertical and lateral flows as shown in the diagram, where the storage is represented by S_i , the vertical input by D_i which in turns depends on R_i . E_i represents the downstream connection between cells, and evaporation. The implementation of convective and stratiform rainfall separation and virtual tracers are presented
- 415 in the top two right panels. The implementation of the shallow landslides model and HydroFlash are schematized in the bottom two right panels.

| Item | Description | Period | Usage |
|-------------------|--|------------------------------|--|
| <u>Radar data</u> | QPE rainfall estimations | 2015-05-17_to 2015-05-18_ | Hydrologic model runs. Rainfall characterization and event analysis. |
| Field campaign | Maximum streamflow estimation trough visual inspection | 2015-05-20 | Hydrologic model comparison for indirect validation. |
| Satellite imagery | Visible channel compositions from the Digital Globe CNES imagery | 2015-05 (post-event) | Flash flood model validation, shallow land-slides model validation, and comparison with pre-event conditions. |
| Aerial photos | Aerial photos taken by the government of Antioquia during 2012. | 2012 | Pre-event conditions comparison. |
| Soils description | Physical description of the soils of the region by Osorio (2008) | 2008 | Hydrologic model setup. |

The model modifications fall in four different categories: (i) the direct use of radar QPE as a source of rainfall information, (ii) the implementation of virtual tracers for surface and subsurface discharge as well as for convective and stratiform water tracing, (iii) the development of two modules for hazard assessment, and (iv) the enforcement of a maximum gravitational storage (H_g) to allow Hortonian runoff (return flow from S_3 (tank 3) to S_2). The virtual tracers are critical to explore separately the relative role of superficial runoff and subsurface flow, as well as the relative importance of convective and stratiform precipitation in flash flood generation. The convective and stratiform classification follows the methodology proposed by Houze et al. (2015)-

425 and Steiner et al. (1995)(tank 2)), and (iv) the development of two modules for hazard assessment. The implementation of eonvective and stratiform rainfall separation and virtual tracers are presented virtual tracers is represented in the top two right panels of the illustrative diagram in Figure6. The hydrological modelallows hazard assessment by coupling a shallow landslide model(Aristizábal et al., 2016)

,

430



Figure 6. Illustrative diagram of the methodology followed in the present study. The top row represents the availability of a detailed DEM and radar-based QPE as the basis of the modeling framework. The second row represents the mains aspects of the distributed hydrologic model used. In each cell five tanks represent the hydrological processes including capillary (tank 1), gravitational (tank 2), runoff (tank 3), baseflow (tank 4) and channel storage (tank 5). The state of each tank varies in function of vertical and lateral flows as shown in the diagram, where the storage is represented by S_i , the vertical input by D_i which in turns depends on the vertical flow through tanks R_i . E_i represents the downstream connection between cells, and evaporation. The implementation of convective and stratiform rainfall separation and virtual tracers is also portrayed. The implementation of the shallow landslides model and HydroFlash are schematized in the bottom row.

3.1.1 Hydrological runoff scheme modification

In the model, horizontal flow equations could be either linear or potential, as shown in equation 1. In the modified hydrologic model, β and α are estimated by the user and then set into the model. In the non-lineal approximation β is a coefficient that summarizes local properties invariant over time,

435 like the slope or the hydraulic conductivity. α is an exponent that change in function of the adopted

approximation. From equations 1 to 3, $A_i(t)$ corresponds to the sectional area of each storage, $A_i(t)$ vary in function of the tank storage $S_i(t)$ according to equation 4.

 $v_{tank}(t) = \beta A_i(t)^{\alpha}$

Non-linear equations in lateral flows could result in a better representation of processes at high resolutions (Beven, 1981; Kirkby and Chorley, 1967). A non-linear approximation to runoff is presented in equation 2. This approximation is a modification of Manning's formula for flow in gullies. According to Foster G.R. (1984), ε and a new low-cost 1d hydraulic flash flood model referred to here as **HydroFlash**. The implementation of e_1 are a coefficient and an exponent used to translate the manning channel concept into multiple small channels or gullies. The values of ε and e_1 are 0.5

and 0.64, respectively (Foster G.R., 1984). A_2 is the corresponding sectional area obtained from S_2 by using the equation (4). And S_0 is the slope of the cell.

The non-linear equation 3 corresponds to an adaptation of Kubota and Sivapalan (1995) formula for subsurface runoff where k_s is the saturated hydraulic conductivity, and the exponent b is dependent on the soil type, assumed equal to 2. A_g is the equivalent cross-section area to the maximum

450 gravitational storage (H_g) . A_3 is the corresponding sectional area of the gravitational storage (S_3) obtained by using equation (4). There is also return flow from tank 3 to tank 2 when $S_3 = H_g$, representing runoff generation by saturation.

$$v_2 = \frac{\varepsilon}{n} S_0^{1/2} A_2(t)^{(2/3)e_1} \tag{2}$$

455
$$v_3 = \frac{K_s S_o^2}{(b+1)A_g^b} A_3(t)^b$$
 (3)

The equations describe the momentum of a kinematic wave approximation. In both cases, velocity depends on the tank storage. These relations are summarized in equation 1, that could be solved numerically coupled with a mass balance equation (equation 4). This equation takes into account the storage at each time step $(S_{tank}(t))$, the longitude of the element (Δx) , the time step size (Δt) .

- 460 and the speed estimated for the flow in the time step $(v_{tank}(t))$. Equation 4 is related to equation 1 through the velocity term for that tank (v_{tank}) and the shallow landslides model and HydroFlash are schematized in the bottom two right panels of the illustrative diagram in Figure 6. cross-sectional area of the tank (A_{tank}) . The solution to v_{tank} and A_{tank} is obtained through an iterative scheme. The total outflow from the tank is calculated using equation 5.
- 465 For the technically inclined reader, the hydrological model and sub-models are written in Fortran 90, and the interface to the model, pre-process, and post-process tools are in python 2.7. The Fortran code is warped to python using **f2py** (Peterson, 2009) and it is publicly available under the Watershed

(1)

Modelling Framework WMF in a web repository ().

$$A_{i}(t) = \frac{S_{tank}(t)}{\Delta x + v_{tank}(t)\Delta t}$$
(4)

(5)

470

$$E_{tank}(t) = A_{tank}(t)v_{tank}(t)\Delta t$$

3.2 Virtual Tracers

3.1.1 Virtual Tracers

Virtual tracers are implemented into the model to discriminate streamflow source in superficial runoff and subsurface flow and to assess the portion of streamflow from convective rainfall and stratiform precipitation, recording at each time stem and each cell the source of water. The model archives the results of the virtual tracing algorithm at the outlet of the basin and at each reach allowing the study of the role of flows from different nature during extreme events at different spatial scales to get more insights about the soil-driven flow regulation. The soil texture and composition could play diverging

480 roles during extreme events. The soil could work as a porous medium in which the water travels fast, making the subsurface flow an essential part of the hydrograph, or on the other hand, its saturation could lead to a decrease in infiltration rates and a potential increase of surface runoff generation.

The flow separation module operates in tanks 2 (runoff storage) and 3 (subsurface storage). The module marks water once it reaches any of those two tanks and the runoff-subsurface flow percentage are taken into account once the water enters tank 5 (the channel). At this point, the scheme assumes that the water in the channel is well mixed, implying that the flow percentage is constant until a new inflow enters the channel.

490 Both spatial and temporal rainfall variability influence the hydrograph Shope (2016). Stratiform rain cells cover large areas and are related to long duration hydrographs with low peak flow. On the other hand, convective rainfall cells cover limited areas and are related to short duration hydrographs with high peak flows. Stratiform rainfall tends to recharge the basin, while convective tends to increase runoff generation and the formation of the hydrograph. In the literature, these associations

495 have often been more qualitative than quantitative (Creutin and Borga, 2003b; Šálek et al., 2006; Borga et al., 2014)

Rainfall from radar reflectivity fields is classified into stratiform and convective using the Steiner et al. (1995) approach before the implementation of the rainfalltracer. At With a similar concept, the model also follows convective and stratiform rainfall. For this, at each time step, the model takes into account

500 the total rainfall, assuming rainfall classified as convective or stratiform, and assumes that at each particular cell the precipitation is either entirely convective or entirely stratiform. This assumption

could lead to estimation errors at basins represented by coarse cells (low DEM resolution) where convective and stratiform precipitation are likely to coexist. In the present study the spatial resolution of the DEM is 12.7m, higher than the resolution of the radar retrievals (about 125m), so

505 the potential convective and stratiform rainfall concurrence is very low, and it could not be identified using the Steiner et al. (1995) approach.Once within the model, rainfall separation follows the methodology proposed for flow type separation.

3.2 Hazards Assessment

510 3.1.1 Hydrologic model calibration

During the 2015 La Liboriana flash flood event, two central processes took place. Shallow landslides occurred in the upper basin , and a flash flood generated flooding, and human and infrastructure losses. The hydrologic model requires a total of ten parameters. Table 3 includes all the parameters used in the model. The values of the parameters were derived from the soil properties described in

- 515 section 2. Due to the lack of detailed information in the region, parameters such as the infiltration and percolation rates are assumed as constant in all the basin. Other parameters such as the capillary and gravitational storage vary in function of geomorphological characteristics of the basin such as the elevation and slope. According to Francés et al. (2007b), during the calibration process, each physical parameter is scaled by a constant value in the entire basin. Table 3 includes the mean value
- 520 for all the parameters used in the model and the scalar value adjusted during the model calibration.

Shallow landslides sub-model

3.2 Shallow landslides sub-model

The shallow landslides submodel coupled to the hydrological hydrologic model is proposed by Aristizábal et al.. The model conceptualizes the stability of a cell based on the concept of an infinite

- slope described by the geomorphological and soil properties of the cell. The model submodel classifies cells into three groups: unconditionally stable, conditionally stable and unconditionally unstable. Figure 7 describes the variables of the model and the balance of forces considered. Three parameters determine stability of each cell: (i) residual soil thickness water table $Z_{i,min}$ estimated as in equation (6)6, (ii) the maximum soil depth at which a particular soil remains stable $Z_{i,max}$ estimated as
- 530 in equation (7), and (iii) the maximum slope at which the soil remains stable $\beta_{i,0}$ estimated as in equation (8).

The geotechnical conceptual model8. In the equations and in the Figure 7 γ is the soil bulk density, is the soil bulk density, γ_w is the water density, is the water density, Z_w is the saturated soil thickness above the slip surface, is the saturated soil thickness above the slip surface, Z is the soil thickness

535 measured vertically, is the soil thickness measured vertically, β is the gradient of the hillslope. And

| Parameter Name | Symbol | Scalar Parameter | Mean Value | Spatial distribution |
|------------------------|--------------------------|------------------------------|------------|--|
| <u>Capilary storge</u> | Hu [mm] | 1 | <u>39</u> | In function of the slope |
| Gravitational storage | Hg [mm] | $\stackrel{1}{\sim}$ | 34 | As a function of the slope |
| Evaporation rate | Etr [mm/s] | 0.1 | 0.01 | As a function of the DEM |
| Infiltration rate | ks [mm/s] | 2.7 | 0.0012 | Lumped |
| Percolation rate | <u>kp [mm/s]</u> | 0.8 | 0.00012 | Lumped |
| System losess | <u>Kf [mm/s]</u> | $\overset{\textbf{0}}{\sim}$ | 0.0 | Lumped |
| Surface speed | <u>vr</u> [m/s] | 0.5 | <u>6.4</u> | As a function of the slope and storage |
| Subsurface speed | <u>vs [m/s]</u> | 1 | <u>7.1</u> | As a function of the slope, Hg and storage |
| Subterranean speed | <u>vb</u> [<u>m/s</u>] | 0.5 | 0.000095 | Lumped |
| Channel speed | <u>vc [m/s]</u> | 1 | 0.95 | As a function of the slope, acumulated area, and storage |

Table 3. Hydrologic model parameters.

,

is the gradient of the hillslope, and ϕ is the soil stability angle. Q_L and Q_R are the resultant forces on the sides of the slice.

$$Z_{i,min} = \frac{C'}{\gamma_w \cos^2\beta \tan\phi + \gamma \cos^2\beta (\tan\beta - \tan\phi)}$$
(6)

540
$$Z_{i,max} = \frac{C'}{\gamma cos^2 \beta (tan\beta - tan\phi)}$$
(7)

$$\beta_{i,0} = \tan^{-1} \left[\tan\phi \left(1 - \frac{\gamma_w}{\gamma} \right) \right] \tag{8}$$

The model assess conditionally stable cells in function of their perched water table for each cell $(Z_{i,w}, \text{ equation (9) 9})$ and the critical satured depth $(Z_{i,c}, \underline{\text{equation (10)}})$. Slope failure occurs when 545 $Z_{i,w}$ is greater than $Z_{i,c}$. $\overline{Z_{i,c}}$ is obtain using equation (10).



Figure 7. The geotechnical conceptual model. Figure and description are adapted from Aristizábal et al. (2016).

$$Z_{i,w}(t) = \frac{S_{3,t}}{W_c - W_{fc}}$$

$$Z_{i,c} = \frac{\gamma}{\gamma_w} Z\left(1 - \frac{tan\beta}{tan\phi}\right) + \frac{C'}{\gamma_w cos^2\beta tan\phi}$$

where At equation (9) $S_{3,i}$ represents gravitational storage, Ws and W_{fc} the soil saturation and field capacity respectively, γ represents soil density, ϕ is the soil stability angle, . And in equation (10) C' represents the soil cohesion and β the cell slope.

Flash flood submodel (HydroFlash)

$$Z_{i,w}(t) = \frac{S_{3,t}}{W_c - W_{fc}}$$
(9)

555
$$Z_{i,c} = \frac{\gamma}{\gamma_w} Z \left(1 - \frac{tan\beta}{tan\phi} \right) + \frac{C'}{\gamma_w cos^2 \beta tan\phi}$$
(10)

3.3 Flash flood submodel (HydroFlash)

It is common to use complex hydraulic 2D and 3D models, such as Iber (Cea and Blade, 2015) or HEC (Gibson et al., 2010) for flood spots identification. This kind of modeling requires detailed information about the terrain and river bathymetry and are usually implemented for a particular 560 river cross section due to the high information demand and high computational costs, precluding the operational implementation of 2D and 3D methodologies in regions with scarce resources. Also, this traditional hydraulic methodology tends to analyze only some network elements, overlooking the complexity of the basin. In this work, we introduce a low-cost 1D hydraulic model for flash flood simulation referred to as HydroFlash. The model extracts the cross-profile from the DEM for each The model requires hydraulic parameters for all network cells to determine flash-flooding spots. Channel width is estimated using the Leopold (1953) approach $W_i = 3.26\overline{Q_i}^{0.469}$. Channel slope $(S_{i,0})$ is obtained as the mean value of the slopes that correspond to the cells of a hydrological reach.

570 The characteristic particle diameter $D_{i,50}$ is assumed equal to 0.138and constant <u>m</u> and constant <u>(Golden and Springer, 2006)</u>. The cross-section (C_s) is obtained from the DEM, for every network cell, perpendicular to the flow direction of the cell ($D_{i,8}D_{i,8}$).

For each time step t and for each stream cell, equation (11)-11 determines the height of the wa-

- ter table Y_i(t) using the simulated streamflow Q_{i,sim}(t) Q_{i,sim}(t) and flow velocity v_{i,sim}(t). The model calculates the friction velocity (v_{fr,i}) using Y_i(v_{fr,i}(t)) using Y_i(t) as in equation (12) derived from Keulegan and Rouse equations (Takahashi, 1991). Equations (13) and (14) (Takahashi, 1991; Savage and Sayed, 1984)
 Equations 13 and 14 allow the estimation of the concentration (c_i(t)) and constitutive coefficients (r_ir_i(t)), respectively. In equation 13 C_{max} represents the maximum sediment concentration;
 according to Obrien (1988) C_{max} is near 0.75 during flash floods. The stream flow plus estimated
- according to Obrien (1988) C_{max} is near 0.75 during flash floods. The stream flow plus estimated sediments and rubble is estimated according to equation (15)15.

$$Y_{i}(\underline{t}) = \frac{Q_{i,sim}}{\underbrace{v_{i,sim}w_{i}}} \frac{Q_{i,sim}(t)}{\underbrace{v_{i,sim}(t)w_{i}}}$$
(11)

$$v_{fr,i}(\underline{t}) = \frac{v_{i,sim}}{5.75log\left(\frac{Y_i}{D_{i,50}}\right) + 6.25} \frac{v_{i,sim}(t)}{5.75log\left(\frac{Y_i(t)}{D_{i,50}}\right) + 6.25}$$
(12)

585

$$c_{i}(\underline{t}) = C_{max}(0.06Y_{i}(\underline{t}))^{\frac{0.2}{v_{fr,i}}})^{\frac{0.2}{v_{fr,i}(t)}}$$
(13)

$$r_{i}(\underline{t}) = \frac{1}{D_{i,50}} \left[\frac{g}{\underbrace{0.0128}} \left(\frac{9.81}{\underline{0.0128}} (c_{i} + (1 - c_{i}) \frac{\gamma_{w}}{\underline{\gamma_{sed}}} \frac{0.5}{\underline{\gamma_{sed}}} \frac{\gamma_{w}}{\underline{\gamma_{sed}}} \right) \right] \overset{1/2}{\cdots} \left[\left(\frac{C_{max}}{c_{i}} \frac{(1/3) - 1.0}{\underline{\gamma_{sed}}} \right) \frac{1/3}{\underline{\gamma_{sed}}} \right]$$
(14)

590
$$Q_{i,sed}(\underline{t}) = Q_{i,sim} \frac{1+c_i Q_{i,sim}(t)}{1-c_i (1-c_i(t))}$$
 (15)

assuming Assuming infinite sediment and rubble supply, $Q_{i,sed}$, $Q_{i,sed}$, (t) is the maximum stream flow for the section. To determine the flooded area, an equivalent $Y_{i,sed}$ a flood depth $F_{d,i}(t)$ must be found in order to obtain an stream flow $(\hat{Q}_{i,sed}\hat{Q}_{i,sed}(t))$ (equation (18)) that equals $Q_{i,sed}$. The estimation of $Y_{i,sed}$ is an iterative process. The model obtains the 18) that equals $Q_{i,sed}(t)$. The

- search of $F_{d,i}$ is done iteratively by making small increments to it. Both flooded area $(A_{i,sed})$ based on $Y_{i,sed}$ and equation (17) $A_{i,sed}(t)$) and flooded section $(F_{f,i})$ are obtained in the process. At each iteration, $F_{d,i}$ is an estimated depth (equation 16), measured from the bottom of the section (b_i) to a guess elevation of the section $(\Delta y \cdot j)$. The depth of $F_{d,i}$ increases with each iteration as j takes values between 1 and the total number of iterations with a step of 1. At the end of each iteration,
- 600 $A_{i,sed}(t)$ is estimated with equation 17, in which $F_{sec,i}$ corresponds to the section *i* extracted from the DEM. Based on the value obtained for $A_{i,sed}(t)$, the model estimates $\hat{Q}_{i,sed}$ (equation 18). The process stops when $\hat{Q}_{i,sed}$ is similar to $Q_{i,sed}$, at this point, the flooded section $F_{f,i}$ corresponds to the values of $F_{sec,i}$ that are below $F_{d,i}$.

$$\underbrace{i,sed}_{\underline{i},\underline{sed}} \underbrace{F_{\underline{i},\underline{i}}}_{\underline{j}} = \frac{2}{5} \underline{r} b_{\underline{i}} \underbrace{(\underline{j} + \Delta y_{\underline{i},sed})^{\frac{3}{2}} S_{\underline{i},0} 0.5_{\underline{i},sed}}_{\underline{j}} \underbrace{j}$$
(16)

$$\hat{A}_{i,sed} = \Delta x \sum_{j=1}^{N} \underbrace{(Y_{i,sed} + \Delta y_{i,sed}) F_{d,i}}_{j=1} - \underbrace{C_{j,s} F_{sec,i}}_{j=1}$$
(17)

$$\hat{Q}_{i,sed}(t) = \left(\frac{2}{5}\right) r_i(t) (j\Delta y)^{\frac{3}{2}} S_{0,i} \hat{A}_{i,sed}(t) \cdot 0.5$$
(18)

Resulting flood maps might evidence the presence of small isolated flood spots and discontinuities at flood spots where flow direction changes from orthogonal to diagonal or vice-versa. We included two post-processing steps to correct these issues by (i) using an image processing erosion algorithm
610 (Serra, 1983) to remove the small isolated flood spots. The erosion is performed once with a 3x3 kernel, and (ii) to solve the flow direction discontinuities, each flooded cell seeks to flood its eight neighboring cells. A neighbor cell is also flooded if the altitude of the original flooded cell plus the flood depth is higher than its altitude.

3.4 Hydrological runoff scheme modification

615 Horizontal flow equations could be either linear or potential, as shown in equation (1). In the modified hydrological model, β and α are estimated by the user and then set into the model.

$v_{tank}(t) = \beta A(t)^{\alpha}$

Non-linear equations in lateral flows could result in a better representation of processes at high resolutions (Beven, 1981; Kirkby and Chorley, 1967). A non-linear approximation to runoff is presented

in equation (2). This approximation is a modification of Manning's formula for flow in gullies. 620 According to Foster G.R. (1984), the values of ε and e_1 are 0.5 and 0.64, respectively. The non-linear equation (3) corresponds to an adaptation of Kubota and Sivapalan (1995) formula for subsurface runoff.

$$\frac{v_2 = \frac{\varepsilon}{n} S_0^{1/2} A_2(t)^{(2/3)e_1}}{2}$$

$$v_3 = \frac{K_s S_o^2}{(b+1)A_g^b} A_3(t)^b$$

Where k_s is the saturated hydraulic conductivity, and b is dependent on the soil type, and it is assumed equal to 2. A_q is the equivalent cross-section area to the maximum gravitational storage (H_g) . There is also return flow from tank 3 to tank 2 when $S_3 = H_g$, representing runoff generation by saturation.

The equations describe the momentum of a kinematic wave approximation. In both cases, velocity depends on the tank storage. These relations could be summarized by the equation (1), that could be solved numerically coupled with a mass balance equation (4). This equation takes into account the storage at each time step $(S_{tank}(t))$, the longitude of the element (Δx) , the time step size (Δt) , and

635 the speed estimated for the flow in the time step $(v_{tank}(t))$. Equation (4) is related to equation (1) through the velocity term (v_{tank}) and the cross-sectional area (A). The solution to v_{tank} and A is obtained through an iterative scheme. The total outflow from the tank is calculated using equation (5).-

$$A(t) = \frac{S_{tank}(t)}{\Delta x + v_{tank}(t)\Delta t}$$

$$F_{tank}(t) = A(t)v_{tank}(t)\Delta t$$

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625

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$$\underline{E_{tank}(t) = A(t)v_{tank}(t)\Delta t}$$

elevation.

4 Results

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The primary results of the present study include the reconstruction of the 2015 Salgar flash flood, the assessment of the importance of soil moisture in the hydrologic response of the basin, and the evaluation of the relative role of stratiform and convective precipitation cores in the generation of the observed extreme event. This section is based on the results from the analysis of the hydrological simulation, as well as shallow landslides and flash floods occurrence and simulation.

650 Figure 5a presents the temporal evolution of the convective-stratiform rainfall partitioning during both Events 1 and 2. The main difference between both events is the timing of the convective

versus stratiform participation within each case. Event 1 started as a stratiform precipitation event moving from the southwest, from the Department of Chocó to the Department of Antioquia across westernmost Andes mountain range. Chochó is the rainiest department in Colombia, and one of the

- 655 wettest places on Earth, due to the inflow of moisture from the Pacific Ocean and the orientation of the Andes mountain range (Poveda and Mesa, 2000; Mapes et al., 2003). After 3 hours of stratiform rainfall, training convective cores move over La Liboriana basin generating intense precipitation peaks during 2.5 hours. It is important to note that these cores did not strengthen within La Liboriana basin; these systems formed and intensified over the western hills of Farallones de Citará draining
- 660 to the Department of Chocó towards Atrato river. The latter is not a minor fact because once the convective system move with a northeast direction, the maximum intensity cores do not fall over the steepest hills of La Liboriana basin but rather near the basin outlet where the slopes are considerably flatter. Figure 5b shows the spatial distribution cumulative rainfall during Event 1, corresponding to a basin-average precipitation accumulation of 47 mm, with the maximum precipitation located towards
- 665 the bottom third of the basin. Event 2, on the other hand, started as a thunderstorm training event with two convective cores moving from the southeast followed by remaining stratiform precipitation. Even though the average cumulative rainfall over the basin was 9 mm less than during Event 1, this event is characterized by orographic intensification within the basin leading to a more heterogeneous spatial distribution and with the highest cumulative precipitation in the steepest portion of the basin
- 670 (see Figure 5b). Event 2 spatial distribution and highly localized observed intensities most likely led to the flash-flooding episode, as it is explored in the remainder of this section.

a) Temporal evolution of the convective-stratiform rainfall partitioning during both Events 1 and 2. The figure shows the total rainfall (yellow), and the convective (blue) and stratiform (green) portions integrated over La Liboriana basin. b) and c) Spatial distribution of the cumulative rainfall during Events 1 and 2 over La Liboriana basin.

4.1 Hydrologic model validation and sensitivity analysis

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Figure 8a presents the results of the hydrological simulation at the outlet of the basin. The model simulation is set to reach a base flow of $3 \text{ } \frac{m^3/\text{sm}^3\text{s}^{-1}}{m^3\text{s}^{-1}}$, a value that corresponds to the discharge measurements during field campaigns days and weeks after the flash flood event and during dry

- 680 spells. The simulation shows that Event 1 generates a hydrograph with a peak flow of $Q_{max} = 160 \frac{m^3/s}{1}$ that did not result in casualties or infrastructure losses, but $m^3 s^{-1}$. It is important to note that during precipitation Event 1 there were no damage nor flooding reports by local authorities. Even though this precipitation event did not generate flooding, it set wet conditions in the entire basin before the occurrence of Event 2 (see the purple line in Figure 8b). Additionally, it is clear
- from the simulation that during the flash flood event the two successive convective cores over the same region (training convection) generated a peak flow of $Q_{max} = 220 \text{ } \frac{m^3/\text{sm}^3\text{s}^{-1}}{m^3}$, value that is in the upper range of the estimated streamflow based on a posteriori post-event field evidence (185-



Figure 8. Summary of the Results from the hydrological simulation. a) Simulated streamflow, runoff and sub-surface flow separation and convective-stratiform generated discharge discrimination. The red square represents the flash flood peakflow interval estimated based on field campaing evidence. b) Mean runoff, gravitational, and capillary storages during the simulation period.

222 $\frac{m^3/sm^3s^{-1}}{m^3s^{-1}}$). Figure 8a also presents the <u>simulated</u> runoff and subsurface flow separation as well as the convective-stratiform generated discharge discrimination. The <u>modeling</u> evidence during

690 Event 2 suggests the convective rainfall fraction dominates the hydrograph formation. In both events, convective (stratiform) precipitation appears to be closely related to the simulated runoff (subsurface flow). On the other hand, the simulated subsurface flow is more important in magnitude than runoff in describing Event 1, while runoff is more relevant for Event 2.

Summary of the Results from the hydrological simulation. a) Simulated streamflow, runoff and
 sub-superficial flow separation and convective-stratiform generated discharge discrimination. b) Mean
 runoff, gravitational, and capillary storages during the simulation period.

Figure 8b presents capillary storage (purple), as well as runoff (continuous blue) and gravitational (dashed blue) storage temporal variability. As expected, runoff storage is only non-zero during the storm duration, while gravitational storage increases considerably during rain events, followed by a

- 700 slow recession. There is an increment of basin-wide capillary storage during Event 1, remaining considerably high the time leading to the occurrence of Event 2. According to the model simulations, the peak flow occurred around 2:20 a.m. on May 18th, which is very accurate compared to the reports from local authorities considering all the data limitations.
- Figure 9 shows the results of a sensitivity analysis of the hydrological simulation during the second rainfall event, varying the infiltration rate, and the surface and subsurface speed parameters. The aim of the sensitivity analysis is to evaluate the robustness of the overall results, considering the fact that the quality and quantity of some of the watershed information is limited. The overall simulation sensitivity results show the main findings described in the previous paragraphs are, in
- 710 fact, robust to almost all changes in the mentioned parameters, with surface runoff associated with convective rainfall controlling the magnitude of the peak discharge during the Event 2. Changes

in the infiltration rate (Figure 9a) result in peak flow changes with a magnitude less than 7%, and changes in the subsurface velocity parameter (Figure 9c) lead to peak flow changes with a magnitude less than 20% the original simulation. The model highest sensitivity, and hence the largest

- 715 uncertainty source, appears to be related to the surface speed parameter (Figure 9b), particularly in the low-end values. Although some of the surface speed values used in the analysis are unrealistically low, it is noteworthy to report that these values lead to the attenuation of the hydrograph and the reduction of the peak flow.
- Figure 10 shows the temporal evolution of discharge during Event 2 in different locations along the watershed's main channel. The upper location corresponds to 15% of the area of the basin, and the other downstream locations to 52%, 76%, and 100% of the watershed, respectively. In terms of volume, 73 Mm³ of the total 144 Mm³ simulated at the outlet of the basin are generated on the 15% upstream part of the watershed, corresponding to about half of the total mass. In terms of peak
- 725 flow, due to the slope and velocity changes, the simulated discharge at the 15% upstream part of the watershed corresponds to 61% of the peak discharge at the outlet of the basin.

4.2 Flash flood processes

In this study, we propose a graphical method to assess the soil-rainfall-discharge coupling holistirainfall-discharge coupling holistirainfall. The first step is to classify all the cells within the watershed in a predetermined number of groups according to their localization and the distance to the outlet. The aim is to establish a coherent and robust spatial discretization, thus allowing to summarize the concurrent spatio-temporal variability of the different processes in 2D diagrams. Figure ?? presents an example of the spatial structure of cell grouping for La Liboriana basin using 10 (left) and 50 (right) groups.

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Example of watershed grouping as a function of distance to the outlet for La Liboriana basin. The left panel corresponds to clustering using ten different groups, and the right panel shows the 50-groups categorization used in the present study.

- Figure 11 presents the proposed 2D diagrams obtained for the simulation of the La Liboriana basin flash flood using a spatial discretization with 50 groups. Figure 11a includes the evolution of the average rainfall over the basin (black line), and the spatio-temporal evolution of capillary storage (filled isolines) and return flow (colored isolines from white to red) by groups. For the analysis, it is relevant to highlight that higher numbered groups are located away from the outlet of the basin and correspond in this case to considerably steeper slopes. Figure 11b presents the evolution of stream-
- 745 flow at the outlet of the basin (black line) as well as the gravitational storage (filled isolines) and runoff (colored isolines) spatio-temporal evolution. Figure 11 shows variations in the capillary and gravitational storages associated with Event 1 in the higher numbered groups. The capillary storage

remains high in almost all the basin until the start of Event 2. According to the conceptualization of the model, the gravitational storage and surface runoff start to interact when the capillary storage is

750 full. In this case, this situation is set up by Event 1. Model runs for Event 2 using dry initial states, show no flooding in the results.

It is well known that the temporal variability of rainfall intensity plays an important role in the hydrograph structure. During Event 1 rainfall accumulated over the basin at a relatively stable rate (Figure 12a). On the other hand, Event 2 presents a significant increase in rainfall rate in the second

- half of the life cycle (Figure 12b). This change in precipitation intensity is associated with a considerable intensification of the training convective cores due to orographic effects. Events 1 and 2 also exhibit differences in the elapsed time between rainfall occurrence and streamflow increment given the relative timing of stratiform versus convective rainfall (see the gray band in Figure 12a and b).
- For Event 1, the median elapsed time between rainfall and streamflow (Et_{p50}) is 1.12 hours while for Event 2 Et_{p50} is 0.79 hours. The median elapsed time between the convective portion and the streamflow (Etc_{p50}) in Event 1 is 0.75 and 0.46 in Event 2. The minimum value of the convective elapsed time Etc_{min} also descends from 0.42 to 0.25 hours. On the other hand, there is an increase of median elapsed time between stratiform rainfall and streamflow (Ets_{p50}) from 1.21 to 1.83 hours.
- 765 In Event 2, the convective rainfall and the runoff show a similar evolution, denoting a strong influence of the convective portion (Figure 12b).

As mentioned before, average rainfall accumulation over the basin for Events 1 and 2 is 47mm and 38mm, respectively. During Event 1 (2), convective (stratiform) average accumulations are 28 (23) and 17 (14) mm, respectively (Figure 13a and b). The maximum rainfall intensities are rela-

tively similar with 150mm/h and 180mm/h for Events 1 and 2, respectively. Despite this, Event 1 does not trigger a flash flood event. The overall evidence suggests that the discriminating factor between both events does not lie in the portions of convective or stratiform rainfall but rather in their spatial distribution.

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Figures 13a and b, and Figures 13c and d show the convective and stratiform cumulative rainfall, and the spatially-averaged convective and stratiform rainfall, both as a function of sub-basin reach, respectively. Figures 13a and b show that while Event 1 exhibit similar convective and stratiform rainfall accumulation for different watershed scales, Event 2 shows a more significant cumulative
contribution of convective rainfall than of stratiform precipitation. Convective rainfall tends to cover less area, and at the same time present a spatio-temporal erratic behavior (Steiner et al., 1995; Houze, 1989). Figures 13c and d provide evidence that convective rainfall present higher variations at small sub-basins than for a larger-order basin. During Event 2, convective accumulation reaches higher values for small and medium sub-basins. Convective rainfall occurrence at the upper sub-basins

- has significant implications due to geomorphological conditions associated to zero-order sub-basins 785 (Sidle et al., 2018). Figure 14 presents Pearson correlations coefficients between the convective and stratiform hydrograph portions and the runoff and subsurface flow. According to this, convective and stratiform rainfall exhibit a weaker relationship with the flow characteristics at small scales (under $5km^2$). This is likely to be associated with increasing variability of rainfall and hydrograph forma-
- 790 tion at small scales (Ayalew et al., 2014). Correlations tend to grow with increasing area, indicating stabilization of the hydrograph formation. Additionally, subsurface flow presents higher correlations during Event 1, while correlations with runoff are higher for Event 2, highlighting the most important process in each case. The relevance of subsurface flow is likely due to the rainfall characteristics during Event 1, with homogeneous rainfall intensity and high rate of basin recharge (see Figure 8b).
- On the other hand, saturation processes and a wet soil profile explain the observed higher correla-795 tions during Event 2.

4.3 Landslide and Flood Simulationsflood simulations

In addition to the hydrological simulation, associated hazards such as floods and landslides are also 800 modeled and discussed in this study. The landslides model as described in the previous section requires additional information including soil depth Z, cohesion C', friction angle ϕ and specific weight γ . According to the description by Osorio (2008), illustrating a clay-slime soil, C' is assumed equal to 4KN, ϕ to 30^0 and γ to 18; Z vary with slope according to Table 1.

- 805 Figure 15a presents the observed landslides triggered by Event 2 based on aerial photos and satellite images (Landsat/Copernicus, and Google) taken before and after the flash flood. Figure 15b shows, by hills, the map of total unstable cells during the simulation period, and Figure 15c shows the time series of the number of simulated unstable cells during Event 2 (continuous purple line) and the mean rainfall over the basin (inverse axes, blue line). Calibration of the landslide model was per-
- 810 formed by finding the maximum overlap between simulated and observed unstable and stable cells, and at the same time reducing the overall number of false positives and false negatives. It is important to note that the calibration strategy is not a cell-by-cell modification of the parameters involved but rather a basin-wide modification of soil properties. A sensitivity analysis of soil parameters is carried out by making small variations of the variables within specified intervals: ϕ between 25 and
- 815 32, γ between 17 and 19, C' between 3.5 and 4.2, and Z between 0.1 and 3 m. The sensitivity analysis suggests that slight variations in the parameter in Z produce significant changes in the modeled landslides, resulting in an overestimation of the number of unstable cells, or no unstable cells at all. Following Table 1, the average soil depth in the basin is only 0.3 m, a value that corresponds to underestimation according to the inspections during field visits. For this reason, the results presented in
- 820 Figure 15 use a Z map scaled by a calibration factor of 3.5, preserving the spatial dependence on the

slope, but achieving a more realistic soil depth and better spatial distribution of landslide occurrence.

The model represents considerably well the spatial distribution of the areas that are prone to trigger shallow landslides during Event 2, showing a significant density of unstable cells in the hills

- 825 where slides took place. However, despite the calibration efforts, the total number of unstable cells is relatively low compared to observations. It is important to note that there was no spatial calibration in order to obtain the right location of the landslides. The calibration only includes the change of the soil depth using a single scalar, constant for the entire basin, in order to maximize the number matching observed and simulated slides. In other words, there is just one single basin-wide parameter
- 830 modified, and not an independent modification of the parameter for every pixel in order to obtain the right distribution. This is important because in that sense, it serves to check the capability of the model to estimate risk areas only considering topography and rainfall data. A pinpoint localization of the unstable cells is still considered a hard task in part due to the small temporal and spatial scale at which landslide processes take place (Aristizábal et al., 2016; Dhakal and Sidle, 2004; Wu and
- 835 Sidle, 1995). Additionally, the lack of detailed soil information increases the simulation uncertainty. Notwithstanding the difficulties, the results suggest that the model simulations could have been used and should be used in the future for early detection and warning to improve both short and long-term risk reduction strategies.
- 840 According to the model results, a significant portion of the landslides happened during the first of the training convective cores reaching the upper basin (see Figure 15c). Due to the high soil moisture, cells located in the mentioned region where prone to failure. The second and more intense convective core, between 1:20 and 2:15 a.m., also triggered additional slides for an extended period. During storm events, shallow landslides become a significant source of gravels and sediments.
- 845 These particles tend to reach the river network, increasing the magnitude of the streamflow and its destructive power. Despite this, there is no current explicit link in the model between the landslides scheme and the hydraulic submodel. Nonetheless, HydroFlash assumes that sediment transport is limited by channel capacity, and not by hillslope supply, which in this case is guaranteed by the elevated number of landslides.
- Figure 16 shows the identification of the flood spots at the peak of Event 2 (May 18th, 2015, 2:00 a.m.) as simulated using HydroFlah. Figures 16b to f present a detail view of the results from the outlet of the basin to the upper region. Cases presented in Figures 16e and f exhibit a satisfactory agreement with observed flood spots (blue shadow). Cases in Figures 16c and d also show a good approximation, but with minor spatial shifts in some sections. The largest spatial differences are ob-
- 855 served in Figures 16b. At the entrance of the urban zone, the model overestimates the flood spots. The model results indicate that 11% of flood spots happen at elements of order 1 and 2, and, 18, 38 and 32% happen at orders 3, 4 and 5, respectively. This also highlights a coherent geomorphological

representation of the flooded channels and hills with the order.

860 5 Discussion

During the morning of May 18th of 2015, 1:30 a.m local time, a flash flood occurred in the steep La Liboriana basin, in the municipality of Salgar, Department of Antioquia, Colombia, leaving more than 100 human casualties, 535 houses destroyed, and significant infrastructure loses. The disaster was reported to departmental and national authorities around 2:00 and 2:30 a.m. Due to the lack of

- 865 local information of soil type, land use and real-time hydrometeorological data, La Liboriana case implies a challenge for flash flood prediction, modeling and, consequently, risk management. The present paper introduces a hydrological hydrologic model-based approach and an integral graphical analysis tool (an integrated spatiotemporal analysis of rainfall evolution, together with soil storages in the basin), not only to simulate and understand all the relevant soil-rainfall-discharge processes
- 870 that led to the 2015 Salgar flash flood while assessing the associated natural hazards, but also to propose it as a radar QPE-based landslide and flash flood guidance low-cost tool for basins with scarce data and regions with limited resources.

The methodology implies the development of a distributed hydrological hydrologic model with 875 the capabilities of tracking independently convective and stratiform precipitation within the model as well as keeping track of the runoff and subsurface portions of the streamflow, coupling a shallow landslide submodel and a one-dimensional flash flood scheme (HydroFlash). The model proposed here indeed allows studying the different hydrological processes relevant to flash flood and landslide occurrence by using different simulation resources, serving as the basis for a better understanding

- 880 of the overall basin response. This overall approach helps to isolate flood generating mechanisms or causative factors both in time and also in space, focusing on the important physical processes and not only on the statistics (Klemes, 1993; Merz and Blöschl, 2003). It is hoped that knowledge improvement leads to the anticipation of the warning and response by risk management entities.
- The evolution of the simulation of Events 1 and 2 show evidence of remarkable behavioral differences. During Event 1 both gravitational and capillary tanks are filled along and across the basin as a result of the quasi-homogeneous rainfall spatial distribution. The return flow is low, and most of the runoff occurs within the first 20 groups (40% of the watershed closest to the outlet). In the period between both events, there is a recession in the capillary and gravitational storages in the
- 890 entire basin. Capillary storage decays considerably slower than gravitational storage. During Event 2, the flash flood <u>triggering</u> event, the first convective core saturates both capillary and gravitational storages in the upper part of the basin and generates both return flow and significant runoff. Due to

soil saturation, the second convective core results mainly in surface runoff. During this event, runoff is generated the lower part of the basin while extreme runoff rates are evident in the upper part of the

895 basin, collocated with the steeper slopes. On the other hand, subsurface flow is more important in magnitude than runoff describing Event 1, while runoff is more relevant for Event 2. The precedent storage and the presence of thunderstorm training profoundly condition the streamflow during Event 2. The overall evidence suggests that precedent capillary moisture in the basin plays an essential role in modulating river discharge. This behavior could be linked to the temporal occurrence and relative

900 importance and timing of stratiform and convective formations previously described.

While convective and stratiform partitioning could influence the runoff and subsurface flow separation, the spatial distribution of rainfall relative to watershed network morphometry structure impose a condition on the hydrological response of the basin. In other words, hydrograph formation is not only determined by the rainfall accumulation or maximum intensity, but also by its spatial structure. The structure of the rainfall associated with La Liboriana event highlights the need to consider

in more detail the role of orographic rainfall intensification in practical applications such as early warning systems. Evidence suggests the spatial structure of the rainfall is at least as important as the geomorphological features of the basin regulating the generation of flash flood events.

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An integrated spatiotemporal analysis of rainfall evolution, together with soil storages in the basin is necessary to study the relevance of antecedent conditions and precipitation type, intensity, and location in the generation of flash flood events. Event 1 increased the overall soil moisture with an associated decrease on infiltration rates similar to results reported by Penna et al. (2011) and Zehe

- 915 et al. (2010), low infiltration increase runoff rates, which finally affects the susceptibility of the basin to flash floods occurrence (Wagner et al., 1999; Penna et al., 2011; Tramblay et al., 2012). La Liboriana geomorphological characteristics, corresponding to a steep tropical basin, determine the potential energy that controls water transit velocity. Water tends to reach faster the channels in order 1 and 2 hills, and, at the same time, the sediment production and transport in these hills tend to be
- 920 larger. Order 3 sub-basins most likely act as transport elements, with no important energy losses. Floods tend to occur in order 4 and 5 sub-basins due to the widening of the channel and slope attenuation.

Different authors have focused on trying to understand the general causative factors behind the occurrence of flash floods finding similar to our results, a significant role of basing geomorphology, orography and local convection. For example, Lehmann and Or (2012), using a shallow landslide model, finds an important role of the topography and the rainfall conditions. Turkington et al. (2014) shows how intense locally driven convection appears to be the main meteorological trigger for flash occurrence in the French Alpes.Camarasa-Belmonte (2016) shows how rainfall intensity and dura-

- 930 tion influences the shape of the hydrograph, with intense rainfall shortening the response time of the basin, and large durations increasing the flood peak. In the Mediterranean region, Boudou et al. (2016) states that in addition to the rainfall, geomorphological characteristics and antecedent soil conditions are key in the generation of flash flooding.
- 935 However useful, the evidence in this work only takes into account two successive events; an analysis of more cases and different spatial scales (different basins) would provide robust conclusions in this direction. It is clear that it is not conclusive enough to focus on a single extreme event, rather than on a spectrum of floods Merz and Blöschl (2003). The model simulation results suggest it is imperative to study in depth the long-term link between the relative basin and drainage network ori-
- 940 entation and the preferred path of precipitation events and its role in defining the frequency of flash flood occurrence. A better understanding of the network-hills-preferential rainfall advection structure could provide information about basins prone to flash floods when information is scarce.

6 Conclusions

- 945 Extreme rainfall events such as the one that triggered La Liboriana tragedy frequently take place in Colombia and the entire global tropical belt over ungauged basins, often triggering flash floods and torrential flows, endangering vulnerable communities due to poor long-term planning and lack of functional early warning systems. There is a global need for better knowledge and understanding of the hydrological and meteorological conditions that, combined, lead to the manifestation of natural
- 950 hazards. Such understanding must result in useful practical applications that improve risk management practices saving lives. In the current work, we approach the problem from a hydrological modeling point of view, trying, despite the data limitations and the uncertainty of the results, to shed some light in the first-order processes that modulate the occurrence of flash floods in the region.
- In the case of La Liboriana flash flood, radar reflectivity fields were available from a C-Band radar operated by the Early Warning System of Medellín and its metropolitan area as part of a local risk management strategy. While the municipality of Salgar is located far outside Medellín's metropolitan area, the radar is about 60.90 km away from Salgar, and the reflectivity retrievals enable the classification of precipitation fields into convective and stratiform areas using widely accepted
- 960 methodologies by the meteorological community. Radar reflectivity is also a proxy for precipitation allowing a quantitative estimation of rainfall fields. This estimation was used together with the hydrological modeling hydrologic model to assess the different basin-wide processes taking place during the flash flood triggering rainfall event. The limitations of the methodology presented in this work do not allow to represent all the detailed small-scale preferential pathways of water in the

965 watershed, but rather focus on the first-order approximation to study the partitioning between runoff vs. subsurface flow. Also, the model results are used to obtain a conceptual idea about the general processes, but it must be taken into account that the simulations are subject to a calibration process that could lead to erroneous conclusions about the physical processes. This could be true even as different steps were taken trying to avoid this situation.

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The overall model simulation methodology reproduces considerably well the magnitude and timing of La Liboriana flash flood discharge peak, as well as showing robustness to changes in the most important model parameters, and reasonably well the areas of regional land-slide occurrence and flood spots location. Simulation Model simulation results indicate that the flash-flood and the

- 975 regional land-slide features were strongly influenced by the <u>observed</u> antecedent rainfall associated with a northeasterly stratiform event that recharged the gravitational and capillary storages in the <u>entire basin</u>. The hydrologic simulation shows that the antecedent event set wet conditions in the entire basin before the occurrence of the flash flood event, governing the streamflow during the latter. The Results of the model simulation also suggest that the first of the two successive convective cores
- 980 (thunderstorm training) over the same region during the second precipitation event (the flash flood event) saturated both capillary and gravitational storages in the upper part of the basin and generated both return flow and significant runoff. The second convective core resulted mainly in surface runoff spatially collocated with the steeper slopes, generating the kinetic energy needed to produce La Liboriana flash flood. Overall results also show an excellent a good agreement between the simulated
- 985 flood spots and the observed ones; this in spite of the limitations imposed by the resolution of the DEM used for extracting cross sections, and the model simplifications described in the Methodology section oversimplifications.
- The Considering all the shortcomings and generalizations, the described model-based approach is 990 useful to isolate potentially useful to assess flood generating mechanisms and as a tool for policymakers, not only for short-term decisions in the context of an early warning system but also as a planning resource for long-term risk management. While several improvements could need to be implemented, including a better representation of hydraulic parameters, and a direct link between landslides and flood spots similar to the strategy presented in the STEP-TRAMM model
- 995 (Fan et al., 2017), the results suggest it is possible to use the low-cost methodology introduced here to not only improve our understanding of hydrological processes but also methodologies such as the one introduced here as a risk management tool in countries and regions with scarce resources. In the case of Salgar, there was radar information available, but in many cases, the only near-real-time precipitation information comes from satellite retrievals. It would be very useful from
- 1000 a practical point of view to assess in which cases satellite information is enough for risk management applications. Comparing the Salgar case with the Mocoa (Department of Putumayo, Colombia) April

1st, 2017 flash flood that resulted in more than 330 fatalities could help address this question.

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- For the technically inclined reader, the hydrologic model and sub-models are written in Fortran 90, and the interface to the model, pre-process, and post-process tools are in python 2.7. The Fortran code is warped to python using **f2py** (Peterson, 2009) and it is publicly available under the Watershed Modelling Framework **WMF** in a web repository (**GitHub**).

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Figure 9. Hydrological simulation sensitivity analysis. Similarly as in Figure 8, all panels show the simulated streamflow, and the runoff and sub-surface flow separation. The left panel shows sensitivity to changes in the infiltration rate parameter, the middle panel to changes in surface speed, and the right panel to changes in subsurface speed.



Figure 10. Temporal evolution of discharge during Event 2 in different locations along the watershed's main channel. The upper location corresponds to 15% of the area of the basin, and the other downstream locations to 52%, 76%, and 100% of the watershed, respectively.



Figure 11. Spatiotemporal Watershed groups and spatiotemporal analysis of Events 1 and 2. a) Example of watershed grouping as a function of of their localization and distance to the outlet for La Liboriana basin using a 50-groups categorization. Each group corresponds to a row in the contour plots b) and c). b) Simulated capillary moisture (filled green-to-blue contours) and returned flow occurrence (white to red isolines). The black line represents the average rainfall over the basin. **b**c) Simulated gravitational moisture (filled green-to-blue contours). The black line represents streamflow at the outlet of the basin. The green-to-blue color bar serves as a reference for capillary moisture and gravitational water content.



Figure 12. Accumulated rainfall and streamflow for a) Event 1 and b) Event 2. The accumulation is expressed in percentage respect to the total value in each case. Median elapsed time and minimum elapsed time () are estimated between total (Et_{p50}, Et_{min}) , convective (Etc_{p50}, Etc_{min}) , and stratiform (Ets_{p50}, Ets_{min}) rainfall and the runoff portion of the streamflow. Gray bands correspond to the periods for elapsed time estimation.



Figure 13. Cumulative rainfall versus the area at each reach of the basin for a) Event 1 and b) 2. Panels c) and d) show the average rainfall versus the area at each reach of the basin. Yellow dots correspond to the total, green dots to convective and blue dots to stratiform rainfall. All panels use a logarithmic scale for the basin area.



Figure 14. Pearson correlations among convective and stratiform portions of the rainfall and runoff and subsurface flow for different reach areas. Dashed lines correspond to Event 1 and continuous lines Event 2.



Figure 15. a) Observed landslides triggered by Events 1 and 2. The figure is based on aerial photos and satellite images (Landsat/Copernicus, and images available on Google) taken before and after the flash flood event. b) Map of total unstable cells during the simulation period. c) Time series of number of simulated unstable cells during Event 2 (continuous purple line) and mean rainfall over the basin (inverse axes, blue line).



Figure 16. Simulated flood spot at the peak of Event 2 in different locations. a) Basin drainage network. White squares correspond to regions of interest highlighted in panes b) to f). The colors of the streams correspond to the Strahler order of the network. b) Zoom at the outlet of the basin, where an important portion of the human and infrastructure loses took place. c) Zoom at La Margarita settlement also affected by the flash flood. d) to f) Zoom at key locations along the principal stream. Observed flood spots are shown in blue polygons and model flood spots in red to white grids.