We would like to thank the editor David Peres and the two anonymous reviewers for the time taken to handle, read and comment our manuscript. We provide below here our response to the reviewer comments in blue fonts, together with the actions we intend to do on the manuscript to address the comments in *blue italics fonts*.

Response to Reviewer #2

General comment: This manuscript aims at analysing the rainfall conditions leading to debris flows in an arid area in the Dead Sea region. To do so, Lidar-based DSM and media posts are used to gather a debris flow inventory. Rain-gage and radar data are employed to characterise the rainfall conditions leading to debris flow initiation. Generally, I appreciate the work. The manuscript is interesting and fits well with the journal topics. I feel, however, that the manuscript needs some major improvement for its publication.

We thank the reviewer for the thorough review.

Response to major comments:

Comment #1: The definition of antecedent rainfall and triggering rainfall should be clarified in the manuscript. In the current version of the manuscript, two different definitions of antecedent rainfall are given. The first definition is provided in Lines 255-256, where antecedent rainfall is defined as "the time passed between the beginning of the storm and the time defined as the offset of the triggering convective cell". The second is given in lines 293-294, where antecedent rainfall is defined as "the rain accumulated on the deposit pixel during the period starting on a 24 h break in rain until the specific measured intensity". This is rather confusing. Usually, the term antecedent rainfall refers to the rainfall that falls in an area during a given period of time before the beginning of the triggering rainfall episode. From the two definitions provided in the manuscript, it is not clear which is the distinction between triggering rainfall and antecedent rainfall.

Thank you for this comment, which highlights an important weakness of our submission: the proper definition of triggering and antecedent rainfall. In the study, we make use of three main concepts: (a) the "initiating storm", which is the storm event during which the DF is initiated, (b) the "triggering cell", which is the high-intensity convective cell that occurred during the "initiating storm" and that provided the final trigger, (c) the "antecedent precipitation", which is the rainfall occurred within the "initiating storm" before the "triggering cell" hit.

Please also note that the manuscript contained a mistake: the initiating storms are indeed separated using 5 dry days (24*5 hours), and not 24 hours. Hence the doubts about the double definition.

We will include a paragraph at the beginning of section 4 in which these concepts are properly defined, and we will then use consistent terminology throughout the manuscript. The paragraph could be as follows: *"We introduce here three concepts that we will use to characterise the properties of the precipitation that led to DF initiation. We define as "initiating storm" the storm event during which a DF is initiated. To this end, storms are defined as wet periods separated by* *at least 5 days of dry weather (i.e., 120 hours with less than 0.1 mm h^{-1} in the radar data). We define as "triggering cell" the high-intensity convective cell that likely provided the final trigger to the DF initiation. Last, we define as "antecedent precipitation" the rainfall observed before the triggering cell and during the initiating storm (i.e., between the beginning of the initiating storm and the beginning of the triggering cell"*.

Comment #2: I suggest modifying the structure of the manuscript. As it is now, the results of the analysis of the triggering rainfall conditions are only presented very briefly in section 4.3 (only one paragraph is used). The results of the analysis of the antecedent rainfall are scattered throughout the manuscript. Part of them are given in section 4.3, where the triggering rain should be characterised. Some others are presented as part of the discussion (section 5.1). This is surprising given the title. I think that including a results section explaining both the analysis of the triggering rainfall and the antecedent rainfall conditions before the discussion would help make your point clearer.

We will reorganize part of the manuscript according both reviewers' suggestions. Specifically, we will move a section from the discussion (5.1) to the introduction (1), and we will move the paragraphs of section 5.1 about antecedent precipitation (which indeed include some results) in the results section (4.3).

Comment #3: In the discussion, the fact that not all intense rainfall events can trigger debris flows is solely attributed to the role of antecedent precipitation. However, other factors such as sediment availability also play an essential role in debris flow initiation. This fact has not been considered. It should be at least mentioned in the discussion and the abstract.

We entirely agree with this reasoning and with the fact that in arid regions sediment availability is often critical. Our field observations, however, suggest that colluvial sediments on the steep slopes in the study area are vastly available and do not represent an important limiting factor. The small size of the steep slope areas is to be considered more of a limiting factor than sediment availability. Just as an example it is important to note that Figure 7 is obtained only focusing on the locations where DF occurred. This implies that the conditions on slope and sediment availability were certainly met, at least for all the storms occurred before the triggering.

To better explain this aspect, we edited this part of the discussion to: *"Given the vast sediment availability, the rarity of DFs in the area is usually explained by the dry weather (i.e., low number of storms) and the small areal extent of the susceptible steep slopes: only convective cells hitting the small susceptible area can trigger a DF."*

Comment #4: [Section 2.1: Geography and geological settings] The authors provide an extensive description of the geological setting of the studied area in which the debris flows occur. However, more relevant information to understand the materials involved in the debris flows is to be provided. Which is the granulometry of the materials involved in the debris flows? Is the availability of sediment homogeneous over the study area? These two factors are relevant as the *soil properties might influence the velocity at which pore pressures are dissipated. Sediment availability plays an important role in debris flow initiation.*

Thank you for this comment. As suggested above, we will provide new text to explain the importance of the sediment availability. Nevertheless, we also recall here that sediment availability is not regarded as a critical limiting factor in the study area, as also confirmed by our field surveys.

The new text could be like: *"The middle part of the escarpment is mostly covered by colluvium composed of fragments originated from the rock mass above. It is important to note that although the colluvium is abundant and mostly found on the middle part of the escarpment, it is usually found on soft layered units (dominated by marl) while the hard layers form cliffs and stairs-like morphology with less or no colluvial cover. While the colluvium coverage may change from place to place along the escarpment due to changes in the exposed layers, it is still abundant and does not represent a limiting factor for DF triggering in the study area." (from Section 2.1).*

Following this comment, we will also add some quantitative information about the grain-size analysis of the source material and a better description of the DF deposits:

In section 2.1: *"The colluvium thickness is changing laterally with an observed maximum value of a few meters. At the surface, the colluvial material is usually grain supported with increasing amounts of fine particles at depth of a few tens of centimetres. The colluvium fine fraction (<2 mm) is dominated by crashed dolomites and some quartz, calcite and phyllosilicates probably from eolian source. This fine material become muddy and unstable once exposed to water."*.

In section 3.2: *"For most of the mapped DFs (N=37), the deposits consist of angular dolomite and limestone fragments, unsorted grains with a maximum size of a few tens of centimetres. This deposit composition reflects the colluvium composition above it which mostly composed of the upper escarpment cliffs and some eolian fine particles. Hence, the source for the debris material is the talus at the base of theses cliffs. Differently, in fewer cases (N=6) located at the bottom of the lower step on the escarpment, the deposits consisted of rounded fragments, apparently derived from the nearby cliff of lacustrine and conglomerate sediments. These same two sources of debris materials were also reported by previous studies in the region (Ben David-Novak et al., 2004)."*

In addition, we will add a figure with a representative example of the slope over the study area, highlighting the contributing slope areas – see Figure A.

<u>Response to specific comments:</u>

Comment #5: [Section 3: Debris flow detection and characterisation] The occurrence of past debris flows is mapped mainly using Lidar-derived DSM. However, due to the relatively low frequency in which lidar surveys have been conducted, this product does not allow determining the triggering times. Media reports are useful but tend to include only events close to urban areas that impact the population. Perhaps the use of satellite images can improve the debris flow inventory in terms of the number of events and determination of the triggering time. Has this possibility been considered?

Yes, this is accurate. We tried to use satellite images for this purpose. Unfortunately, we couldn't find high-resolution (<10 m/pixel) satellite images of the study area for the relevant period. We did find that the Sentinel-2 mission has the relevant area, however, the resolution was too poor to observe the relatively small-size DFs. Since we started this project in 2019, we are now following each event more closely and have connections with the nature reserves in the area that report us about relevant events if occurred. In addition, soon we will install several time-lapse cameras and it seems that also the resolution of the satellite images getting better.

Comment #6: [Section 4: Rainfall data] From the text in section 4.1 it seems that rain-gage measurements are only used to adjust the radar rainfall estimates. However, line 199, states that rain gages are used to fill in the gaps in the rainfall time series at the locations of debris flows. In such cases, the rainfall accumulations at the rain-gage sites could be very different from the rainfall falling at the catchments where debris flows are triggered. Have you adjusted the rainfall measurements in some way?

It seems the reviewer misread the sentence as the radar data was not filled with rain gauge data. The sentence actually says that: *"In order to make sure that we did not miss a critical event, we compared the radar data with rain gauge stations."*. As mentioned in the submitted manuscript, we found that only two events in the whole period 2013-2019 were missing.

Comment #7: [Line 11]: The term short-lived debris flow is not widely used. It might be a good idea to provide the definition earlier in the text. Currently, the term is not defined until line 119.

Thanks for this comment. Our attempt to specify the peculiar size of our DFs with the term short-lived DF was clearly not successful, as both reviewers seem to dislike it. To avoid further confusion, we will change the term throughout the manuscript, including the title, to debris flows (DFs).

We will include additional clarifications behind our choice in the text, as follows: *"The DF deposits are located along small ephemeral streams that drain the cliff area above them and present evidence of previous debris flow activity. This suggests that they were mobilized by flow events and therefore considered as debris flows (DFs), as suggested by Hunrg et al. (2001). The DFs we examine are small-sized, with a runout distance between the source location and deposit of a few tens of meters."*

Comment #8: [Lines 201-206] How do you define antecedent rainfall? What criteria are used here to distinguish between antecedent rainfall and triggering rainfall?

Thank you for this important comment. We kindly refer to the reply to comment #1.

Comment #9: Fig 5, line 265: typo: red triangles.

Thanks, will be corrected.

Comment #10: Fig 6 The caption should be improved. What do the black dots represent?

Thanks for pointing this out. The black dots represent the locations of the rain gauges.

The caption will be improved to: *"The cliff-top (dashed line) together with the Dead Sea shoreline mark the narrow band of steep escarpment where debris flows may potentially triggered. Black dots show the location of the rain gauges. (a) Antecedent precipitation – map of the total rainfall during the March 2014 event until the onset of the trigging cell. (b) The total precipitation observed during the triggering cell (10:30-11:05). (c) Peak intensity of the triggering cell (5 min time interval). (d) Peak intensity of the triggering cell (30 min time interval)."*

Comment #11: [Section 4.3: Characterisation of the triggering rainfall] Reading the sub-section title, I expect to find an extensive description of the triggering rainfall events. However, this topic is addressed only in the first paragraph. Lines 253-261 focus on the antecedent rainfall.

We will adapt the section title to better represent the content: *"Characterization of the rainfall leading to debris flows"*

Comment #12: Line 316-327 I wonder which is the sediment availability in the different catchments where debris flows have been reported. Assuming that you had a complete inventory, it could be the case that some rainstorms did not trigger any debris flow simply because there was not enough prepared sediment in the catchments (see: Bovis, M. J., & Jakob, M. (1999). The role of debris supply conditions in predicting debris flow activity. Earth Surface Processes and Landforms, 24, 1039–1054).

Thanks for this comment. The issue of colluvium and sediment availability is crucial as it is one of the three factors needed for DF triggering (together with slope and water). At this concern, we need to point out two aspects. Our field observations, however, show that sediment availability is hardly a limiting factor in most of the slopes of the study region. In fact, we deem that slope steepness is more of a limiting factor than sediment availability.

To make this aspect clearer, we will include additional information on the description of the study area: *"The ~10 km long studied escarpment can be generally divided into three parts: Lower soft sediments, Middle colluvium and upper cliffs. In many places along the lower parts of the escarpment (altitude < 300 m below the mean sea level), the carbonate rock slopes are covered by lacustrine and fluvial sediments, deposited during high lake stands in the Pliocene-Pleistocene periods (Bartov et al., 2002, 2007; Sneh, 1979; Begin et al., 1980). Many of these exposures are soft and/or cohesionless, mostly composed of carbonate and some chert pebbles. The upper third of the escarpment, usually the steepest, is rocky and composed of hard carbonate rocks (mostly dolomites). The middle part of the escarpment is mostly covered by colluvium composed of fragments originated from the rock mass above. It is important to note that although the colluvium is abundant, it is usually found on soft layered units (dominated by marl) while the hard layers form cliffs and stairs-like morphology with less or no colluvial cover. While the colluvium coverage may change from place to place along the escarpment due to changes in the exposed layers, it is still abundant and does not represent a limiting factor for DF triggering in the study area. The colluvium thickness is changing laterally with an observed maximum value of a few meters. At the surface, the colluvial material is usually grain supported with increasing amounts of fine particles at depth of a few tens of centimetres. The colluvium fine fraction (<2 mm) is* *dominated by crashed dolomites and some quartz, calcite and phyllosilicates probably from eolian source. This fine material becomes muddy and unstable once exposed to water. Both, the lacustrine and fluvial sediments together with the colluvial deposits constitute the typical source material of DFs in the study area (Ben David-Novak et al., 2004).''*

In addition, we will add to the revised manuscript two additional figures A and B (see below) that will give the reader another visual description of the studied DFs and sediment availability on the studied slopes.

We will also rephrase part of the discussion in section 5.1 to: *''Given the vast sediment availability, the rarity of DFs in the area is usually explained by the dry weather…''*

It should also be recalled that, despite our efforts, our inventory cannot in any way be considered as complete. For instance, section 5.1 of the submitted manuscript, which will now be moved earlier in the Results section, provides as example of DFs that were only identified at a later stage in the study based on the results of the study.

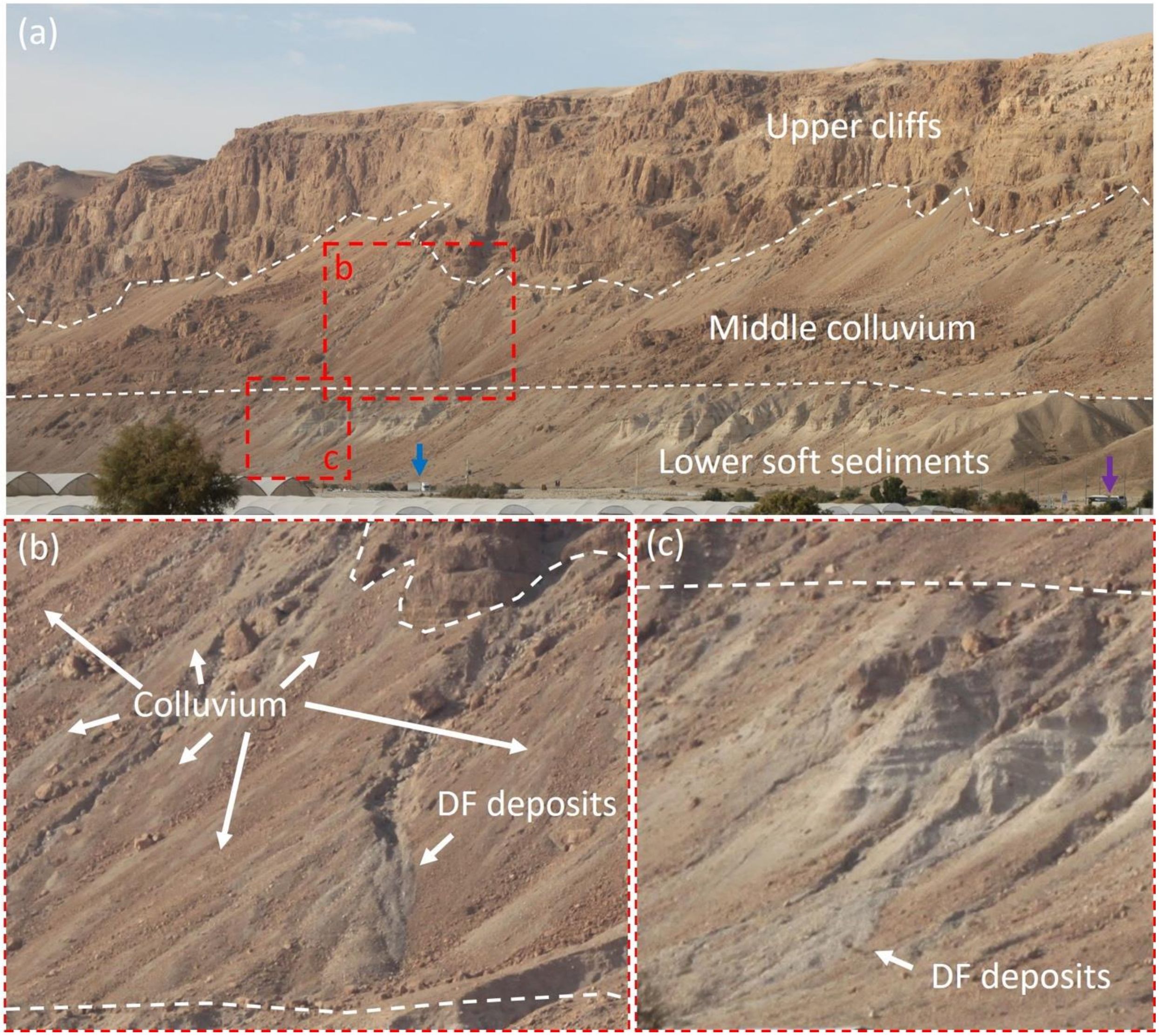

Figure A. The studied escarpment and the observed DF deposits. (a) The northern part of the study area where group 1 DFs were observed. The escarpment is generally divided into three parts: the upper cliffs, middle colluvium, and lower soft sediments. A truck and a bus are marked for scale by blue and purple arrows, respectively. The extent of the zooming-in photos are marked by red rectangles. (b) A section of the middle colluvium part of the escarpment. Colluvium cover (some are pointed by white arrows) with some large boulders is cut by small ephemeral streams that ends with DF deposits. The source material is usually clearly seen in the colluvium above these deposits. (c) A DF lobe at the end of a short ephemeral stream. The deposits source from the light-color lacustrine sediments.

Figure B. An example of DF deposits triggered prior to 2013. A distal lobe (white arrow), two levees (blue arrows) and a wide and shallow channel in-between them at the end of ephemeral stream drained the cliff area.