Title: Rapid assessment of abrupt urban mega-gully and landslide events with Structure-from-Motion photogrammetric techniques validates link to water resources infrastructure failures in an urban periphery.
Author(s): Napoleon Gudino-Elizondo et al.
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Reply to Reviewer #1 Comments

We thank the Reviewer for taking time to review the manuscript. The helpful and constructive comments put us in an excellent position to further improve the paper. The text below contains our response in a point-by-point format. To clearly distinguish reviewer comments from our responses, the reviewer comments are indented.

> *General comments:*
> The paper by Gudino-Elizondo et al. entitled "Rapid assessment of urban mega-gully and landslide events with Structure-from-Motion techniques validates link to water resources infrastructure failures" analyzed the effectiveness of SfM photogrammetric techniques for rapid erosion assessment following water resources infrastructure failures (WRIF) events that affected the Urban development in Tijuana, Mexico. The study monitored for a five-year period three hazardous mass-movement events including two mega-gullies and one landslide and evaluate the significance of WRIF events with respect to mass movement hazards and sediment budgets at neighborhood- and watershed scales.
> Overall, this is an appropriate subject area for NHESS journal, and the amount of data collected is very important from a risk monitoring and prevention perspective. However, this work should try to better illustrate the application of the photogrammetric technique to the case of study, adding some aspects related to data post-processing and error assessment. I believe that this paper has great potential and interesting aspects that could be improved to make it more appealing to a reader. It requires an upgrading, maybe assessing the limits and errors associated with the used topographic techniques and the comparison with other technologies and studies in terms of gullies and landslides monitoring. With some improvements, this work can be interesting and useful for the scientific community.

We thank the reviewer for remarking on the importance of this work and it's fit within the NHESS journal. We also thank the reviewer for the general suggestions to improve the paper. Based on your feedback and also the feedback from Reviewer #2, we revised the original manuscript following a four-part plan to improve the paper: (1) we clarified our focus on "abrupt" earth surface hazards which occur over a time scale of hours within the periphery of expanding urban areas and as a result of the combined effects of rainfall and water resources infrastructure failure (WRIFs), (2) we emphasized that rapid-response SfM-photogrammetry is a promising approach to document these abrupt hazard events, and we added more information about post-processing data including errors and uncertainties as recommended by the Reviewer, (3) we also added more contextual information (e.g., history of development, climate, presence of unpaved roads) around our observations to enable a richer interpretation of these important data as recommended by Reviewer 2, and (4) we reported the ways in which this work informs our understanding about the triggers and processes that are responsible for these "abrupt" hazards.

We regret that our original submission did not clearly explain our interest in "abrupt" events, i.e., mega-gullies and landslides that evolve over a matter of hours. The abrupt nature of these events is an important detail for justifying the importance and timeliness of rapid-response SfM-photogrammetry to document abrupt mega-gullies and landslides. This detail also bears on the originality of our contribution: to our knowledge, this is the first study to provide documentation of abrupt mega-gullies from a combination of rainfall and WRIFs, and only the second study to document abrupt landslides from a combination of rainfall and WRIFs. Since abrupt earth surface hazards in urban areas pose major safety and damage risks, with little opportunity for early warning and emergency response, primary data documenting these events and reporting their triggers is a very important responsibility of the scientific community.

Specific comments

- Abstract: I suggest rewriting it to make it more attractive to the reader perhaps emphasizing the innovative aspect of this work and the usefulness of these results in terms of the mitigation of WRIF hazard problems.

The authors agree that the abstract needs a revision which highlights the innovative aspects of the work, specifically the timescale of the WRIF's. For example, in the revision we have used the adjective "abrupt" throughout to better clarify the short timescales that WRIF's occur. While many studies have used remote sensing methods to document mega gullies and landslides, the rapid-response approach that document here is a direct response to the occurrence of mega gullies and landslides that occur very quickly (hourly timescale). It is precisely this context where we wish to emphasize this value of photogrammetric documentation and SfM processing, and the level of accuracy that is possible.

The revised abstract is shown below:

Abstract.

Water resources infrastructure failures (WRIFs), such as leaks and breaks in water supply pipes, have been postulated as triggers of abrupt mega-gully and landslide hazards, especially in low- and middle-income countries, but such phenomena are under-documented in the literature. To obtain primary data on the size, frequency and triggers of abrupt mega-gullies and landslides in urban areas, rapid assessment methods based on Structure from Motion (SfM) photogrammetric techniques were developed and deployed over a five-year period in Los Laureles Canyon, a rapidly urbanizing watershed in Tijuana, Mexico. Three abrupt earth surface hazards were observed including two mega-gullies and one landslide, and all were linked to a combination of rainfall and WRIFs: (1) water main breaks resulted from rainfall-driven gully erosion that undermined supply lines, and the resulting water jets caused abrupt mega-gully formation; we provide the first-ever detailed documentation of this process in an urban environment; (2) antecedent saturation of a hillslope from a leaking water supply pipe contributed to an abrupt landslide during a storm event. The return period of the storms that triggered the WRIFs was ~1-2 years, suggesting that such triggering events occur frequently. WRIF-based earth surface hazards were also a non-negligible contributor to sediment generation at the watershed scale. While the number of observed events is small, these results suggest that WRIF can, in some cases, be the single most important process generating abrupt and life-threatening earth surface hazards on the poor urban periphery. Future studies of the triggers and mechanisms of abrupt urban mega-gullies and landslides should consider the role of WRIFs in antecedent saturation and erosion by broken water supply lines.

- Introduction: this part should be underlined the innovative aspects of the work, motivated the choice of technologies used for the surveys, and highlighted the usefulness of the data obtained.

We agree. In response to this suggestion, as well as feedback from Reviewer 2, it is clear that the earlier version of the paper did not adequately frame the context of this work – making it challenging to appreciate the significance of the methods that we describe, our general findings about urban earth surface hazards, and how these findings can inform hazard mitigation (i.e., "usefulness of the data").

The instruction has now been structured as follows. The first paragraph introduces the reader to earth surface hazards in marginalized neighborhoods on the periphery of large cities in low- and middle-income countries, where there is little oversight of construction and development including the expansion of water distribution systems. Moreover, we allude to a growing challenge globally based on the rapid expansion of urban areas. The revised introduction is repeated below for clarity:
"Mega-gullies and landslides are significant earth surface hazards in urban areas, particularly in marginalized neighborhoods on the periphery of large cities in low- and middle-income countries (Sidle et al., 2011; Anderson et al., 2014; Makanzu Imwangana et al., 2014; Fu et al., 2020). Mega-gullies and landslides can undermine or damage housing and civil infrastructure and present life-threatening safety risks (Calvello et al., 2016; Peng et al., 2017; McAdoo et al., 2018). Mega-gully and landslide hazards are increasing at a time of rapid urbanization as a result of limited oversight of planning and construction as well as socio-economic pressures that force populations to settle in high-hazard areas (Hardoy et al., 2013; Retief et al., 2016; Miller et al., 2019). For example, in Latin America, urban expansion on the periphery of large cities often occurs on steep slopes (Sepúlveda and Petley, 2015), and unregulated expansion

often results in poorly planned and unmaintained infrastructure that is vulnerable to erosion and destabilization (Griffin and Ford 1980; Kjekstad and Highland, 2009; Biggs et al., 2010; Bianchini et al., 2017; Costa et al., 2018; de Albuquerque et al., 2020)."

The second paragraph now focuses the reader's attention on the specific type of urban surface hazard that is relevant to this work: abruptly occurring landslides and mega-gullies resulting from the interaction of water resources infrastructure failures (WRIFs) and rainfall.

"Earth surface hazards that occur abruptly are of particular concern from a safety and damage perspective, because there is little time for warnings and other emergency response measures. The literature characterizes the formation of mega-gullies as gradual, occurring over periods of years or more, and as a result of landscape changes such as deforestation, roads, and urban development (Archibold et al., 2003; Adediji et al., 2013; Makanzu Imwangana et al., 2015). In both agricultural and urban area, gully formation is associated with rain-generated runoff (Valentin, et al., 2005). However, mega-gullies may also form abruptly in the presence of a high velocity water jet from a pressurized pipe, a process similar to hydraulic mining used in mining operations in California during the 19th century (Gilbert, 1917). Furthermore, under rapid urbanization with limited oversight of design and construction, water supply systems are vulnerable to breaks that trigger hydraulic mining and the abrupt formation of mega-gullies on time scales of hours to days. In Tijuana, Mexico, local authorities have observed hazardous mega-gullies from pipe breaks and hydraulic mining (Chief of Civil Protection, Tijuana Mexico, personal communication, 2016), but the phenomenon has not been documented in the literature. Landslides may also occur abruptly. Landslides refer to a wide range of phenomena associated with the downslope movement of earthen material (e.g., rock or soil) under the influence of gravity, but (rotational) soil slides are the most common landslide type and abrupt events have been recognized as a significant threat to public safety (Highland and Bobrowsky, 2008). Landslides occur when the weight of earth material down a slope exceeds its strength (Highland and Bobrowsky, 2008), a process known as overloading that typically occurs with high soil moisture content following rainfall (Kuo et al., 2018; Valenzuela et al., 2018; Zhuo et al., 2019; Monsieurs et al., 2019; Marino et al., 2020). Recent studies have also shown that leaky pipes and septic tanks contribute to overloading (Demoulin and Hans-Balder, 2021). In summary, there are multiple lines of evidence that both water resources infrastructure failures (WRIFs) and rainfall contribute to abrupt earth surface hazards within urbanizing areas. More broadly, WRIFs have been linked to numerous other land surface processes such as the generation of sinkholes (Kim et al., 2018), erosion (Guo et al., 2013), and destabilization of soil (Van Zyl, et al., 2013). However, the occurrence of abrupt mega gullies from WRIFs and the interdependence with rainfall has not been a focus of previous research, which is needed given the threat of fatalities posed by abrupt hazards and the global growth of urban areas in the Anthropocene (Criqui, 2015; Ercoli et al., 2020)."

With the problem defined, the third paragraph explains that it can be addressed using remote sensing methods and SfM, yet such work has not previously been documented/demonstrated:

"Monitoring and analysis of abrupt earth surface hazards in urban areas is challenging. Earthwork typically proceeds quickly after an event to clean up or restore sites impacted by displaced sediment, and within days, the site is often so disturbed that it becomes impossible to perform a detailed investigation including measurement of feature size and identification of triggers. Access for monitoring also raises safety concerns due to the steep and unstable slopes. Structure-from-motion (SfM) photogrammetry presents a promising new approach to address these problems. SfM can safely monitor mass movement features with either on-ground or airborne platforms (Nadal-Romero et al., 2015; Eltner et al., 2016; Kaiser et al., 2018; Fugazza et al., 2018; James et al., 2019; Ma et al., 2020), and can be deployed quickly after an event to scan a site—providing data that can be used to estimate the dimensions and volumes of sediment displaced by erosional features. Furthermore, recent advances in the combination of UAS, SfM and MultiView-Stereo (MVS) algorithms facilitate data acquisition and processing to obtain high resolution point clouds, Digital Surface Models (DSMs) and orthophotos (Zhang et al., 2019)."

And finally, in the fourth paragraph we present an overview of our study, including our objectives and a description of the originality of the work:

"Herein we present a 5-year observational study whereby SfM was deployed in a rapid-response mode to document the frequency and magnitude of abrupt earth surface hazards, to document the relative roles of WRIFs and rainfall in hazard formation, and to quantify the amount of sediment generated by the WRIF hazards compared to other rainfall-runoff processes. The study is conducted in Los Laureles Canyon watershed (LLCW) located in the urban periphery of Tijuana, Mexico, and builds on previous work by the authors to document soil erosion, sediment generation, and flood hazards at the watershed scale (Biggs et al., 2010, Luke et al., 2018, Gudino-Elizondo et al., 2019; Goodrich et al., 2020). To our knowledge, no study has examined the role of WRIFs in abrupt earth surface hazards, a topic of growing importance in the Anthropocene. The objectives of this paper are three-fold: (1) to provide primary data on size, frequency and triggers of abrupt mega-gullies and landslides that occur in an urban periphery, (2) to demonstrate a SfM based approach suited to the rapid response needs of abrupt earth surface hazards, and (3) to evaluate the significance of WRIF events with respect to mass movement hazards and sediment budgets at neighborhood- and watershed-scales."

Specific comments

- Methods:
    1. A GoPro 3+ camera was used to carry out the SfM surveys, but it was not shown how the problems related to image distortion were solved given the use of a fisheye lens with a flight altitude very high.

Thank you for bringing up this point, we edited the text to clarify this issue: "Photogrammetric surveys were performed using a modified nonmetric camera (GoPro Hero3+) with a non-distortion lens (Peau Productions, CA, USA, http://www.peauproductions.com/) mounted either on an Unmanned Aerial System (UAS) (DJI, Phantom2) or a telescoping painter's pole (approximately 2-3 m long)" (lines 132-134).

2. Where are GCPs/ECPs located in the study area (a figure could be added about this)? Are the errors related to ECPs referred to the DSMs? and the errors related to point cloud?

We thank the reviewer for raising this important point. Figures 3, 4, and 5 have been revised to denote the spatial location of the GCPs/ECPs and were incorporated in the revised manuscript. Errors related to the point clouds, DSMs and DoDs were described in the methods section: "The horizontal and vertical RMSE of the point clouds, or geo-registration error, was estimated using the subset of the GCPs not used to produce the SfM point cloud, called Error Control Points (ECPs). Previous work indicates that 4 to 5 GCPs with a few additional ECPs are adequate for SfM processing (James et al., 2017). The RMSE for the DoD was computed as the square root of the sum of the squared errors for each DSM (Alfonso-Torreño et al., 2019)." (lines 148-151). Additionally, error assessment were further discussed in section 4.1.

3. Are the difference of DSM (DoDs) thresholded to account for the errors or do they represent raw differences?

We reported raw differences in the manuscript, but we also estimated the RMSE for the DoDs and these are reported in Table 3.

4. It would be useful to add more information about the SfM workflow, in particular, the post-processing of the point cloud (e.g. filtering, errors) through to the DSMs.

We reported in the methods sections that we followed general SfM workflows using Agisoft. Briefly, we used a set of GCP's to scale and georeferenced the point clouds and a subset of GCPs (ECP's) for accuracy metrics, both surveyed at sub-centimeter to 3cm resolution. Additionally, we added additional information about the errors related to the point clouds and DoD calculations in the Results and Discussion sections.

5. Has the problem of co-registration of point clouds been considered in making multi-temporal DSMs?

Yes. We compared elevation profiles in stable areas and no significant changes were observed (<7 cm). We also reported in the manuscript that co-registration errors were negligible (line 222).

Discussion

Misses an in-depth analysis on the problems and errors caused by the technologies used, how to improve these aspects, and a comparison with other works using the same techniques.

We agree that the discussion needs to be expanded to reflect on the technology, and we addressed this recommendation on the revised paper. Please see lines 340-344, 346-350, 351-359, and 367-369.

"SfM photogrammetric techniques have been widely used to quantify geomorphic changes in many environments with equivalent resolution compared to more sophisticated topographic techniques (i.e. TLS, LIDAR). Accuracies, limitations and disadvantages of both SfM and DoDs applications have been widely described in the existing literature (Wheaton et al., 2010; James et al., 2012; Carrera et al., 2020).".

"James and Robson (2012) introduced the relative precision ratio for UAS-SfM applications (i.e., ratio of measurement precision to observation distance), and found that a precision ratio of 1:950 indicates acceptable accuracy over a range of scales. For a flight height of 75 m, the James and Robson (2012) standard gives a desired DSM error of 7.8 cm, which compares well with the horizontal (3 cm) and vertical (7 cm) errors estimated here. The errors in the DSMs were very small (<=5 cm) compared to the size of the features (5-10 m)."

"Elevation differences outside of the disturbed areas were <7 cm, indicating minimum co-registration errors. Errors in sediment volume estimates were also small (1 to 3%). The DoD also helped to characterize the landslide as a deep rotational slope failure, consistent with other landslides reported in Tijuana, which are linked with unplanned urbanization on hilltops and enhanced pore pressure induced by uncontrolled water leakage (Oliva-Gonzalez et al., 2014). We also note from the DSM analyses that the terrain slope was associated with the depth of incision of WRIF mega-gullies. Mega-gully B was 2-3 times deeper than mega-gully A, which formed on a relatively flat area. Accuracies achieved from these observations, both from individual point clouds and DoD's calculations, are in line with the needs for erosion hazards surveys and sediment budget applications (Dietrich, 2016; Alfonso-Torreño et al., 2019; Ma et al., 2020)."

"Recent advances in UAS-mounted Real-Time or Post-Processing Kinematic (RTK, PPK) georeferencing systems allow rapid mapping over relatively large areas without GCPs (Zhang et al., 2019), enhancing the potential for rapid response surveys programs, especially in dangerous and inaccessible terrains."

Technical corrections

Figure 1: It would be better to put someplace names in the background to better identify the position of the catchment because it is not clear where it is located. Or put an image with its location on a larger scale next to it.

Agree. Figure 1 has been updated according to this suggestion and was incorporated into the revised manuscript:

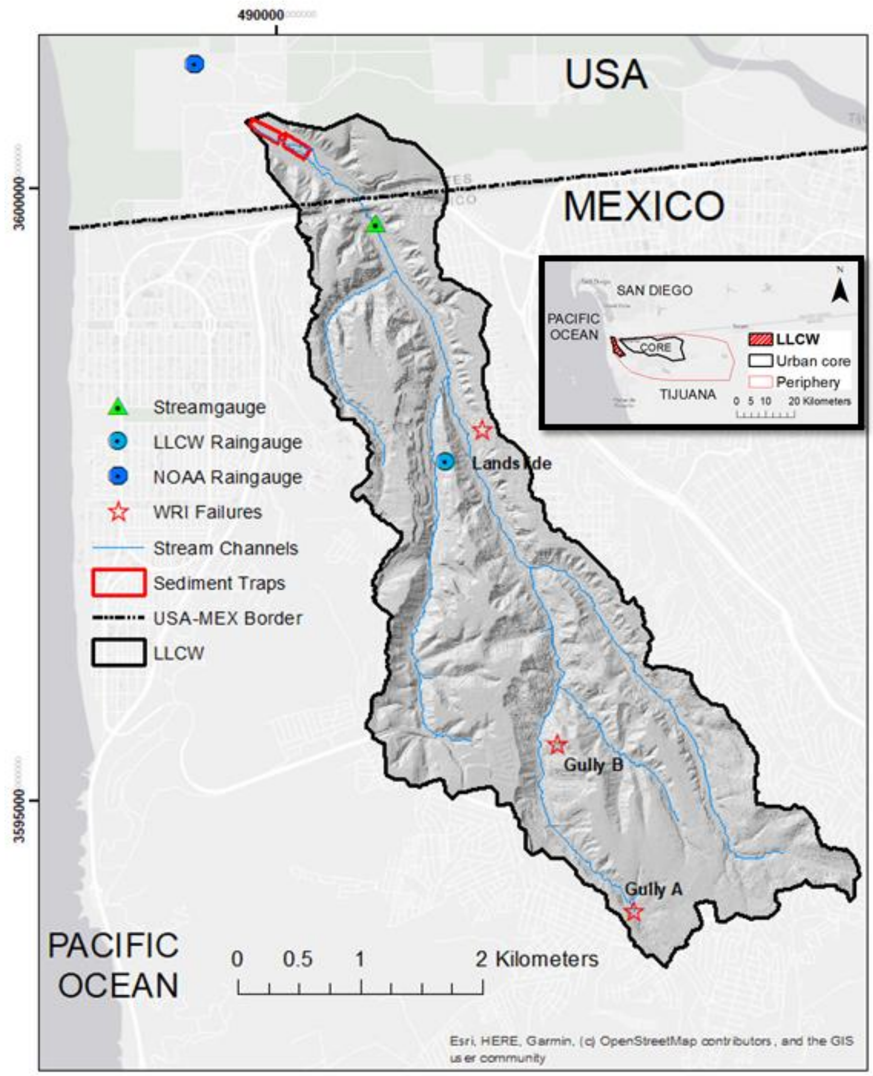


Table 1: Use UAV or UAS, not both because it is confusing for the reader.

Agree, we edited the table and the text throughout the manuscript using UAS consistently.

Table 1: I would avoid entering "RMSE of ECPs" here, which should be reported in the results.

Agree, we removed "RMSE of ECPs" from table 1. These values are reported in section 3.

Line 123: "the difference DSM" > it is better to use the acronym DoD, which is widely used in this context of multi-temporal surveys.

Agree, we edited the text using the DoD acronym throughout the manuscript and added two references (Wheaton et al., 2010; James et al., 2012) in lines (142-144). "(3) erosional volumes were computed (ArcGIS 10.6.1, ESRI, Redlands, California) by subtracting the DSM from a reference DSM representative of the pre-event land surface (Wheaton et al., 2010), and (4) the difference of DSMs (DoD) was integrated to calculate the total sediment volume (James et al., 2012)."

Lines 175 and 180: I think the reference should be to Figure 2d.

Agree, we edited the text to referred to Fig. 2d (now Fig 3d).

Figure 2: What is the purpose of Figure 2c? is not explained in the manuscript.

Thanks for bringing up this point. We replaced Figure 2c (now Fig 3 c)to show the DoD results to better illustrate the mechanism of the landslide. Please see the revised Figure 3:

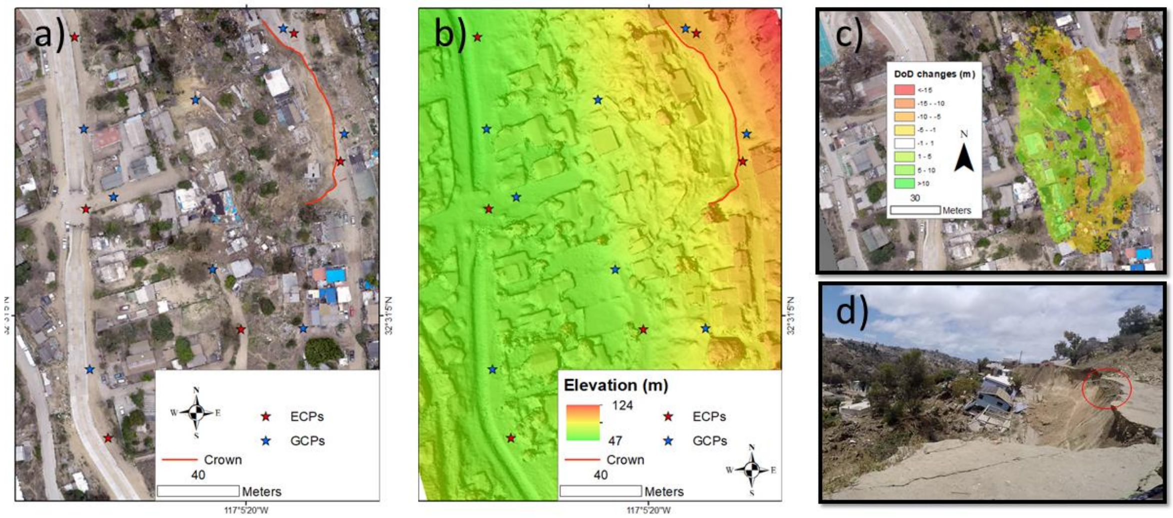


Figure 3: here and in other captions the word DEM is used instead of DSM. In order to be consistent in the manuscript, it is good to specify the type of digital model used and always indicate it in the text.

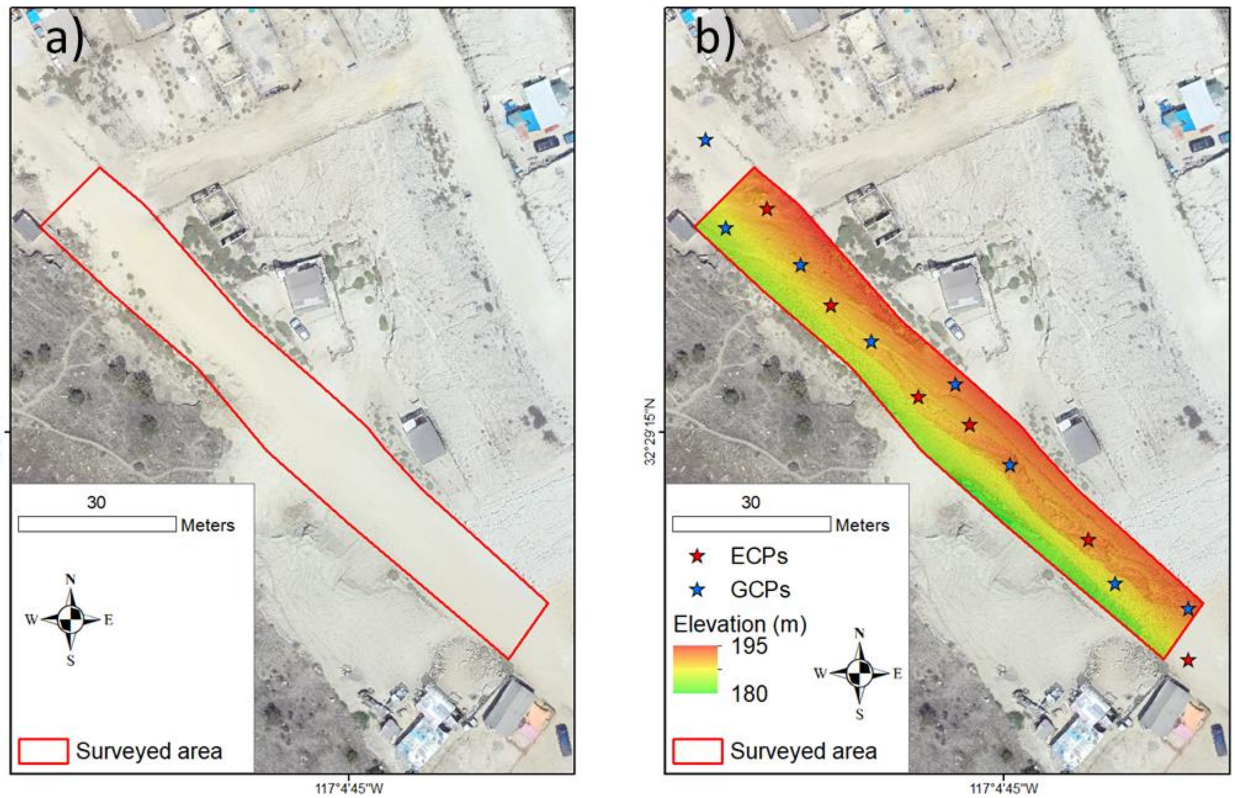
Agree, we edited the text throughout the manuscript for consistency.

Lines 191 and 194: should be moved to the discussion section.

Thank you for this great suggestion, we moved these sentences to the discussion section.

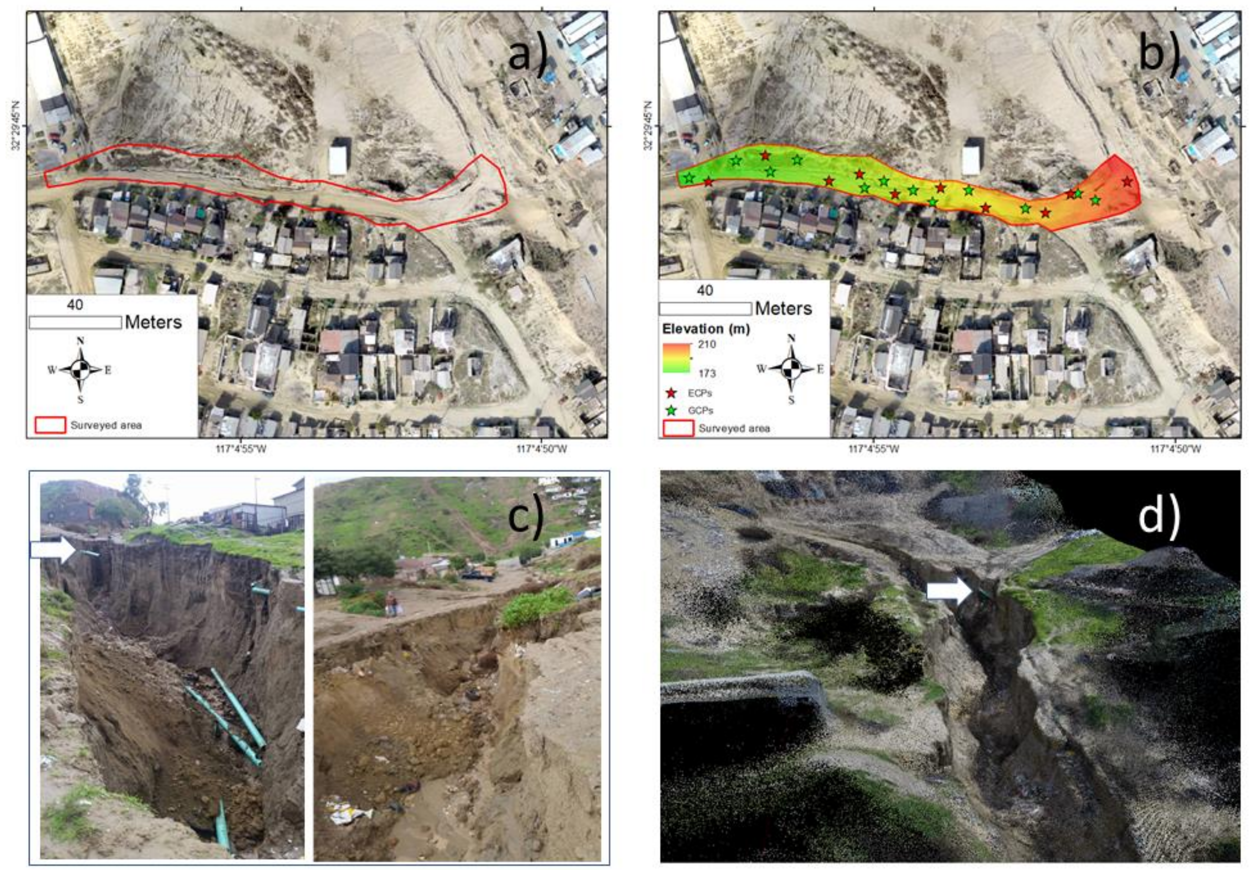
Figure 3: It is not clear what the blue stars refer to. A legend is needed.

Agree, we edited Figure 3 (now Fig 4)to clarify the distribution of GCPs and ECPs, respectively:



Line 221: the citation of Figure 4d, I don't think is located in the correct place and it is still not clear what the blue star in the figure refers to.

Agreed, we removed this citation from the text here, and edited Figure 4 (now Figure 5) to clarify this issue. In figure 5c and 5d (previously fig 4c,d) we want to highlight the location of the buried pipe-break (white arrows) and provide context of the difference between measured and modeled distances:



Line 228: after 'DSM' perhaps Figure 4b should be mentioned?

Thanks for noticing, we edited the text to address this comment.

Line 234: Figure 4a should be mentioned before the others (Figure 4b, c, d) in the text. Remember that order matters.

Agree, we edited the text to address this comment (Line 247).

Table 2: is not very clear. A better division between data measured in the field and estimated by the model would be better (not by indicating simple asterisks).

Agree, we edited table 2 subdividing measured and modeled data:

Erosional hazard event	Sediment Generation Mechanism (tons)				
	Measured		Modeled		Total
	Water Resources Infrastructure Failures	Channel Erosion	Sheet and Rill	Rainfall-runoff gullies	
Landslide	31,900 ± 280	7,610	5,310	10,500	55,300
Mega-gully A	1,360 ± 35	2,290	4,710	49	8,410
Mega-gully B	4,340 ± 155	5,910	12,100	160	22,500

> Table 3: sediment units are missing in columns 2 and 3.

Thanks for noticing, we edited table 3 to address this comment.

> Line 379: here the word DEM is used instead of DSM. It is better to choose which term to use throughout the manuscript.

Agree, we edited the text throughout the manuscript for consistency.

Reply to Reviewer #2 Comments

We thank the Reviewer for taking time to review the manuscript. The helpful and constructive comments put us in an excellent position to further improve the paper. The text below contains our response in a point-by-point format. To clearly distinguish reviewer comments from our responses, the reviewer comments are indented.

> **General comments:**
> In this research, the authors investigate the occurrence of two mega gullies and one deep-seated landslide in an urbanised watershed. They show that these three mass movements, although outliers in term of size in the watershed; are processes associated with non-exceptional rainfall events. The failure of water resources infrastructure (WRIF) is shown as playing a key role in their occurrence, exacerbating the influence of rainfall. The contribution of these three mass movements is important in the overall sediment budget of the watershed. In terms of methods and techniques, the research is based on the acquisition of very-high spatial resolution topographic data from UAV and SfM processing and the use of a process-based erosion model.

This research that clearly stresses the role of human activities on the occurrence of hazardous geomorphic processes of climatic origin is an interesting topic that falls well within the scope of NHESS. However, at this stage, although this research brings interesting information, it still suffers from weaknesses; which leads me to the conclusion that the material presented here is not ready for publication.

We wish to thank the reviewer for reviewing the manuscript and providing feedback which has helped us to address a number of weaknesses in our presentation. A major conclusion that we draw from this valuable feedback is that we did not adequately frame this study and clarify our objectives, and thus we have completely rewritten the abstract and introduction – which was additionally suggested by Reviewer 1. In doing so, we have followed the suggestion of Reviewer 1 to draw attention to the performance of photogrammetric documentation with SfM in a rapid response mode – including additional details about our methods and errors. But more broadly, we have revised the introduction to emphasize our interest in "abrupt" earth surface hazards in urban areas resulting from the interaction of WRIFs and rainfall, which are especially dangerous since there is no time for early warning and emergency response. We are aware of only one study that has documented water leaks impacting urban landslides (Demoulin and Hans-Balder, 2021), and we are not aware of any previous documentation of the formation of mega-gullies through a high velocity water jet - what we describe as "hydraulic mining". Our second objective is then to provide primary documentation (field observations) of the occurrence of "abrupt" earth surface hazards resulting from the interaction of WRIFs and rainfall, and to report what we learned about their occurrence to the extent that it could be useful for hazard mitigation. Indeed, risk reduction measures are a strong possibility given that human infrastructure plays a major role in these events. To further clarify the originality of this work, we note that previous literature generally characterizes the formation of mega-gullies as gradual, over periods of years or more, and as a result of landscape changes such as deforestation, roads, and urban development (Archibold et al., 2003; Adediji et al., 2013; Makanzu Imwangana et al., 2015). Furthermore, mega-gullies are largely known to occur in relatively wet conditions. The annual mean precipitation in the Makanzu Imwangana et al 2015 paper is 1432 mm, which is 7 times higher than the observed in Tijuana. Our focus on abrupt mega-gullies in an arid region marks a major departure from previous knowledge about mega-gullies.

We revised the original manuscript following a four-part plan to improve the paper: (1) we clarified our focus on "abrupt" earth surface hazards which occur over a time scale of hours within the periphery of expanding urban areas and as a result of the combined effects of rainfall and water resources infrastructure failure (WRIFs), (2) we emphasized that rapid-response SfM-photogrammetry is a promising approach to document these abrupt hazard events, and we added more information about post-processing data including errors and uncertainties as recommended by the Reviewer 1, (3) we also added more contextual information (e.g., history of development, climate, presence of unpaved roads) around our observations to enable a richer interpretation of these important data as recommended by Reviewer, and (4) we reported the ways in which this work informs our understanding about the triggers and processes that are responsible for these "abrupt" hazards. Since abrupt earth surface hazards in urban areas pose major safety and damage risks, with little opportunity for early warning and emergency response, we believe primary data documenting these events and reporting their triggers is a very important responsibility of the scientific community.

> First of all, the study is rather descriptive and does analyse the role of WRIF in isolation without really questioning the importance of other factors such as overloading, the pervasive leak of the water system, the latency between the time the environment is built and the slope/erosion process occur, etc. We would welcome deeper analysis with regard to these processes, especially in a timeline perspective, and expect reference to the relevant international literature to support and discuss the observations. For example:
>
> *Demoulin, Alain, and Hans-Balder Havenith. "Causes and Triggers of Mass-Movements: Overloading." Treatise on Geomorphology (2021): in-press.*
> *Lacroix, P., Dehecq, A., Taipe, E., 2020. Irrigation-triggered landslides in a Peruvian desert caused by modern intensive farming. Nature Geoscience 13, 56–60. doi:10.1038/s41561-019-0500-x*
> *Makanzu Imwangana, F., Vandecasteele, I., Trefois, P., Ozer, P., Moeyersons, J., 2015. The origin and control of mega-gullies in Kinshasa (D.R . Congo). Catena 125, 38–49. doi:10.1016/j.catena.2014.09.019*
> *Van Den Eeckhaut, M., Poesen, J., Dewitte, O., Demoulin, a., De Bo, H., Vanmaercke-Gottigny, M.C., 2007. Reactivation of old landslides: Lessons learned from a case-study in the Flemish Ardennes (Belgium). Soil Use and Management 23, 200–211. doi:10.1111/j.1475-2743.2006.00079.x*

The authors agree with the reviewer that the first version of this paper was overly descriptive. We have addressed this point in two distinct ways. First, within the introduction, we have added a paragraph to described both landslides and mega-gullies and the processes that influence them. For “landslides”, which covers a very wide range of earth surface hazards, we clarify our interest in rotational slides in soil, which is the most common type of earth surface hazard in urban development, and the role of water in creating an overburden stress that triggers motion. We thank the reviewer for the citations, including Demoulin and Havenith (2021), which were helpful and not available at the time of our first submission. For mega-gullies, we introduce “hydraulic mining” from a water jet from a high pressure water main as a mechanism by which a mega gully can form in a matter of hours. This stands in contrast to previous research whereby mega gullies form over months to years as a result of rainfall runoff, which in turn is influenced by land use change. Second, within our discussion section (lines 399-416), we have added information about the timeline of construction and development in the region so the reader can contemplate issues of latency between initial development and the occurrence of the hazardous event. For example, we added information about the age and landscape evolution of the neighborhoods that experienced these WRIFs, reported in previous work that the areas with unpaved roads are prone to gully erosion, highlighting the chronic soil exposure and vulnerability of unpaved roads to WRIFs (see Biggs et al 2010). This is an excellent point for the purpose of primary data on the timeline of infrastructure failure, and this modification is repeated below for clarity:

“The decadal development of the urban surface is a critical control on the occurrence of WRIFs. While other studies highlighted mega-gullies that develop over years and decades, our mega-gullies developed over single storm events with little or no latency between urbanization and formation, and pose significant "abrupt" hazards to the population. The spatial location of the WRIFs is governed by the temporal sequence of urbanization and land cover transformation that occurs over decades (Biggs et al, 201). In Tijuana, mega-gullies occurred on unpaved roads in relatively recently urbanized areas (< 20 years urban) in the poor periphery, where the water distribution network was buried ~0.5-1m below the surface and easily undermined by rainfall-runoff erosion of the unpaved road. Satellite observations suggest roads remain unpaved for decades following urbanization in Tijuana (Biggs et al, 2010), with consequent chronic exposure of the community to WRIFs. Roads are gradually paved over several decades, starting with the main transit corridors and followed by smaller roads in residential neighborhoods. As the network is paved, the water distribution network is more protected from road destruction during storm events. We thus anticipate that the occurence of mega-gullies due to WRIFs will become less common with buildout and road paving but could remain a chronic problem in marginalized neighborhoods on the urban periphery, where socioeconomic status is low (Biggs et al, 2012). The landslide, by contrast, occurred in an area that had been urbanized for longer (~40 years); this kind of hazard could occur in older and wealthier neighborhoods on steep slopes if the water supply network develops leaks (Oliva-González et al., 2014). While other factors such as overloading by heavy construction and water towers may contribute to landslides in some urban contexts, the buildings in our study were single story single family residential units with minimal foundations and likely small impact on landslide risk (Demoulin et al, 2021). Rather, overloading by soil moisture from WRIFs was likely the trigger of the landslide in Tijuana."

Finally, we draw the reviewer's attention to what we learned about the interdependence between rainfall runoff and the WRIF in the generation of these earth surface hazards. In the case of the mega-gullies, rainfall-driven gully formation in unpaved roads exposed a pressurized water main, which then failed under its own weight causing a high pressure water jet that subsequently created a mega-gully through hydraulic mining. In the case of a landslides, a hillslope pre-saturated from a leaky water main failed during a rainstorm as a result of the combined weight of the soil and water. Hence, in both cases, we are successful documenting the factors that explain the occurrence of these events, both of which are not able to be easily predicted by traditional engineering methods or modelling.

> A second point for improvement would be on the analysis of the DSM information that can help to better characterise the processes and discuss their mechanisms. Here the multitemporal information is only used to derived volume estimates and dimension parameters, while in can reveal much more than that on how a landslide or a gully has formed.

We agree with the reviewer that, in general, DSM information about earth surface features captured over time can help to characterize processes and understand mechanisms. However, this is not a realistic possibility (at this time) for abrupt events which are the focus of this paper. These events occur unexpectedly during storms, and it generally requires several hours to gain notification through emergency services personnel and to travel to the site with the photogrammetric equipment. During our experience in the field, we found that by the time of our arrival, the water mains have been turned off and the mega-gully has stopped growing. Similarly, the landslide we observed was abrupt and motion had ceased by the time of our arrival, limiting documentation to a comparison between a pre-DSM and a post-DSM. However, we used the DSM information to better characterise the processes and discuss their mechanisms in the revised manuscript. We used the DoD results of the landslide to better illustrate the rotational morphology of this feature, and we expanded the discussion of the mega-gullies characterization to document the role of the terrain slope on the depth of the incision.

The analysis and discussion around the importance of these three mass movements on the sediment budget suffer from data bias. From three observations on a small watershed, general statements are difficult to be made. The authors need to be more nuanced and one would welcome extra information from the regional surroundings, for example on other landslides and erosion processes that occur there. For example, the landscape seems to offer ideal conditions for gully erosion and we can wonder whether the two mega-gullies are exceptional in size as compared to what occurred elsewhere in the city and in less urbanized areas.

First, the authors agree that it is difficult to generalize our results due to the small sample size, and we are committed to a manuscript that fairly presents our observations, and what we can learn from them, without over generalization. Furthermore, we also believe it is very important to report these data irrespective of the number of events based on our systematic monitoring approach, the absence of previous studies that have ever documented events like these, and the potential implications for public safety and risk management. In particular, we note that five years of monitoring was required to document these three events, and as a result of this work we are in a position to report to readers of the journal about the size of these events and the role of WRIFs alongside other factors

Second, and in response to the comment about what has occurred elsewhere, the authors note that Fig. 7 in the original manuscript showed a quantitative comparison of the WRIF mega-gullies with rainfall-runoff gullies observed both in the study area and elsewhere (Castillo et al., 2016).

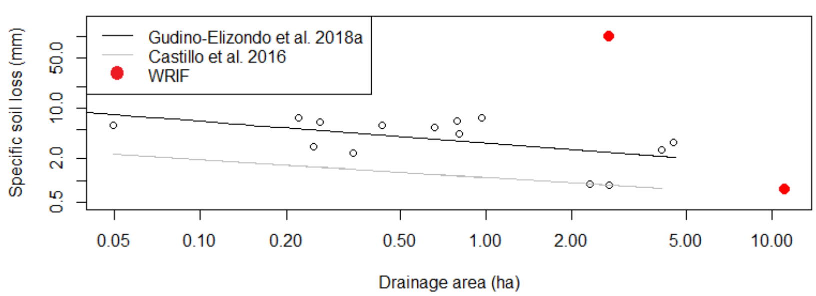


Figure 7. Specific soil loss of mega-gullies caused by WRIF (red dots) compared to previously reported gullies in Tijuana, Mexico (circle points and black line, Gudino-Elizondo et al., 2018a) and trends for ephemeral gullies reported from other sites (gray line, Castillo and Gómez 2016).

Third, we added a high-resolution aerial photograph (Figure 7 in the revised paper) to provide context of the exceptional size of these mega-gullies compared to rainfall-runoff gullies in the study area, and to help readers visualize how a water supply pipe under an unpaved road can be exposed and damaged by a rainfall-runoff gully network:

Figure 7. High-resolution photograph showing the contrast between rainfall-runoff and WRIF gullies in the study area.

An emphasis is brought on the used of SUV and SfM. However, there is not really an novelty here as these techniques are well known and, in this research, it is "just" applied to produce three DSMs over the three study sites. This methodological part should not be given a high importance and not be presented as a research objective in itself. Note also that it is not always clear on how the photogrammetric data were obtained and processed.

We apologize for the oversight on our part with respect to introducing "abrupt" hazards, which motivate photogrammetry and SfM as a rapid-response technology for documentation purposes. In our four-part plan to prepare a revised manuscript, emphasis on the rapid-response monitoring approach is Part 2 and improvements to the presentation of photogrammetric data and processing is Part 3. In particular, we expanded our description of data post-processing and error assessment in section 4.1 as requested by Reviewer 1.

Technical details on how the climatic data and soil modelling data are processed are needed. It is rather difficult to understand clearly how the results were obtained.

Thank you for bringing up this point, we edited the text to clarify this issue. Technical details about the climatic data were expanded in the methods sections (lines 115-117 and 124-130):

“A tipping-bucket rain gauge station ("LLCW raingage" in Fig. 1) was installed in the watershed, and a pressure transducer (PT) (Solinst, water level logger) was installed in a concrete channel at the watershed outlet and logged water level at 5-minute intervals (Fig. 1)”.

“A long-term record of rainfall is available from the NOAA Tijuana River Estuary gauging station, located near the outlet of the LLCW, which provides daily rainfall for the period 1980 to 2018, and estimates of daily rainfall back to ~1950 were reconstructed by regression with a nearby gage at Lindbergh airfield in San Diego (Brand et al., 2020). These data are used here to estimate the return period of storm events during the study period. Gudino et al., (2019) used data from the tipping-bucket rain gauge (LLCW Raingage in Fig. 1) to force a watershed erosion model, which was validated with stream gauge data and observed sediment loads at the outlet. Rates of sediment generation by sheetwash, rill, gully and channel erosion estimated by the model were compared with sediment generation from WRIF features.”

Technical details about the soil modeling are described in the methods sections (lines 160-165)

“The Annualized AGricultural Non-Point Source (AnnAGNPS) model (Bingner et al., 2015) was applied to the LLCW to simulate discharge and sediment load during storm events and to develop an inventory of sediment generation rates by mechanism at the watershed scale. The AnnAGNPS model was previously calibrated and validated for runoff and observations of sediment generation in LLCW (Gudino-Elizondo et al., 2018a, 2018b, 2019b), and the applications here rely on this calibration. The simulation period was from water year 2012 to 2017 to match the observation period of the mega-gullies and landslide”.

A more detailed description on the soil modeling can be found in Gudino-Elizondo et al (2019), which we have appropriately cited within the paper.

The authors have already published several research papers on erosion processes over that study area and it is not always very clear, especially with regard to what concerns the modelling approaches and SfM methodologies, where the novelties are.

Our previous research was directed at characterizing watershed hydrology and soil erosion processes in the context of sediment management and ecosystem protection resulting from rainfall-runoff and land use change (urbanization). This study’s novelty over our previous work stems first and foremost is our focus on abrupt earth surface hazards versus sediment management and ecosystems. Secondly, the study’s novelty is in a focus on WRIF-generated earth surface sediment fluxes versus rainfall/runoff generated fluxes. Finally, we present and include original data and model results that were not previously published.

I have also made some comments and suggestions directly on the manuscript.

We greatly appreciate the numerous detailed comments and suggestions placed on the original manuscript. We addressed every comment and suggestions directly in the revised manuscript and are described below:

Specific comments on the manuscript:

Line 28: mega gullies does not need steep terrain to occur. In the following reference nice examples are found.

We agree with the reviewer and have modified the text according to this suggestion.

Line 30: gullies are not considered as mass movements.

We agree with the reviewer and have modified the text according to this suggestion.

Line 31: gullies can also be life-threatening

We agree with the reviewer and have modified the text according to this suggestion.

Line 34: i do not agree with these statement that the hazards are concentrated in developing regions. For example, the global landslide susceptibility assessment made by Stanley and Kirschbaum does not show such a pattern.

We agree with the reviewer and have modified the text according to this suggestion.

Line 36: periphery of what?

We agree with the reviewer and have modified the text and Figure 1 according to this suggestion.

Line 38: are they relevant references? These studies seems to be dedicated to land cover...

We agree with the reviewer, more relevant references were added according to this suggestion:

Kjekstad and Highland, 2009; Bianchini et al., 2017; Costa et al., 2018; de Albuquerque et al., 2020.

Line 43: it is not clear how hydraulic erosion could influence slope instability.

We agree with the reviewer and have modified the text to clarify our point.

Line 45: references are needed here, especially because this is a key focus of this research.

The authors agree with the reviewer and thank them for this comment. We added a relevant reference for this sentence in the manuscript (Kazmi et al., 2017)

Line 180: figure 2d?

Yes, thanks. We edited the text here and apologize for any confusion.

Line 183: the DSM differences could be visually analyzed in order to better understand the mechanisms of the landslides.

The authors agree with the reviewer and appreciate this comment. We added a figure (3c) showing the DoD changes. However, data limitations at the landslide site (including soil moisture status, depth of regolith, root density and decay, etc) prevent us from being able to better assess the mechanisms which formed this landslide. However, communication with local authorities and residents, confirms that the landslide also occurred in a few hours between the first recognitions of cracks in the terrain and the major landslide displacement. The usage of the DoD map helped to better represent the geometry of the landslide as a deep rotational slope failure that often occur after a long wet conditions (Zêzere et al., 2005; Fuhrmann et al., 2008; Robbins, 2016; Monsieurs et al., 2019), and also observed in Tijuana (Oliva-González et al., 2014). We added text to manuscript (lines 225-226 and lines 353-355):

"The DoD map (Fig. 3c) shows the geometry of the landslide as a deep rotational slope failure, which is consistent with the model proposed by Highland and Bobrowsky (2008) in USGS (2021)."

"The DoD also helped to characterize the landslide as a deep rotational slope failure, consistent with other landslides reported in Tijuana, which are linked with unplanned urbanization on hilltops and enhanced pore pressure induced by uncontrolled water leakage (Oliva-Gonzalez et al., 2014)."

Figure 2 caption: DSM or DEM?

Agree. the authors thank the reviewer for pointing out this important distinction and have modified the Figure caption and revised this issue throughout the manuscript.

Line 200: is there information on the leak of the water pipe system before the occurrence of the gully? It is usually known that all water system suffer from leaks.

Yes, the residents reported a broken pipe supported with photographs evidence (personal communication, Tijuana Metropolitan Planning Institute), and rainfall-runoff gully erosion exacerbated the mega-gully under a 1-2 year return period storm. Based on our observations, we reported that water main breaks resulted from rainfall-driven gully erosion, and the resulting water jets were the cause of abrupt mega-gully formation.

Line 238: what is are the differences between the application of the model in this research and the application of the same modelling approaches over the same study area by Kretzschmar, T., Taguas, E. V., Liden, D., 2018. Modelling ephemeral gully erosion from unpaved urban roads: Equifinality and implications for scenario analysis. Geosciences 8. doi:10.3390/geosciences8040137

The paper mentioned above (Gudino-Elizondo et al., 2018b) was focused on the gully erosion modeling and scenario analysis at the San Bernardo neighborhood, where Gully B occurred. Conversely, the application of the AGNPS model in this paper considered sediment production at the Los Laureles Canyon watershed scale (Gudino-Elizondo et al., 2019). Please also note that the simulation period was 2012 to 2017 water years to match the observational period of mega-gullies and landslides.

Line 249: such comparisons must be considered with care as it focusses on measurement made on very small study areas. One cannot make robust conclusion based on so few observations (hence the potential of being highly biased in the reasoning).

In the original manuscript (now lines 277-282) we write the following: “This analysis shows that mass movement associated with WRIFs was significant on an event basis. Mega-gully B generated 4,340 tons (Table 2), which is approximately 80 times the area-normalized annual erosion rate for gullies (tons/ha) and 10 times the total sediment generated by other rainfall-generated gullies (Gudino Elizondo et al., 2018a, Gudino Elizondo et al., 2018b). The WRIF-triggered landslide mobilized more sediment than all of the rainfall-based processes combined, while the mega-gullies triggered by pipe failures and hydraulic mining were responsible for 16 and 20% of the total sediment generation across the watershed (Fig. 5).”

In this case, we are reporting direct measurements in the past tense as well as results from a calibrated model, and we are not making a generalization that this is true everywhere or in the future. Nevertheless, we have very carefully revised the conclusions section of the revised paper to ensure that we avoid unfair generalizations, and we thank the reviewer for drawing our attention to this concern.

Line 269: such general statement cannot be made on the basis on three observations over a period of a few years and, in addition, for such a small study area.

Thank you very much for bringing this up this important point. Again, the authors agreed with the reviewer that we are presenting a few observations of WRIF erosion hazards features. However, to the authors knowledge, this research is the first attempt to draw attention and report systematically these events in the existing literature.

In the original manuscript (now lines 297-302), we write the following "The small sample size implies a high degree of uncertainty in all of these estimates; nevertheless, these rates of occurrence are far higher than typical design standards for water resources infrastructure in urban areas. For example, large flood control channels are typically designed with a 0.2-2% annual exceedance probability, and smaller drainage systems in urban areas are often designed for 5-10% annual exceedance probability. Hence, WRIF-based hazards observed during this study are many times more frequent (21-60%) than typical design standards for flood control systems in urban areas (0.2-10%) and thus deserving of greater attention for public safety, infrastructure resilience and environmental protection."

In this case, our paragraph begins by acknowledging the small sample size and potential for uncertainty. Furthermore, there is no generalization here. We report that the observations made during this study are many times more frequent that typical design standards for flood control systems, which is factual. The final issue is subjective – that the high rate of WRIF-based hazards made them deserving of greater attention for public safety, and resilience. However, we would argue that most public safety officers confronting a hazard that was as much as 10 or even 100 more frequent than other more established hazards would agree that it was deserving of greater attention, which could mean additional research and/or data collection. Nevertheless, we have very carefully revised the conclusions section of the paper to ensure that we avoid unfair generalizations, and we thank the reviewer for drawing our attention to this concern.

Please note that we also mentioned this uncertainty in the abstract and in more detail in the discussion section (lines 371-383):

"Stochasticity in WRIFs and WRIF-based sediment hazards is high. Failures may or may not happen in any given storm (here we observed 3 failures in 14 storm events), and when failures occur, the volume of sediment generated across three events varied by over an order of magnitude. This makes it difficult to generalize and estimate sediment generation by infrastructure failure for other events lacking field observations. However, the data do allow a first-order estimate of annual-average sediment generation from WRIFs which is useful for sizing sediment basins that protect downstream ecosystems from excess sedimentation and for estimating average-annual excavation costs. We found in previous research that rainfall-runoff gully erosion rates are higher on steep sandy soils (Las Flores soil type) (Gudino-Elizondo et al., 2019) and a rainfall threshold to generate rainfall-runoff gullies on those unpaved roads

(>25mm) was also observed (Gudino-Elizondo et al., 2018). Therefore, WRIF mega-gullies in Tijuana are more likely to occur on sandy soils on steep terrain during storm events equal or greater than the threshold precipitation typically required to produce rainfall-runoff gullies on unpaved roads (Figure 2). Such estimates would not likely be applicable outside of the LLCW, but the photogrammetric methods deployed here to monitor sediment generation are easily transferrable to other systems, and data on sediment generation from multiple sites would provide a basis for improved understanding and possibly transferrable models."

Nevertheless, we very carefully revised the conclusions section of the paper to ensure that we avoid unfair generalizations, and we thank the reviewer for drawing our attention to this concern.

Line 346: check the units

The authors have double checked the units and confirmed they are correct, and thank the reviewer for their comment.

Line 347: check the units

The authors have double checked the units and confirmed they are correct, and thank the reviewer for their comment.

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