Review: **“Cost estimation for the monitoring instrumentalization of Landslide Early Warning Systems”** by Sapena et al.

RC2: 'Comment on nhess-2023-41', Anonymous Referee #2

Technological advances in recent years, and in particular the emergence of the Internet of Things paradigm, low-cost programmable electronics and sensors, ubiquitous (wireless) communication infrastructure and a wide range of data-based services and resources available on the Internet, bear the great potential for filling a much-needed gap of monitoring high-risk geographic areas with sufficient density in order to allow for effective early warning of disasters of natural origin. The potential merits of such technological solutions are nevertheless challenged by still hard to quantify costs and benefits, therefore slowing down their adoption by decision makers. The paper deals with this relevant topic and offers some new insights into the cost of implementing an early warning system for landslides. The work is based on data gathered from field work, experience with a real-life sensor network deployment, and analysis of various databases of historical landslide events. This is a clear strength of the work.

We sincerely appreciate the positive feedback. The recognition of the paper's relevance and contribution to providing new insights into the cost of implementing a LEWS is encouraging. We are grateful for the acknowledgement of the work's strength. We would like to assure the reviewer that we will carefully address all concerns and incorporate the suggestions into an improved version of the manuscript. We are committed to enhancing the quality of our manuscript based on the reviewers' comments.

Despite the above, I have three main concerns regarding the article in its current form:

Concern no. 1: Section 2 on material and methods provides a description of a number of tasks undertaken for merging and filtering databases and geographic information systems about historic landslides, field observation and demographic information in order to identify the most suitable candidate areas for deploying monitoring sensor networks. Regretfully, however, the description lacks enough detail for the work to be reproducible. To give a few examples on p. 8: Statements such as "...we use topographic, geological and precipitation factors..." (What are these factors? How are they used?), "...we rely on socio-demographic factors..." (same as before), "...we tested several methods..." (Which methods?) "...and 500 pixels proved to be the most appropriate..." (By what criterion?), are not sufficient in a scientific article.

Answer 1: Thank you very much for your comment. We agree that section 2.3 lacks certain information to make the work completely reproducible. We apologize for that, we shortened this section in the original manuscript for the brevity of the manuscript. Based on your suggestion, we adapt this part now to be clearer.

Regarding the first paragraph, where we mentioned without any further detail the topographic, geological, precipitation and socio-demographic factors, we did it in an introductory sense for section 2.3. These factors and their preprocessing are explained in the successive paragraphs (i.e., topography-derived factors lines 198-212; geological-derived factors lines 213-217; precipitation-derived factor lines 218-224; and socio-economic factors lines 225-233). However, we understand that this can be misleading. Therefore, we will improve the introductory lines as follow:

“*For modelling landslide susceptibility, our methodology incorporates a range of influential factors including topographic, geological, and precipitation data. In addition, to aid in identifying suitable sites for the implementation of LEWSs, we consider socio-demographic factors, which are subsequently further elaborated upon*”.

With regard to the flow accumulation threshold for mapping the stream network, the selection of an appropriate value is influenced by the desired stream density and the specific characteristics of the study area. While a universally agreed threshold value does not exist, it is common to use values ranging from approximately 100 to 1000 pixels or 0.05 to 5 km^2 drainage area, considering factors such as data scale, resolution, and landscape attributes [15, 16]. In our study, we tested several values across this range and found that 500 contributing pixels (i.e., 12,500 m²) yielded the closest correspondence with the official drainage system map from the Master plan (POT) of Medellín. Furthermore, a visual evaluation of the results revealed a satisfactory representation of the majority of streams. It is worth emphasizing that the threshold value is subject to variation based on the study requirements and the user's preferences. We acknowledge the importance of highlighting this aspect in the current version of the manuscript. Therefore, we will clarify the paragraph as follows:

"*Regarding the stream network, there is no universally agreed upon flow accumulation threshold for determining streams due to its dependence on various factors, including desired stream density, data scale, resolution, and landscape attributes. Nonetheless, it is common practice to employ threshold values within a range of approximately 100 to 1000 pixels or 0.05 to 5 km2 drainage area [15, 16]. In our study, we evaluated multiple values within this range, and determined that a threshold of 500 contributing pixels (equivalent to a minimum stream inflow of 12,500 m²) achieved the closest correspondence with the official drainage system map from the POT of Medellín. Furthermore, a visual examination of the result revealed a satisfactory representation of the majority of streams.*"

[15] Reddy, G. O., Kumar, N., Sahu, N., & Singh, S. K. (2018). Evaluation of automatic drainage extraction thresholds using ASTER GDEM and Cartosat-1 DEM: A case study from basaltic terrain of Central India. The Egyptian Journal of Remote Sensing and Space Science, 21(1), 95-104.

[16] Tarboton, D. G., Bras, R. L., and Rodriguez-Iturbe, I.: On the extraction of channel networks from digital elevation data, Hydrol. Process., 5, 81–100, https://doi.org/10.1002/hyp.3360050107, 1991.

Concern no. 2.: For the cost evaluation the authors emphasize that only the costs of the implementation of the wireless geosensor network are included in the cost function, while cost of aspects such as risk evaluation, social interventions, social work and network maintenance are not included. While it is valid to isolate the cost of the technology (the geosensor network) form other costs, it is also the case that a number of cost factors considered for the technology in this work are missing. In particular, the cost of operating the network over time is an essential aspect that decision-makers must know. Securing budget for just deploying the network is not enough: it's wasted money if not accompanied by proper maintenance. Maintenance costs include replacement parts, the cost of vandalized or stolen sensor nodes, cost of human resources in the field for doing maintenance and in the lab for repairs, plus tools for fieldwork, transport to and from sites, etc. Other operational costs include the cost of Internet access to and from the gateways, cost of databases and severs in the Cloud and possibly software tools. The cost of manufacturing the sensor nodes should include a yield factor for the various parts (purchased off the shelf or manufactured in house). Finally, a realistic cost estimate should include some rental cost for office and workshop space and utilities (electricity at least). Otherwise, who pays for that once the decision-maker places an order?

Answer 2: Thank you for your comment. We understand your concern and we acknowledge the importance of obtaining accurate figures regarding the operational and maintenance costs of LEWSs. However, it is important to note that the LEWS currently installed in Bello Oriente, that we used as a reference in the cost estimation for the instrumentalization, is only a prototype and not yet fully operational. As a result, we lack the necessary experience and data to provide precise estimates for the "normal" operation costs of an LEWS. While we could speculate on potential numbers, we are cautious about making inaccurate guesses that lack a solid foundation for publication. We believe that it would be more reliable to wait until the system has been operational for at least one year, as this would allow us to gather sufficient data to provide meaningful cost estimates.

Concern no. 3: The argumentation about cost-effectiveness in Section 3 centers on various ways of prioritizing how to choose the deployment sites under budget restrictions. While considering these aspects does make sense, there is a more fundamental prior question that is not addressed nor discussed: what is the benefit of deploying the technology at each site? What is the cost-benefit relationship for each site, is it worth the cost? Intuition says it is, but only if the answer is yes, then the presented prioritization comes into play. Similarly, the argument on p. 18 "if the city would use the same budget to instrumentalize 9 EWS" is hard to follow: the city probably does prioritize based on cost-benefit and (correctly) decides to prioritize other expenses. The argument about re-balancing budget only holds water if the cost-benefit relationships are understood.

Answer 3: Thank you for raising these issues. LEWSs are widely recognized as effective means of providing timely warnings. However, the high costs associated with their implementation have hindered their global adoption. In this study, our aim is to address some of these limitations by proposing a low-cost LEWS specifically designed for highly exposed areas. To enhance the affordability and sustainability of the system, the wireless network of low-cost sensors, which have solar panels, is based on the Internet of Things (IoT) technologies. This approach not only improves system maintenance but also optimizes cost-effectiveness by strategically targeting areas with the most highly vulnerable populations. By focusing on the highly vulnerable areas, we can maximize the benefits of the LEWS while keeping implementation costs manageable. This approach ensures that resources are allocated where they are most needed, benefiting the local community and enhancing the overall effectiveness of the system. By combining innovative technology, community involvement, and cost optimization strategies, our study aims to overcome the barriers associated with expensive implementation and promote the wider adoption of LEWS in landslide-prone areas.

With respect to your very important questions "what is the benefit of deploying the technology at each site? What is the cost-benefit relationship for each site, is it worth the cost?" – this is of course, very difficult to answer. From an economic point of view, we can determine where it is best employed to have the best ratio cost vs. exposed inhabitants. However, it is clear that there are more aspects with respect to saving lives, social networks, communication between informal dwellers and the city-planning agency, among many more that have a high value which is difficult to quantify.

In the supplementary material, we included Table S1 and Figure S1 to provide a comprehensive summary of this information (https://nhess.copernicus.org/preprints/nhess-2023-41/nhess-2023-41-supplement.pdf). These present a site-by-site analysis, indicating the potential locations for LEWS implementation, the population that would be protected, and the breakdown of highly vulnerable individuals within that population. Additionally, the table includes the average landslide susceptibility and other relevant factors. Moreover, we have included the estimated cost to implement the LEWS for each site, as well as the cost per person. This allows for a clear understanding of the financial implications and cost-effectiveness of the proposed LEWS implementation in each specific location, enabling decision-makers to make informed choices regarding the prioritization and implementation of LEWS.

We have taken into consideration your concerns and acknowledge the need to further address the cost-benefit relationship of deploying LEWS at each site. Section 3.3 and the supplementary material provide a foundation for understanding the benefits associated with the implementation of LEWS at different locations and their cost-effectiveness. To address these concerns more comprehensively, we will delve deeper into the cost-benefit relationship in the discussion section of the paper. For example:

"This study seeks to overcome the barriers hindering the global adoption of LEWS, which are recognized for their effectiveness in providing timely warnings in communities at risk. Specifically, we address the high costs associated with their implementation by proposing a low-cost LEWS tailored for highly exposed areas. To enhance affordability and sustainability, we utilize a wireless network of low-cost sensors equipped with solar panels. This approach not only improves system maintenance but also optimizes cost-effectiveness by strategically targeting areas with the most highly vulnerable populations. By focusing on these areas, we maximize the benefits of the LEWS while keeping implementation costs manageable. Consequently, resources are allocated where they are most needed, benefiting the local community and enhancing the overall effectiveness of the system. Our study combines innovative technology, and cost optimization strategies to promote the wider adoption of LEWS in landslide-prone regions. By doing so, we aim to overcome the barriers associated with

expensive implementation, ultimately making LEWS more accessible and beneficial to communities at risk."

"From an economic standpoint, it is possible to determine the most effective allocation of resources in terms of the cost-to-exposed inhabitants ratio. Nevertheless, it is evident that there are numerous additional factors that add significant value to the benefits but are challenging to quantify. These factors include reducing risks by increasing risk awareness, fostering social networks, facilitating communication between informal dwellers and city planning agencies, and many others"

Regarding the argument mentioned on page 18, our intention was to highlight the potential of the introduced cost function by providing an example of how many LEWS could be implemented with a specific budget (i.e., COP 2,000,000,000 (≈ €397,000)), considering different cost-effectiveness scenarios. The purpose of this demonstration was to illustrate how different site selection strategies, based on various priority scenarios, can impact the total number of implemented LEWS, the population covered, the cost per person, and other relevant factors. We recognize the need for clarification in this section to ensure a better understanding of the purpose behind this exemplary exercise. We will enhance the explanation to clearly communicate the objective, emphasizing how it serves to demonstrate the relationship between budget allocation, site prioritization strategies, and the resulting outcomes.

Comment 4: On a related matter, a number of potential sites are ruled out because it is complicated to deploy networks there. What is the proportion of population that could benefit from the monitoring networks if unlimited budget was available? How much population would need other kinds of solutions?

Answer 4: Thank you for addressing these questions. By combining the landslide susceptibility map with the population map (Figure 4), we have identified a considerable number of individuals who are potentially at risk. Specifically, we found that there are 172,721 people residing in areas with a very high landslide susceptibility level (≥ 0.7) (Figure 4B, red cells). Among these individuals, 165,247 are considered highly vulnerable (which accounts for 95% of the exposed population). Furthermore, we have determined that there is a population of 379,308 individuals living in areas exposed to medium-high landslide susceptibility (ranging between 0.5 and 0.7 susceptibility, Figure 4B, orange cells). Among this group, 301,278 people are considered highly vulnerable, which represents approximately 79% of the total population in those areas.

These findings indicate that a significant portion of Medellín's population is settled in landslide-prone areas. Specifically, 7.5% of the total population resides in very high landslide susceptibility zones, while 16.4% are settled in medium-high landslide susceptibility areas. It is noteworthy that more than half a million people live in areas with a landslide susceptibility level of at least 0.5. If financial constraints were not a limitation, the implementation of LEWSs could greatly benefit these individuals. However, prior to implementing the LEWs, it is crucial to conduct inspections in the respective areas to assess the suitability of the system in each location.

When addressing the challenges of implementing solutions in highly-dense built-up areas where subsurface sensors are not feasible, we propose the implementation of a network of LoRa sensors as an alternative approach. These sensors can provide valuable data for monitoring and detecting landslide risks in these areas. However, the information is more uncertain as a result of the absence of subsurface monitoring. To assess the feasibility of this alternative configuration, we suggest utilizing the proposed function to estimate the associated costs.

We will address these issues in the result and discussion of the paper.

Comment 5: There are a number of specific comments and technical corrections that should be addressed. The following list is not comprehensive:

1. P. 2: "among many other things" is somewhat too colloquial for a research paper. "Untapped potentials", should read "untapped potential".

Thank you for noticing, we have addressed these issues and improve the overall writing style of the paper as suggested also by RC1.

2. P. 7: "30.200 report of potential mass movements": how many of those are unique and distinct events?

   Unfortunately, the employed DAGRD landslide database has certain limitations. Firstly, the database may suffer from inaccuracies since it relies on citizen reports before technicians visit the site to classify whether an event is a mass movement or not. Consequently, incidents such as cracks or humidity could be incorrectly reported as mass movements. Secondly, the reports are limited to urban areas, which may have only a minor impact on our study since we combine susceptibility with populated areas. To mitigate these limitations, we have incorporated additional databases, including other landslide databases, remotely-sensed landslides, and the hazard map. By prioritizing the locations from these databases in the selection of training data, we aim to reduce the influence of non-mass movement reports. Additionally, when choosing sample locations, we ensure a minimum distance of 5 meters between each sampled point, corresponding to the spatial resolution of the spatial data, to avoid selecting samples within the same pixel. As explained in section 2.4, we have utilized 2,800 recorded landslide events from the combined databases and 5,000 from the hazard map, which were then split into train and test data sets. This approach is intended to minimize the impact of false reports on our analysis.

   Unfortunately, we cannot determine the exact number of unique reports in the DAGRD landslide inventory. However, we believe that if two distinct locations experience structural damage due to a common landslide, even if they are geographically distant from each other, they can still contribute to training a model aimed at mapping landslide susceptibility.

3. P. 9: "measurements from 215 stations"? Are these all stations available in the Aburrá valley, is this a subset? How were they chosen? "Root mean square error of 506 mm". Seems a lot. Can you put it in perspective, give some insight? What is a number that could be expected?

   Yes. We used all available stations in the Aburrá valley, which include a total of 215 stations. Our aim was to generate a continuous map of rainfall data by interpolating the accumulated precipitation values over the course of a year from these stations. To achieve this, we employed the Ordinary Kriging Optimized Smoothed (OKOS) method, accompanied by cross-validation. For this process, we selected 70% of the stations for training and utilized the remaining 30% for testing. Our evaluation provided a Root Mean Square Error (RMSE) value of 506 mm/year, which represents the discrepancy between the predicted and observed yearly precipitation accumulation. Being the mean value of precipitation across all stations 1,425 mm/year, the normalized RMSE, indicating the relative error, is approximately ± 35%. Although this may seem like a significant error, it is consistent with existing literature, which commonly reports normalized RMSE values ranging from 30-35% [17] and 17-29% [18].

   We selected the OKOS method based on its lower RMSE compared to other methods tested during the process of interpolating annual precipitation. To determine the most accurate interpolation, we conducted six test rounds using two commonly recommended methods validated in the literature [19]: Inverse Distance Weighting (IDW) with three rounds and Ordinary Kriging (OK) with three rounds, each with different settings.

[17] Bostan, P. A., Heuvelink, G. B., Akyurek, S. Z. (2012). Comparison of regression and kriging techniques for mapping the average annual precipitation of Turkey. International Journal of Applied Earth Observation and Geoinformation, 19, 115-126.

[18] Antal, A., Guerreiro, P.M.P., Cheval, S. (2021). Comparison of spatial interpolation methods for estimating the precipitation distribution in Portugal. Theor Appl Climatol 145, 1193–1206. Doi: 10.1007/s00704-021-03675-0

[19] Ly, S., Charles, C., Degré, A. (2013). Different methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at watershed scale. A review. Biotechnol. Agron. Soc. Environ.,17(2), 292-406.

4. P. 10: "Training a statistical model". Which one? Can you give a reference?

   With "statistical model" we refer to the Random Forests model that is explained afterwards. Random forest is a statistical- or machine-learning algorithm used for prediction, in this case the probability of a landslide event. To clarify this, we will modify the sentence by stating: "*training a Random Forest statistical model*".

5. P. 11: The word "sensor" is used in place of "node" (one node can have several sensors). This confuses the reader.

   Thank you for this comment. We will check the use of the words sensor and node and modify them accordingly based on the context.

6. P17.: "Amount of people". Better word: population. The word "cheap" should be avoided. In-expensive, low-cost.

   Thank you for pointing out these issues. We will address them. We will replace "*amount of people*" with "*population*" and "*cheapest*" with "*least expensive*".

7. Table S1 is cited several times, but it is not available.

   We apologize for the misunderstanding, we provided Table S1 and Figure S1 in the supplementary material that can be found on the Preprint nhess-2023-41 – Supplement link or on the following link: https://nhess.copernicus.org/preprints/nhess-2023-41/nhess-2023-41-supplement.pdf

8. Acronyms not defined: CSM-EXT, AOI

   Thank you. We will introduce the Continuous Shear Monitor measurement cable and extensometers (CSM-EXT) term, while the Area of Interest (AOI) used in the formula will be changed by "*site*" in this case, since it is more appropriate.

9. All pages: phrases beginning with "we" are by far too many, this should be revised.

   Thank you for your feedback. We appreciate your comment, and we will improve the writing style of the manuscript. We will minimize the use of "we" throughout the document. We are committed to improving the overall clarity and quality of the manuscript.

I encourage the authors to revise their paper and improve it, because this kind of work, while complex and difficult to do, is very much necessary.

We sincerely appreciate your positive feedback and the valuable insights you have provided. Your comments and concerns have been duly noted, and we are committed to addressing each of them in the revised version of the manuscript.