**RESPONSE TO COMMENTS (Referee #2)**

**Integrating SMART principles in Flood Early Warning System Design in the Himalayas (NHESS-2025-2081)**

**Authors: Sudhanshu Dixit[1], Sumit Sen[1*], Tahmina Yasmin[2], Kieran Khamis[2], Debashish Sen[3], Wouter Buytaert[4], David M. Hannah[2]**

[1]Centre of Excellence in Disaster Mitigation and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

[2]School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham, UK

[3]People's Science Institute, Dehradun, India

[4]Department of Civil and Environmental Engineering, Imperial College London, London, UK

*Correspondence to sumit.sen@hy.iitr.ac.in

**Dear Editor and Reviewer,**

The authors would like to thank the reviewer for the careful review of our manuscript and for providing us with their valuable comments and suggestions, which we have found very helpful in improving the quality of the manuscript. We have carefully addressed all your comments and integrated your insightful suggestions into the revised manuscript. In the subsequent detailed response, we have addressed each comment individually. Comments are written in red, and our responses follow each comment in black. All the new details added in the manuscript are highlighted as text in italics. For your reference, the sources cited in our responses can be found in the references section on the last page of this document. We look forward to your positive feedback and hope you will find the revised manuscript satisfactory.

**Response to Reviewer 2**

1. The study presents an integrated approach to the design of early warning systems for flash floods in both urban and mountainous environments, combining real-time monitoring technologies with the active involvement of local communities.
   The authors implement a high-resolution hydrometeorological network, based on LiDAR sensors and advanced measurement instruments, aimed at providing a detailed characterization of the rainfall and hydrological regime of the study basin. The data collection and analysis highlight a marked spatial variability in precipitation (up to more than 180 mm between stations only a few kilometers apart), a crucial factor for forecasting localized flood events.
   The SMART model constitutes the conceptual core of the study and, although not clearly defined, is described as a dynamic and adaptive system. The comparison with global reanalysis (ERA5) and satellite (GPM) datasets shows that these sources fail to

adequately capture the complexity of precipitation patterns in mountainous areas. In contrast, the SMART approach proposed here, based on real-time local data, integrates basin dynamics and adapts alert thresholds in a context-specific manner. A key methodological feature is the definition of thresholds based on percentiles of water level data, validated through community participation, which makes the system more flexible and responsive to actual environmental conditions. Although the work represents an original contribution to the literature on early warning systems for extreme events, it also presents some limitations, several of which are acknowledged by the authors themselves.

Thank you very much for your thoughtful and thorough assessment of our study. We appreciate your recognition of the integrated approach to early warning system design, which combines state-of-the-art monitoring technologies with active community participation across an urban, mountainous, and Himalayan catchment.

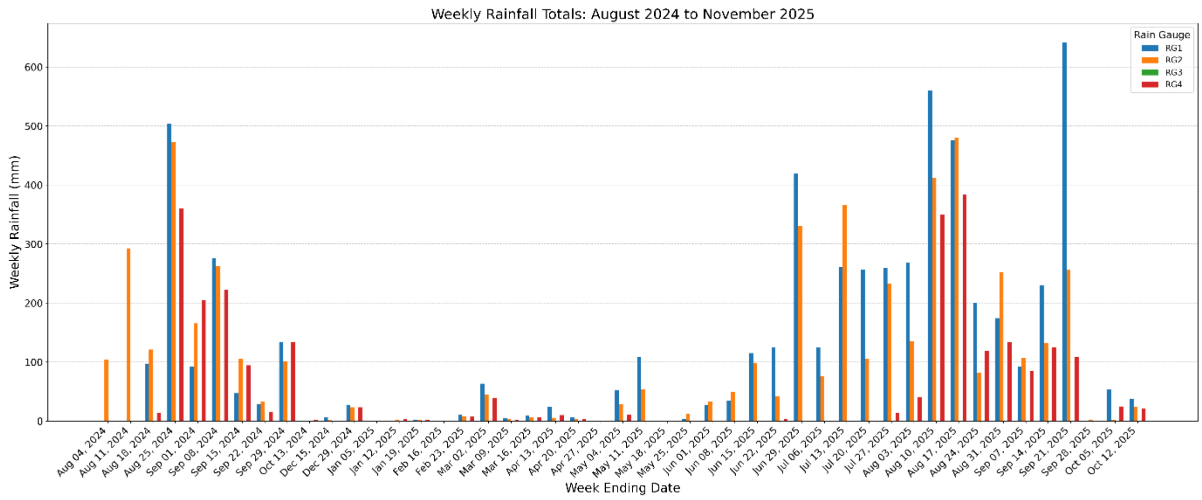
We are pleased that you found the implementation of the high-resolution hydrometeorological network and characterization of rainfall regime valuable, as well as the investigation of spatial precipitation variability, which is one of the critical factors in flash flood warning. As highlighted, the comparison with global datasets (ERA5 and GPM) shows the need for locally adaptive systems, and our SMART model aims to address this through real-time data integration and dynamic, context-specific alerting.

We appreciate your acknowledgment of our percentile-based thresholding methodology, which we validated through community involvement, as a flexible and responsive approach in data-scarce regions. As you noted, while our study makes an original contribution, we remain committed to further refinement and transparency. We have acknowledged limitations in greater detail in the revised version.
Thank you again for your constructive review and encouragement, which help strengthen the study's relevance and impact.

2. Limited spatial and temporal extent – The study focuses on a single small catchment (Bindal, 44.4 $km^2$) and a relatively short observation period of approximately one year (September 2022 – August 2023). This timeframe is insufficient to robustly assess the system's performance with respect to interannual variability or its ability to capture rare extreme events. The authors themselves acknowledge that the hydrological response of the basin is strongly influenced by local-scale factors, underscoring the need for further testing and validation across broader spatial and temporal scales.

Thank you for bringing this important issue related to spatial and temporal scope to our attention. The Bindal catchment (44.4 $km^2$) is representative of various Himalayan urban and semi-urban areas, which commonly range between 30 and 100 $km^2$, making our findings relevant to similar contexts (Bharti et al., 2020; Mani et al., 2025). Additionally, we would like to emphasize that conducting sustained hydrometeorological monitoring in the Himalayan region is logistically challenging due to steep terrain, limited accessibility, harsh climatic conditions, and frequent sensor damage during extreme

events. These factors contribute to a broader regional challenge, namely a severe scarcity of continuous, high-resolution datasets, which limits rigorous long-term analysis.
Concerning temporal coverage, we acknowledge that the original observation period of approximately one year (September 2022 – August 2023) is limited for capturing longer-term interannual variability and rare extreme events. To address this, we have extended our analysis to include additional rainfall data from August 2024 to October 2025, which reveals significant rainfall variability, with differences ranging from 50 mm to 200 mm between adjacent rain gauges within a single week, as shown in the figure below. This extended temporal dataset, included in the supplementary materials in bar plot form, provides further evidence of the system's spatially variable events within the watershed, indicating that the spatial variability remains consistent.




However, due to funding constraints, deploying and validating the SMART approach in additional watersheds remains challenging. *Nonetheless, the conceptual strength of SMART lies in its adaptive, community-engaged framework that captures local hydrological dynamics and integrates participatory validation, enabling it to provide actionable warnings tailored to catchment-specific conditions.* We have emphasized these points and limitations in the revised manuscript and highlighted the necessity for future broader spatial and temporal validation studies.

**3.** Lack of operational validation – The study does not include a verification of the system under real operational conditions, nor does it present application-based simulations for future events. Moreover, no performance metrics are provided — such as lead time, false alarm rate, or the accuracy of dynamic thresholds — which are essential for a quantitative assessment of the system's effectiveness**.**

Thank you for highlighting the absence of operational validation and detailed performance metrics in our study. We acknowledge that metrics such as lead time, false alarm rate, and threshold accuracy are crucial for assessing the effectiveness of early warning systems under real conditions. Due to limited funding and resource constraints, this research was designed as a conceptual and demonstration study, focusing on the technical feasibility and local relevance of our approach in a data-scarce Himalayan context.

At this stage, we have not yet conducted real-event operational deployments or simulated future events. However, our results provide encouraging indications regarding the potential of our proposed framework to be made operational. Specifically, we observed that the lag time between rainfall peak and water level peak varies between 15 to 45 minutes, which in future operational scenarios could be harnessed as actionable lead time for flood warnings. We agree that operational validation, which includes simulations and robust quantitative metrics, is the key next step, and we have emphasized this in the revised discussion of future work.

4. Dependence on percentile thresholds – The system relies on statistical thresholds derived from percentiles of water level data; however, the study does not provide an in-depth analysis of the model's sensitivity to variations in these thresholds, nor does it address its ability to manage exceptional or out-of-scale events.

Thank you for raising the important issue regarding the system's reliance on percentile-based water level thresholds, and your request for more detail on sensitivity and robustness to exceptional events. *In our study, the thresholds were defined through both a statistical approach and community validation, using a comprehensive dataset of water levels spanning a five-minute interval from April 2022 to May 2024, comprising over 200,000 water level data points at a single location. This extensive record enabled us to capture a wide range of hydrological conditions and extract major flood events. These statistically derived thresholds were subsequently reviewed and verified by community members based on both historical experience and recent observations.*

It is recognized that percentile-based thresholding is a common and practical approach, particularly in settings with limited resources, and has been applied in recent literature for early warning systems (Jiang et al., 2023). *One positive aspect of our method is its adaptability; as more data are collected over time, the thresholds can be recalibrated, steadily enhancing their robustness to changing hydrological conditions.*

5. Non-formalized community involvement – Although the study places significant emphasis on local community participation, it does not present a structured and replicable methodology for systematically integrating community knowledge into the decision-making process. Furthermore, operational details on how surveys and consultations were conducted are lacking. The overall effectiveness of the system largely depends on the level of community engagement and technical capacity — factors that may limit its transferability to other socio-cultural contexts.

The operation and maintenance of EWS can only be ensured through the active participation of the concerned residents. The research team first conducted a transect survey of the entire Binal watershed in consultation with the residents to identify flood prone areas along the river. This helped in identifying four flood prone stretches in the lower reach of the Binal watershed, based on nature and the extent of damage from previous flood episodes. Thereafter, the team visited the affected families in these flood-prone areas, requesting their participation in PRA and FGD exercises to develop an effective EWS based on their inputs, which would benefit them in the future.

During the PRAs, all sections of the community, including men, women, youth, and elderly people, as well as those with different livelihood sources, were encouraged to participate. Before engaging them in the activities, it was essential to create an atmosphere that fostered active participation. The community leaders played a critical role in personally mobilizing the concerned families. The place and time for interaction were determined based on the suitability of the residents for each of the concerned stretches.

In each of the FGDs, 20-30 residents shared their experiences about flooding, its causes, and related damages. They indicated water levels of past flood episodes, which later helped in finalizing the threshold values. At the end of these interactions, the households concerned felt the need for an EWS as it would save the lives of people, their livestock, and their assets. As a result, they took an active interest in suggesting sites for the installation of rain gauges and water level sensors. They also assured the research team of taking care of the installed devices. Once the devices were installed, the research team regularly visited the different stretches, jointly observing the water levels and flood damage during the monsoon period, which helped gain confidence in the communities concerned and in finalizing of the flood threshold.

6. Absence of predictive hydrological or hydraulic modelling – The study focuses primarily on monitoring activities and descriptive data analysis, but does not incorporate physical or predictive runoff models capable of simulating future scenarios or assessing the impacts of anthropogenic changes and climatic variations. The authors themselves acknowledge the need to integrate hydrological modelling components to enhance the operational effectiveness of the early warning system.

Thank you for bringing this important point to our attention regarding the absence of predictive hydrological or hydraulic modeling components in our work. As acknowledged in the manuscript, the present study provides a framework that demonstrates the feasibility and value of a high-resolution, community-engaged monitoring and early warning system in a data-scarce Himalayan setting. We have installed four telemetry rain gauges with a temporal resolution of 15 minutes and three water level sensors collecting data every 5 minutes. This community-engaged framework captures local hydrological dynamics and integrates participatory validation, enabling it to provide actionable warnings tailored to watershed-specific conditions. Given current resource and funding constraints, our efforts were directed at establishing proof-of-concept for real-time monitoring and participatory threshold validation, rather than on the development and integration of comprehensive predictive models at this stage. We fully agree that integrating process-based, physics-driven hydrological and hydraulic models, which enable the simulation of future scenarios and climatic variations, will be a critical future step in enhancing operational effectiveness and early warning capabilities. This is highlighted as a clear priority in the future scope in the revised manuscript.

**Specific Comments:**

7. Abstract: It should be clarified more explicitly whether the implemented procedure is intended for nowcasting or forecasting purposes. Although the term forecasting is mentioned in line 101 of the introduction, the use of real-time precipitation and runoff monitoring tools might suggest a nowcasting application, which is generally impractical for a catchment of such limited size. Therefore, the operational objective

of the system should be specified more clearly. It is presumed that the real-time data were primarily used to calibrate a forecasting model.

Thank you for your valuable feedback. We recognize the importance of distinguishing between nowcasting and forecasting in hydrometeorological applications. The Bindal watershed exhibits a range of response times from 15 minutes to 2 hours and 30 minutes. Specifically, this response time varies from 15 to 45 minutes during heavy and very heavy rainfall events. Given these rapid dynamics and short lead times, the system, is best categorized as a nowcasting system. While the introduction previously mentioned "forecasting," we have revised the manuscript and abstract to nowcasting. The real-time data are primarily used to trigger and refine nowcast-based alerts, rather than calibrating or operating a forecasting model.

8. Figure 2: It would be advisable to clarify whether the four key components hold the same level of importance within the methodological framework. The graphical representation appears to suggest equal weighting, but a brief explanation in the text would help to better understand any hierarchical or functional relationships among them.

Thank you for your suggestion regarding clarification of the methodological framework illustrated in Figure 2. We confirm that all four key components hold equal weight within our approach and are closely interdependent. To address your comment, we have added a sentence in the manuscript at the end of the methodology description (lines 131–134), stating "*These four key components are equally important and are operationally interlinked, forming a sequential and interdependent framework essential for the robustness and effectiveness of the early warning system (Figure 2).*"

9. Lines 140–145: Including a geographic reference figure in this section would enhance the spatial understanding of the study area and clarify the subdivision of the river segments. At present, Figure 3 provides only partial information, and its placement far from the relevant text reduces its immediacy and readability.

Thank you for this helpful suggestion for improving spatial clarity in the manuscript. We agree that including a geographic reference figure closer to lines 140–145 would enhance the understanding of the study area. In response, we have updated Figure 3 to more comprehensively illustrate the locations and boundaries of the relevant river stretches and reposition the figure in section 3.1 nearer to the corresponding text section to improve immediacy and readability. A direct reference to Figure 3 will also be added in lines 140–145 to guide readers efficiently to the spatial context.

The updated figure can be found in the revised manuscript (Figure 3).

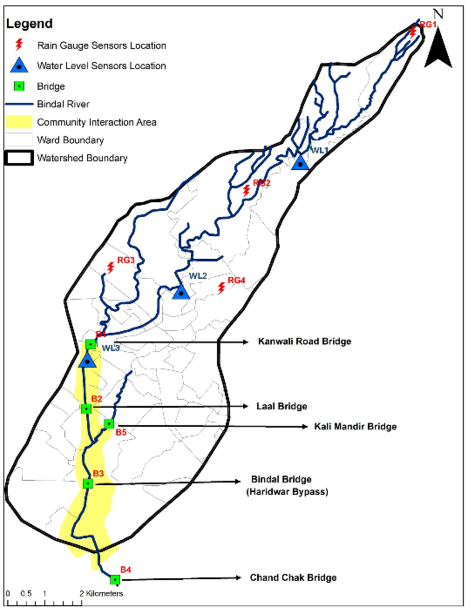
10. Paragraph 3.1 – Community Interaction: In this section, it is not clearly explained how community interaction contributed to the definition or adjustment of the thresholds. Including examples of the questions asked to participants, along with a map of the

most vulnerable areas and an explanation of how these maps were produced, would make the methodology more transparent and easier for the reader to understand.

Thank you for this critical comment regarding the role of community interaction in defining and adjusting threshold values. We have revised section 3.1 to provide a more precise and detailed explanation of this process. Participatory exercises, stakeholders' workshops and structured household interviews were used to specifically engage members of the local communities from the flood prone areas for determining the threshold values. Participants during PRAs and FGDs, held separately for the four identified flood prone stretches of the river, reported their historical experiences and observations of different water levels corresponding to different flood episodes from their memories. They were encouraged to mark the water levels on the respective social-resource maps prepared by them. Figures 3a) and 3b) have now been added, indicating the most vulnerable colonies generated based on the above mapping exercises and community interactions. This qualitative knowledge was used to validate the statistical percentile-based thresholds derived from the monitoring data, allowing us to fine-tune and adjust these thresholds to better reflect local flood perceptions and realities. The process of participatory validation ensured that the alert levels were not only statistically robust but also meaningful and actionable for the affected populations, thereby enhancing the overall effectiveness and acceptance of the early warning system.

11. Lines 175–180: It is recommended to revise Figure 1 by moving part 1a to this section, in order to immediately show the location of the sensors and facilitate comprehension, avoiding the need for the reader to flip back several pages. It would also be useful to indicate the distance of the discharge measurement sensors along the river channel.

    Thank you for the insightful suggestion. To improve readability and spatial comprehension, we have added a new figure (3a) to Section 3.1, located around lines 175–180, which allows readers to immediately view the sensor locations without needing to refer back.



Additionally, we have included a new supplementary table providing detailed information on the water level sensors along the river channel.

| Sensor | Name | Latitudes | longitudes |
|---|---|---|---|
| **Rainguage1** | RG1 | 30.39833333 | 78.09541667 |
| **Rainguage2** | RG2 | 30.35973333 | 78.05485 |
| **Rainguage3** | RG3 | 30.34092778 | 78.02178889 |
| **Rainguage4** | RG4 | 30.33598611 | 78.04876389 |
| **Waterlevel1** | WL1 | 30.335517 | 78.038947 |
| **Waterlevel2** | WL2 | 30.36703333 | 78.06797222 |
| **Waterlevel3** | WL3 | 30.31888889 | 78.01607222 |

**.Table ST2: Location details and geographic coordinates of the hydrological monitoring network sensors in the Bindal watershed. Latitudes and longitudes are provided in decimal degrees.**

| | RG1 | RG2 | RG3 | RG4 | WL1 | WL2 | WL3 |
|---|---|---|---|---|---|---|---|
| **RG1** | 0 | | | | | | |
| **RG2** | 6.48 | 0 | | | | | |
| **RG3** | 9.38 | 4.49 | 0 | | | | |
| **RG4** | 6.86 | 3.58 | 2.96 | 0 | | | |
| **WL1** | 7.55 | 2.84 | 1.73 | 0.85 | 0 | | |
| **WL2** | 5.39 | 2.14 | 6.97 | 4.67 | 4.67 | 0 | |
| **WL3** | 11.16 | 6.65 | 2.55 | 3.78 | 3.32 | 7.35 | 0 |

**Table ST3: Inter-sensor distance matrix for the Bindal watershed hydrological monitoring network {km}.**

12. Lines 188–193: It may be more effective to place the entire Figure 1 in this section to ensure consistency between the text and the illustrations. Alternatively, a new figure could be added in Chapter 2, specifically dedicated to the description of the study area.

Thank you for your suggestion. As mentioned in our response to comment no. 11, we have added a new Figure 3a in section 3.1 to enhance readability.

13. Line 240 (Table 2): It is advisable to adjust the table background, as the first row is difficult to read due to the low contrast between the text and the background color. Increasing the contrast would significantly improve readability.

Thank you for your valuable observation regarding the readability of Table 2. We have removed the table background and text colors in the revised manuscript to increase contrast. Same table is shown below for your reference.

| Type of alert | Threshold | Action |
|---|---|---|
| Warning | 99.99 percentile of Water level | Flood-like situation: Evacuate. |
| Advisory | 99.9 percentile of Water level | Flood-like situation: Stay away from banks |

| | | |
|---|---|---|
| Watch | 99.5 percentile of Water level | Stay alert |
| Information statement | 99 percentile of Water level | No action required |
| Cancellation | Below 99 percentile of Water level | Safety confirmed |

14. Some comments from the interactive discussion are not repeated here, but I fully agree with them and suggest the authors address those points as well.

Thank you for your positive feedback and for emphasizing the importance of addressing all comments raised during the interactive discussion. We have carefully reviewed all such points and incorporated corresponding revisions and clarifications throughout the manuscript and response letter. We appreciate your thorough evaluation and support, which have greatly strengthened the quality and clarity of our work.

**References added:**

Bharti, N., Khandekar, N., Sengupta, P., Bhadwal, S., & Kochhar, I. (2020). Dynamics of urban water supply management of two Himalayan towns in India. Water Policy, 22(S1), 65-89.

Mani, A., Kumari, M., Badola, R. (2025). "Urban Watershed Management in the Doon Valley: A Geospatial Assessment of Himalayan Watersheds." Journal of Landscape Ecology.