RESPONSE TO COMMENTS (CC1)

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

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Dear Editor and Reviewers,

The authors would like to thank the reviewer for their careful review of our manuscript and for providing valuable comments and suggestions, which we found very helpful in improving the manuscript's quality. 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.

1. The paper addresses critical societal and scientific problems which is important to enhance flood early warning system. The authors have conducted a thorough review of related documents and considering the local community's inclusiveness and participation through various techniques, as well as the involvement of stakeholders in the current study, is vital. However, there are many editorial corrections; the authors should review the manuscript to improve coherence, consistency, and overall paper quality.

Thank you for your careful consideration and thorough evaluation of our manuscript. We sincerely appreciate your encouragement and motivation for this article. The authors agree that the manuscript can be improved in light of coherence, consistency, and overall paper quality. Please see the detailed responses below for each of your comments.

2. Line 15: we employ the SMART principle… It is essential to define abbreviations when they are first introduced. What is SMART? Please also consider the same comments for all abbreviations and acronyms as well.

Thank you for your careful examination. *SMART refers to **S**hared understanding of risks, **M**onitoring of risks, building **A**wareness, **R**esponse action on **T**ime*. For brevity, we have used the acronym in the abstract, as it should be limited to 200 words. However, in the main manuscript (Introduction Line 88) the acronym has been explained thoroughly before being used in the subsequent sections

3. Line 19: Monitoring reveals that during a monsoon month, a 187 mm difference in rainfall… this sentence is not clear, rewrite the whole statement. Is this 187 mm difference, seasonal or monthly record? I think there is monsoon season not monsoon month.

Thanks for pointing out the lack of clarity in the sentence. Here, the authors indicate that the two stations recorded a total rainfall difference of 187 mm during the monsoon month of September 2022. We have revised lines 19-21 as follows:

"*Monitoring reveals that during the monsoon month of September 2022, a 187 mm difference in rainfall was recorded, with correlations between rainfall at different stations with r = 0.82 down to 0.20 across distances increased from 2.74 to 8.24 km, highlighting significant spatial variability*."

4. Line 23: secondary datasets failed to accurately capture the magnitude and heterogeneity of precipitation patterns. what are the secondary datasets? It is good to disclose them if possible.

Thanks. The secondary datasets used in this study are GPM IMERG (Global Precipitation Measurement Integrated Multi-Satellite Retrievals for GPM) and ERA5. We have revised lines 22–24 as follows:

'*In contrast to the locally collected data, secondary datasets (GPM IMERG, ERA5) failed to accurately capture the magnitude and heterogeneity of precipitation patterns, raising concerns about their reliability for flash flood studies at this scale*.'

5. Line 61: Furthermore, there was a significant increase in global urban… you should use a more recent estimated data…(UN, 2011) is too old for such information.

   Thank you for your careful examination. We have modified the statement according to the latest available data and referenced sources. The revised manuscript now reads: '*Furthermore, there was a significant increase in the global urban population, with the proportion rising from 30% in 1950 to 55% in 2018, and it is projected to increase to 68% by 2050 (UN, 2019).*'

6. Line 74: ...to detect and predict FFs … Define abbreviations when first used FFs? And once defined use the short form consistently throughout the document e.g., Flood Early Warning Systems (EWS) used multiple time, such as Line 71, 76 and 96 correct it.

Thank you for the valuable comment. We have defined all abbreviations at their first occurrence (e.g., Flash Floods (FFs) and Early Warning Systems (EWS)) and have ensured consistent use of the short forms throughout the manuscript. The revisions have been made at Lines 71, 76, and 96 accordingly.

7. Line 100: We hope this study's findings will contribute… better if this sentence is modified in such way: The findings of this study is anticipated to contribute…

Thank you for your insightful suggestion regarding line 100. We have modified the sentence to improve clarity and formality. The revised sentence now reads:

"The findings of our study are anticipated to develop adaptive and context-specific flood forecasting approaches, serving as an essential step towards effective and localized flood risk management."

8. Line 110: Figure 1 Figure 1: Based on Figure 1, the LULC map, it is understandable that the Watershed is urban watershed. Have you considered the effect of urban drainages systems, interactions of urban solid waste on the flood generations? What is the source and ground resolution of DEM used in this study? As the watershed area is smaller the effect of DEM resolution used for topography analysis in such studies are important

Thank you for your observation regarding urban drainage systems and the role of urban solid waste in flood generation. In the present study, these aspects have not been explicitly considered because our focus is on developing a community-integrated, data-driven early warning system rather than a physically or process-based model. Our approach is centered on integrating community inputs and real-time data streams for flood warning

We appreciate your comment on the importance of DEM resolution, particularly for small watershed studies where topographic details are critical. In our study, the ALOS PALSAR digital elevation model (DEM) is used, which provides a spatial resolution of 12.5 meters.

9. Line 143: Chandchak Bridge which covers an area of 3.0 km on the right bank and 2.7 km on the left bank….is this area or length/width? Or convert the Unit into km.sq.

Thank you for your observation. We have revised lines 137-144, as follows.

Effective communication with the community is essential for implementing an early warning system. This involves understanding the community's perspective on flooding and its impacts. It helps enhance our understanding of context specific risks, vulnerabilities, and exposure levels. Moreover, the community fosters a sense of ownership and builds trust in the EWS for floods. As per the transect survey conducted by the research team and discussions held with local stakeholders, the lower reach of the Bindal River is more affected by floods as compared to its upper and middle reaches. Therefore, the lower reach of the Bindal river was further divided into three different stretches (i) from Kanwali Road Bridge to Laal Bridge – 1.82 km, (ii) from Laal Bridge to Bindal Bridge (located at Haridwar Bypass) - 2.11 km, and (iii) from Bindal Bridge (located at Haridwar Bypass) to Chandchak Bridge – 2.28 km. In addition to the above, another stretch covering a small tributary of Bindal i.e. from Kali Mandir (located at Kargi Patel Nagar Bypass Road) Bridge to Lohia Nagar –2.40 km, was also considered. For detailed community interactions, an area of 4.21 sq. km. was considered covering all the flood prone areas of neighborhood situated on both the banks of the river, along the above stretches. These neighborhoods come under 12 wards of Dehradun city. Community consultations were further held with the different neighborhood residents along both banks of the river as per the above stretches. The communities in these neighborhood mainly include households who have migrated and settled from Bihar, Uttar Pradesh, and other parts of Uttarakhand.

10. Have you used a standard formula or procedure to select sample size of the survey 100? It may be important to indicate it in the manuscript how you decided to select 100 affected participants from the total population of the study area.

Thank you for bringing the concern regarding the sampling procedure and size to our attention. The section (Lines 160-163) has been rewritten to clarify the concerns raised.

According to the PRAs and FGDs conducted with the residents of neighborhoods located along the four selected stretches of the Bindal river, it was found that the severity of flood damages was much more in the second stretch (Laal Bridge to Bindal Bridge) as compared to third stretch (Bindal Bridge to Chandchak Bridge) and first stretch (Kanwali Road Bridge to Laal Bridge), in decreasing order. The neighborhoods along the fourth stretch were reported to be the least affected. A qualitative case-study research methodology was adopted, for which the five most vulnerable localities were further identified along the three stretches during the participatory resource mapping exercises. In each of these five localities, 20 households were selected in consultation with the ward members, considering differences in their sources of livelihoods (Services, Business, Labour, and Unemployed) to understand the disparity of impacts during floods, if any. This resulted in a total sample size of 100 households for the case study of Bindal floods. These surveys helped identify the most affected households and understand the impact of flooding on them. It revealed that households having more unemployed members and income primarily from labour, living closer to the riverbanks, suffered the most through loss of household assets and needed more recovery time.

11. Line 155: What is Season diagramming? Is it seasonal analysis of the flood peak? So many new terms.

Thank you for highlighting the terminology confusion. We confirm that 'season diagramming' refers to the analysis of monthly variation in river discharge, including flood peaks, for the four different river stretches considered for the study. Specifically, it involved a participatory assessment of flood magnitude across different seasons.

12. Line 173: If also achieves a maximum… Correction: It also achieves a maximum.

Thank you for pointing out this grammatical error. We have corrected the sentence in the revised manuscript to "*It also achieves a maximum*".

13. It is important to indicate the rain gauges and water levels recorders' detailed locational information, preferably in Table X and Y coordinates with altitude and period of data records as well.

Thank you for your valuable recommendation. In response, we have added detailed tables (ST2) in the supplementary materials, which provide the latitude and longitude coordinates for all rain gauges and water level recorders used in this study. For completeness and ease of reference, we have also included these tables below in the response document. Please note that water level sensors were installed on April 1, 2022, and rain gauges on September 1, 2022. Data collection from these sites has been continuous via telemetry, with interruptions only occurring when sensors malfunctioned. The data collection promptly resumed following maintenance and repair, resulting in minimal gaps in the observational record.

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

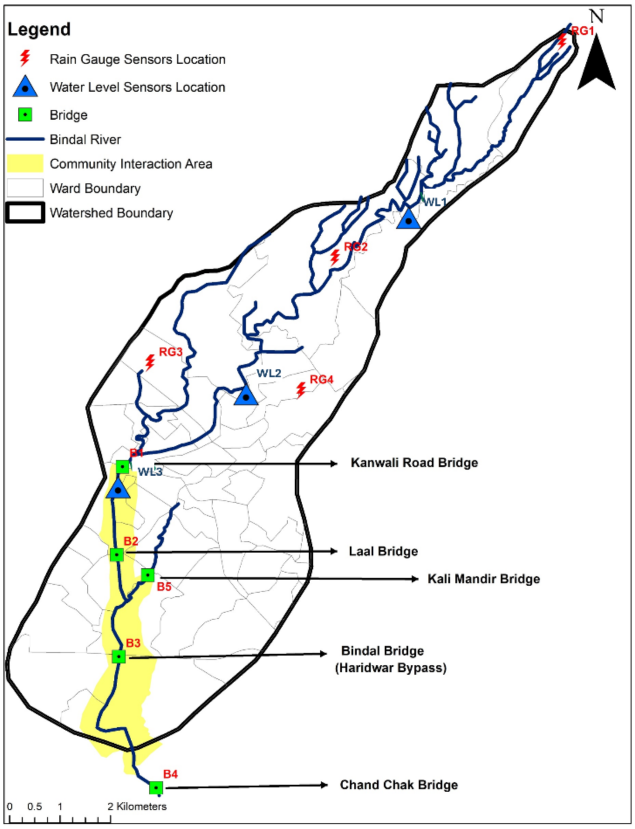
14. Line 211: Performance Evaluation of Secondary Datasets, is it right to say secondary datasets or Global climate datasets? Please refer to use the right term. Remote sensing data are not secondary data.

Thank you for raising this important point regarding dataset classification. Sorry for any confusion caused. We use the term "secondary datasets" here collectively to refer to data that the authors did not collect firsthand but obtained from external sources, including satellite remote sensing and global climate products. This terminology is also used in research, such as Venkatesh et al. (2020), who explicitly refer to satellite and reanalysis precipitation products as secondary datasets when applied in hydrological evaluation and modelling.

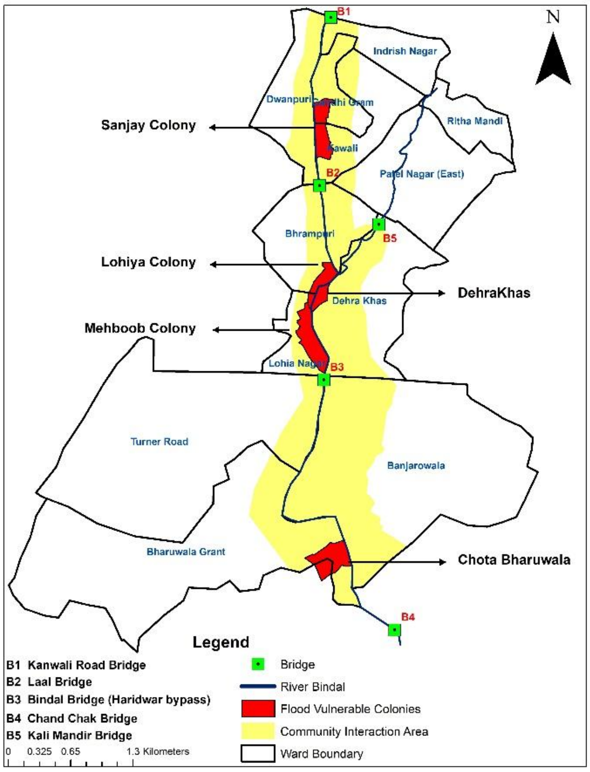
We understand that terminology can vary and appreciate the importance of clarity. However, in our study, since these datasets are externally sourced rather than primary data collected via field observations, we consider the term "secondary datasets" appropriate and consistent with several usages in hydrologic and climate science literature.

15. Figure 3 can be presented in a more improved way, with gauging stations, urban colonies and other important map features included in it.

Thank you for your valuable suggestion to enhance Figure 3 by including additional map features. We agree that these improvements enhance the clarity and informativeness of the figure by providing better spatial context for the study area. Accordingly, we have revised Figure 3 by incorporating the requested features and ensuring that all map elements are clearly labeled and visually distinguishable. We have repositioned the figure



and placed it below Section 3.1, which provides clearer reference to the locations discussed in the community interaction section. This placement will also support Section 3.2 by helping readers better understand the positions of the rain gauge and water-level monitoring stations. Additionally, we have added a new Figure 3b in Section 4.1, which provides a zoomed-in view of the updated figure for improved detail and interpretability.



The updated figures are available in the revised manuscript.

16. Table 2 Five levels of flood alerts, their thresholds, and the action required. The Threshold used to define flood alert are very high and narrow ranges as indicated in Table 2. Can you visualize the difference in the flood threshold of 99.99 vs 99.9? Are this threshold economically feasible? Please also review related papers and field experience on this Table 2.

Thank you for your insightful comment regarding the flood alert thresholds detailed in Table 2. The table is summarized as follows:

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

In our study, thresholds were determined using a data-driven approach consisting of two components: (1) statistical analysis to identify extremes, and (2) community-based assessment and validation. We utilized a long-term, high-resolution water-level dataset recorded at five-minute intervals from April 2022 to May 2024, comprising more than 200,000 data points from a single monitoring station. This extensive dataset enabled us to capture a wide range of hydrological conditions, including major flood events. The statistically derived thresholds were subsequently reviewed and validated by local community members, who contributed their historical knowledge and recent experiences to classify appropriate actions and assess the likelihood of risks to property and life. An important advantage of this statistical approach is that the thresholds will continue to become more robust as additional data are collected over time, ultimately supporting more precise and reliable early warnings.

Although the numerical difference between the 99.99 and 99.9 percentiles may appear small, the large number of observations means that the associated exceedance events are substantial, with more than 20 water level observations for one threshold and over 200 for the other in some cases. These differences translate into significant variations in flood magnitude, which depend on the local river cross-sectional width at sensor locations. And, as data collection continues, these observed datasets will grow, enabling the thresholds to become more robust over time.

For example, at the sensor WL3 site, where the river width is approximately 26 m, the difference in water level between the 99.9 and 99.99 percentile thresholds is 0.27 m. At a narrower site, WL1, where the width is ~12 m, this difference increases to about 1.0 m. In the context of this narrow, small river system, such differences are meaningful and clearly distinguish hazard levels.

17. Spatio-temporal variability

For depicting the spatial variability of rainfall over the catchment, it is also important to produce the spatial change in the form of map-based spatial surface or preferably interpolated map with suitable techniques in addition to Figure 4.

Thank you for this valuable suggestion. We have incorporated monthly spatial rainfall distribution maps generated using Inverse Distance Weighting (IDW) interpolation for the Bindal watershed. These new maps show rainfall heterogeneity across the catchment for each month from September 2022 to August 2023, with active rain gauges for each respective period. IDW is a widely used spatial interpolation technique that estimates continuous rainfall surfaces from discrete measurement points, providing clearer insight into localized rainfall patterns.

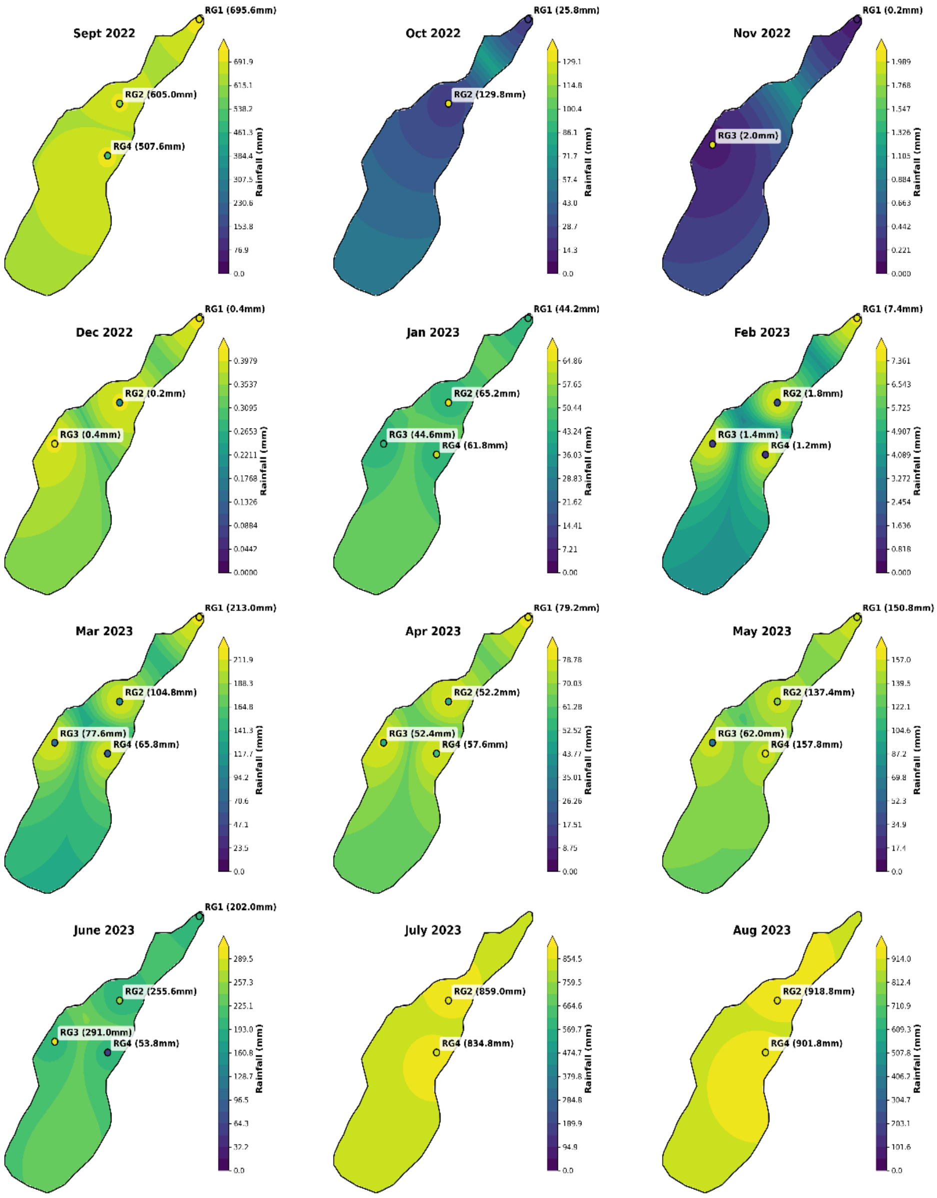


Figure: Monthly cumulative rainfall spatial variation across the Bindal watershed from September 2022 to August 2023. Rainfall distribution is generated using Inverse Distance Weighting (IDW) interpolation with a power parameter p=2. The maps display rainfall values (mm) along with the locations of the active rain gauges used for interpolation during each respective month.

However, a key limitation of spatially interpolated maps, such as IDW, is that they represent cumulative rainfall totals over a given month and thus cannot capture temporal variation or variability within individual rainfall events during that period. Unlike monthly cumulative rainfall line plots, which effectively visualize the number of rainfall events, their magnitudes, and spatial differences during each event, spatial maps provide only a static view of rainfall distribution for the entire month. These factors limit the spatial plot to reflect dynamic intra-month rainfall characteristics, such as intensity and timing, and frequency of event changes.

Therefore, to maintain focus and clarity, these spatial rainfall maps are included in the supplementary materials rather than the main manuscript, complementing the temporal rainfall analysis presented in Figure 4.

18. Line 333: The above analysis, which part of the above? Please refer to the Figure or Table.

Thank you for pointing out the need for clarity. We have revised the sentence to explicitly refer to the analysis presented in Figures 4 and 5 to guide the reader clearly to the relevant visual data supporting the discussion. The revised manuscript now states: "*The above analysis shown in Figures 4 and 5...*"

19. Based on Table 4 Statistical comparison of secondary rainfall (GPM-IMERG and GPM) with observed rainfall, it shows the annual rainfall (mm) GPM 5306.53, and GPM 1495.8 mm significantly varied. Have you made a bias correction or downscaling analysis? It is essential to bias-correct global databases before application.

Thank you for highlighting the importance of bias correction and downscaling in the use of global rainfall datasets. We acknowledge that bias correction and downscaling are crucial steps in enhancing the applicability of global datasets for local hydrological modeling and applications. *In this study, we did not perform explicit bias correction or downscaling prior to comparison, as our objective was to assess the raw, inherent performance and biases of two readily available, high-temporal-resolution secondary rainfall products (GPM-IMERG and ERA5) relative to ground-observed rainfall. The rationale for this approach was to determine whether these global products, due to their accessibility and high temporal resolution, could adequately capture the variability and magnitude of precipitation within the smaller, topographically complex semi-urban Himalayan watershed.* The results indicate that neither raw product sufficiently captures the observed precipitation magnitude and variability (as discussed in Section 4.3), highlighting the necessity of a sensor network (rain gauges) to capture the hydrometeorological dynamics of the Himalayan watershed.

We will include this justification in Section 3.3 of the revised manuscript to clarify the rationale behind this approach.

20. Line 383 to Line # 387, the statements are not clear, please re-write them.

Thank you for your valuable comment regarding the clarity of the statements in lines 383 to 387. We agree that the original text could be clearer. Accordingly, we have rewritten this section to improve readability and provide a more precise explanation of the analysis and figure presentation. The revised text now reads as follows:

"*Rainfall and water level data were analyzed to understand watershed dynamics and their relationship with flood warnings. The peak rainfall intensity at 15-minute intervals was calculated for each rain gauge during three distinct periods: (a) Monsoon 2022, (b) Non-monsoon 2023, and (c) Monsoon 2023. Figure 7 presents the probability density functions (PDFs) of the 15-minute maximum rainfall intensities recorded at each rain gauge for these different seasons. The Y-axis represents density, a smoothened estimate of the probability distribution of the data*.

21. In general leaf shaped or elongated watersheds generate less flood peak compared to oval or circular shaped watersheds, other factor kept constant. The current or Bindal watershed is more or less leaf shaped, I also assume that is why the peak flows a bit

lagged the peak rainfall event evident from Figure 8. Can you please discuss this issues more based on the result obtained in the current study?

Thank you for your insightful observation on the influence of watershed shape on flood peak characteristics. As you pointed out, the Bindal watershed exhibits a leaf-shaped or elongated form, which typically results in a delayed and reduced flood peak compared to more compact, oval, or circular watersheds.

In our study, the hydrograph analysis (Figure 8) indeed shows a noticeable lag between peak rainfall and peak flow, consistent with the hydrological response of elongated basins. The longer flow paths and varied travel times within such watershed geometry contribute to this lag, attenuating the flood peak. Furthermore, this shape may influence runoff concentration times and flood wave propagation, which aligns with our observations.

Reference added:

Venkatesh, K., Krakauer, N. Y., Sharifi, E., & Ramesh, H. (2020). Evaluating the performance of secondary precipitation products through statistical and hydrological modeling in a mountainous tropical basin of India. Advances in Meteorology, 2020(1), 8859185.

United Nations, Department of Economic and Social Affairs, Population Division (2019). World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations.