# Reconstructing the magnitude and characteristics of the 2013 Kedarnath disaster using its geomorphic signature

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## 1 - INTRODUCTION

In **2013**, a **cloudburst** triggered **thousands of debris flows** and **landslides** within several hours devastating the town of **Kedarnath** in Uttarakhand, in the **Indian Himalaya**. **Cloudbursts are poorly understood** due to a lack of rain gauges and high-resolution satellite imagery **[1].**

***Abstract***

Abundance of debris, rainfall, snow melt, and the outburst of the Chorabari Tal lake produced a **catastrophic sediment-laden flood** killing over **5000-6000 people [2].** Most studies investigate the **Mandakini catchment** where the main flood event occurred, but no systematic assessment of the event in the wider **Upper Alaknanda** catchment has been done, which is vital as these hazards are likely to **increase** in **frequency** and **magnitude** with **climate change.**

***Therefore, this study aims to:***

1. Construct an **inventory** of debris flows and landslides
2. Identify **first-order controls** of debris flooding from topographic, channel, sediment supply, and trigger characteristics
3. Determine the **spatial extent** and **intensity** of the cloudburst

## 2 - METHODS

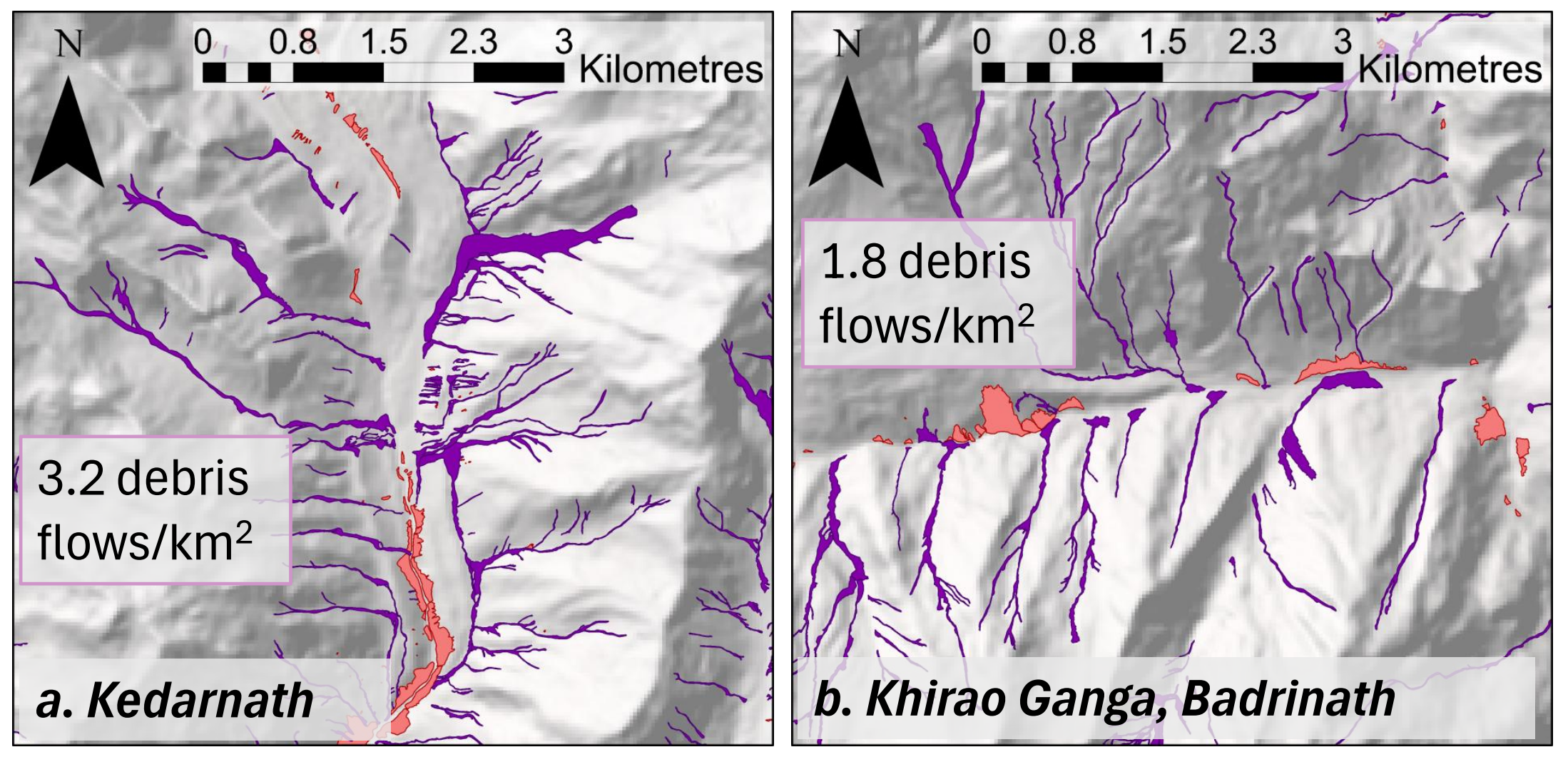

*Figure 1. Detailed manual mapping of debris flows (purple) and landslides (pink) in a) Kedarnath, and b) the Khirao Ganga, south of Badrinath. Locations highlighted in Figure 8.*

Debris flows and landslides **manually** mapped using a set of criteria established from previous work **[3]**. Polygons were produced in Google Earth Pro. For each polygon we differentiated between hillslope and channelised debris flows and whether the flow was new or a remobilisation.

**Totals are higher than published recorded amounts [4]**

*Table 1. Debris flow and landslide inventory totals*

| | Kedarnath (Mandakini, 1640 km$^2$) | Badrinath (Upper Alaknanda, 1530 km$^2$) | Total |
|---|---|---|---|
| Debris flows | 616 | 580 | 1196 (60%) |
| Landslides | 597 | 187 | 784 (40%) |
| **Total** | 1213 (61%) | 767 (39%) | **1980** |

**References:** **[1]** Hobley, D.E.J. et al. (2012). *Geology*, 40(6). **[2]** Champati Ray, P.K. et al. (2016). *Natural Hazards*, 81. **[3]** Roback, K. et al. (2018). *Geomorphology*, 301. **[4]** Sekar, A. et al. (2026). *Geomorphology*, 500. **[5]** RGI Consortium (2023). *Randolph Glacier Inventory.* **[6]** Roda-Boluda et al. (2023). *JGR Earth Surface*, 128(11).

## 3.1 – RESULTS: Density and area analysis

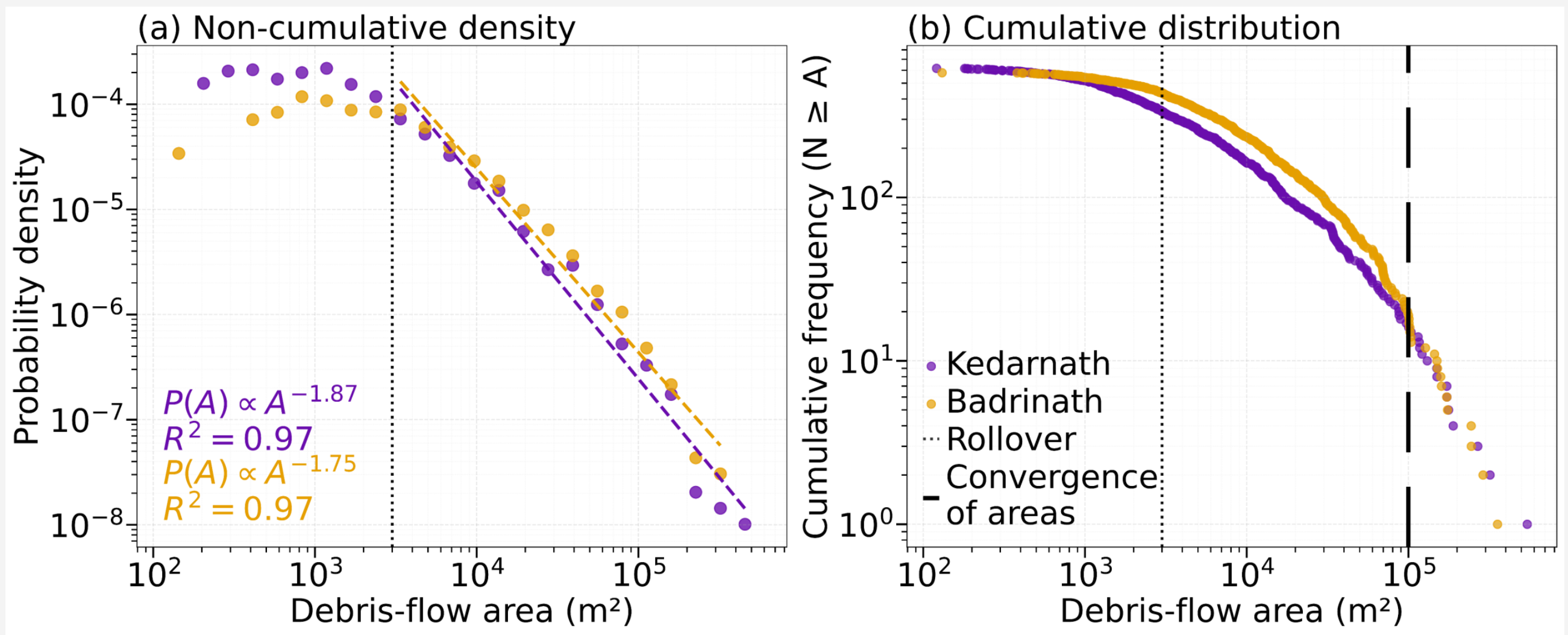

*Figure 2. a) non-cumulative and b) cumulative area-frequency distribution of debris flows*

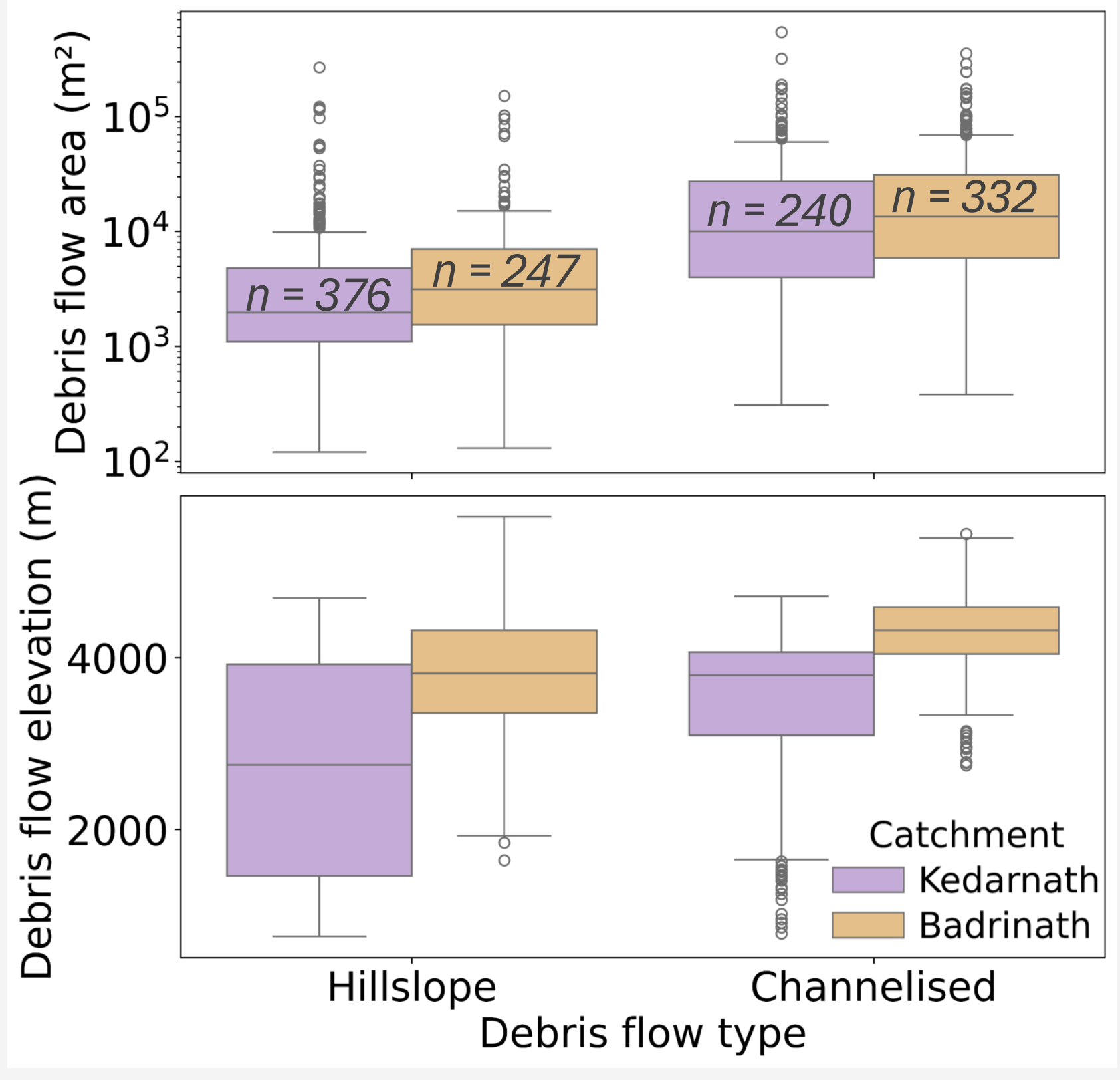

*Figure 3. Debris flow area and elevation of source area for debris flow type.*

A **large number** of **hillslope** and **channelised** debris flows were triggered.

The frequency of debris flows for **Kedarnath** and **Badrinath converges** above a drainage area **threshold of 10$^5$ m$^2$.**

The debris flows in **Badrinath** were, on average, **larger** than in **Kedarnath** and more likely to be **channelised** and occur at **higher elevations.**

## 3.2 – RESULTS: Elevation controls

In both **Badrinath** and **Kedarnath**, **debris flows** occurred at **higher elevations** in the catchments **(3200 - 4800 m).**

In **Kedarnath**, debris flows occurred at **lower elevations.** We attribute this to the overall lower elevation of the study catchment.

Broadly, individual **debris flow areas increase at higher elevations,** with a 3 orders of magnitude increase at 1600 m.

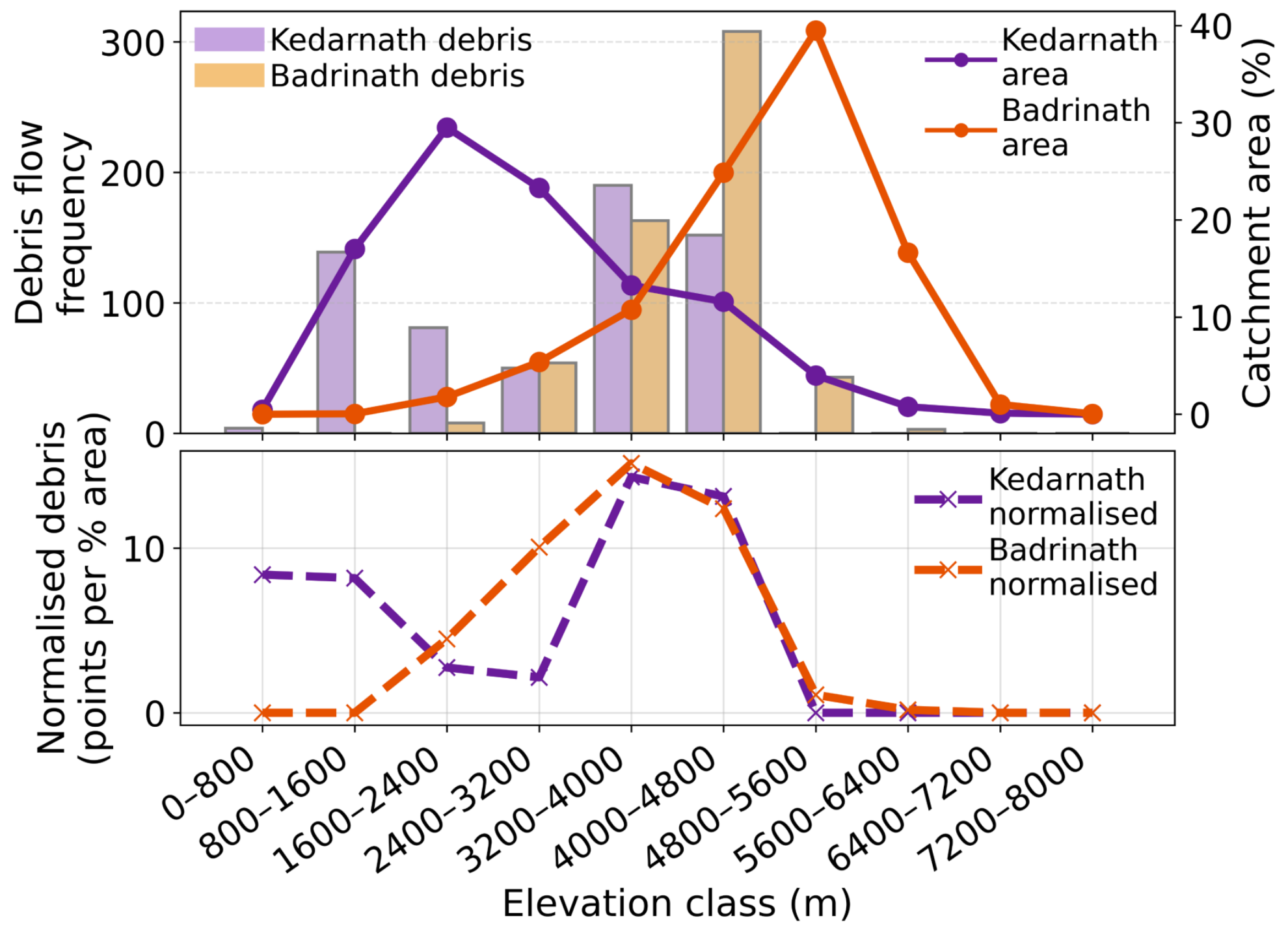

*Figure 4. a) Debris flow frequency and study area elevation (% of total catchment) area in 800 m bins and b) Number of debris flows per normalised % catchment area in 800 m bins.*

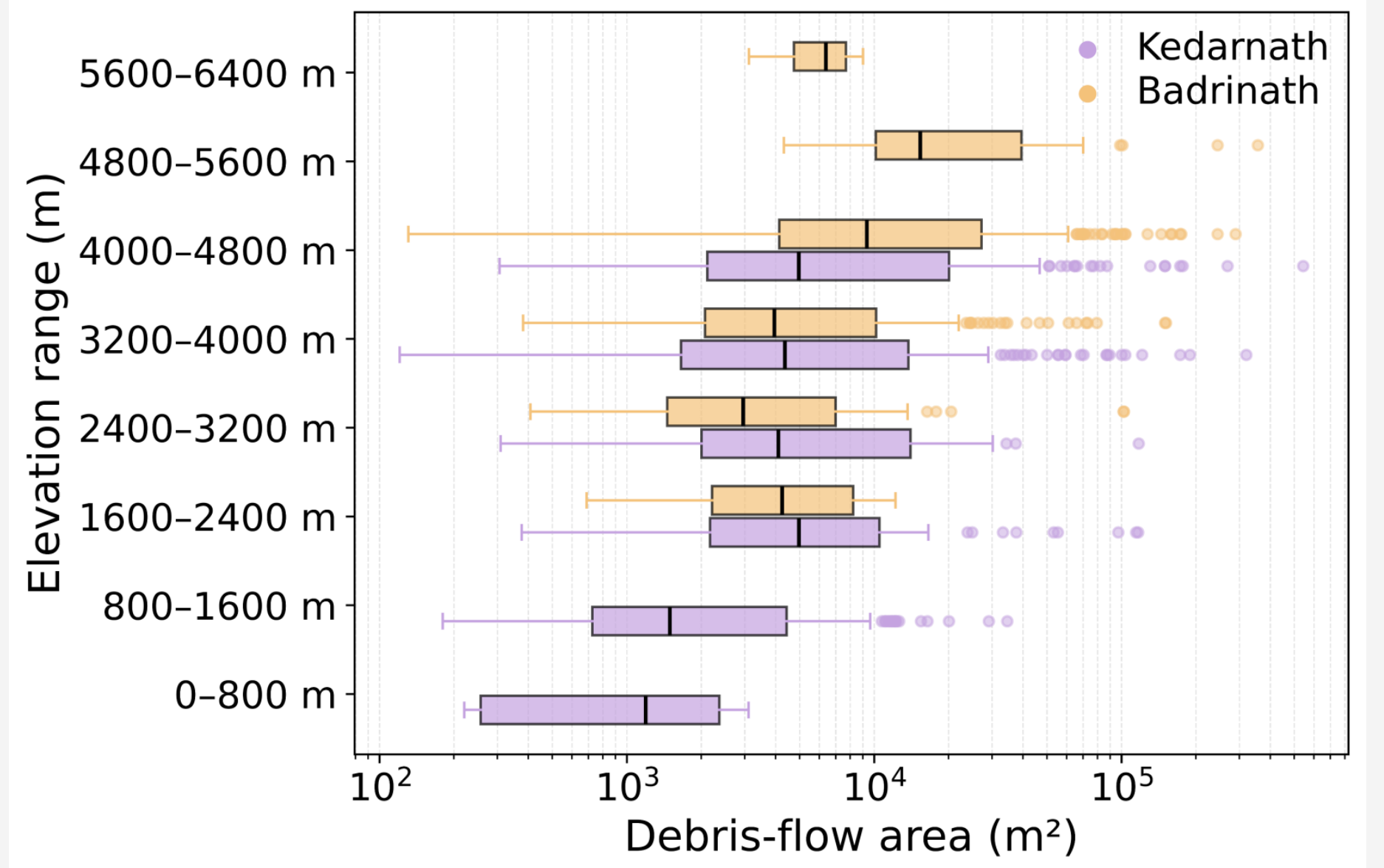

*Figure 5. Debris flow areas against catchment elevations*

## 3.3 – RESULTS: Glacial Controls

**Total** catchment **glacier coverage** is **27% (Badrinath)** and **3% (Kedarnath) [5].**

**Most debris flows** occurred in catchments between **5 and 15% glacial coverage** with **exception** to the **0% coverage** with Kedarnath.

**Patterns of normalised** debris flows between 0 and 20% glacier coverage match between **Kedarnath** and **Badrinath.**

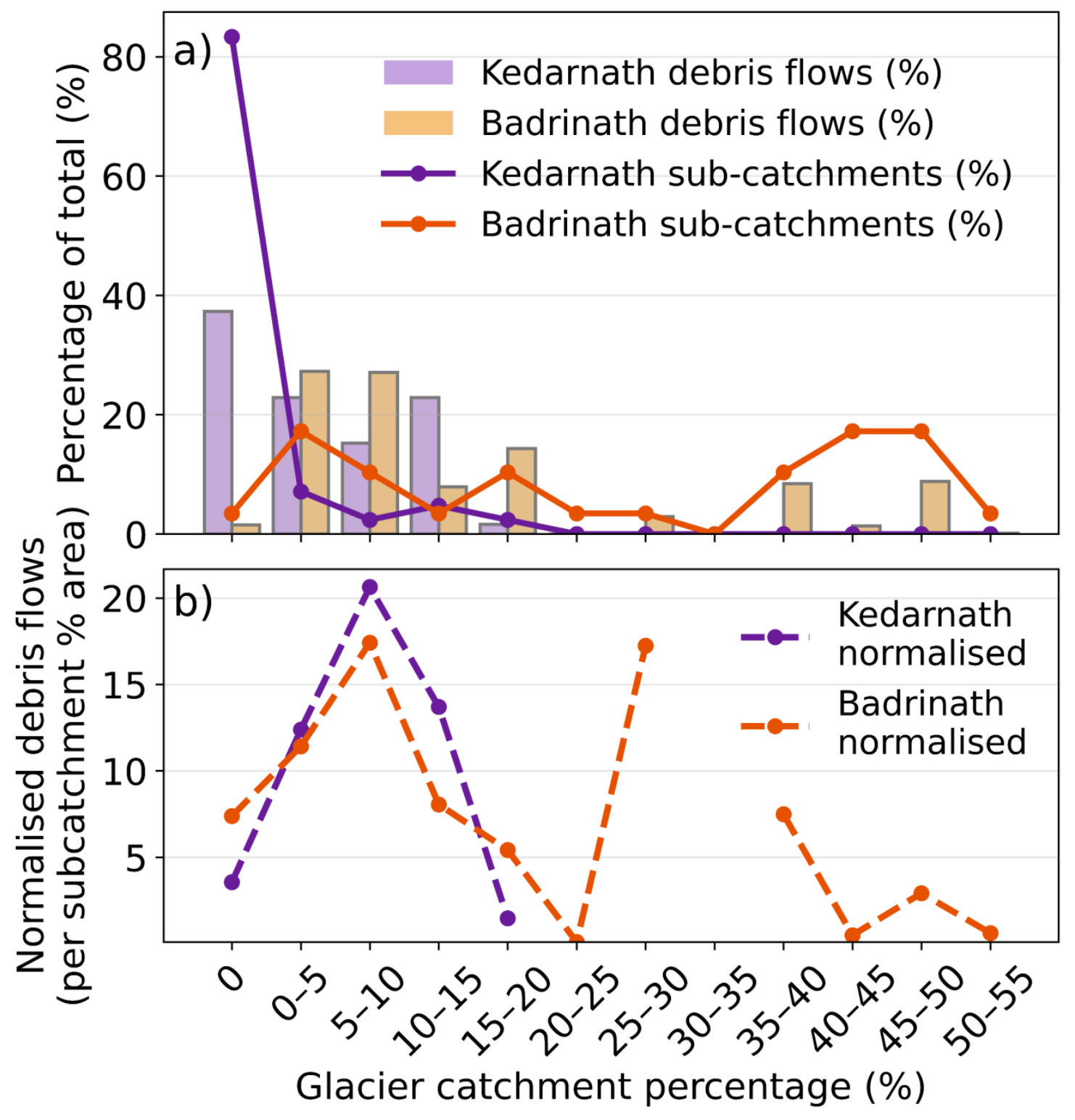

*Figure 6. a) Debris flow frequency and b) normalised debris flow frequency against % area of sub-catchments*

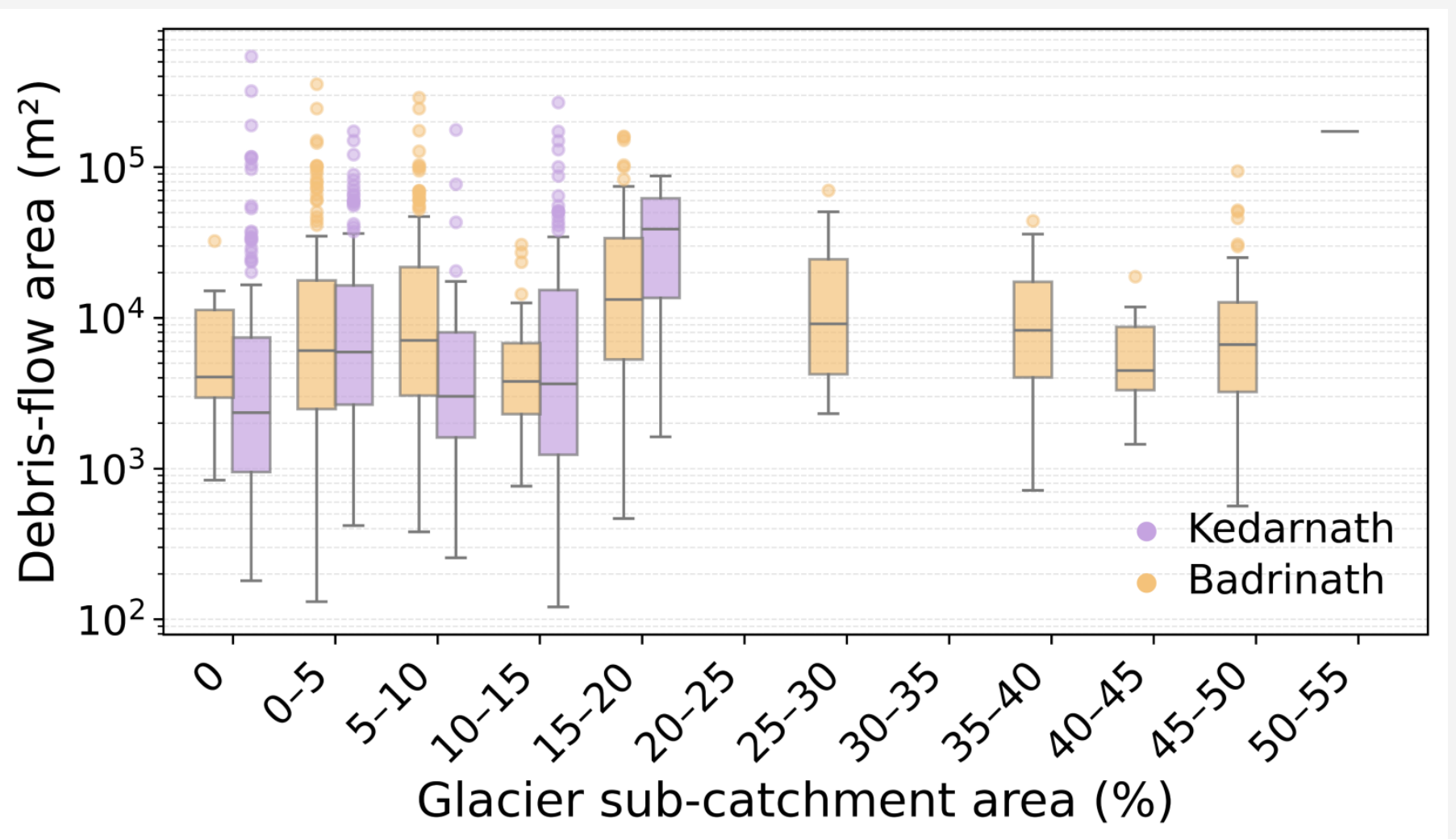

*Figure 7. Debris flow areas against sub-catchment glacier coverage*

Debris flow areas **don't have a strong relationship** with sub-catchment **glacier coverage**

Kernel **density (heat map)** of debris flow points is over **2 orders of magnitude** higher at **a. Kedarnath** (30°44'05.07" N 79°04'00.83" E) than at **b. Khirao Ganga** (30°41'05.15" N 79°29'28.51" E)

***Spatial and areal density of debris flows***

Debris flow locations are **dominant** in the **north** of the Mandakini catchment, and in Badrinath **along the Alaknanda river** and tributaries, until the **landscape** becomes too **glaciated**

Transition to more **debris flow** processes north of the Mandakini valley

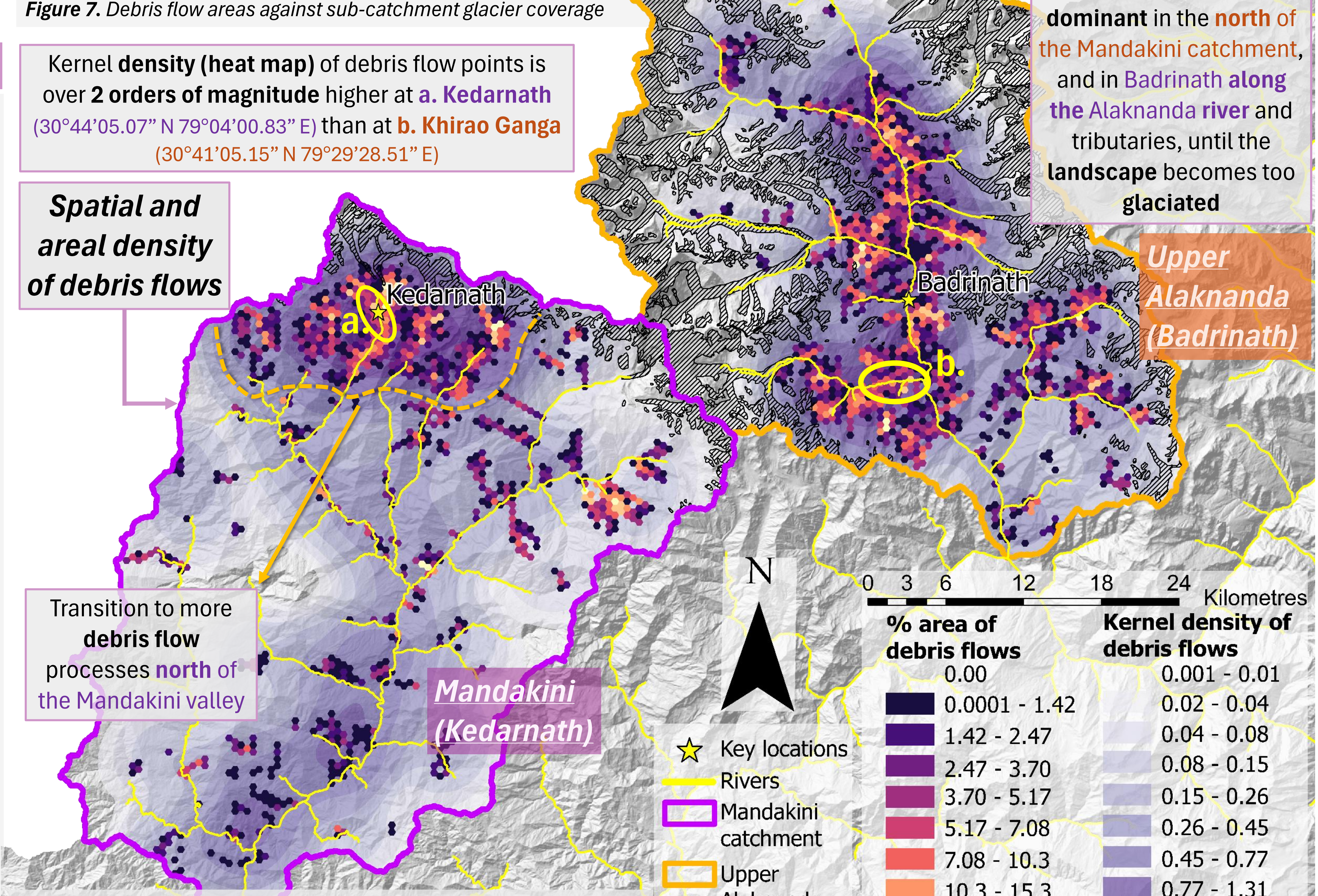

*Figure 8. Kernel density of debris flow distribution overlaid by the spatial distribution of debris flows by area % coverage in 0.25 km$^2$ hexagons of Mandakini and Upper Alaknanda catchments, Uttarakhand, India.*

## 5 - CONCLUSION & NEXT STEPS

**1)** The **number of mass movements** caused by the 2013 cloudburst has been **underestimated [4]**

**2) Elevation is a clear control on debris flow generation**, likely due to **paraglacial** processes **[6]**, and concentration of the **cloudburst**. The **relationship** between **glacier coverage and debris flow** frequency and **area** is **less clear**. This might be due to cloudburst location or difficulty in mapping debris flows in heavily glaciated catchments.

Differences in **landsliding**, **slope**, **channel steepness**, **valley width**, **geology**, **tectonics**, and levels of **remobilisation** are important next steps to determine differences in debris flooding between catchments.