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'HiFlo-DAT': A flood hazard event-disaster database for the Kullu District, Himachal Pradesh, Indian Himalaya.

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ABSTRACT

'HiFlo-DAT' (**Hi**malayan **Flo**od **Dat**abase) contributes to the disaster risk reduction (DRR) agenda of developing methodologies for the assembly, analysis, and application of disaggregated/ sub-national disaster loss data; here for mountain floods in the Kullu District, Himachal Pradesh, India. The HiFlo-DAT architecture is aligned to international best practice/ local needs. It uses English-language documents, principally newspapers and government reports (1835-2020), and comprises 128 flood events, at 59 locations, over 175 years (1846-2020). This open-access database brings a substantial improvement over existing compilations. Subject to the fidelity of historical event recording, analyses highlight temporal/ process patterns inclusive of flood-rich periods (1890-1900s; 1990s-present: 68% of events), increasing flood occurrence towards the present, the prevalence of rainfall causation (55%), and the dominance of summer monsoon flooding (June-September: 87%). Spatially, of the 59 locations recording floods, 76% record a single event, 24% have two or more events, and four tributaries record 8-14 events. Key flood impact receptors were roads (55 floods), bridges (54 floods and 94 impacts) and vulnerable labourer-migrant communities (70% fatalities and 83% affected) notably associated with construction projects in remote/ exposed locations. Key opportunities for policy and practice development include transference of the HiFlo-DAT methodology across the wider Indian Himalayan Region and trans-boundary basins; multi-disciplinary approaches to corroborate and extend documentary-based databases; improved access to public archive materials; routine integration of historical flood data into DRR/ climate change adaptation management planning and infrastructure development design; and deeper multi-agency partnership to record contemporary flood impacts to provide effective data for current/ future DRR.

KEY WORDS: Flood, hazard, disaster, database, India, Himalaya

LENGTH MANUSCRIPT: 7728 (intro. to conclusion)

1. INTRODUCTION

In considering flood hazard/ risk in mountain catchments it is important to contextualise the global significance and diversity of mountains. Gardner (2015), Walz *et al.,* (2016), Hock *et al*. (2019), Sharma *et al.* (2019), and Adler *et al.* (2022) provide synthesis, where the capital of mountains includes their biodiversity, cultural heritage, and ecosystem services (e.g., energy, water, food) for global human populations. Mountains can however be remote, form disputed trans-boundary settings, may have populations with higher levels of poverty, and have hazard-prone environmental systems. Rapidly changing environment-society conditions in mountains are increasing disaster exposure, vulnerability and risk; driven by integrated stressors including climate variability, habitat degradation, conflict, globalisation, infrastructure development, tourism, urbanisation and population change. Amplifying concerns and contributing to an urgent call for action, are complex/ contested future climate change trajectories in the Indian Himalayan Region. These signal increased temperatures, typically increasing precipitation but with regional diversity, likely increasing summer monsoon precipitation which generates many floods, and likely decreasing low flow and more extreme high flow events within river channels (Mathison *et al.,* 2013; Rao *et al.,* 2014; Krishnan *et al.,* 2019; Dixit *et al.,* 2023). We are reminded of these challenges by high-magnitude hazard events across the Indian Himalayan Region. For example, the September 2014 floods in the Kashmir Valley in north-west India (Ballesteros-Cánovas *et al.,* 2020) and further east in Uttarakhand, the Kedarnath disaster in June 2013 (Dobhal *et al.,* 2013; Allen *et al.,* 2016; UNDRR, 2022) and the Chamoli disaster in February 2021 (Shrestha *et al.,* 2021; Shugar *et al.,* 2021, NDMA, 2022). More broadly Vaidya *et al*. (2019), using CRED EM-DAT (global disaster data; 1980-2015), establish that Hindu Kush Himalaya nations account for 21% of all major disaster events, in which India recorded 438 events (second to China). Furthermore, floods are a prominent hazard type both globally (CRED-UNISDR, 2016; CRED-UNDRR, 2020) and in the Himalayan region (Shrestha *et al.,* 2015; CRED-UNDRR, 2020). Taking a 5-year snapshot of CRED EM-DAT data (2016-2020) for India, shows recorded floods accounted for 44% of hazard events (n= 36), 68% of deaths (n= 6549), 53% of affected persons (n= 53.9 million) and 57% of damage costs.

The UNDRR 'Sendai Framework for Disaster Risk Reduction 2015-2030' (SFDRR) is the key policy driving DRR efforts, of which India is a signatory. Regional policy groups bring further focus; India is a member of the 'Asia-Pacific Ministerial Conference on Disaster Risk Reduction' (APMCDRR) who adopted the Asia-Pacific Action Plan 2021-2024 in December 2021, and 2024-2027 in October 2024 (UNDRR, 2021; 2024). Building on the precursor Asia Regional Plan (AMCDRR 2018) these plans target the development of methodologies for the compilation of disaster loss data to help reduce future disaster impacts; aligning with SFDRR Priority 1 *'understanding disaster risk'*, inclusive of *'the collection, analysis, management and use of relevant data and practical information and ensure its dissemination…'* (clause 24a). India has operationalised this and other DRR priorities via National, State and District disaster management authorities. A small number of States have existing multi-hazard atlases of historical events (e.g., Gujarat, Himachal Pradesh, and Uttarakhand), 'Memoranda of Loss and Damages' of contemporary events (e.g., 2013-2024 in Himachal Pradesh), and 'Post Disaster Needs Assessments' (e.g., 2023 Monsoon floods/ landslides in Himachal Pradesh; HPSDMA, 2023a, 2023b). In parallel, national efforts (NDMA, 2021) to extend understanding of flood risk include a national 'Flood Affected Area Atlas of India' (NRSC, 2023), based on satellite imagery (1998-2022), but has limited information for Himachal Pradesh. Alongside this the India Meteorological Department (IMD) maintains an annual record of 'Disastrous Weather Events' (1967-present). This details heavy rainfall/ flood events, at state and district levels, but entries are typically over generalised. More broadly, large bi-lateral initiatives like the 'Indian Himalayas Climate Adaptation Programme' (IHCAP) in Himachal Pradesh, not only assembled historical flood data, but also recommended *'the dissemination of information and training related to hazard zones, elements-at-risk and best practices'* (IHCAP, 2017). Thereby empowering local agencies and communities to reflect on their hazard/ risk perceptions and to foster greater societal engagement for risk informed development and disaster preparedness/ resilience near river channels.

Accordingly, standing observations likely persist, that Indian disaster data recording and analysis requires more coordination (Rautela, 2016); governance structures are not capitalising on the depth of local knowledge (Ogra *et al.,* 2021); that data holdings remain 'incomplete' and 'incomprehensive' (HPSDMA, 2016) and are not regularly maintained/ updated; and there is a tendency for insufficient data disaggregation and missing data (i.e., gaps) in existing databases resulting in skewed appreciation of disaster risk and thus inefficient/ ineffective DRR (UNDRR, 2022; UNDRR 2023). Similarly, an independent assessment by ADPC-UNDRR (2020, p20) reports: *'despite these initiatives and stakeholders involved, risk and disaster information in India has remained fractured across various agencies, ministries and administrative levels, with little cross-compatibility and harmonization which limits comprehensive analysis of risks in the country…'.* Encouragingly a change to legislation, i.e., The Disaster Management (Amendment) Bill 12 December 2024, may support greater action, as this mandates the creation of national and state level disaster databases (NDMA, 2024).

These debates withstanding, global hazard/ disaster databases such as ADRC (Asian Disaster Reduction Centre, Japan), EM-DAT (Emergency Events Database: Centre for Research on the Epidemiology of Disasters, Belgium), NatCatSERVICE (Munich Re, Germany) and Reliefweb (UN Office for the Coordination of Humanitarian Affairs) are all established portals. Other inventories, such as the Dartmouth Flood Observatory: Global Active Archive of Large Flood Events (University of Colorado, USA; Brackenridge, no date) and IFNet (Infrastructure Development Institute, Japan) also operate internationally but with a focus on flood events. These all have restrictive criteria for database inclusion, typically focussing on the largest/ most devastating events, thus filtering out smaller flood events of local significance (Adhikari *et al.,* 2010; Llast *et al.,* 2013a; Aceto *et al.,* 2017, UNDRR 2023) and assume the trigger process type is clearly identifiable. Whilst these global compilations can assist macro-level policy/ practice, they can be a poor fit to a country's needs. Instead, national/ sub-national stakeholders require more comprehensive, localised and hazard process specific databases to effectively implement national policies for development planning and anticipative risk management (Adhikari *et al.,* 2010; ADPC-UNDRR, 2020; Ogra *et al.,* 2021; UNDRR, 2023).

Given these Indian flood disaster challenges and policy targets to enhance data quality, the objectives of 'HiFlo-DAT' (**Hi**malayan **Flo**od **Dat**abase) are to: (1) use documentary archives to generate a new, locally focussed and open-access database of historical floods in the Kullu District (Himachal Pradesh, India), enabling a revised appraisal of past floods characteristics; (2)

outline a transferable methodology for flood databases, applicable to the wider Indian Himalayan Region (>530,000 km^2, extending 2500 km across 13 States/ Union Territories/ Districts); and to (3) offer recommendations for policy-practice development.

2. STUDY REGION AND EXISTING FLOOD DATABASES

2.1 Kullu and Manali Tehsils, Kullu District, Himachal Pradesh

Situated in northern India, the Kullu District (Figure 1) has a resident population of c. 440,000 (Census of India, 2011), swelled by transient economic migrants, tourists, and pilgrims (>1 million influx in 2004; Singh 2008) which exacerbate exposure, vulnerability and risk to hazards (Gardner, 2002). The succession of governance (pre-colonial, British colonial, and post-Independence) in this region is significant, as this has conditioned the language, quantity and current location of historical materials which may detail past floods. Accordingly, HiFlo-DAT uses globally dispersed English-language records, incorporating the period of British colonial administration (1846-1947: 'Kulu sub-division of Kangra District'; where 'Kulu' is the pre-independence spelling of both the area and principal settlement), post-1947 Indian independence under Punjab administration (1947-1966) and Himachal administration (1966 onwards).

HiFlo-DAT's spatial extent is the area of the Manali and Kullu Tehsil's (Figure 1) in the northern part of the Kullu District (3561 km^2, c. 0.67% of the Indian Himalayan Region; Village Info, 2021). Selecting these Tehsil's yields many English-language documentary records during the colonial to post-independence periods, perhaps with greater abundance than most of the Indian Himalaya. This reflects: (1) being focal points of former British colonial administration/ meteorological monitoring in Kulu and Naggar (Punjab Government, 1918; Chetwode, 1972); (2) reporting interest by former media, e.g. the Civil and Military Gazette (newspaper) had a correspondent based in Kulu in the late 19th Century; (3) alignment with long-standing/ more intensively settled locations, key trade/ transport routes and economic activity in the District (Harcourt, 1871; Chetwode, 1972); and (4) a high frequency of hazard events as a consequence of local seismic, hydro-meteorological (i.e., Indian summer monsoon, winter snowfall, snowmelt) and active sediment transfer cascades (Gardner, 2002; Sah and Mazari, 2007; Gupta *et al.,* 2024). Moreover, these areas are rapidly developing, changing the hazard-risk equation, for example hydro-electric power schemes (Diduck *et al.* 2021), road widening and tunnelling (PWD, 2021; Chauhan, 2020), proposed Kullu-Manali airport runway extension (Vashisht, 2021), planned railways (Tribune, 2020), and tourism growth (Sood *et al.,* 2017).

2.2 Kullu District Hazard-Disaster Profile

Accounts of hazard-disaster events, in the Kullu District incorporate research (Gardner, 2002; Sah and Mazari, 2007; IHCAP 2016), government/ NGO policy-practice (Pragyan, 2016; Sarpotdar, 2016; DDMA, 2017; HPSDMA, 2017), and community-based knowledge (Johnson *et al.,* 2018; BSU and GBPNIHE, 2020); commonly including earthquakes, floods, slope failures, snow avalanches, fires, crop infestations and epidemics. Existing databases of flood events for the Manali and Kullu Tehsils (Table 1), showcase the paucity of publicly available data, reporting 1-15 flood events since 1994. This may in part reflect known losses of documentary records during past hazard events. For example, the 21 May 1894 Phojal Nalla flood destroyed the record offices in Dawara and Dobhi (Civil and Military Gazette, 1894); more recently the 4 September 1995 Beas River floods washed away records in Patlikuhal. HiFlo-DAT responds, being a new open-access compilation of historical floods, empowering more effective flood risk assessments, disaster risk reduction, and development in the Kullu District (Ballesteros Cánovas *et al*., 2017; Allen *et al.,* 2018).

3. **'HIFLO-DAT' METHOD**

3.1 An overview

Developing a robust database for the Kullu District, which is potentially transferable across the Indian Himalayan Region necessitates extended methodological articulation. Our approach was highly consultative, grounded in best practice and project managed, empowering a bi-lateral team to work with globally dispersed materials. Figure 2 details the key phases: HiFlo-DAT design, data selection, data capture, data review, data entry, database analysis, and dissemination.

3.2 HiFlo-DAT design and structure

A workshop in Delhi (June 2018) comprising Indian State and District government, DRR NGOs and researchers, distilled user aspirations for the database design: a simple and intuitive format; a comprehensive set of data fields inclusive of temporal and spatial attributes; use of commonly accessible file types; and online hosting. This consultation was nested in appraisal of existing global hazard/ disaster databases. Using evaluation of research outputs via Scopus ® (13 keyword combinations, 5518 hits), alongside inspection of existing flood and/ or disaster databases, i.e., ADRC; CRED EM-DAT; Dartmouth Flood Observatory; and PAGES (Past Global Changes) flood working group. These were filtered to n= 64 sources and systematically reviewed detailing database structures/ fields/ hierarchies, data entry and validation protocols, analytical foci, and communication approaches. Whilst representing global knowledge, these sources are dominated by European databases reflecting a concentration of practice. Specifically focussed on Mediterranean and/ or mountain catchments in Portugal (Leal *et al.,* 2018: 'DISASTER'), Spain (Barnolas and Llast, 2007: 'INUNGAMA'; Llast *et al.,* 2009: 'PRESS-GAMA'; Barriendos *et al.,* 2014: 'PREDIFLOOD'), France (Lang *et al.,* 2016: 'BDHI'), Germany (Copien *et al.,* 2008: 'HANG'), Italy (Lastoria *et al.,* 2006: 'APAT'; Petrucci *et al.,* 2018: 'PEOPLE'), Switzerland (Hilker *et al.,* 2009: 'WSL'), Greece (Diakakis and Deligiannakis, 2017), and multi-nationally across the north-west Mediterranean (Llast *et al.,* 2013a, 2013b: 'HYMEX').

For accessibility HiFlo-DAT is shared as an English language MS Excel © spreadsheet for textual data and Google Earth © mapping for locational data. The HiFlo-DAT architecture (Figure 3) includes 'groupings' of like information and sub-divisions into 'categories'; these vary slightly between the 'unmerged sheet' (i.e., data entry of individual sources) and 'merged sheet' (i.e., flood event synthesis from one or more sources). Groups (n= 10-11) detail database management, source citation, event timing (when), location (where), causation (what), environmental and societal impacts (what and who), and the event management lifecycle. Herein 'categories' (n= 80-95) provide detailed quantitative and qualitative data according to entry rules.

3.3 Documentary source selections and capture approaches

HiFlo-DAT uses English-language documents from public and private collections in India, the UK and the USA. Since 2013 the research team have systematically evaluated materials, but most intensively 2018-2020, at the Prime Ministers' Museum and Library (PMML, formerly the Nehru Memorial Museum and Library [NMML], Delhi) and the British Library (London).

Table 2 details key repositories, their accessibility and the material types collected; including newspapers, reports, published literature and a wider array of materials inclusive of grey-literature (e.g., exploration and mountaineering accounts). These collections were selected and accessed with the aid of catalogues (where existing) alongside the expert knowledge of curators and research partners. These provide capacity to reconnect society with forgotten flood events, despite constraints on comprehensiveness associated with editorial style and decision making on inclusion for publication (Jeffers, 2014).

Table 3 details the overlapping sources used in HiFlo-DAT: dominated by national and regional newspapers and government reports for 1835-2020 (185 full years). Amongst digitally searchable newspapers (i.e., The Indian Express, The Times of India, and The Tribune) keyword combinations (n= 22-92) with spelling variants of hazard processes and location/ person names permitted filtration at the point of collection, resulting in n= 662 files. These span 1838-2020 (i.e., 182 full years), with all month coverage, and continuous regional insight via ‘The Tribune’ from 1881.

In contrast, analogue sources (i.e., microfilm and hardcopy) were targeted reflecting time-cost constraint; largely limited to summer monsoon months (i.e., June-September). These correspond with the dominant rainfall-generated flood season in South Asia (Singh and Kumar, 2013; Kale, 2014), including mountain states, such as Ladakh (Bhan *et al.,* 2015), Himachal Pradesh (Sah and Mazari, 2007, IHCAP 2016) and Uttarakhand (Gupta *et al.,* 2013). Unfiltered materials (n= >162,823 files) were captured using photography (.jpeg) and scanning (.pdf), enabling off-site review. Core were ‘The Civil and Military Gazette’, a regional newspaper (Lahore, Pakistan) alongside one of its precursor publications ‘The Moffusilite’. These bring semi-continuous coverage 1845-1963 (104 of 119 years), although following partition (August 1947) information about India substantially declines.

3.4 Documentary source review approaches

Extracting relevant information from source materials was a substantial undertaking. The workflow is detailed in Supplementary Materials 1; key steps being: (1) team distributed review to identify potentially relevant information; (2) moderation of team selected materials resulting in a final selection. For consistency team data review was guided by a protocol note and contemporary map. A record sheet detailed whether an account had application (i.e., a negative or interim positive hit). Hereafter rigorous moderation confirmed that all materials were reviewed; followed by a check on whether accounts detail overbank flood processes and generate impacts in-area (i.e., Manali and Kullu Tehsils). Decisions were guided by local stakeholder consultation and cross-referral to modern and historical documents/ maps. All accepted interim positive accounts were given a unique # source number (# 1-267); these were iteratively reduced to a final n= 220 # sources to populate the HiFlo-DAT database (section 3.5).

3.5 'HiFlo-DAT' database population (unmerged and merged), validation and open access

As detailed in Figure 3 and section 3.2, HiFlo-DAT has two Microsoft Excel © worksheets, i.e., unmerged and merged (n= 29,047 and 10,139 cells respectively). Like Lang *et al.* (2016) this architecture facilitates initial data entry followed by flood event synthesis. This is necessary given an individual # source may provide details of multiple floods in time and space, whilst also recognising that knowledge of a discrete flood (F-event) is often a synthesis of one or more # sources. The workflow is detailed in Supplementary Materials 1 (steps 3-6) and 2.

Quantitative and qualitative data entry to the unmerged worksheet is strictly controlled, complying with cell entry explanations, does not over interpret the # sources, and uses third party information (e.g., maps, imagery, and websites) to best validate historical information. Supplementary data includes historical rainfall records (see section 3.6), and carefully selected latitude and longitude coordinates using Google Earth. This generates n= 308 entries from n= 220 # sources.

The merged worksheet is generated by sorting # sources into flood event groups, first by date and second by location. Where a flood event ranges from valley-scale/ coupled drainage network footprints to more localised occurrences. These groups are then synthesised into single rows of data constituting each F-event entry (n= 128). The sometimes fragmentary and contested nature of grouped # source data requires judgements to be made and data ranges to be specified; for consistency Supplementary Materials 2 details the rules adopted. All steps in this process are cross-checked to assure data accuracy. Fulfilling user group aspirations (section 3.2) the database outputs are open access via BathSPAdata (Resource 1).

3.6 Historical instrumental rainfall data series

Historical daily rainfall data (rain-day format) are integrated into HiFlo-DAT bringing better understanding of floods. These are for Naggar Farm (c. 1660 m AMSL; Lat. 32.115647°, Long. 77.160752°; 1891-1950 and 1962-May 2017) and Kullu (exact location unknown; 1891-1950). They offer a new and carefully constructed synthesis of 'Daily Rainfall of India' reports (1891-1950) held at the British Library (IOR/V/18/62-120), and ICAR-IARI-Katrain data 1962 to present- as partly used (1962-2009) by Jangra and Singh (2011). In using these data, it is recognised that individual floods may not be rainfall generated, and the recorded rainfall may not be spatially representative.

4. **HIFLO-DAT RESULTS AND DISCUSSION**

Showcasing the contribution of HiFlo-DAT (merged) to knowledge of historical flooding in the Kullu District, key characteristics are evaluated, including temporal and spatial signatures, and environmental, societal and human impacts. Whilst these HiFlo-DAT results advance understanding of historical floods, it is important to caveat their fidelity. As they are drawn from 'reported' documentary data, it is appropriate to recognise they will not be an absolute record of historical flood occurrence and future flood risk across the region. Indeed, it may be the case that the spatial distribution of historical floods is in part informed by population density and infrastructure presence, which conditioned past awareness and societal interest.

4.1 Temporal characteristics

Over 175-years (1846-2020) using 127 of 128 events with an affirmative year, 57 years recorded one or more floods (32.6% of all years), whilst the longest period of no-floods is 26 years (1912-

1937). Corresponding mean annual frequencies are 0.73 events (all years) and 2.22 events (in flood only years). Herein, two years record 9 events (1894 and 2018); two years record 5 events (1846 and 1899); four years record 4 events (1898, 1901, 1994, 1998); and nine years record 3 events (1875, 1889, 1900, 1905, 1938, 1995, 2003, 2011, and 2015). Figure 4(A) depicts the annual frequency, cumulative frequency and 10-year running mean of floods. Here attention is drawn to flood-rich periods, e.g. 1890-1900s and 1990s-present (i.e., steeper cumulative curve) in contrast to flood-poor periods (i.e., flatter cumulative curve). Employing a 1-tailed (positive) classic Mann-Kendall test with continuity correction, using XLSTAT, indicates a statistically significant trend in the time series. Being able to reject the null hypothesis (computed p-value less than α), in favour of the alternative hypothesis, signifies an increasing number of annual floods over 175 years (K $\tau = 0.205$; significance level [α]= 0.05; p-value= 0.00024).

Figure 4(B) shows 17 of 19 decades registering floods (all except the 1850s and 1920s), at mean decadal frequencies of 6.68 events (all decades) and 7.00 events (1840-2010; complete decades). The record shows five decades with higher frequencies (>10 events), each accounting for >10% of the population. Again, the two flood-rich multi-decadal spans are evident, i.e. 1890-1909 (35 events, 27.6%) and 1990-2019 (51 events, 40.2%). The Mann-Kendall 1-tailed (positive) test returns no statistically significant trend in the series of event counts per decade (K $\tau = 0.127$; significance level= 0.05; p-value= 0.240).

Figure 4 (C) shows monthly frequencies and percentages of flood events; the importance of the summer monsoon season in generating floods is evident with June to September accounting for 111 events or 87.4% of the population. Extending this, Figure 4 (D) uses 30-year periods according to India Meteorological Department (IMD) defined seasons. Here monsoon season dominance ranges to 50-100% of events in each period but typically exceeds 80%. Whilst it appears that the monsoon season accounts for an increasing proportion of flood events since the 1930s, the Mann-Kendall 1-tailed (positive) test returns no statistically significant trend of annual flood event frequency in the monsoon season 1869-2020 (K $\tau = 0.103$; significance level= 0.05; p-value= 0.051).

4.2 *Spatial characteristics*

Figure 5 (A) and Resource 2 show the location of all n= 128 floods. These incorporate all positional accuracy categories (see Resource 1), where S= specific location or sub-catchment, G= generalised as an indicative location or an extensive impact area, and U= unspecified regional location. On Figure 5 (A) there are n= 59 plotted points, reflecting multiple flood occurrences at some locations. Overall, these demonstrate a broad spread of historical floods along the length of the Kullu Valley, specifically the Beas River corridor and its tributaries. The Parbati River sub-catchment has fewer recorded flood event locations (n= 9), but this does not automatically translate into a lower future flood risk.

Figure 5 (B), using n= 128 floods, reveals the frequency distribution using graduated circles. The two purple circles are surrogate locations incorporating 'U' category positional accuracy data, and therefore potentially overstate the frequency of flood events at these locations but remain representative of wider impacts in the catchment for these individual events. The largest circle (n= 22, U= 15, G= 7) is the right bank of the Akhara Bridge over the Beas River (Lat. 31.962323°; Long. 77.115693°). The smaller circle (n= 6; U= 3, G= 3) is the mouth of the Parbati River (Lat. 31.898510°; Long. 77.148252°). These withstanding, overall, 76.3% (n= 45 of 59) of 'locations' have a single recorded flood occurrence, the remainder have multiple recorded floods, with 10.2% (n= 6 of 59) having two floods, and 13.6% (n= 8 of 59) having three or more floods.

Refining this evaluation, Figure 6 (A) is a rank analysis, using a restricted dataset, i.e., 110 floods with affirmative locational data (i.e., S and G categories). This shows the number of times each location was affected (y-axis) against the rank (x-axis, ranks 1-59), where the starting rank (1) is for the highest number of events. Here n= 14 locations with two or more recorded events account for 59.1% of the total flood 'events' (n= 65 of 110), and those with a single recorded event are 40.9% (n= 45 of 110). Overall, they are approximately power law distributed ($y = 10.522x^{-0.655}$; R^2= 0.93). The location most afflicted by flooding is the Beas River (n= 28 of 110, 25.5%), albeit this is spatially extensive, with events being recorded at multiple locations. At a more granular level, four Beas River right-bank tributaries are prevalent: Phojal Nalla (13 events, 11.8% associated with a single dominant point location; but 14 events when considering multiple named points), Mohal

Khad (10 events, 9.1%), Bajaura Khad (9 events, 8.2%, but 10 events at multiple named points), and Sarvari Nalla (5 events, 4.5%; but 8 events at multiple named points). The fourth ranked (7 events, at the Akhara Bridge location in Figure 5 B) is one of multiple locations associated with Beas River.

Figure 6 (B), using 110 floods, reveals the reported distance density pattern for the entire 1846-2020 period, with 10 km (geodesic distance) concentric bands from a node at the Akhara Bridge on the right bank of the Beas River (Lat. 31.962323°; Long. 77.115693°). This shows a dominance of flood events within 20 km of Kullu and decreasing outwards. Specifically, 0-10 km (41 events, or 37.3% of the total), 10-20 km (40, 36.4%), 20-30 km (14, 12.7%), 30-40 km (10, 9.1%), 40-50 km (5, 4.5%). However, spatio-temporal signatures are more complex when segregated into 30-year time slices from 1840 (excepting 2020- a single year). Herein, Figure 7, based on 109 floods (as F12 has inexact timing) reveals clustering of floods within 20 km for 1840-1869 and 1900-1929; in contrast floods are consistently more widespread for 1870-1899 and 1990-2019, within 40 km and 50 km, respectively, corresponding to flood rich periods. The remaining periods 1930-1959, 1960-1989, and 2020 have some of the lower event frequencies and more variable patterns. A further analysis of the geodetic distances from the node to each flood position (excluding 2020, so n= 108), demonstrate that minimum distances are always < 1km, and maxima fluctuate between 13.5 and 43.4 km. More revealing are average distances which in the aggregated period 1840-1959 range 8.3 ± 4.8 to 10.9 ± 9.2 km, compared to the aggregated period 1960-2019 ranging 15.1 ± 14.2 to 19.9 ± 13.3 km. This generalised outward expansion may reflect better reporting, growth of societal activities into more peripheral locations, and increasing event frequencies. Despite this, no floods are recorded in the headwaters of the Parbati river catchment (i.e., > 50km distance from Akhara Bridge).

4.3 Hydro-meteorological and geomorphic characteristics

Interconnections between meteorological, hydrological and geomorphological processes are important in understanding floods. Herein, processes recorded as responsible for each flood (n= 128) were: 14.8% river floods (long-duration rainfall), 39.8 % flash floods (short-duration rainfall), 39.8% unspecified floods; with the remainder being landslides (3.1%), snowmelt (0.8%) or unknown (1.6%). Withstanding the technical accuracy of source reporting, this suggests a dominance of rainfall causation. However, the likely importance of slope instability-channel coupling is poorly appreciated. For example, HiFlo-DAT captures named secondary processes, and these signal n= 12 landslides, n= 1 debris-flow, and n= 3 Landslide Lake Outburst Floods (LLOF) resulting from avalanche, landslide and earthquake derived barriers. Whilst seemingly rare, LLOFs in 1875 (F9), 1894 (F20) and 1905 (F52) generated large and impactful floods. As LLOF incidence is likely to increase with climate change and anthropogenic development in the region (e.g., IHCAP, 2016; Ballesteros-Cánovas *et al.,* 2017), future DRR needs to better accommodate LLOF risk, which NDMA (2020) acknowledges as a current gap.

Considering rainfall, reported quantitative data are sparse, including intensity (n= 1, 25 mm h^{-1} at Bhuntar airport, 2001), depth (n= 5: 63-127 mm, 1995-2018) and duration (n= 20: 0.5-61 h, 1888-2018). Wider qualitative narratives (n= 92 events) are typically too opaque for quantitative database entry, but they do indicate intensity is dominated by 'heavy/ torrential rainfall' (n= 49 events) in contrast to 'light rain' (n= 1) and 'showers/ intermittent rain' (n= 3). Duration expressions, include 'steady-continuous/ incessant/ sustained' rainfall (n= 21), and indicate many floods are associated with multiple episode rainfall (n= 13). Considering event type phrasing, 'Thunderstorm/ Cloudburst' are dominant (n= 38 events) in contrast to 'rain' (n= 7), 'monsoon' (n= 2) and 'snowmelt' (n= 2). Changing vernacular is apparent, reporting 'Thunderstorms' 1889-1939, and 'Cloudburst' 1994-2020 (excepting 1899 and 1902). This language has wider implications, as many DRR agencies (e.g. DDMA, 2017; HPSDMA, 2017) often classify cloudbursts as an independent hazard process type, rather than an integrated meteorological mechanism which may result in channelised flood flows. This process-decoupling may hinder effective DRR in complex cascading systems.

Furthermore, independent rainfall records for Naggar Farm and Kullu (see section 3.6), offer some corroboration of event timing, rainfall event locations and antecedent conditions. For example, source narratives for the 21 May 1894 Phojal Nalla LLOF (F20) detail preceding heavy winter snowfalls, rain on the 15th May impacting the snow cover, and flood transferred snow deposits downstream. In corroboration, the Naggar Farm data (c. 10 km east), usefully detail: (1)

18/4/94 to 11/5/94 1 mm of rainfall, and thus likely sunnier days resulting in snowpack metamorphosis; (2) 12-16/5/94 59.4 mm of rainfall, which would have enhanced snow melt or brought new snow layers at elevation; and (3) 17-21/5/94 0 mm of rainfall. This record likely supports the absence of rainfall flood causation, and instead a snow avalanche/ landslide flood mechanism.

Considering flood flow characteristics, alike rainfall quantitative data are sparse. Discharge records (n= 3: 2482-44,855 $m^3 s^{-1}$), are reconstructed (Phojal Nalla and Seri Nalla/ Beas River, F20 and F111) and measured (Beas River, F86). Wider narrative expressions are abundant, detailing: location (main river [n= 27], and tributary [n= 20]), timing (n= 18), magnitude (velocity [n= 2], relative size [n= 23], stage [n= 14]) and hydrograph changes (rising and falling stage [n= 20], and flood waves [n= 4]). Whilst accounts of sediment load/ turbidity are rarer (n= 6).

Reported geomorphological impacts include channel incision (n= 8), channel aggradation (n= 18), avulsion (n= 21), bank erosion/ failure (n= 15), overbank deposition (n= 21), tree damage/ woody debris (n= 32), and slope instability (n= 19). Extracting quantities from narrative accounts (n= 55), reveal over bank deposits ranged fines to boulders up to 6 m deep, but inundation areas are rarely reported; in channel deposits are boulder sized up to 40 m deep; lateral channel shifts up to 500 m; and tree damages up to the thousands in a single event. These are likely a snapshot, as no source was a dedicated geomorphological appraisal.

4.4 Environmental and societal asset impact characteristics

Table 4 synthesises impacts to environment and society assets; whilst likely subject to source biases and incomplete capture/ quantification, it provides insight into historical flood losses. Frequency counts express the number of flood events recording the impact type, and magnitude of impact is more diverse according to the asset type, comprising counts of individual assets, counts of reports (the same as frequency), and distance/ area. Data reveal a concentration on transport infrastructure, in particular bridges (54 floods, 94 impacts) and roads (55 floods, 47.3 km of damage/ burial/ interruption). Though noteworthy are the impacts to domestic properties (22 floods impacting 445 buildings) and agriculture and horticultural land (28 floods, 102.6 ha).

Further evaluating bridge impacts reveals the number of bridges damaged/ lost in these floods range 1 to 12 (average 1.74 bridges). Temporally, over 19 decades, 12 record impacts and 7 do not; 4 decades account for 67% of all reported bridge impacts: 1890s (20.4%), 1900s (18.5%), 1950s (13.0%) and 2010s (14.8%). Spatially, qualitative accounts detail 81 impacts (of the 94 total), at 29 locations, of which nearly half have a single bridge impact, and the remainder experienced repeated bridge impacts. Most accounts (65%) detail bridge losses, opposed to bridge damage (35%). These are identified as road bridges (35%), foot bridges (20%) or unspecified (45%). The top 5 locations of recurring impacts are Dobhi (n= 12, 1894-2018, largely Phojal Nalla tributary, with episodes 1894, 1952-1957 and 2018); Kullu (n= 8, 1846-1995, largely Sarvari Nalla tributary); Bajaura (n= 8, 1899-1903, Bajaura Khad tributary); Mohal (n= 7, 1887-1902, Mohal Khad tributary); and Akhara in Kullu (n= 6, 1894-2019, Beas River [Main River]). These data reveal that Kullu, the largest settlement, is most afflicted. Further, tributary rivers are dominant, exhibiting short episodic impact periods (i.e., Bajaura and Mohal) and recurring impacts (i.e., Dobhi, Kullu).

Considering road impacts, these are recorded 1846-2020, in which 13 decades record impacts and 6 do not. Herein 5 decades each record ≥10% of occurrences (i.e., 1890s, 1950s, 1990s, 2000s, 2010s). Moreso, 74.5% of occurrences are since 1950, and 1990-2019 accounts for 50.9%. This skew perhaps reflects more recent expansion of road networks and motorised transport. Spatially, 36.4% of events have local impacts, 47.3% are undefined, and extensive impacts are 16.3%, including in 1894, 1995 and 2018. Narratives are thin, for example, 8 detail the length of impacted road (0.15-30 km), 6 give the duration of disruption (3 hours to 4 days), and a single account outlines the recovery cost (F86, September 1995). Exploring the nature of impacts, terminology is opaque but indicates: 21 events caused damage/ disruption; 19 breached/ inundated the road; 12 caused loss by destroying/ washing away the road; and 17 impacted prevented/ disrupted traffic flows.

Establishing reporting rationales for environmental and societal impacts is challenging, but they may reflect societal interest at the time of reporting. For example, Sah and Mazari (1998), Berkes *et al.* (2000) and Johnson *et al.* (2018) remark that the traditional mountain economy of the Kullu District focusses attention on productive land which provides subsistence and income via market trade, access to which is governed by roads and bridges. This focus on transport infrastructure continues, as it underpins the growing tourist economy. For example, in the July-August 2023 Himachal Pradesh flood-landslide disaster, particular concern surrounded impacts on transport infrastructure. Closing 1300 roads and washing away c. 40 bridges (Sana *et al.,* 2024), with estimated recovery costs of Rs 2458 Crore (c. £235 million in 2024), being 27% of the total recovery cost (HPSDMA, 2023a).

4.5 Human impact characteristics

Selected quantitative and qualitative data highlight the harmful impact of floods on humans. The former being: (1) 'Total Fatalities' (i.e., sum of fatalities and the missing), hereafter 'fatalities'; and (2) 'Total Affected' (i.e., sum of the homeless and injured), hereafter 'affected'. HiFlo-DAT records 253 fatalities, across 24 events, where deaths per fatal event (range 1-50, average 10.5) occur in two periods: 1894-1905 (6 events and 78 fatalities) and 1994-2018 (18 events and 175 fatalities). Furthermore, 1322 people were affected across 15 events (range 1-500, average 88.1 people per event), occurring in two time periods: 1889 (1 event and 40 affected) and 1994-2012 (14 events and 1282 affected). These data show losses across all three centuries, but with a strong skew from the 1990s, although the 1894 Phojal Nalla flood recorded the largest fatalities (n= c. 50).

Qualitative accounts reveal vulnerability and exposure dimensions. Regarding vulnerability an important recipient population (i.e., who) are those associated with the keywords: migrant, labourer, herder, trader, worker and muleteer. 69.6% (n= 176) of all fatalities are associated with event narratives with one or more of these words (8 events; flood event numbers [see Resource 1] = 20, 35, 81, 96, 97, 99, 108, 113). With the same filters (5 events; flood event numbers = 97, 99, 101, 108, 111) are associated with 1090 or 82.5% of all affected persons. These are important findings, evidencing demographic vulnerability in a mountain setting; such contributions are considered pivotal by the UNDRR (2023) in overcoming aggregated data obstacles.

Regarding exposure (i.e., where and what), the activities of the recipient population notably include those engaged in construction work typically in remote tributary locations (keywords: cable laying, construction, HEP, road avalanche shed), and importantly many were encamped in labourer colonies near to rivers at the time of the flood events (keywords: sleep, camp, community). 48.2% (n= 122) of all fatalities are associated with event narratives with one or more of these words (7 events; flood event numbers = 35, 81, 97, 99, 100, 108, 113). With the same filters (4 events; flood event numbers = 97, 99, 100,108) are associated with 191 or 14.4% of all affected persons. Furthermore, many fatal losses occurred during the night hours (23:25 to 03:00 IST) with no or limited warning.

These analyses in the Kullu District highlight the recent vulnerability and exposure of migrants/ labourers engaged in large-scale construction activities. Unfortunately, these circumstances recur across the Indian Himalaya, for example, high-profile events in Uttarakhand include the February 2021 Dhauliganga flood at Raini HEP and Tapovan HEP (with many fatalities), and November 2023 Silkyara Bend–Barkot tunnel collapse (with no fatalities, but large rescue costs). To reduce risks, further investigation is warranted, including consideration of what DRR benefits may be derived from more effective development /construction planning, design and management.

5. WIDER DISCUSSION: APPLICATIONS OF 'HIFLO-DAT'

5.1 Enhanced knowledge for informed decision-making in the Kullu District

HiFlo-DAT detailing 128 floods, at 59 locations, over 175 years (1846-2020) in the Manali and Kullu Tehsils (Kullu District) reconnects society to past knowledge of flood occurrence and impacts. This is a major contribution, substantially improving upon existing compilations of past floods (Table 1: 1-15 entries from c. 1994) in terms of event frequency, timespan, and depth of information. Furthermore, analyses of HiFlo-DAT highlight increasing flood occurrence towards the present; dominance of rainfall causation in the monsoon season; high-magnitude LLOF events; hotspot tributaries subject to repeated floods (subject to limitations of documentary reporting patterns); and key impact receptors, namely roads, bridges and labourer-migrant communities associated with construction projects. These data and analyses are only of value if they inspire and inform action (UNDRR, 2023) strengthening local government and NGO decision making. Future tangible gains may include improved project selection and design for both disaster risk reduction/ climate change adaptation (i.e., mitigation of hazard exposure and vulnerability, and resilience generation) and infrastructure development schemes (e.g., hydro-electric power, road widening and tunnelling, planned railways and airport runway upgrading, and settlement expansion). For example, in the absence of HiFlo-DAT, in May 2024 the HP State Executive Committee (HPSDMA, 2024) approved substantial funding for flood protection works (Rs. 1761.57 Crore, c. £161.1 million in 2024). These 11 projects focus on the Beas River corridor, adjoining an at-risk national highway and key settlements; however, HiFlo-DAT brings alternative focus on tributary flood hazard/ disaster losses. This perspective supports a growing call for informed decision making in the Kullu District, in respect to hazard and climate change challenges. For example, Allen *et.al* (2018) detail how risk assessments using dendrogeomorphic and Glacial Lake Outburst Flood (GLOF) modelling data serve as ‘input for the prioritisation and design of adaptation actions’. Similarly, Chand *et al.* (2024) articulate how flood vulnerability assessments strengthen resource allocation decisions. Whilst Gupta *et al.* (2024) underline the need for hydro-meteorological process-cascade understanding for evidence-based policy making.

5.2 Transference of the methodology to the wider Himalaya and across trans-boundary basins

Whilst HiFlo-DAT is of direct value to the Kullu District, it can also help address fragmentary disaster loss data across the Indian Himalayan Region (Rautela, 2016). Specifically, HiFlo-DAT brings a grounded (i.e., best-practice and locally aligned) and robust methodology (see section 3) for the selection, capture, review, synthesis and analysis of documentary flood data. Wider application is however influenced by the quantity and quality of historical documentary sources. Accordingly, database assembly in more remote locations, with less established documentary histories than in the Kullu District case, may benefit from greater incorporation of grey-literature and local knowledge sources.

In offering this perspective, we are mindful of the time, cost and endeavour required to access and process documentary data sources, especially for dispersed and hardcopy collections. Therefore, as a pilot-scale test of transferability, in May-June 2023, we took the HiFlo-DAT methodology to the high-altitude Dhauliganga catchment upstream of Joshimath (Chamoli District, Uttarakhand). This location was selected to bring multi-event historical context to the large-scale February 2021 disaster (Shugar *et al.,* 2021, NDMA, 2022) which may otherwise dominate local disaster risk reduction narratives, locations, and policy. Like the Kullu District approach, we explored documentary archives; this time prioritising digital resources for accessibility, particularly via the British Library, supplemented by review of hardcopy materials held by the Chamoli District Government in Gopeshwar. In addition, drawing on expertise (Johnson *et al.,* 2018; BSU and NIHE, 2020) we hosted workshops in mountain villages (i.e., Raini, Pagarsu, Kosa and Malari) to explore local knowledge of past hazard-disaster events. The interim headline is one of success in deploying the HiFlo-DAT methodology to a different location, where local knowledge was of elevated importance given fewer accounts emerged from documentary records in this very remote location. This result should bring confidence that with appropriate team expertise and project resources, the transferability of the HiFlo-DAT methodology is both beneficial and achievable.

Of further merit would be trans-boundary implementation of HiFlo-DAT, given hazard process cascades may transcend national boundaries. Existing national (NDMA, 2019) and international policy positions (e.g., UNDRR, 2018; 2021; 2024; and UNDRR and WMO 2023) already make the case for such transboundary hazard-disaster collaboration. Such may be particularly valuable for higher-magnitude LLOF/ GLOF floods, which are likely to increase in frequency associated with climate change driven glacial retreat and lake formation, permafrost degradation and slope instability. Indeed, NDMA (2020) recommend the need for a 'systematic database of GLOFs and LLOFs' as a foundation for more effective future management. For example, in response to the trans-boundary (China [Tibet]-India), 2000 and 2005 River Sutlej LLOF disasters (Gupta and Sah, 2008), early warning systems (NDMA, 2020) were implemented. It would however be interesting to re-evaluate these interventions with the benefit of new long-term historical flood knowledge.

5.3 Reflections on HiFlo-DAT data quality and further validation opportunities

Within HiFlo-DAT the technical specificity, depth and breadth of information afforded by documentary sources are variable. This likely reflects differential access to flood locations, lagged communication, audience/ societal interest, reporting/ editorial biases, author roles/ responsibility/ positionality, language, available technologies and technical expertise (Adamson, 2014; and

Jeffers, 2014; 2021). Whilst more recent accounts tend to offer greater detail, there are notable exceptions. For example, floods at Phojal Nalla (F20, 1894) and Bajaura Khad (F35, 1899) are well articulated. Conversely, the September 2018 Phojal Nalla flood (F124), may seem to offer a reasonable level of detail; however, our site inspections in October 2018, could significantly extend detail of geomorphological and societal impacts. This may raise questions about the factors influencing the inclusion and calibre of data entries in HiFlo-DAT. Both are conditioned by the original assembly of information, the subsequent accessibility of information, and how it is processed. As detailed in section 3, a robust regime was implemented in the construction of HiFlo-DAT, including filtering out accounts which did not clearly articulate evidence of flood processes or were opaque (e.g., elevated flow discharge), cross-referencing sources/ existing databases and exploring third-party data such as Google Earth. Whilst HiFlo-DAT offers a significant step forward, it is bound by these data quality and quantity contexts. It is therefore valuable to highlight opportunities which may extend and test these and other historical flood databases. Systematic developments may include comparison to: (1) existing dendrochronological flood data in the Kullu District (Shah *et al*., 2013; Ballesteros-Cánovas *et al.,* 2017); (2) new multi-disciplinary (hydro-meteorological, bio-geomorphic and sedimentological) flood reconstructions using landscape evidence of past flood impacts (Kale, 2008; Hobley *et al.,* 2012); (3) local knowledge oral accounts, for example the 1894 Phojal Nalla flood is recounted in song (Johnson *et al.,* 2018; https://vimeo.com/285841577 [12 min. 06 sec.]); (4) village documents such as Panchayat record books (Johnson *et al.,* 2014, 2018); (5) local language newspaper archives and video media; (6) untapped English language newspapers, increasingly accessible via digitisation; (7) diaspora family records not in official collections; (8) a wider array of Government of India data, such as a deeper dive into data underpinning the IMD 'Climate Hazards and Vulnerability Atlas' (Table 1; IMD, 2022) and the Central Water Commission (CWC) 'Flood Damage Statistics 1953-2020' (CWC, 2022); and (9) modelling outputs.

5.4 Developing future DRR policy and practice

The introduction details current DRR policy-practice, including the importance of methodologies for the compilation of disaggregated disaster loss data at sub-national scales. Contributing to this agenda, we offer reflections related to: (1) specificity of historical databases; (2) data specificity and partnerships using technology for recording contemporary event impacts; and (3) access to archive data in service of global challenges.

UNDRR (2023) in articulating the importance of data disaggregation, do so particularly regarding socio-economic metrics and generating data for contemporary events. We would extend this further, as HiFlo-DAT demonstrates the value of assembling disaggregated architectures across all metrics for past flood events. Having more detailed historical data will support the review and updating of existing key documents (e.g., Disaster Management Plans) and databases such as state-level HVRA collections (NDMA, 2021).

The September 2018 Phojal Nalla flood (F124) revealed an untapped opportunity in developing more detailed records of contemporary events. We were able to compare the depth of our knowledge from live-time social media and field reconnaissance a month afterwards, versus that conveyed by the media and official reports. This demonstrated the residual capacity of technical knowledge/ collaboration across sectors and disciplines. Whilst also highlighting the role digital technology (e.g. social media imagery/ videos, mobile apps, and emerging AI capabilities) could contribute to capturing and evaluating flood processes and impacts. Such technologies are a growing enabler for decentralised/ local community engagement and ownership of hazard and disaster knowledge at a local level (Alexander, 2014; NDMA, 2019; BSU and NIHE, 2020; NDMA 2020; UNDRR 2023).

Ease of access to archives is variable (Tables 2 and 3), and at times the experience is inefficient, restricted, and bound by paywalls; this only acts to inhibit disaster risk reduction and sustainable development progress. Whilst growing digitisation and open access collections may reduce the time and costs for data mining of historical data (Yzaguirre *et al.* 2016), many collections remain outside this scenario. Accordingly, in serving societal interest, there is a pressing need (e.g., Koll, 2024) for better inter-agency connectivity to facilitate improved access to public archive collections. Furthermore, efforts would be accelerated by long-term research funding supporting the systematic review of archive materials aligned to global challenges.

6. CONCLUSIONS

Disaster risk challenges are prominent in mountain environments and Asia more generally, where floods are a significant hazard/ disaster loss process. International disaster risk reduction efforts, including the UNDRR Sendai Framework, highlight prevailing gaps in disaster loss databases, especially at sub-national scales. Accordingly, developing methodologies for the systematic assembly and analysis of such disaggregated data is a pressing need to reduce future disaster losses in an era of climate change. 'HiFlo-DAT' (**Hi**malayan **Fl**ood **Dat**abase) is an important contribution to this agenda, initially focussing on the Kullu District, Himachal Pradesh, India. It delivers a sizeable improvement in local knowledge, detailing 128 historical flood events, at 59 locations, over 175 years (1846-2020) reconnecting society/ governing organisations/ NGOs to their past documentary knowledge of historical flood occurrence and impacts. Further synopsis and visualisation is given by the accompanying HiFlo-DAT Film (Supplementary Materials 3). Going forward our discussions highlight new opportunities, in overview:

(1) Engage responsible agencies to embrace historical flood data to better inform their disaster risk reduction/ climate change adaptation strategies, and to assist sustainable design of infrastructure projects in mountain environments.
(2) The wider Indian Himalaya and trans-boundary basins would benefit from systematic approaches to assembling and sharing historical flood data, alike HiFlo-DAT.
(3) Documentary based databases should be compared, corroborated and extended, where possible, using an array of sources, including local language and local community data, Government of India collections, diaspora accounts, and dendrochronological/ hydro-geomorphic reconstruction. As an array of data are required to inform more comprehensive future flood risk assessments.
(4) Recording details of future events would benefit from multi-agency partnerships to deliver richer information aligned to database needs and should consider how to effectively capture digital data.
(5) Improving historical archive access, via new inter-agency cooperation would enhance strategic disaster risk reduction and sustainable development needs.

DECLARATION OF COMPETING INTEREST

There are no interests to declare in relation to this research.

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DATA AVAILABILITY

Resource 1 'HiFlo-DAT' database source and flood event spreadsheets (.xlsx):
https://doi.org/10.17870/bathspa.28053218

Resource 2 'HiFlo-DAT' event locations (.kmz):
https://doi.org/10.17870/bathspa.28053254

SUPPLEMENTARY MATERIALS

Material 1 Key actions and rules in the generation of 'HiFlo-DAT' Unmerged (i.e., sources)

Material 2 Key actions and rules in the generation of 'HiFlo-DAT' Merged (i.e., flood events)

Material 3 'HiFlo-DAT' Film: https://vimeo.com/1037424595

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FIGURE & TABLE CAPTIONS

Fig. 1 ‘HiFlo-DAT’ spatial location: Manali and Kullu Tehsils in the Kullu District, Himachal Pradesh, India. (DEM dataset: ASF DAAC, 2007; Kullu District: c. 31° 58’ N; 77° 06’ E; 5503 km^2; 1089 to >6500 m AMSL)

Fig. 2 Synopsis of the ‘HiFlo-DAT’ production journey

Fig. 3 ‘HiFlo-DAT’ database architecture

Fig. 4 Temporal analyses of floods in the Kullu District 1846-2020, (A) annual; (B) decadal; (C) monthly; and (D) seasonal

Fig. 5 Spatial analyses of floods in the Kullu District, (A) flood event locations; and (B) frequency of floods by location

Fig. 6 Spatial analyses of floods in the Kullu District, (A) rank analysis of flood spatial recurrence; (B) spatial pattern of floods over the entire time

Fig. 7 Spatial pattern of floods over 30-year time slices (1840-2020)

Table 1 Key existing hazard/ disaster databases incorporating historical floods in the Kullu District, Himachal Pradesh

Table 2 Key documentary archive organisations in India, the UK and the USA underpinning ‘HiFlo-DAT’

Table 3 Key continuous documentary data sources selectively used for ‘HiFlo-DAT’

Table 4 Frequency and magnitude of flood event impacts on environmental and societal assets

Database	Author	Spatial Extent	Temporal Range	Number of Entries for Kullu District	Number of Entries for Manali/ Kullu Tehsils (Years)	Public Availability and Link	Baseline Datasets	Comment
District Disaster Management Plan (2017)	Kullu District Disaster Management Authority (DDMA)	Regional: District	1988-2003	9, 'prominent flash floods'	5 (1995-2003)	**YES:** https://hpkullu.nic.in/documents-2/	?	NA
HVRA ('Hazard Vulnerability and Risk Atlas')	Himachal Pradesh State Disaster Management Authority (HPSDMA)	Regional: State	Unknown	c. 10	c. 10	**PARTIALLY**: http://www.hpsdma.hp.gov.in/Home_Disaster.aspx	Household surveys	Public version has redacted flood location data. However, screenshots of the full database maps in HPSDMA presentations show historical flood locations (no metadata)
IHCAP (Indian Himalayas Climate Adaptation Programme)	Indio-Swiss consortium	Regional: State	1950-2014	44 'significant flood' events for the State, and most in the Kullu District	?	**NO:** previously available, but the website is now redundant	Scientific publications, technical reports, existing databases (DFO, EM-DAT) and media sources	IHCAP reports provide synopsis accounts, but more detailed data are not in the public domain
IMD ('Disastrous Weather Events', which populate the 'Climate Hazards & Vulnerability Atlas')	India Meteorological Department	National	1967-2020 (excepting 1977)	c. 25 affirmative flood process accounts[#1]	c. 15 (1994-2019)	**YES:** https://imdpune.gov.in/library/publication.html	IMD reports and wider media information	Data are typically over-generalised/ aggregated, making determination of process and location specifics challenging, which leads to count exclusions
ADRC	Asian Disaster Reduction Centre, Japan	Global	1998-present [#2]	1	1 (2003)	**YES:** https://www.adrc.asia/latest_disaster.php	Media, governmental/ NGO reports and remote sensing sources	NA
DFO: 'Global Active Archive of Large Flood Events' (Dartmouth Flood Observatory)	University of Colorado, USA	Global	1985-present [#2]	7	3 (1994- 2003)	**YES on request:** http://floodobservatory.colorado.edu/index.html	Media, governmental, instrumental, and remote sensing sources	Data on spatial location can be generalised, which prevents detailed local assessments
EM-DAT ('Emergency Events Database')	Centre for Research on the Epidemiology of Disasters (CRED), Belgium	Global	1900-present [#2]	5	3 (2003-2012)	**YES:** https://emdat.be/	UN/ NGO/ insurance reports, research publications and media	Data on spatial location can be generalised, which prevents detailed local assessments

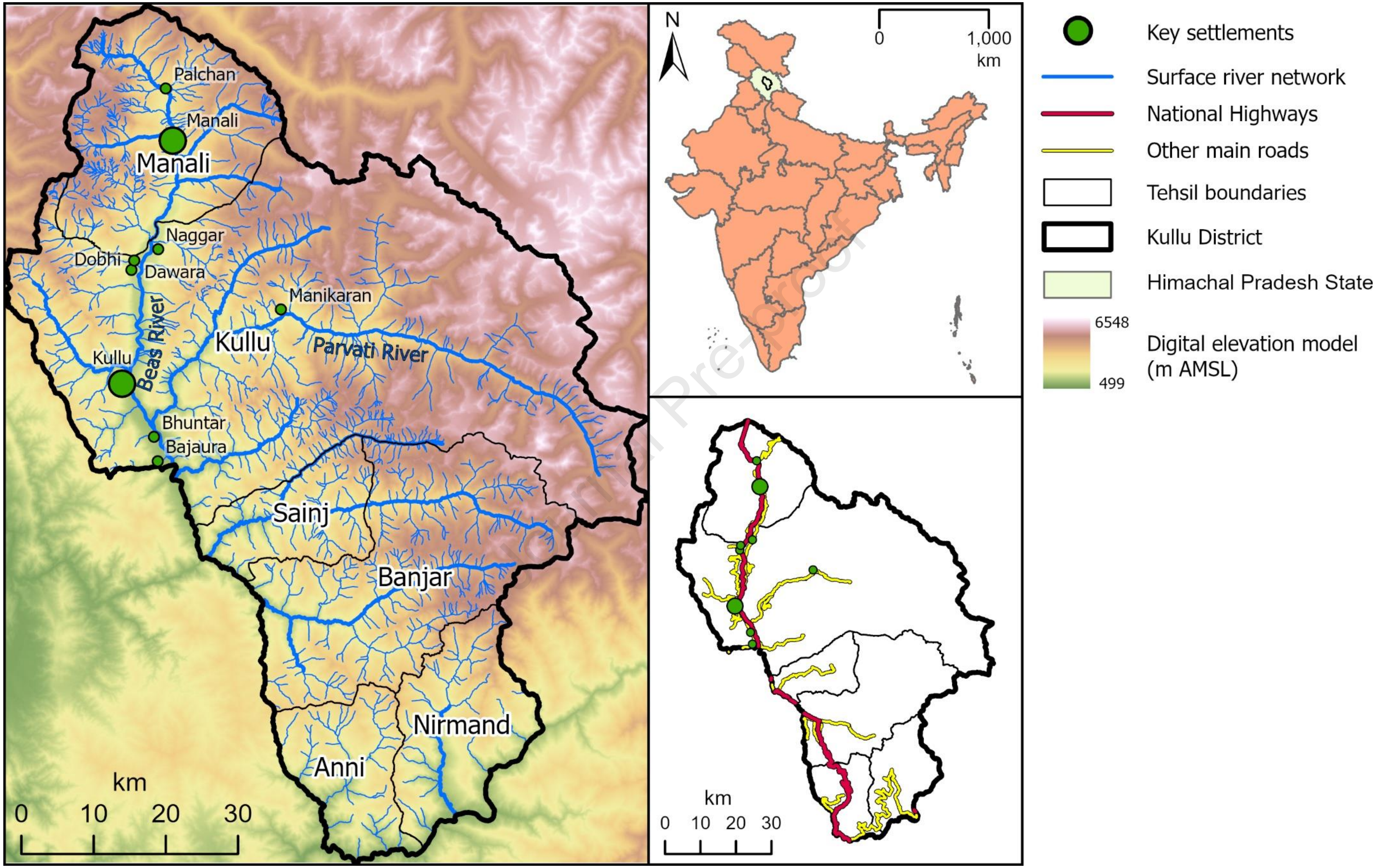
#[1]= IMD (2022) reports 51 flood events in the Kullu District in the period 1969-2019 ; #[2]= July 2020 end point of database review here

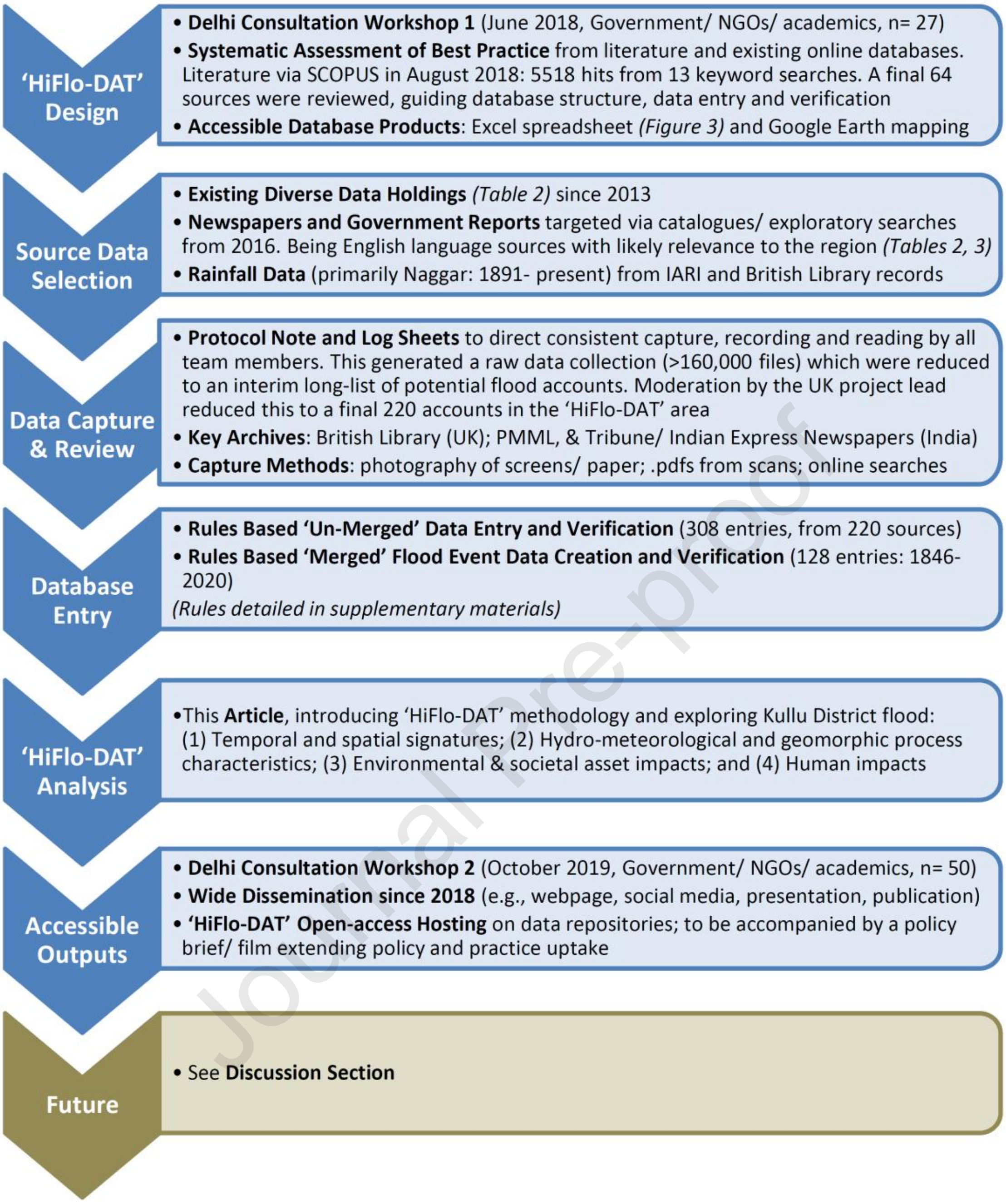
Country	Key Organisation					Accessibility Conditions					Material Type Collected						
	Name	Location	Type	Digital/ Online Catalogue *(At Time of Access)*	Access Year(s)	Open Access	Request	Paid Permit	Outputs Pay	Outputs Free	Newspaper	Report/ Records	Numerical Data Series	Book/ Article/ Thesis	Personal Documents	Webpage	Other
India	DDMA, Kullu District	Kullu	Government Authority	No	2015, 2018	✓	✓			✓		✓				✓	
	HPSDMA, Himachal Pradesh	Shimla	Government Authority	No	2015, 2018	✓	✓			✓		✓				✓	✓
	Himachal Pradesh State Archive	Shimla	Archive	Paper Offline	2013-2015		✓			✓		✓		✓	✓		
	Himachal Pradesh University	Shimla	University Library	No	2013		✓			✓		✓		✓			
	ICAR Indian Agricultural Research Institute	Katrain	Government Organisation	No	2014, 2017		✓		✓				✓				
	Indian Institute of Advanced Studies	Shimla	Research Library	Yes	2015		✓		✓					✓			
	Kullu Library	Kullu	Library	No	2015		✓			✓				✓			
	National Archives of India	Delhi	Archive	Yes	2016		✓	✓	✓			✓			✓		✓
	Prime Ministers' Museum & Library	Delhi	Archive	Yes	2017-2018		✓	✓	✓		✓						
	Punjab State Archive	Chandigarh	Archive	Paper Offline	2014-2016		✓			✓		✓	✓	✓	✓		
	Ratan Tata Library	Delhi	University Library	Yes	2016		✓			✓		✓		✓			
	The Times of India	Online	Publisher Website	Yes	2020	✓				✓	✓						
	The Tribune	Chandigarh + Online	Publisher Archive + Website	Yes	2015-2016, 2020 (Online)	✓	✓			✓	✓			✓			
	The Indian Express	Panchkula	Publisher Archive	Yes	2017		✓		✓		✓						
UK	British Library	London	Archive	Yes	2016-2020, 2022	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓
	Pagoda Tree Press	Bath	Archive	No	2015, 2017		✓		✓	✓		✓		✓			✓
	Penelope Chetwode Collection	Brighton	Family Archive	No	2017		✓			✓				✓	✓		✓
	RGS-IBG	London	Archive	Yes	2013		✓		✓					✓			✓
USA	American Alpine Club	Golden, CO	Library	Yes	2016		✓			✓		✓		✓			
	PAHAR	Denver, CO	Personal Collection	No	2016		✓			✓							✓

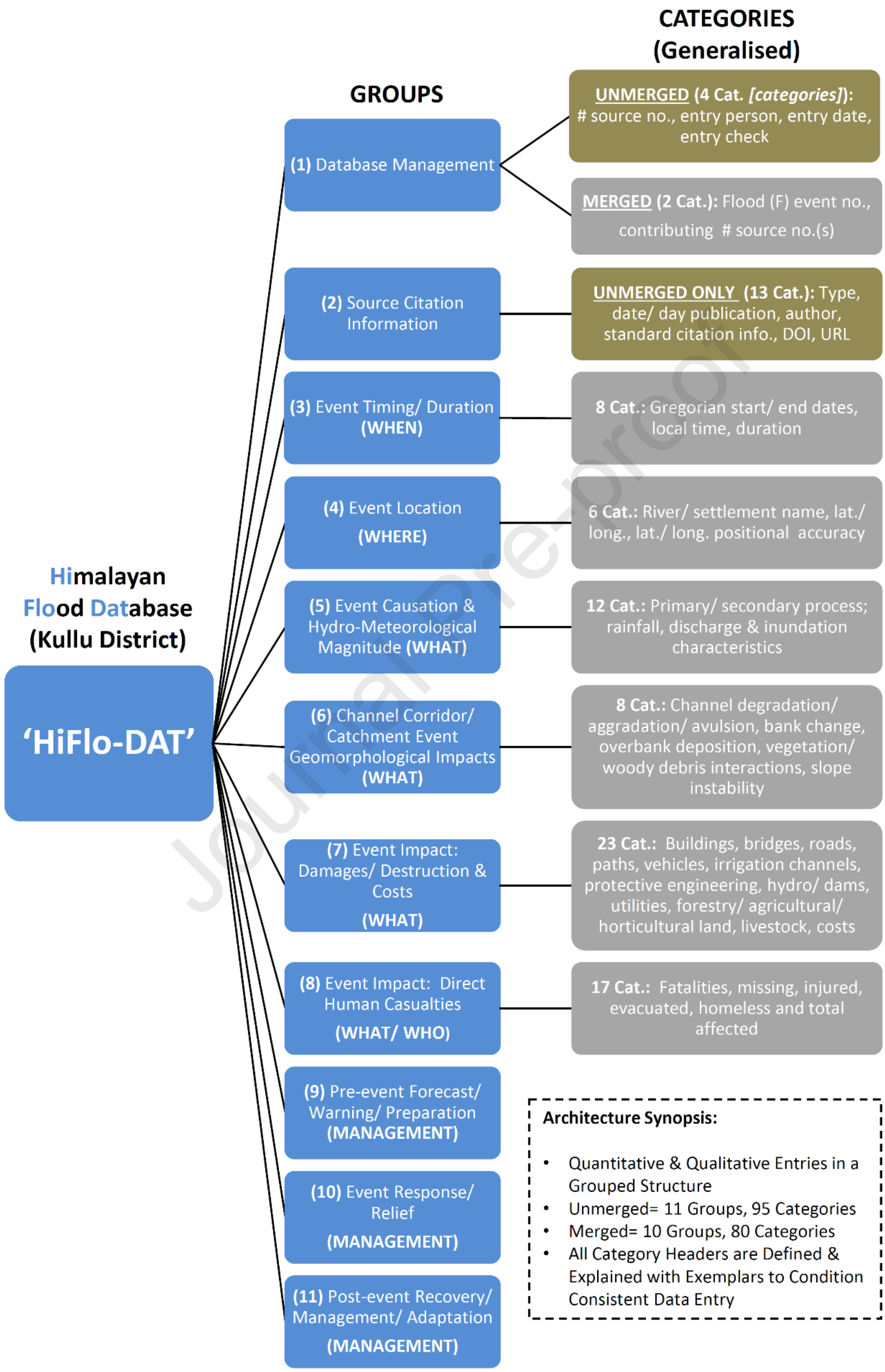
Source Series Details				Timespan Reviewed				Data Output Characteristics		
Publication Name	**Provider**	**Focus**	**Newspaper (N) or Report (R)**	**Start Year**	**End Year**	**Year Count**	**Months**	**File Format**	**Number of Files** [#6]	**Filtered or Unfiltered at Capture**
The Indian Express (Delhi Edition)	The Indian Express	National	N	1954	2017 (April)	64	ALL	.JPEG	36	Filtered (Common Keywords)
The Indian Express (Chandigarh Edition)				1977	2010	34				
The Times of India	BL (British Library)	National	N	1838	2005	168	ALL	.PDF	90	
	Online			2018	2020 (July)	3			10	
The Tribune	The Tribune	Regional	N	1881	2016	136	ALL	.PDF	513	
	Online			2016	2020 (July)	5			13	
Civil and Military Gazette (CMG) [#1]	BL	Regional	N	1876	1914	39	June-Sept. (where available) (1894 Jan. - Oct.)	.PDF	39,947	Unfiltered
				1947	1949 [#5]	3				
	PMML (Prime Ministers' Museum & Library)			1915	1938	24	June-Sept. (where available)	.JPEG	65,461	
				1947	1949 [#5]	3				
				1956	1963	8				
Englishman	PMML	National	N	1894	1894	1	May-Sept.	.JPEG	2,109	
India Administration Report (IAR) [#2]	BL	Regional Sections	R	1855	1870	16	Annual Publication	.PDF	339	
								.JPEG	904	
Mofussilite	BL	Regional	N	1845	1845	1	June-Sept. (where available)	.PDF	6,052	
				1847	1875	29				
Report on the Administration of the Punjab Territories (RAPT) [#3]**/ Punjab Administration Report (PAR)**	BL	Regional	R	1849	1855	7	Annual Publication	.PDF	629	
				1868	1883	16		.PDF	1,755	
				1884	1934	51		.JPEG	4,865	
The Friend of India/ Statesman (FOI) [#1, 4]	BL	National	N	1835	1882	48	June-Sept.	.PDF	9,507	
	PMML			1883	1889	7		.JPEG	(31,255)	
				1915	1927	13				

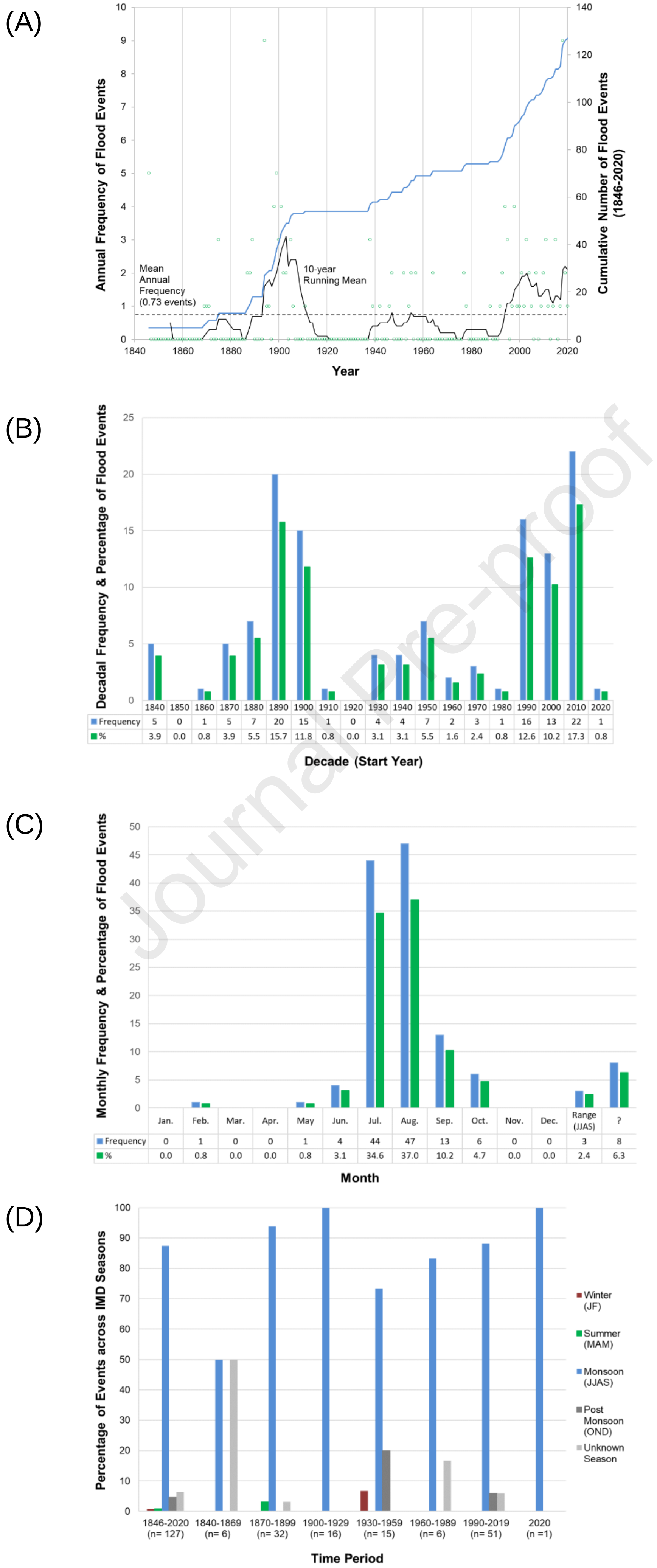
#1 During the project BL holdings were microfilm only, since 2020 searchable digital copies are being uploaded to the British Newspaper Archive
CMG: https://www.britishnewspaperarchive.co.uk/titles/civil--military-gazette-lahore (In January 2024= 1876-1951, 1954-1963)
FOI: https://www.britishnewspaperarchive.co.uk/titles/friend-of-india-and-statesman (In January 2024= 1852-1883)
#2 IAR: A precursor national publication to PAR with Punjab regional sections
#3 RAPT (1849-1855): A precursor to both the IAR (1855-1870) and PAR (1868-1934), showing changing reporting regimes
#4 FOI: To prioritise, HiFlo-DAT only reviewed holdings sourced from the BL (1835-1882). PMML holdings (n= 31,255 files, and after 1927) remain un-reviewed
#5 Repeated entry as different monthly holdings at PMML and BL for the Independence/ Partition period, so best assembled from both sources
#6 A file count of n= 1 varies between part of, single and double pages

Asset Group	Asset Type Damaged	Flood Events Recording Impact to the Asset Type (Frequency)	Sum Frequency of Impacts for Asset Group	Sum Magnitude of Impacts to the Asset Type
Buildings & Property	Domestic property	22	52	n= 445
	Shops/ Stalls/ Kiosks	12		n= 159
	Other Business/ Hotels /Industrial	8		n= 80
	Communal property	9		n= 52
	Religious/ Cultural	1		n= 2
Transport Infrastructure	Bridge	54	118	n= 94
	Road	55		47.3 km
	Track (unsurfaced)	2		2 reports
	Pedestrian pathway	7		7 reports
Vehicles	Damaged	4	10	n= 16
	Washed away	6		n= 13
Water & Slope Infrastructure	Watermills	5	30	n= 58
	Irrigation channels (Kuhls)	2		2 reports
	Protective engineering (channel & slope)	8		8 reports
	HEP/ Dams	4		4 reports
	Water supply	11		11 reports
Power & Communication Utilities	Electrical power	9	19	9 reports
	Telecommunications	5		5 reports
	Postal	5		5 reports
Plants, Trees & Animals	Forestry land	14	55	14 reports
	Agricultural/ Horticulture land	28		102.6 ha
	Orchards (trees)	5		n= 758
	Livestock	8		n= 430

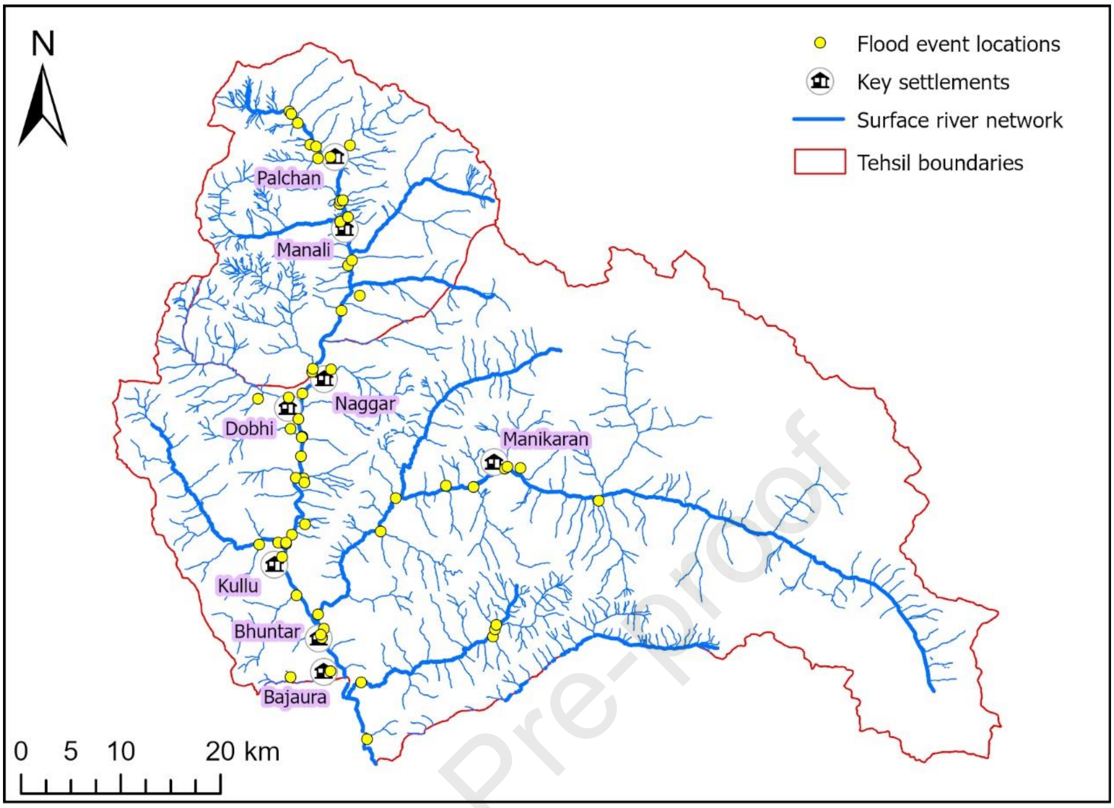

Palchan
Manali
Manali
Naggar
Dobhi
Dawara
Manikaran
Beas River
Kullu
Parvati River
Kullu
Bhuntar
Bajaura
Sainj
Banjar
Nirmand
Anni
km
0 10 20 30
N
0 1,000 km
km
0 10 20 30
Key settlements
Surface river network
National Highways
Other main roads
Tehsil boundaries
Kullu District
Himachal Pradesh State
6548
499
Digital elevation model (m AMSL)


'HiFlo-DAT' Design
• Delhi Consultation Workshop 1 (June 2018, Government/ NGOs/ academics, n= 27)
• Systematic Assessment of Best Practice from literature and existing online databases. Literature via SCOPUS in August 2018: 5518 hits from 13 keyword searches. A final 64 sources were reviewed, guiding database structure, data entry and verification
• Accessible Database Products: Excel spreadsheet (Figure 3) and Google Earth mapping
Source Data Selection
• Existing Diverse Data Holdings (Table 2) since 2013
• Newspapers and Government Reports targeted via catalogues/ exploratory searches from 2016. Being English language sources with likely relevance to the region (Tables 2, 3)
• Rainfall Data (primarily Naggar: 1891- present) from IARI and British Library records
Data Capture & Review
• Protocol Note and Log Sheets to direct consistent capture, recording and reading by all team members. This generated a raw data collection (>160,000 files) which were reduced to an interim long-list of potential flood accounts. Moderation by the UK project lead reduced this to a final 220 accounts in the 'HiFlo-DAT' area
• Key Archives: British Library (UK); PMML, & Tribune/ Indian Express Newspapers (India)
• Capture Methods: photography of screens/ paper; .pdfs from scans; online searches
Database Entry
• Rules Based 'Un-Merged' Data Entry and Verification (308 entries, from 220 sources)
• Rules Based 'Merged' Flood Event Data Creation and Verification (128 entries: 1846-2020)
(Rules detailed in supplementary materials)
'HiFlo-DAT' Analysis
•This Article, introducing 'HiFlo-DAT' methodology and exploring Kullu District flood: (1) Temporal and spatial signatures; (2) Hydro-meteorological and geomorphic process characteristics; (3) Environmental & societal asset impacts; and (4) Human impacts
Accessible Outputs
• Delhi Consultation Workshop 2 (October 2019, Government/ NGOs/ academics, n= 50)
• Wide Dissemination since 2018 (e.g., webpage, social media, presentation, publication)
• 'HiFlo-DAT' Open-access Hosting on data repositories; to be accompanied by a policy brief/ film extending policy and practice uptake
Future
• See Discussion Section

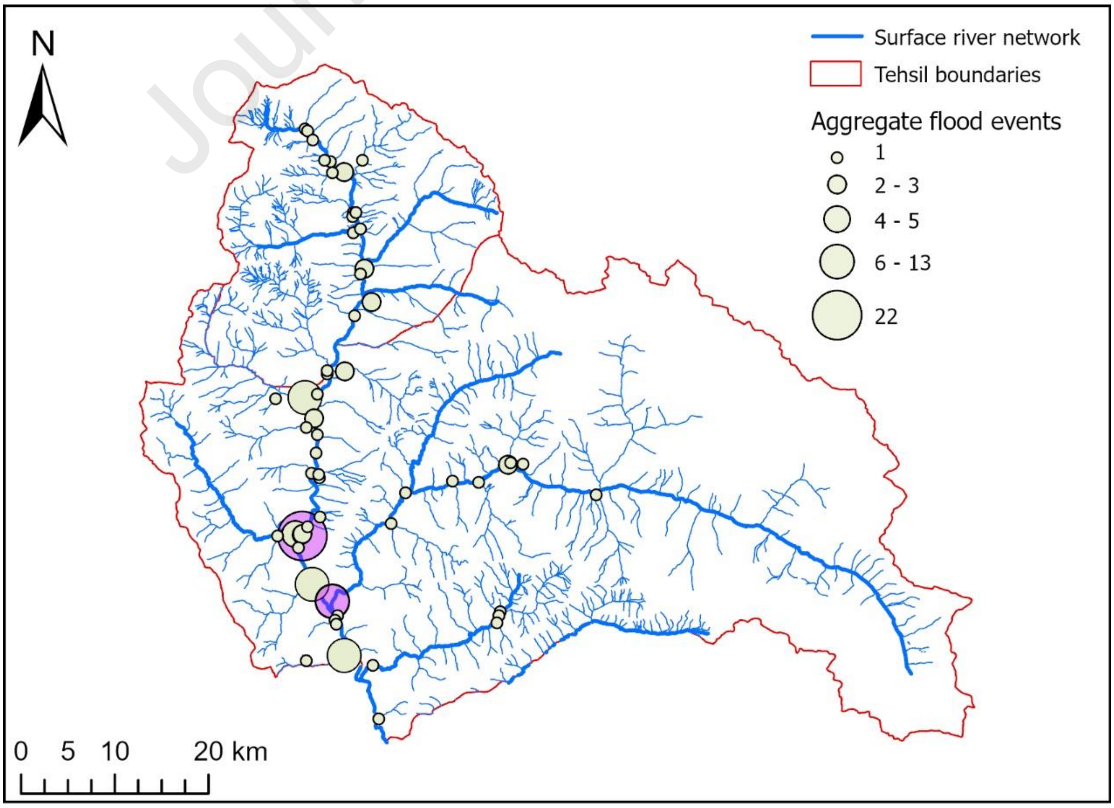

CATEGORIES
(Generalised)
GROUPS
Himalayan
Flood Database
(Kullu District)
'HiFlo-DAT'
(1) Database Management
UNMERGED (4 Cat. [categories]): # source no., entry person, entry date, entry check
MERGED (2 Cat.): Flood (F) event no., contributing # source no.(s)
(2) Source Citation Information
UNMERGED ONLY (13 Cat.): Type, date/ day publication, author, standard citation info., DOI, URL
(3) Event Timing/ Duration (WHEN)
8 Cat.: Gregorian start/ end dates, local time, duration
(4) Event Location (WHERE)
6 Cat.: River/ settlement name, lat./ long., lat./ long. positional accuracy
(5) Event Causation & Hydro-Meteorological Magnitude (WHAT)
12 Cat.: Primary/ secondary process; rainfall, discharge & inundation characteristics
(6) Channel Corridor/ Catchment Event Geomorphological Impacts (WHAT)
8 Cat.: Channel degradation/ aggradation/ avulsion, bank change, overbank deposition, vegetation/ woody debris interactions, slope instability
(7) Event Impact: Damages/ Destruction & Costs (WHAT)
23 Cat.: Buildings, bridges, roads, paths, vehicles, irrigation channels, protective engineering, hydro/ dams, utilities, forestry/ agricultural/ horticultural land, livestock, costs
(8) Event Impact: Direct Human Casualties (WHAT/ WHO)
17 Cat.: Fatalities, missing, injured, evacuated, homeless and total affected
(9) Pre-event Forecast/ Warning/ Preparation (MANAGEMENT)
(10) Event Response/ Relief (MANAGEMENT)
(11) Post-event Recovery/ Management/ Adaptation (MANAGEMENT)
Architecture Synopsis:
Quantitative & Qualitative Entries in a Grouped Structure
Unmerged= 11 Groups, 95 Categories
Merged= 10 Groups, 80 Categories
All Category Headers are Defined & Explained with Exemplars to Condition Consistent Data Entry


(A)
Annual Frequency of Flood Events
Cumulative Number of Flood Events (1846-2020)
Mean Annual Frequency (0.73 events)
10-year Running Mean
Year
(B)
Decadal Frequency & Percentage of Flood Events
1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
Frequency 5 0 1 5 7 20 15 1 0 4 4 7 2 3 1 16 13 22 1
% 3.9 0.0 0.8 3.9 5.5 15.7 11.8 0.8 0.0 3.1 3.1 5.5 1.6 2.4 0.8 12.6 10.2 17.3 0.8
Decade (Start Year)
(C)
Monthly Frequency & Percentage of Flood Events
Jan. Feb. Mar. Apr. May Jun. Jul. Aug. Sep. Oct. Nov. Dec. Range (JJAS) ?
Frequency 0 1 0 0 1 4 44 47 13 6 0 0 3 8
% 0.0 0.8 0.0 0.0 0.8 3.1 34.6 37.0 10.2 4.7 0.0 0.0 2.4 6.3
Month
(D)
Percentage of Events across IMD Seasons
Winter (JF)
Summer (MAM)
Monsoon (JJAS)
Post Monsoon (OND)
Unknown Season
1846-2020 (n= 127)
1840-1869 (n= 6)
1870-1899 (n= 32)
1900-1929 (n= 16)
1930-1959 (n= 15)
1960-1989 (n= 6)
1990-2019 (n= 51)
2020 (n =1)
Time Period

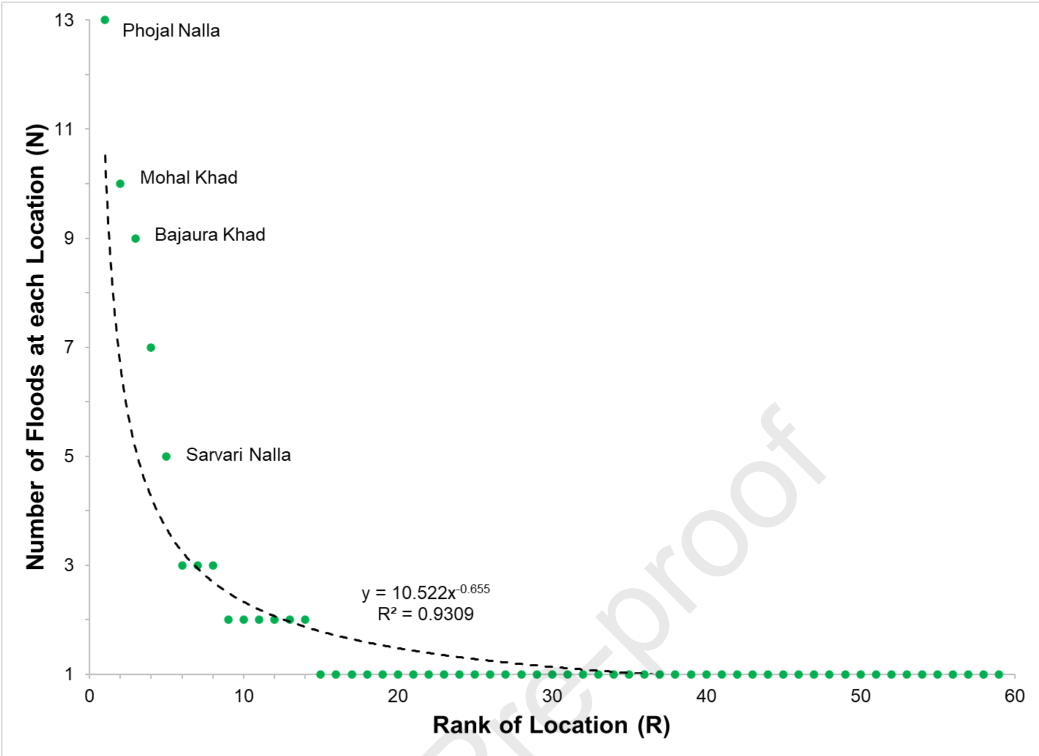
(A)


N
Flood event locations
Key settlements
Surface river network
Tehsil boundaries
Palchan
Manali
Naggar
Dobhi
Manikaran
Kullu
Bhuntar
Bajaura
0 5 10 20 km

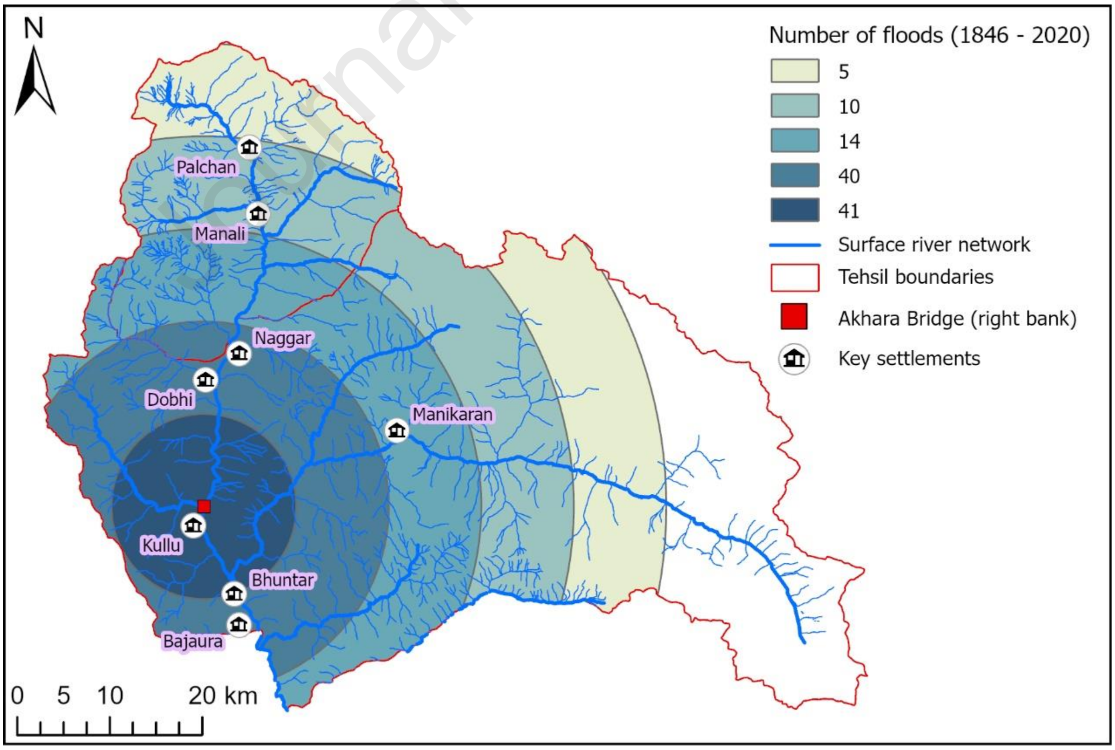
(B)

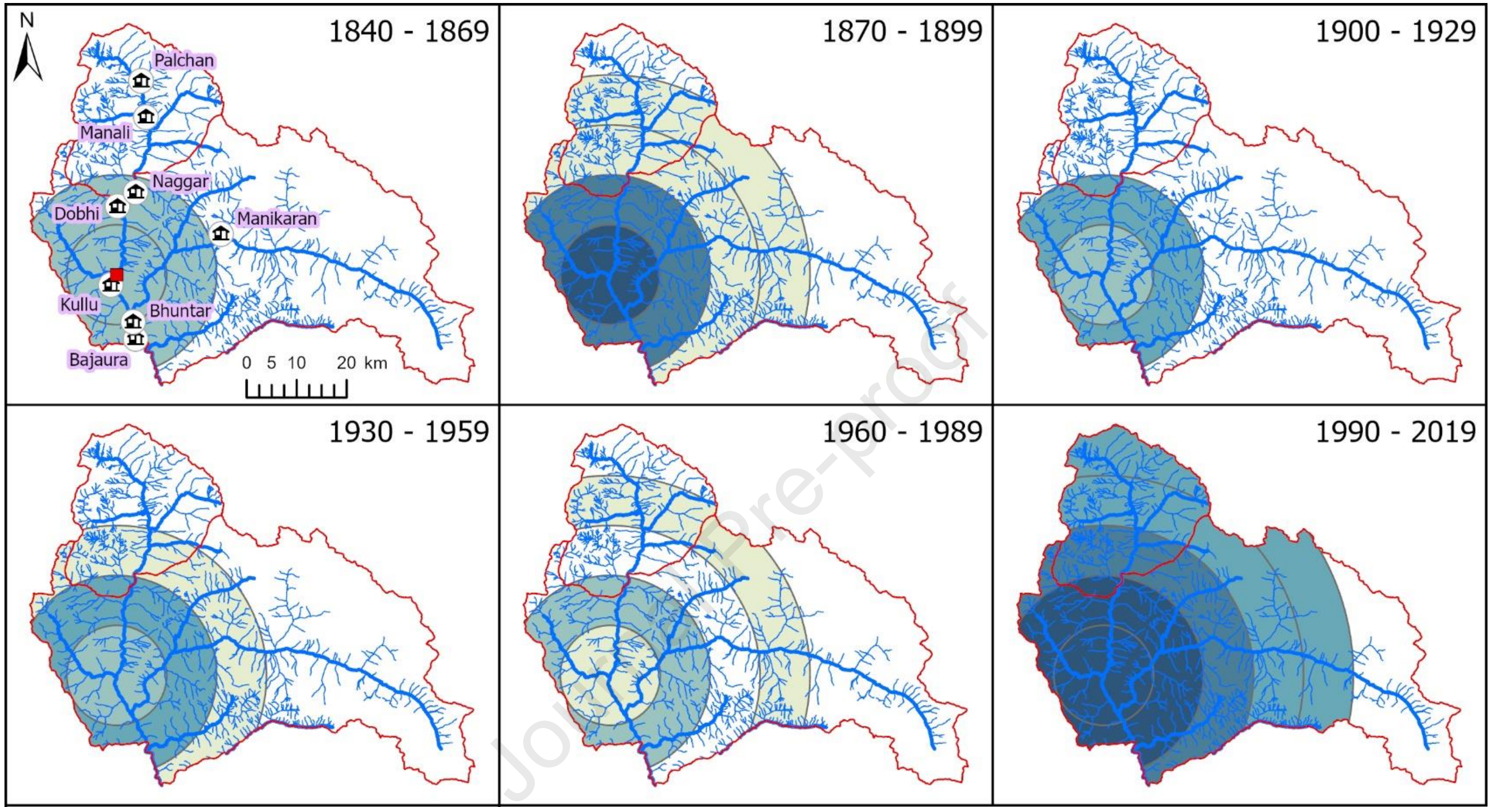

N
Surface river network
Tehsil boundaries
Aggregate flood events
1
2 - 3
4 - 5
6 - 13
22
0 5 10 20 km

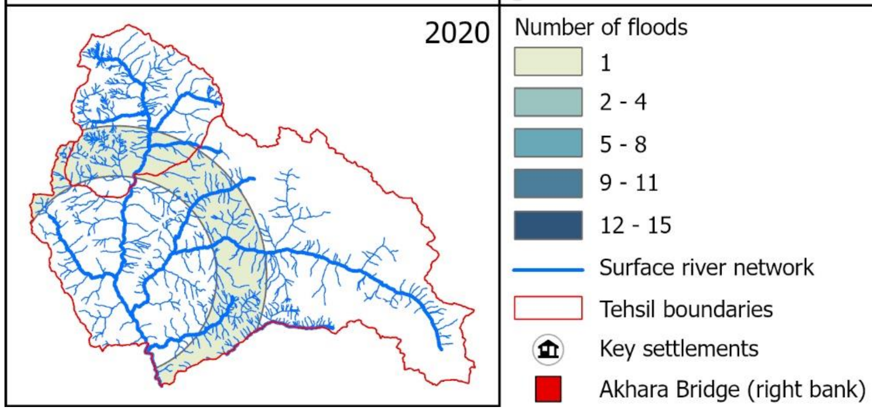
(A)


13
11
9
7
5
3
1
0
10
20
30
40
50
60
Phojal Nalla
Mohal Khad
Bajaura Khad
Sarvari Nalla
y = 10.522x-0.655
R² = 0.9309
Number of Floods at each Location (N)
Rank of Location (R)

(B)


N
Number of floods (1846 - 2020)
5
10
14
40
41
Surface river network
Tehsil boundaries
Akhara Bridge (right bank)
Key settlements
Palchan
Manali
Naggar
Dobhi
Manikaran
Kullu
Bhuntar
Bajaura
0 5 10 20 km





Distance Ring (km)	ALL Years	1840-1869	1870-1899	1900-1929	1930-1959	1960-1989	1990-2019	2020
0-10	41	4	15	4	4	1	13	0
10-20	40	2	10	8	5	2	13	0
20-30	14	0	1	0	1	0	11	1
30-40	10	0	1	0	0	1	7	0
40-50	5	0	0	0	0	0	5	0
Total	110	**6**	**27**	**12**	**10**	**4**	**49**	**1**
		109 (as 1 event has an inexact date)						

- 'HiFlo-DAT' (**H**imalayan **Fl**ood **Dat**abase): Kullu District, Himachal Pradesh, India
- New world-leading knowledge: 128 floods, 59 locations, 1846-2020 (175 years)
- Increasing flood incidence and losses towards the present
- Vulnerable communities (70% fatalities) associated with construction projects
- Robust method for assembly of disaggregated/ sub-national disaster loss data

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: