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Comprehensive Assessment of the July 2023 Extreme Flood Event in the Beas and Parbati Valleys, Himachal Pradesh

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Abstract

Between July 8 and July 11, 2023, the Upper Beas Basin and its major sub-catchments—including the Parbati, Sainj, Solang, and Phojal valleys—experienced an unprecedented hydro-meteorological catastrophe. A synoptic-scale interaction between a high-amplitude Western Disturbance (WD) and an active Indian Summer Monsoon (ISM) surge generated 72-hour rainfall totals exceeding 300 to 500 mm across central Himachal Pradesh, with localized precipitation anomalies up to 812% above monthly baselines. This meteorologically compounded event triggered extreme surface runoff, near-saturation soil moisture conditions, and rapid snowmelt, resulting in peak discharge rates between 3,000 and 4,200 m^3/s along the upper Beas mainstream.

The resulting flows rapidly transitioned into hyper-concentrated sediment loads saturated with para-glacial debris, driving extensive geomorphic transformations. Channel bed scouring of 3 to 8 meters occurred in steep bedrock gorges, while lower-gradient reaches suffered lateral bank erosion extending up to 100 meters, channel avulsion, and widespread terrace undercutting. Concurrently, more than 1,000 mass-wasting events—including debris flows, landslides, and temporary landslide dam outburst floods (LDOFs)—bulked the sediment supply and amplified hydro-dynamic force downstream. Infrastructure failures were widespread: extensive segments of National Highway 3 (NH-3) collapsed due to toe scour, bridge structures failed under high hydro-dynamic drag and woody debris impoundment, and major run-of-the-river hydroelectric projects suffered severe desilting chamber clogging and gate operational failures.

The paper is based on the available secondary data in many studies, journals, books, magazines, govt. records and other reliable secondary sources. This study presents a detailed assessment of the synoptic triggers, hydrologic dynamics, hydro-geomorphic mechanisms, and structural failure modes of the event, concluding with policy recommendations for climate-resilient infrastructure, floodplain zoning, and multi-hazard early warning systems in the High Himalayas.

Key Words: <u>Tectonic Concvergence, River System, Land Forms, Cloud Bursts, Dam outbursts</u>

1. Introduction

The Himalayan mountain system is among the most hydro-dynamically active and geo-morphologically fragile landscapes on Earth. Driven by ongoing Indo-Eurasian tectonic convergence, rapid uplift rates, high relative relief, and steep topographic gradients, its river basins are highly susceptible to sudden landform alterations. In the Western Himalaya, the upper catchment of the Beas River—located within the state of Himachal Pradesh, India—drains an area of approximately 5,421 km2 upstream of Aut. The valley system encompasses several major tributaries, including the Parbati, Sainj, Tirthan, Phojal, and Solang rivers. Historically, the region has been shaped by monsoon-driven fluvial processes, para-glacial sediment evacuation, and localized cloudbursts.

However, the extreme hydro-meteorological event of July 8–11, 2023, represented a watershed shift in the scale and intensity of natural hazards in the North-western Himalaya. Over a 72-hour window, sustained convective precipitation affected the headwaters of the Beas and Parbati basins. The resulting floodwaters were not clear-water flows; instead, they evolved into hyper-concentrated sediment fluids carrying immense volumes of boulders, gravel, mud, and uprooted trees.

The disaster caused more than 400 fatalities across the state, displaced over 50,000 people, destroyed hundreds of public and private structures, and inflicted direct economic damages exceeding ₹10,000 crore (USD ~$1.2 billion). Critical transportation arteries, notably National Highway 3 (NH-3) connecting Mandi, Kullu, and Manali, experienced widespread collapses.

The severity of the disaster was magnified by human interventions within the landscape. Rapid urban expansion onto active river terraces, rampant construction of hospitality infrastructure directly within historical floodplains, unscientific slope cutting for linear infrastructure, and uncontrolled muck dumping from road widening and hydroelectric construction altered the natural hydrology and flood-carrying capacity of the main channel and its ephemeral tributaries. Understanding the complex interactions between synoptic atmospheric forcing, hydro-geomorphic processes, and anthropogenic vulnerabilities is essential for developing climate-resilient development strategies in high-relief mountain valleys.

2. The Study Area

The study area focuses on the Upper Beas Basin and the Parbati Valley sub-basin, spanning elevation gradients from ~750 m above sea level (masl) near Mandi to over 6,000 masl in the high peaks of the Pir Panjal and Great Himalayan ranges.

2.1 Geology and Tectonic Framework

The region is tectonically active and crossed by several regional thrust faults, including the **Main Central Thrust (MCT)**, the **Jutogh Thrust**, and the **Chail Thrust**. These tectonic boundaries divide the valley into distinct lithological units:

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- **Higher Himalayan Crystalline (HHC):** Composed of high-grade metamorphic rocks such as garnetiferous schists, migmatites, and granitic gneisses. Highly jointed and fractured,

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these rocks are prone to deep-seated rockfalls and wedge failures in the upper catchments (Solang, Upper Parbati).

- **Lesser Himalayan Sequence:** Dominated by metasedimentary rocks, including quartzites, phyllites, slates, and limestones. Highly weathered with thick overburden soils, making them susceptible to shallow debris slides and planar failures during prolonged rainfall events.

2.2 Geomorphology and Drainage Network

The Beas River is a 6th-order stream fed by more than 1,400 tributaries. The valley morphology alternates between narrow, bedrock-confined gorges (e.g., Pandoh-Aut gorge, Larji gorge) and broad alluvial basins (e.g., Kullu-Manali valley).

The floodplains and valley floors consist of quaternary landforms, including:

1. **Fluvial Terraces (T1 and T2):** T1 represents younger, low-lying alluvial terraces elevated 2 to 6 meters above the normal summer riverbed. T2 represents older, elevated surfaces (10 to 25 meters high). Most urban settlements, hotels, and agricultural lands in Manali, Raison, Katrain, Kullu, and Bhuntar are built directly on T1 and T2 terraces.
2. **Alluvial Fans and Debris Cones:** Formed at the mouths of steep tributaries (e.g., Phojal Nala, Palchan Nala, Chhoj Nala). These fans consist of poorly sorted, unconsolidated paraglacial sediment, coarse boulders, and matrix-rich debris.
3. **Mid-Channel and Point Bars:** Unconsolidated gravel and boulder accumulations that migrate during high-flow conditions.

3. Literature Review

Scientific understanding of extreme hydrometeorological hazards in the Himalayas has evolved from single-hazard evaluations to complex, multi-hazard cascade frameworks.

3.1 Synoptic Drivers of Extreme Himalayan Precipitation

Early research by *Bookhagen et al. (2005)* and *Dimri et al. (2015)* established that while the Indian Summer Monsoon (ISM) supplies the bulk of annual precipitation in the Central and Western Himalaya, extreme localized floods are frequently triggered by collisions between mid-latitude Western Disturbances (WDs) and monsoonal air masses.

Hunt et al. (2018) demonstrated that upper-level troughs associated with WDs create strong dynamical forcing, enhancing vertical motion and drawing deep monsoonal moisture inland. *Vellore et al. (2016)* documented similar atmospheric setups during the June 2013 Kedarnath disaster and the September 2014 Kashmir floods, identifying atmospheric river-type moisture transport as a primary factor in high-intensity convective storms across high-relief topography.

3.2 Hydro-Geomorphic Cascades and Sediment Transport

The concept of the paraglacial sediment cascade in mountain catchments—developed by *Church and Ryder (1972)* and expanded for the Himalayas by *Korup et al. (2010)*—explains why high-altitude rivers carry large volumes of coarse bedload during floods. Glacial retreat leaves behind vast deposits of loose morainic material on steep slopes.

Wulf et al. (2012) analyzed flood-induced sediment dynamics in the Northwestern Himalaya, demonstrating that extreme runoff rapidly mobilizes this stored material, shifting the flow regime from clear-water transport to hyper-concentrated sediment slurry. *Chaudhary et al. (2022)* and *Gupta et al. (2024)* observed that under hyper-concentrated flow conditions, fluid density increases significantly, enabling the transport of multi-ton boulders and increasing shear stress on riverbeds and structural foundations.

3.3 Anthropogenic Hazard Amplification

Recent literature emphasizes the role of human activity in turning natural weather events into disasters. *Rana et al. (2021)* and *Dhiman et al. (2022)* documented how unscientific slope cutting for four-lane highway projects alters slope stability, increasing landslide occurrences along transportation corridors.

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Studies by *Tiwari et al. (2022)* and *Himdhara (2024)* highlighted how the lack of active floodplain zoning in Himachal Pradesh led to encroachment on low-lying river terraces (T1). Furthermore, *Baruah et al. (2020)* documented how unmonitored muck disposal from tunnel excavations and road construction raises riverbed levels, reducing channel cross-sectional area and increasing lateral erosion risks during high-discharge events.

- Himdhara

4. Meteorological Triggers and Synoptic Setup

The extreme rainfall event of July 8–11, 2023, was caused by a rare compound meteorological setup.

4.1 Atmospheric Circulation and Moisture Transport

Synoptic analysis using ERA5 reanalysis data revealed a deep, slow-moving upper-tropospheric trough in the Westerlies positioned over northern Pakistan and Jammu & Kashmir. Simultaneously, an active monsoonal depression over central India maintained a strong pressure gradient, driving a high-flux low-level jet of warm, moisture-laden air from both the Arabian Sea and the Bay of Bengal toward the Western Himalaya.

The meeting of cold, dry upper-level air within the WD trough and warm, moist lower-level monsoonal air created extreme atmospheric instability over central Himachal Pradesh. Precipitable Water Vapor (PWV) values exceeded 55 kg/m2, well above historical 99th-percentile baselines for the region.

4.2 Precipitation Quantities and Spatial Anomaly

Ortho-rectified radar estimates and Indian Meteorological Department (IMD) surface station observations recorded extreme 48-to-72-hour rainfall totals across Kullu, Mandi, and Solan districts between July 8 and July 10:

- **Kullu District:** Received 812% excess precipitation over its long-period average for the corresponding period. Stations like Manali recorded over 220 mm of rain within 24 hours.
- **Mandi District:** Recorded localized 48-hour totals exceeding 350 mm.

- **High-Altitude Sub-Catchments:** Rain gauge networks in the Solang, Tosh, and Sainj catchments logged rain intensities exceeding 60–80 mm/hour during peak convective bursts on the night of July 9.

Rainfall Anomalies across Districts		
District	72-Hours Total (in mm)	Anomaly V/s Historical Average
Kullu	320 – 480	+812 % Excess
Mandi	280 – 410	+450 % Excess
Solan	300 - 390	+520 % Excess

5. Hydrological Modelling and Discharge Acceleration

The rapid conversion of rainfall into surface runoff was driven by high antecedent moisture levels and snowmelt runoff.

5.1 Antecedent Moisture Conditions and Snowmelt Coupling

Using SMAP (Soil Moisture Active Passive) satellite data, *Gupta et al. (2024)* established that topsoil volumetric moisture across the Upper Beas catchment had reached 85–95% saturation prior to July 8 due to moderate rainfall earlier in the month.When the main rainstorm struck, infiltration capacity was rapidly exceeded, resulting in near-total conversion of rainfall into direct surface runoff (Rn≈P). Additionally, the high freezing-level altitude during the warm monsoonal convective storm forced rain-on-snow conditions across high-elevation snowpacks (above 4,000 masl) in the Parbati and Solang headwaters, contributing an estimated 10–15% additional volume to peak discharge rates.

5.2 Peak Flow Estimates Across Key River Reaches

1. **Upper Beas at Manali (Bahang/Palchan):** Normal peak discharge ranges between 200 and 400 **m^3/s**. During the night of July 9, estimated peak flow reached **1,800–2,200 m^3/s**, destroying riverside infrastructure.
2. **Beas Mainstem at Kullu & Bhuntar:** Below the confluence with the Phojal and Parbati rivers, peak discharge reached an estimated **3,500–4,200 m^3/s**, approaching the 100-year return period design limit.
3. **Pandoh Dam Releases:** To maintain structural safety, dam operators were compelled to open all spillway gates, discharging a peak controlled flow exceeding **9,800 m^3/s** (345,000 cusecs) into the lower Beas gorge toward Mandi.

6. Hydro-Geomorphic Processes and Landscape Transformations

The extreme hydrodynamic forces transformed the Beas and Parbati from clear-water fluvial streams into hyper-concentrated sediment-laden fluids.

6.1 Hyper-Concentrated Sediment Flows and Density Bulking

As floodwaters swept down steep tributary channels, they entrained vast quantities of glacial till, paraglacial deposits, and landslide debris. Volumetric sediment concentrations (Cv) in tributaries like the Tosh, Malana, and Phojal streams exceeded 20–35%, transitioning the flow regime from turbulent water flow to hyper-concentrated fluid flow.

This elevated fluid density (ρf>1.3–1.5 g/cm3) increased buoyant lift forces on large boulders, allowing multi-ton rocks (3 to 6 meters in diameter) to be transported as bedload. The abrasive boulder-laden slurry acted as a hydraulic hammer, scouring riverbeds and destroying concrete structures along its path.

6.2 Channel Morphodynamics: Widening, Avulsion, and Bed Scour

1. **Lateral Bank Erosion:** In wide alluvial stretches (Raison, Kullu, Bhuntar), the Beas mainstem widened its active channel by **30 to over 120 meters**. Undercutting of low terraces (T1) led to the sudden collapse of hotels, parking lots, and long sections of NH-3.
2. **Channel Avulsion:** Near Bhuntar airport and the Parbati-Beas confluence, sediment accumulation raised the primary riverbed, forcing the river to carve new channels through surrounding floodplains and agricultural lands.
3. **Vertical Bed Scour vs. Aggradation:** In narrow bedrock gorges upstream of Pandoh and near Aut, high shear stress scoured the riverbed by 3 to 8 meters. Conversely, in lower-gradient zones where the valley widened, the sudden drop in transport capacity caused massive aggradation, raising riverbed levels by 2 to 5 meters with coarse gravel and boulders.

6.3 Landslides, Slope Failures, and Landslide Dam Outburst Floods (LDOFs)

Over 1,000 slope failures were mapped across the Beas and Parbati valleys following the storm. These failures fell into three primary categories:

- **Shallow Debris Slides:** Occurred on saturated soil-mantled hillslopes along highway cuts where vegetation had been removed.
- **Deep-Seated Rockslides:** Triggered along structural joints in Higher Himalayan Crystalline formations in the upper Parbati and Solang valleys.
- **Ephemeral Damming (LDOFs):** In steep, narrow tributaries—notably Malana Nala and Chhoj Nala—debris flows temporarily blocked the channel, forming short-lived landslide dams. When these unconsolidated dams breached minutes to hours later, they released high-discharge surge waves into the mainstem, further amplifying peak flood levels.

7. Infrastructure Failure Mechanisms

The 2023 event highlighted major vulnerabilities in the design and placement of civil infrastructure throughout the high-relief valleys.

7.1 National Highway 3 (NH-3) Undercutting and Slope Collapses

Long segments of NH-3 between Pandoh, Aut, Kullu, and Manali were destroyed. The primary failure mode was **toe-erosion of unanchored retaining structures**. Roadways constructed on unconsolidated river terrace materials were supported by shallow gabion walls or gravity retaining structures. High-velocity floodwaters scoured the toe of these slopes, undercutting the retaining walls and causing mass collapse of the roadbed. In cut-and-fill highway sections, saturated fill slopes failed as mudflows, severing critical transport links.

7.2 Bridge Hydrodynamics, Pier Scour, and Debris Impact

Multiple bridge structures failed across the catchment, including concrete girder bridges, historical steel truss bridges, and suspension footbridges:

- **Hydrodynamic Drag & Debris Clogging:** Upstream logging debris, uprooted trees, and structural fragments accumulated against bridge piers and undersides. This blocked water flow, creating a damming effect that increased hydrostatic pressure and lateral hydrodynamic drag until structural collapse occurred.
- **Scour Depth Exceedance:** Severe bed scour exposed and undermined pier foundations, leading to differential settlement, tilting, and deck collapse.

7.3 Hydroelectric Headworks and Gate Failures

Run-of-the-river (RoR) hydroelectric projects in the sub-basins were severely impacted:

- **Malana-I and Malana-II HEPs:** Extreme sediment and debris flows choked intake structures. At Malana-II, spillway gates failed to operate after becoming jammed with tree trunks and gravel deposits. Water overtopped the dam crest, damaging auxiliary structures and forcing downstream evacuations.
- **Sainj and Parbati-III HEPs:** Sediment loads far exceeded the handling capacity of desilting chambers. Turbid, sand-laden water entered powerhouses, causing severe abrasion damage to turbine runners and forcing emergency plant shutdowns.

8. Role of Anthropogenic Drivers and Development Patterns

While the rainfall event was exceptional, human activities significantly amplified the resulting destruction.

1. **Floodplain Encroachment:** Over the past three decades, rapid tourism-driven urbanization led to extensive construction of multi-story hotels, commercial buildings, and municipal

structures on active T1river terraces and alluvial fans. These developments constricted the natural flood channel, reducing cross-sectional area and increasing flow velocities and erosive power during high-discharge events.

2. **Unregulated Muck Disposal:** Excavation material from four-lane highway construction and hydroelectric tunnelling was frequently dumped along steep riverbanks. Floodwaters rapidly mobilized this loose material, increasing sediment concentrations and raising riverbed levels downstream.
3. **Deforestation and Drainage Alteration:** Widespread forest clearance along slopes weakened root-cohesion in top soils, while improper roadside drainage concentrated runoff onto unstable cut slopes, accelerating gullying and landslide initiation.

9. Disaster Management, Response Evaluation, and Policy Recommendations

The July 2023 disaster demonstrated that existing hazard mitigation and spatial planning frameworks in the Western Himalaya require significant updates.

9.1 Evaluation of Emergency Response

The response by the National Disaster Response Force (NDRF), State Disaster Response Force (SDRF), Indian Air Force, and local authorities prevented greater loss of life. Over 70,000 tourists and residents were evacuated despite broken communications and damaged transport corridors. However, early warning systems failed to accurately predict the localized severity of flash floods and LDOFs in upper tributaries, highlighting critical gaps in high-altitude hydro-meteorological monitoring networks.

9.2 Policy Recommendations for Regional Resilience

1. **Strict Enforcement of Floodplain Zoning:** Enforce non-build buffer zones along the Beas, Parbati, and tributary rivers based on 100-year flood hazard mapping. Structures on active T1 terraces should be relocated or retrofitted.
2. **Climate-Resilient Highway Design:** Trans-Himalayan transportation corridors must shift from shallow retaining structures to deep pile foundations anchored in bedrock. Road alignments should maintain adequate setback distances from active river channels.
3. **Upgraded Bridge Hydraulics:** Future bridge construction must use longer single-span or cable-stayed designs to minimize riverbed piers, prevent woody debris trapping, and provide high clearance above projected 100-year flood levels.
4. **Strict Muck Management Audit:** Establish digital, GIS-tracked monitoring of excavated material from highway and tunnel projects to enforce disposal in designated, structurally reinforced containment sites outside floodplains.
5. **Multi-Hazard Early Warning Systems (MHEWS):** Expand automated weather stations (AWS), X-band Doppler weather radars, and stream-gauging networks into high-altitude headwaters. Integrate automated alarm systems downstream of landslide-prone tributary gorges to warn against potential LDOFs.

10. Conclusion

The July 2023 catastrophe in the Beas and Parbati valleys illustrates the growing risk posed by compound extreme weather events in high-relief Himalayan mountain environments. The interaction between a Western Disturbance and monsoonal moisture generated extreme precipitation that triggered severe hydro-geomorphic responses: hyper-concentrated sediment flows, vertical channel bed scouring, extensive lateral bank erosion, channel avulsion, and over 1,000 mass-wasting events.

The extent of the destruction was exacerbated by anthropogenic factors, including urban expansion onto active river terraces, unscientific slope cutting, and improper muck disposal in active floodplains. Addressing these vulnerabilities requires a shift in regional planning strategies. Sustainable development in the Higher Himalaya must integrate science-based floodplain zoning, climate-resilient engineering practices, rigorous environmental monitoring, and multi-hazard early warning systems to mitigate risks in a changing climate.

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