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EDITORIAL

Flash floods in Uttarakhand Himalaya: Reasons and remediation

The Himalayan region has been suffering from different kinds of climate-induced geological hazards, out of which the flash floods have been often due to one of the causes of erratic rainfall or cloudbursts, ice/snow avalanches, glacial lakes outburst, landslide lakes outburst, fluvial extremes, abrupt river incisions, reservoir-dam failure, or a combination of two or more of these. The floods have instigated loss of lives and livestock, and/or damage to properties and structures leading to disasters of variable magnitudes. The aspects that have been responsible are, climate change or global warming and stresses persuaded by unplanned anthropogenic activities. It is to be stated that 'çloudburst' is defined as more than 100 mm rainfall per hour, suddenly occurring over a small area. The 'flash flood' is the fast and impulsive inundation, while the normal 'flood' is slower and more prolong that affect generally larger areas with steadily increasing water level. The constricted drainage system and narrow river valley have been attributed to the rainfall-triggered flash floods at many places. There has been cascading effect also due to earthquakes, (caused by plate convergence), to landslides to landslide-lake formation followed by its sudden rupturing to flash floods. It is the landscape and geomorphological features of the Himalaya that control the damage pattern during a catastrophe.

Several factors such as unauthorized civil constructions, non-abiding by building codes, erection of infrastructures in unscientific manner, exposure to vulnerable areas like river beds/banks, and lack of awareness, are attributed to the reasons of disasters. The youngest Uttarakhand (UK) state in the Indian Himalayan Region is ~85% mountainous, and has experienced flash floods and other geological cataclysms from time to time. To mention a few dreaded flash floods are, complete burst of Chorabari Lake leading to glacial lake outburst flood (GLOF) in 2013, Gangotri debris-flow that devastated a large area in 2017, ice-rock mass avalanche at Dhauliganga-Rishiganga catchment in 2021, snow-avalanches in Kedarnath and Hemkund Sahib in 2022, cloudburst events in Arakat-Uttarkashi (2019), Dharchula-Pithoragarh (2023) and Maldevta-Dehradun (2022), and rainfall triggered surge-type flash floods in Dharali-Uttarkashi (2025). The UK Himalaya has also witnessed disasters caused by rainfall-triggered 2003 landslides at Varunavrat Parbat in Uttarkashi, and massacre by earthquakes like Uttarkashi (1991) and Chamoli (1999) due to tectonic movement. Hence, we synthesize some key flash floods in the UK Himalaya to comprehend the reasons and provide their plausible remediation.

On 16th September 2025, Sahastradhara and surrounding areas of Dehradun, were ravaged by flash floods and landslides due to heavy rainfall or cloudburst. Several shops, hotels, homes and infrastructure were washed away or severely damaged, a few people went missing, popular tourist spot was flooded, and pathways were waterlogged. Again on 5th August 2025, a rainfall triggered landslides and massive mud-water flash floods in the Kheer Ganga river destroyed the Dharali village of Uttarkashi district, claiming 5 persons dead, 50 feared missing, several goats swept away, and many houses, shops, homestays and roads destroyed. The brunt of the massacre is also visible at nearby regions of Horsil and Sukhitop. The entire area in mountainous terrain is known for its scenic beauty. It is also the way to pilgrimage site and trekking route to Gangotri glacier and Gomukh, source for the Bhagirathi River. The higher Himalayan crystalline rocks, composed of gneisses, schists and migmatites, are highly weathered, fractured and jointed under the influence of cooling and warming phenomena. of climate variation. The glacio-fluvial deposits or loose debris materials, soaked with snow/glacier melt water, over the steep mountainous slope of more than >45^{O}; rainfall at higher elevation; narrow valley with high inclines, created a surge-type flash flood by rapidly mobilizing the mud-water at downstream. However, the disaster was due to unregulated buildings in front of the Kheer Ganga river curve and construction on the alluvial fan and floodplain that disrupted the river's historical drainage path. Since the rainfall is shifting upward, the stations must be deployed at higher elevation for rainfall recording. We also need to look into high resolution drone-based and remote sensing data for establishing the fact of this disaster.

Another climate-surprise disaster in the UK Himalaya was heavy rainfall-triggered slope breakdown near Maldevta-Dehradun in August 2022. This smashed the channel and bank of Song and Baldi rivers for a 15 km stretch between Sarkhet and Thano, and completely eroded Sarkhet, Kumalta and lower portion of Maldevta town. It destroyed/washed away some huts and temporary stalls built on the banks of the river. The cloudburst in Arakot-Uttarkashi in August 2019 made double-impact as flash flood in Arakot nala and landslides at nearby region. This flash flood caused 19 people dead, 8 feared dead, and 15 injured, affected 38 villages covering an area of ~70 km^2, and stranded ~400 people at various places. The Lasko valley in Pithoragarh district of UK state near Indo-Nepal border also witnessed rainfall-induced disaster in September 2022, which caused 6 fatalities, 11 reported missing, 72 houses severely damaged and more than 62 families deserted at multiple places. During this catastrophe, roads were destroyed, land-degraded, small landslides occurred, minor bridges collapsed, and Lasko valley was also damaged. The reasons of the flash flood have been due to constricted drainage systems through which so much rainwater could not be drained out through the confluence of the Kali river and Lasko nala. In fact, water receded back and inundated upstream villages on the riverside.

In October 2022, intermittent snow avalanches took place in the Mandakini catchment area adjacent to the Kedarnath Temple town. From the analysis of aerial data and ground survey, it was established that the snow-avalanches originated ∼6 km uphill of Kedarnath town from the peak of Companion Glacier in the Mahalaya Parvat (5970 masl), closet to the Chorabari Glacier. As the run-out and deposition zones are situated ∼5 km uphill of Kedarnath town, it does not pose threat to the temple township by avalanche hazards. The study from the slope morphology, grass clearing, snow drifts, and debris cones have identified fifteen avalanches in this area. The climate-related other incidence is the Atalakodi snow avalanche in Hemkund Sahib in April 2022. This destroyed a section of the trail between Ghangria and Hemkund Sahib. The Atalakodi route is considered a potential site for future snow avalanches. The historical data in this area, shows fatalities due to past avalanches. One of these was in 1998 that buried 27 pilgrims, and another was in 2008 that resulted into 8 deaths and 12 injuries. The Atalakodi avalanche, affected an area of ~4 km long and ~150 m width. The steep slopes, structures and lithologies have been attributed for the snow avalanches in Kedarnath and Hemkund Sahib. The ropeway, environment impact assessment, and construction at no-risk zone have been recommended for the mitigation from such disasters.

Around 968 glaciers and 1,265 glacier lakes with variable sizes,, occur in the UK Himalaya. The large moraine-dammed lakes with appreciable slopes, evolving activities and habitation in downstream, and comparatively fast melting of associated glaciers are critical parameters to be considered for assessing the glaciers-related hazards, which mean glacier detachment primarily that lead to debris flow and flash floods secondarily. A typical example is the 2021 Chamoli disaster caused by a massive avalanche of ice-rock mass in the peak winter on 7th February. The gigantic ice-rock (27 million m^3 in volume) fell down to 3600 masl in the Dhauliganga-Rishiganga basin from a height of 5600 m, got fragmented and melted by its impact and created slurry materials leading to huge deluge. The reason of ice-rock mass detachment has been attributed to the heavy snow precipitation over the hanging glacier and development of cracks and fissures in the underlying basement rocks due to freezing and thawing processes. The debris materials flew down the slopes, disconnected villages by disintegrating roads/bridges, and smashed hydro projects, as well as killed more than 200 people. By analyzing seismological data, retrieved from a nearby station, the scientists from Wadia Institute of Himalayan Geology could identify seismic precursors of glacial avalanche, first of its kind, for about 3 and a half hour’s duration before the main event of ice-rock avalanche. This study led to the establishment of a network of seismological stations along with the hydro-meteorological stations, real time transfer of data through VSAT/ GSM, automatic scrutiny and integration of data using suitable AI/ML algorithms and development of an integrated early warning system (IEWS). Such a system is to be developed and deployed at other basins for detection and early warning of glacial hazard.

High sediment transfer continues and might impact hydro-projects in downstream by silting reservoir and/or corroding turbine blades. The stakeholders of hydropower projects must build the IEWS for their dams and take care of maintenance. Understanding the sediment dynamics necessitates for debris flow simulation. The combined remote sensing, field observations and numerical modelling show that 7 million m^3 of debris, deposited by 2021 Chamoli glacial avalanche, was removed along a 30-km-long domain from near its origin by pre-monsoon and monsoon river flows in 12-months post event. The study also showed bed-load and suspended sediments traveling up to 85 km from the event source, which have wider implications to water quality in downstream. Continuous monitoring of sediments and water fluxes using web-based sensors, are essential for safeguarding the ecology of downstream region as well as the health of reservoirs and dams. Therefore, study on fluvial dynamics is crucial for assessing the water availability, management, and protection from devastating flash floods during monsoon.

The June 2013 Kedarnath calamity was caused by GLOF, moraine failure, and insistent rainfall, which inundated 5500 villages, killed 6000 people, detained more than 1 lakh pilgrims in peak summer, and destroyed huge properties and structures. This also led to more than 10,000 small, medium and large landslides in the UK Himalaya. The GLOF’s are caused by multiple factors like glacier thinning or recession, sediment/water discharge, lithology, structures, climatic variability, moraine collapse, rainfall, etc. By studying these parameters, we can monitor the glaciers and associated lakes in a comprehensive manner. The drone- or satellite-based techniques can be developed for mapping lake-bathymetry and volume of lake water, as well as to estimate the glacier’s thickness and volume of water stored within the glaciers-ice in inaccessible regions. However, the ground penetrating radar and sonar survey can be carried out in the accessible area for the estimation of glacier’s thickness and volume of lake-water respectively. The geotechnical, geophysical or geoengineering surveys, can provide strengths of moraine-dammed walls of glacial lakes against breaching. The rate of water accumulation, amount of downslope, infrastructure and habitation in downstream are acute factors for assessing the glacier-lake related hazards. The hydro-meteorological stations are to be deployed at higher elevations to monitor air temperature, humidity, precipitation, wind speed, wind direction, glacier melt and flow, sediments discharges etc. The elevation dependent warming and its impact to melting of glaciers, need to be modelled. Controlled puncturing or spillways of glacial-lakes, tunneling, laying pipelines inside and pumping or siphoning off water, can be thought of as a remedial measure from GLOF disaster.

The Bhilangana lake in the Tehri-Garhwal region of UK Himalaya, situated at ~4750 m height, has grown to ~0.40 km^2 area in the last 55 years. The associated Khatling glaciers have been observed thinning as per the study made by the scientists of Wadia Institute of Himalayan Geology The air temperature gradient (0.79^{O}C/decade) has been increased noticeably in the past decade as compared to the average temperature gradient (0.28^{O}C/decade) over the last three decades. Again, downslope of this region is more than 20 degrees. Thus, close monitoring and assessment of the lake is need of the hour to avert any disaster due to GLOF, as have been observed by complete outburst of Chorabari lake in 2013. This may lead to cascading effects - landslides, landslide lakes outburst floods, debris flow, etc.

The debris flows in the mountainous regions have been caused by landslides, glacial/snow avalanches and floods. The Malpa (Pithoragarh) landslide is one of the worst rain-induced landslides that wiped away entire Malpa village, and generated ~1 million m^3 of rock fall and debris flow. The landslide killed ~ 220 people including 60 pilgrims travelling to Tibet as a part of 'Manas Sarovar Yatra'. A debris flow occurred in the foreland of Gangotri glacier by its former tributary Meru Bamak glacier in July 2017. The Meru Bamak stream was completely dissected that exposed ice-cored left lateral moraines. The study brought out deposition of ~6.5 million m^3 of debris in frontal region of the Gangotri glacier as fan-type. A sharp increase of suspended sediments reaching up to ~3 km downstream, was also noticed. The recession of Gangotri glacier, degraded ice-cored moraine, loose sediments in front of Meru Bamak, and continuous rainfall might have played role to such debris flow. However, it did not incur any disaster due to absence of habitation and structures at nearby area.

The 2003 landslide in sparingly vegetated Varunavrat Parbat, on right bank of the Bagirathi river with Uttarkashi town at its foot, was triggered mainly by the rainfall that was much above the normal, and partly by the groundwater and anthropogenic activities. The debris slide at the top and rock fall in the middle started on the day rainfall ceased, and continued for the next 15 days. The clay-filled joint structures, rock types and degree of slopes were other factors. In similar topographic setting, the 1500 mm of rainfall in monsoonal months, as reported for the Varunavrat landslides, can be considered threshold for landslides. The landslides can be forewarned by coupling slope instability with the rainfall threshold in a vulnerable slope region by establishing a network of web-based sensors like rain gauges, piezometers, inclinometers, extensometers, InSAR, etc., and real-time data assimilation and development of landslides IEWS using IoT based or AI/ML algorithms.

It is to be mentioned that abundant moisture in the atmosphere and increase in land/sea temperatures have been responsible for the torrential rainfall in July-August (2023) in both, the Himachal and UK Himalayas. The confluence of SW monsoon from the Arabian Sea and weak westerly disturbances from the Mediterranean Sea moving eastward has intensified rainfall in the Himalayan region. The warming of atmosphere due to CO_2 or other GHG emission increases the capacity of holding more moisture in the air leading to cloudburst or heavy and sudden rainfall at focused region in the Himalayan regions. The elevated Himalaya acts as a barrier that pushes the moisture-content air upward and get cooled at higher height, leading to condensation and moderate to heavy rainfall in the Himalayan terrain.

The landslides in hilly areas and flash floods in plains have been accredited mainly to the climatic factor – concentrated rainfall over a short span of time, as well as slow but continuous normal rainfall over a longer period of time. The other factor is the land degradation – the top most part, made up of incompetent rocks, is highly weathered under the influence of climate change. The third factor is the anthropogenic stresses like deforestation, unauthorized construction, slope instability due to toe cutting in unscientific way, improper drainage system that allows percolation of water from house-hold kitchen and toilet into the subsurface. The rain water makes the top loose soil saturated and heavy, and underground percolation in a haphazard manner, accelerates the mass movement over the plane of weakness in slope areas causing the landslides under gravity.

For remediation of disaster due to flash floods, pragmatic check dam policy and rational shifting of people from flood-prone riverbanks to safe and stable areas is suggested. It is necessary to develop the flood early warning and alert system by deploying water level sensors, rain gauge sensor, hydrometric gauge, cameras etc. that can be radio-linked with the central station. Installation of Doppler radar and lightning sensors would also aid in monitoring, and can be an effective strategy for damage control. Based on habitation, geomorphology, presence of infrastructure and other natural features for a given region, different scenario of flash floods or snow avalanches, can be created with different amount of rain or snow precipitation, which will provide precautionary measure to local government authorities in such a moment.

The warming of Himalaya at a faster rate than any other places on the globe in the present climate change situation, is aggravating the geological hazards further. The indicators of climate change on the Himalayan perspectives are visible as glaciers mass loss, expansion and formation of glacier lakes, upward shifts of tree-line and snow-line, rainfall occurrences at higher elevation, and reduction of snow covered area and its early melting. It is projected to face the consequences of further warming with possible rise of 2.6 to 4.6^{O} C by the end of 21st century and complete disappearances of glaciers, if the temperature continues to rise without any control. Again, the Himalaya is stressed by the cascading effects due to tectonic forces leading to earthquakes to landslides to the formation of temporary lakes over streams, followed by their sudden breaching to flash floods. The slope regions of high altitude Himalayas, are becoming weak due to erosion and weathering caused by freezing and thawing processes, and degraded by forest fires. The hassles are worsened additionally by the anthropogenic loads by illegal civil constructions on un-stabilized slopes, habitation over riverbanks and riverbeds, and infrastructure built without proper environment impact assessment. The climate change has not only intensifying the geo-hazards but also posing threat to water scarcity for agricultural and drinking purposes, disruption to hydropower generation due to changes of river dynamics, health insecurities due to heatwaves and pollution, loss of biodiversity and ecosystem, and disturbances to livelihoods and tourism sectors. The future precipitation patterns are also not very clear with some models suggesting augmented rainfall, while others expect diminutions, emphasizing the need for localized assessment.

It must be pointed out that energy is the main driver for socio-economic growth of any country. It is mainly the fossil fuels (coal, oil and natural gas) that supply 80% of the world's gigantic energy requirement till date. However, burning of fossil fuels emanate CO_2, which has been ascribed to the global warming and climate change. The coal produces the maximum amount of CO_2, followed by oil, and the least amount by natural gas. To meet the UN's initiatives of carbon neutrality by 2050 and net zero carbon by 2070 in order to limit further rise of temperature by 1.5 to 2.0^{O} C, we need to make a (i) breakthrough into the renewable or green energy sectors; or (ii) intensifying gradual transition to low-carbon and environment-safe fuels through gasification of coal/oil and development of hybrid technology for synergising two or more different kind of energy resources; or (iii) fortifying carbon capture, utilisation and sequestration experiments by innovative catalytic chemical reaction in which captured carbon can be converted either into usable products like carbonates and methanol, and/or used for enhanced oil recovery and production of marine gas-hydrates by CO_2-CH_4 molecular substitution.

The Himalaya is stressed under the influence of climate change resulting into melting of glaciers and snow fields impacting water availability and agricultural practices, altering weather patterns, land degradation, enlarged geological and hydrological disasters and disruption to ecosystems. Additional stresses are built by the anthropogenic activities. To address such complex issues necessitates a multi-dimensional approach, comprehension of hill-specific challenges and technological barriers for sustainability, integration of scientific understanding with local knowledge, strengthening adaptation and mitigation efforts including the nature based solution (NbS), engagement of native communities, and promoting local and global partnership to build resilience, warrant sustainable future, and secured safe living in the Himalaya.

To comprehend the geological hazards due to flash floods and provide plausible remediation, we need to identify the most vulnerable zones based on geoscientific investigation. Secondly, a network of web-based sensors is to be established at the hotspots for transmission of data from field to processing centre in enabling long term monitoring through analysis and assimilation of data using AI/ML or IoT. The next step is to develop an IEWS to alert and safeguard the people and properties against the disasters. Once the alert system is fully functional in a catchment, similar network can be deployed at other hazard-prone basins or areas of the Himalaya. The system would be designed by deploying different kinds of sensors for diverse types of geo-hazards due to landslides, glaciers/glacier lakes related threats, and floods. It is to be clarified that the investment for development and deployment of IEWS is much more economic than the cost involved in rehabilitation and restructuring, and damages to homes and infrastructure. The loss of invaluable lives cannot be equated in terms of money.

The Himalaya possesses plethora of resources: glaciers and snow field, springs and riverine system, precious minerals and ores, geothermal, hydrocarbon and hydro-power energy resources, medicinal plants, tourist attraction etc. that can be harnessed for the socio-economic growth, agro-cultural development, and strategic advancement but by following certain guidelines and abiding by mountain-specific building codes. A balance between the exploitation of these resources for economy and optimal conservation of the Himalayan fragile ecosystem, must be implemented. Adaptation to NbS like, (i) plantation, vegetation and restoration of forests for protection of slopes and reduction of soil erosion that can reduce the probability of risks due to landslides, (ii) refurbishment of wetland and degraded riverbanks, and maintenance of natural drainage system to control the floods, (iii) rejuvenation of springs and groundwater recharge areas for mitigation of water scarcity and (iv) implementation of sustainable agroforestry and integrated farming for resilience of ecosystem, are to be made effective by empowering local communities for ensuring long-term success.

The traditional knowledge like usage of light-weight construction materials; implementation of limited storied buildings, and satellite townships instead of having populace around one business town; strict implementation of heavy penalty against unauthorised construction and deforestation; impervious drainage system that will not allow random infiltration of waste water into the subsurface; building retaining walls, wire-mesh, insertion of bolts and shotcrete for arresting slope failure; slope stability assessment before any construction or hill-cutting in a slope region; stringent codes on muck disposal after rock cutting; non-exposure to highly vulnerable areas; disaster-resilient building or retrofitting old buildings; periodic assessment of load bearing capacity at different scales; environment impact assessment, etc. are some of the other measures, which can be considered for mitigation and way forward. We have to sensitize the locals on how to live with the disasters; inculcate fundamental education on the causes and consequences of disasters; build trained manpower for disaster management - preparedness, response, restoration; draw attention of stakeholders to scopes and opportunities for alleviation of challenges; build climate-adaptable and disaster resilient future; and figure out the sustainable growth. The traditional practices, adaptation capacity for resilience, and invaluable knowledge of local communities must be fostered for firming readiness mechanisms and addressing inherent vulnerabilities, which can prepare better for and recover from increasing risks of the UK Himalaya posed by disasters and climate change. It is to be stated that the major hindrances to the adaptation and adoption of several strategies and way forward are the dearth of funds, deficiency of knowledge, absence of technology and lack of mandatory policy

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