Pt. Govind Ballabh Pant

Memorial Lecture: XXVIII

Dr. Navin Juyal

September 10, 2022

at

Kosi-Katarmal

Almora

G.B. Pant National Institute of Himalayan Environment

(An Autonomous Institute of Ministry of Environment, Forest and Climate Change, Govt. of India)

Kosi-Katarmal, Almora, 263 643, Uttarakhand, India

Dr. Navin Juyal

- Former Senior Scientist, Physical Research Laboratory, Ahmedabad, Gujarat
- Fellow of the Indian Geophysical Union
- Fellow of the Geological Society of India

Specialization:
- Geomorphology and Quaternary Geology
- Paleoclimate and Climate Extremes

Awards & Recognitions:
- Recipient of National Geoscience Award.
- Member Governing Body, Research and Advisory Council, Birbal Sahni Institute of Palaeosciences, Lucknow.
- Former Associate Editor, Journal of Earth System Sciences, Springer-Nature Publications.
- Member High Power Committee constituted by the honorable Supreme Court of India to assess the environmental degradation and impact of hydroelectric projects during the June 2013-Disaster in Uttarakhand.
- Former member, Program Advisory Committee, Earth and Atmospheric Sciences, SERB, DST, GoI.
- Former member Expert Committee on "Integrated program on dynamics of glaciers in the Himalaya", DST, GoI.

Research and Development Experience:
- Dr. Navin Juyal did his Master from HNB Garhwal University in 1980 and Ph.D. in 2004 from MS University Baroda. He retired as Senior Scientist from the Physical Research Laboratory, a unit of Department of Space, Govt. of India, in Ahmedabad. He is currently working on the understanding of causes and consequences of extreme weather events in Himalaya.

- Dr. Juyal spent nearly 30 years in basic research which involved understanding the pattern of climate variability during the last 100 thousand years. The emphasis of his research was to understand the long-term (multi-millennial) and short-term (centennial) scale impact of climate change on the earth surface processes and landform evolution.

- Some of the major research projects undertaken by Dr. Juyal include, 'The causes and consequences of climate change in Himalaya with emphasis on pattern of glacier advances and retreat covering the NW to central Himalaya'; 'Climate-human interaction and extreme hydro meteorological events'; 'Reconstructing the pattern of past climate variability using the relict glacial lake sediment and fluvial deposits' etc.

- Dr. Juyal has also worked on 'Understanding the pattern of dune dynamics and dryland river response to regional and global climate change'; and 'Land-sea interaction (sea level changes) along the western coast of India with emphasis on the emergence and decline of Harappan civilization'.

- Dr. Juyal has more than 100 research papers in peer reviewed journals with around 3400 citations.

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Inevitable climate warming, cryosphere degradation, and landscape instability in the Himalayan region

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Global warming-induced melting and thawing of the cryosphere are severely altering the volume and timing of water supplied from High Mountain Asia, adversely affecting downstream food and energy systems that are relied on by billions of people (Dongfeng Li et al., 2022)

Background: Fragility, diversity, and divinity is the hallmark of the Himalayan region that emerged from the Indian and Eurasian plate collision. Rapid changes in altitude (ranging from <1000 to >7000 m) across short distances led to tremendous variations in climate, earth surface processes, and human activities (cultural diversity). The climate varies from the sub-tropical humid (in the southern plains) to the alpine tundra-like climate of the snow-clad ridges in the northern hinterland. The variation is even more dramatic along the slopes of the mountain ranges. For example, while the Doon valley has a sub-tropical humid climate Mussoorie, which is just 1.3 km higher, has a temperate climate. Himalaya is blessed with reasonably good rainfall (average ~1550 mm), which along with snow and glaciers feed major rivers and innumerable streams.

Considering that the impact of climate change is looming over the Himalaya, Government of India launched an ambitious project the *National Mission for Sustaining the Himalayan Ecosystem (NMSHE).* Similarly, Government of Uttarakhand also formulated *"Uttarakhand Action Plan on Climate Change (UAPCC): Transforming Crises into Opportunity"* in 2014. The report cautioned that extreme precipitation events are likely to increase in Uttarakhand which may cause flash floods, landslides, and damage to the Himalayan ecosystem. Further it is projected that flooding may increase to over 30% of the existing magnitudes and will have severe implications for the existing infrastructures. The worst hit would be the higher altitudes, where severity of the temperature change would be amplified and consequently may cause serious ecological imbalances, affecting adversely the surface runoff factor, temperature gradient, surface radiation, etc.

I am fortunate to have this opportunity to talk in front of the dedicated team of scientists of G.B. Pant National Institute of Himalayan Environment (GBPNIHE) and other luminaries who are committed to the cause of Himalaya. I sincerely express my

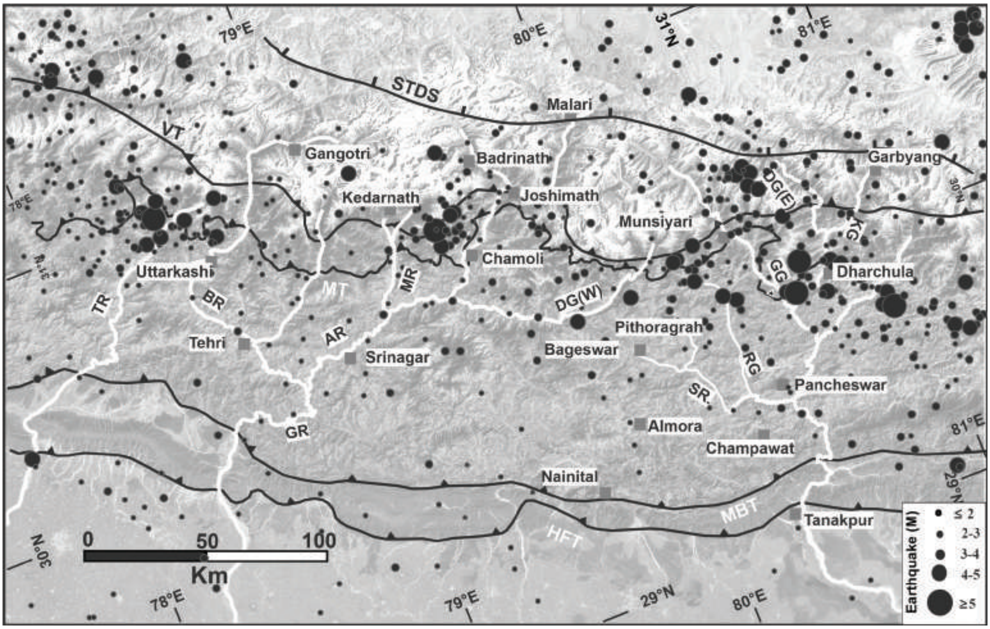


Figure 1. Digital Elevation Map (DEM) of Uttarakhand showing major tectonic boundaries along with the distribution of earthquakes. MT- Munsiari Thrust, VT- Vaikrta Thrust, MBT- Main Boundary Thrust, HFT- Himalayan Frontal Thrust, TR- Tons River, BR-Bhagirathi River, AR- Alaknanda River, GR- Ganga River, MR- Mandakini River, DG9E)- Dhauli Ganga East, KG- Kali Ganga, RG-Ram Ganga, SR- Saryu River, DG(W)- Dhauli Ganga West.

gratitude towards the director of the institute for considering me worth delivering the talk on the foundation day. Over the last few decades, GBPNIHE is working relentlessly towards finding ways for the sustainable development of the Himalayan region and its natural resource management and augmentation. In this talk I dwell upon some of the important aspects that I feel require concerted efforts, particularly keeping in mind the threat posed by the accelerated impacts of climate change. Since the majority of my research was devoted to the Uttarakhand Himalaya, you will see a kind of bias in citing examples from this region.

The Emergent Himalaya: Himalaya is an outcome of continent-continent collision (convergent tectonics) and therefore, the rocks are fractured, fissile and differentially dislocated. The continued compressive movement led to the generation of terrain boundary thrusts. These form north to south are the South Tibetan Detachment System (STDS), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) (Figs.1 and 2). The thrust besides generating the topographic relief also demarcates the lithological discontinuities. Thus, the emergent Himalayan topography besides dictating the pattern of precipitation variations (Fig. 2), created immense local and regional diversity in the climate which in turn dictated the spatial and temporal variability in the ecological niches leading to the heterogeneous distribution of biodiversity elements.

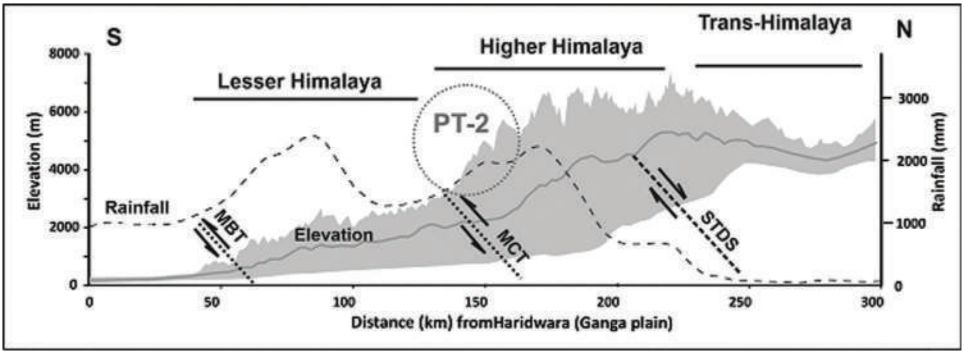
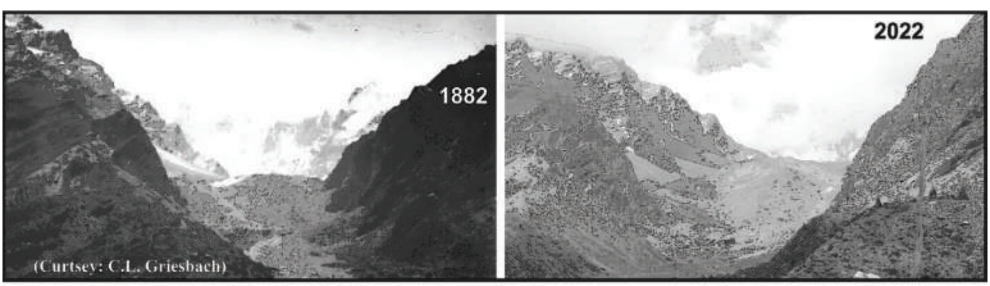


Figure 2. Topographic profile from Haridwar past Malari with rainfall profile overlain (dashes). Grey swath shows min. and max. topographic elevations with average elevation (solid line). PT-2- Physiographic Transition-2. Also shown are the approximate positions of the major thrusts demarcating the Lesser, Higher and Trans-Himalaya. MBT- Main Boundary Thrust, MBT- Main Central Thrust, STDS-South Tibetan Detachment System (Courtesy: Dr Naresh Rana)

Himalayan Cryosphere: Perhaps the most critical region in which vanishing glaciers will negatively affect water supply in the next few decades would be parts of Asia, including India. Popularly known as the Hindu Kush Himalayan (HKH) region, spanning 2,400 kilometers across six nations (India, Pakistan, Afghanistan, China, Bhutan, and Nepal), it contains more fresh water than any other region outside of the North and South Poles. Snow and glacier melt play an important role in the timing and magnitude of water availability for more than 750 million people who live within the Indus, Ganges, and Brahmaputra basins, including about 200 million living in the headwater regions (Glaciers of the Himalayas, 2021). The snowfall and glacier melt are important controls on the timing and availability of surface water at many locations within the basins, especially in the headwater regions.

Studies indicate that the recent glacier advancement in the Himalayas occurred during the globally recorded Little Ice Age (LIA), which began around the 16th century AD and terminated around 1850 AD (Oerlemans, 2005). Since the end of LIA, an almost worldwide recession in glaciers has been observed, a trend that also applies to most of the glaciers in the Himalayas. The receding glaciers have left behind enormous sediment that can be seen sequestered in multiple Himalayan valleys below the present glacier snout.



Nilang glacier Zad Ganga valley, Uttrakhand Himalaya

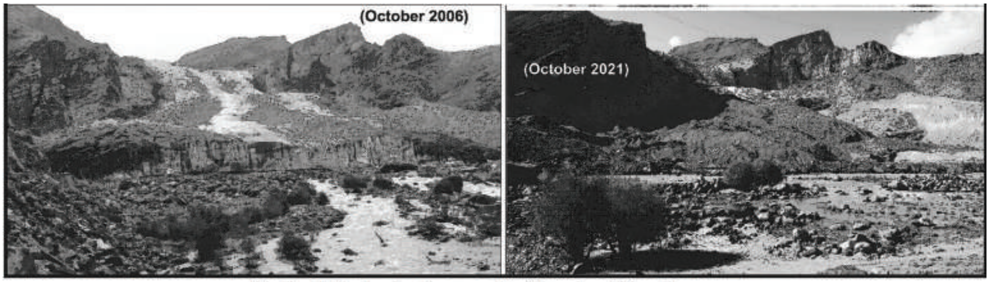


Figure 3. Upper panel; Nilang glacier (Bhagirathi valley). Thirty years after the termination of LIA and today. Note that there is no significant recession observed over the last 140 years. Lower panel showing the recessional trend of Parkachik glacier in Suru valley (western Zanskar ranges), a significant recession can be seen in the last 15 years.

LIA is used as a benchmark of natural climate variability against which the anthropogenic-induced climate change can be evaluated. It is feared that if the current trend of warming continues, the rivers largely depending on snow/ice melt are likely to suffer hydrological disruptions to the extent that some of the most populated regions such as the Ganga plain may 'run out of water' during dry season.

Monitoring Glacier Health: There is a need to monitor the pattern of glacier response to climate change in the Himalayas. The current methods provide a skeletal pattern of glacier dynamics which suggests that glaciers are indeed on a recessional trend. For example, the simplest method widely used is by recording the annual location of the glacier terminus (mouth/snout). Such an observation/recording could be a transient response to short-term climate variability and at times location specific. The rate of retreat depends on several factors which include elevation, topographic slope and aspect, debris cover, and ice thickness. In most cases, the above variables (boundary conditions) are not critically considered while reporting the retreat rates. This seems to be one of reasons for the variable recessional rates reported from the same glaciers. Nevertheless, if we summarize the existing data, it does indicate that the higher retreat rates appear to be associated with glaciers located at the lowest altitudes on gentle slopes, with thin ice near the terminus, having variable debris-cover. Further, there seems to be a broad agreement that under the warm earth scenario, smaller glaciers (<5 km) located at the lowest elevations with a southerly aspect, and the hanging glaciers 'cut off from a substantial accumulation area', are likely to disappear first (Armstrong, 2010).

Majority of the estimates on rate of glacier retreat/advance are based on measuring the glacier length change rather than more comprehensive and scientifically rigorous glacier mass balance measurement. A glacier can be divided into an upper zone of accumulation where the glacier experiences an annual net mass gain and a zone of ablation where the glacier experiences a net mass loss. The elevation contour at which these two zones meet is called the equilibrium line altitude (ELA) where the glacier's annual net mass balance is zero and responds sensitively to climate (temperature and precipitation). Since glacier length variation is a delayed

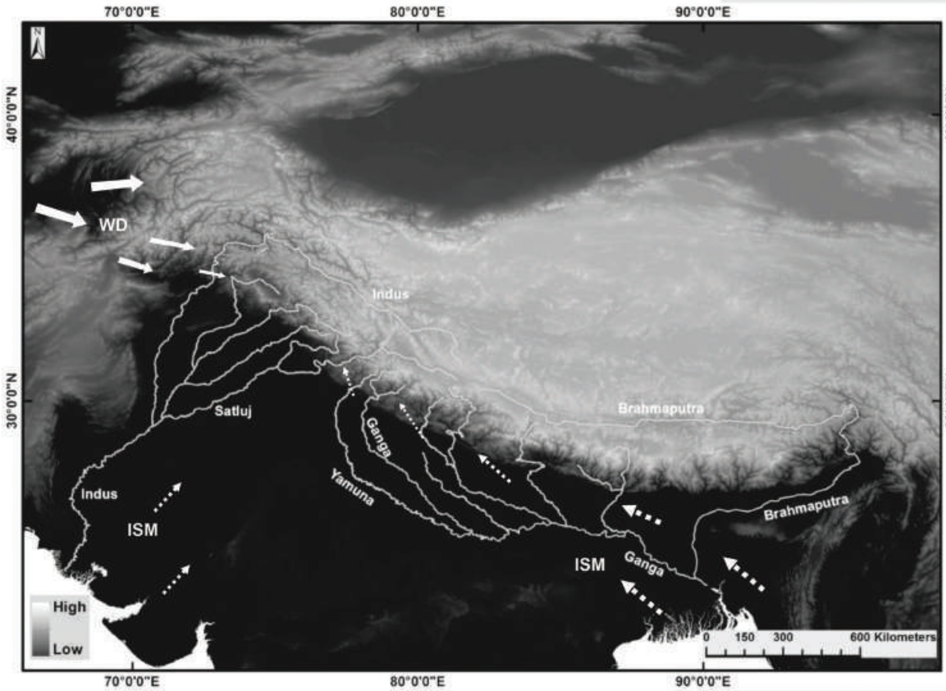


Figure 4. Digital Elevation Map (DEM) of the Himalayas depicting the influence of two weather systems viz. the mid-latitude westerlies (solid arrows) and Indian Summer Monsoon (dotted arrows).

response to climate change and is affected by many factors mentioned above, therefore, glacier mass balance is considered a more direct and immediate glacier response to climate variability (Bhattacharya et al., 2016). Recent study based on satellite remote sensing data indicates a declining rate of recession of Gangotri glacier (from 19.7 ± 0.6 m/a during 1965– 2006 to 9.0 ± 3.5 m/a during 2006–2015). This could be because the earlier studies were largely based on the reference position of the snout marked on 1962 Survey of India topographic map (Bhattacharya et al., 2016), which could be misleading. Further, there are contrasting results obtained in terms of glacier ice loss from two adjoining basins. For example, compared to the Bhagirathi basin, glacier ice loss in the Saraswati valley (Alaknanda basin) is two times higher. Considering that the glaciers are located on a common catchment divide (adjoining valleys), could it be because of the complex interaction of geology, geomorphology, orientation, and climate? Needless, to say that the *science of glacier-climate interaction in the Himalayas is still in an embryonic stage. It seems each glacier respond differently to a common climate forcing and calls for exploring the key elements impacting the glacier health.*

Prevailing Climate and Warming Trend: The Himalayan ranges are dominated by two weather systems, the Indian Summer Monsoon (ISM) and the Mid-Latitude westerlies. The contribution of these two systems varies spatially along and across the Himalaya (Fig. 4). For example, the eastern and central Himalaya is dominated by the ISM, whereas the NW Himalaya receives precipitation from the westerly disturbances embedded within the Mid-Latitude Westerlies (Fig. 4). Further, the south-north increase in relief also dictates the rainfall variability particularly the ISM which is manifested by heterogeneous distribution of biodiversity. In Uttarakhand Himalaya, for example, the floristic composition varies from temperate-deciduous forest below 1000 m to alpine pastures above 3500 m. The valleys experience mean summer temperatures between 15 and 25 °C and are much colder in winter.

Regions with elevations above 4500 m experience severe winter, with temperatures far below freezing point and precipitation in form of snow. Studies indicate that the Himalayas is witnessing significant temperature changes in the twentieth century. The warming trend during the first (second) half of the twentieth century was about 0.10 °C (0.16 °C) per decade, which later increased to 0.32 °C per decade from the beginning of the twenty-first century (Yan and Liu 2014). The warming rate is reported to be more substantial in winter as compared to other seasons in most parts of the Himalayan region. This is a matter of concern as persistent increase in winter temperature may adversely impact the glacier mass balance and earth surface processes.

Climate-Glacier Linkage: Increase in greenhouse gases have led to increase in average global air temperature during the last century. However, if the temperature rise was the major contributor for the recent recession of Himalayan glaciers, the rate of recession should have shown minimum variability. In fact, there are suggestions that glaciers in monsoon dominated central Himalaya (Uttarakhand) should expand during the global rise in temperature because of an increase in the monsoonal precipitation. We think this is an over-simplistic interpretation given the fact that monsoon is not solely driven by the land-sea thermal contrast and there are other equally important boundary conditions. One may as well argue that the recent recession trend could as well be a temporary transient climatic expression manifested by the Himalayan glaciers.

Most importantly, the present recession estimates are based on limited time series data to evolve any policy measure for conservation and judicious management but are biased towards a small region viz. few glaciers from the western and central Himalayas. Unless we have long time series data covering the eastern, central, western, and north-western Himalayas, our inferences about the impact of climate (temperature and precipitation) would remain speculative. In view of this, the central segment of Himalaya, which include Uttarakhand becomes important as the glaciers in this region respond to both the ISM and westerly disturbances (Fig. 4) Further, studies undertaken so far are focused on discretely located glaciers employing limited glaciological parameters. Some attempts have been made to develop long-term regional climatic index- a proxy for mass balance would allow us to evaluate the glacier variability in Himalayas more quantitatively and establish the relationship between glacial, climatic, hydrologic, and biotic systems.

Cryosphere Response: Recession of high-mountain glaciers in response to climatic change frequently results in the development of moraine dammed glacial lakes. Moraine dam failure is often accompanied by the release of large volumes of water and sediment, termed as Glacial Lake Outburst Floods (GLOFs). Therefore, to reduce the risk of GLOFs, the glacial lakes need to be monitored for their hydrological characteristics along with efforts to release the stored water from those lakes, which have the potential to generate the GLOF as demonstrated in Thorthormi glacier in Bhutan Himalaya. While global climate change significantly affects the environment over the high mountain regions of Asia, its impact on the Himalayan cryosphere is a major threat to the regional water resources. The recent studies (e.g., Rana et al., 2021; Li et al., 2022) suggest that the 7th February 2021 Rishi Ganga flash flood could be the geomorphic expression of climate warming in the Himalayan region.

The extreme weather events in the Himalayan region are showing an increasing trend and Uttarakhand Himalaya is no exception. This is manifested by increasing frequencies and magnitude of (spring season) forest fire events, avalanches, flash floods and landslides. Sabin and Krishnan (2020) in their recent paper on "Climate Change Over the Himalayas" showed that human-induced climate change has led to accelerated warming of the Himalayas and the Tibetan Plateau at a rate of 0.2 °C per decade during 1951–2014 where high-elevation areas (altitude > 4 km) underwent amplified warming at a rate of about 0.5 °C per decade. Many areas in the Himalayan region, except the high-elevation Karakoram

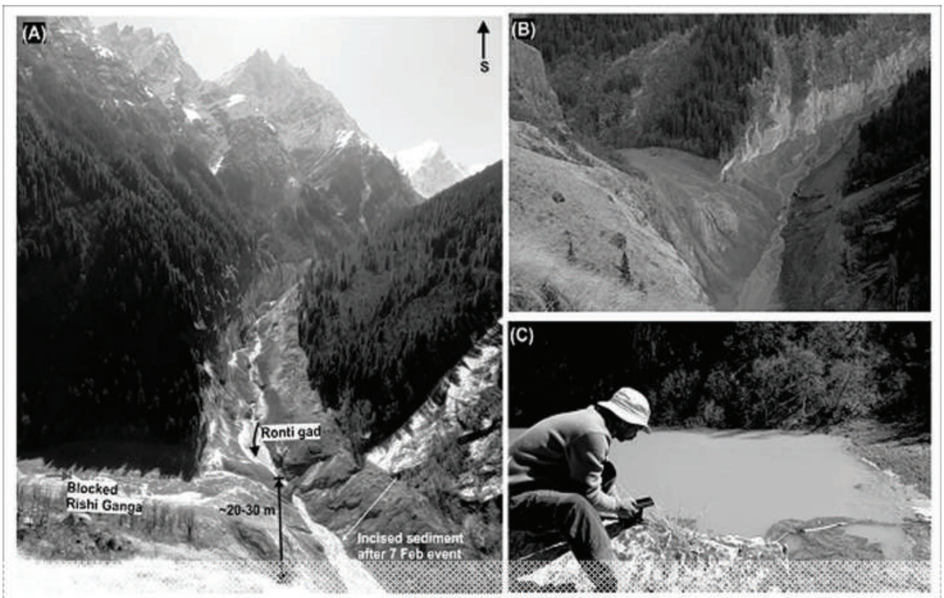


Figure 5. (A) Raunthi Gad from where the Feb 7th flash flood was triggered that caused large-scale destruction (human life and barrages) in Rishi Ganga and Dhauli Ganga (W). (B) The blocked of Rishi Ganga caused by the debris transported by Ronti Gad. (C) Temporary Lake formed on Rishi Ganga (modified after Rana et al. 2021).

Himalayas, experienced significant decline in wintertime snowfall and glacier retreat in recent decades. Future warming in the region, which is projected to be in the range of 2.6–4.6 °C by the end of the twenty-first century, will further exacerbate the snowfall and glacier decline leading to profound hydrological and agricultural impacts in the region (Sabin and Krishnan, 2020). Similarly, the glaciogenic sediment sequestered in the higher Himalaya valleys (above 2500 m) pose potential threat for generating destructive floods as the climate becomes warmer (Fig. 5).

Black Carbon (BC): The black carbon content has increased rapidly since 1990s, coinciding with the accelerating glacier retreat through mechanisms like atmospheric warming and albedo reduction (Ramanathan and Carmichael, 2008). The successful strategy to retain the freshwater benefits of Himalayan glaciers would need reduction in black soot emissions so as to restore more pristine high-reflectivity snow and ice surfaces, as well as stabilize and possibly reduce greenhouse gases. In addition to BC, there is growing concern that the absorbing aerosols at high elevations can also enhance the warming rate and indirectly amplify the melting of snowpacks and glaciers (Ramanathan and Carmichael 2008).

A recent study from Chirbasa (proximal to the Gangotri glacier snout) indicated presence of BC aerosol in the ambient air (Negi et al., 2019). The study speculates that BC in the pristine Himalayan site will not only deteriorate the air quality along with the influence on atmospheric conditions (radiation budget, hydrological cycles, monsoon circulation), but also likely to adversely impact natural resources (glaciers, snow, flora and fauna etc.). Therefore, to mitigate the impact of BC aerosols in the high Himalaya, its origin from anthropogenic sources needs to be reduced by providing a sustainable and eco-friendly alternate source of energy (solar, geothermal etc.) for the activities that are responsible for BC generation besides active control on forest fires and other biomass burning activities (Negi et al., 2019).

Landslides and Flash Floods: Landslides and flash floods are coupled phenomena in the Himalayan region. The existing data indicate that there is a high concentration of landslides, which at times give rise to catastrophic floods, are located on the southern flank of the Higher Himalaya, also known as the Physiographic Transion-2 (PT-2; Fig. 2). Majority of the floods recorded during the last 1000 years were triggered by the Landslide Lake Outburst Floods (LLOFs) (Wasson et al., 2013; Sharma et al., 2017). The PT-2, which receives focused and high intensity rainfall due to an abrupt increase in the topographic relief (Fig. 2) is represented by a 5 to 20 km wide sheared zone are covered with ancient and recent landslide debris. Infrequent activation of slopes many a times blocks the lower order streams- breaching of such streams results in unusual high magnitude flash floods in the Himalayan valleys (Wasson et al., 2013; Sundriyal et al., 2015).

Paraglacial Zone and Flash Floods: One of the major environmental concerns in the Higher Himalaya is the large volume of paraglacial debris left by the receding glaciers sequestered in multiple transverse valleys. These valleys can be found at an altitude of ~2500 m and above. These valleys are located proximal to former glacier extents and currently are dominated by non-glacial process. The paraglacial zone is ecologically fragile and geologically unstable due to the re-sedimentation and transfer of glacial sediments within and beyond the high-mountain landscapes (Sundriyal et al., 2015 and references therein). Thus, it can be suggested that paraglacial zone is a dynamic system, constantly adjusting to changing glacier boundary conditions due to local and regional climate variability. Therefore, a small trigger (short-lived extreme weather event) is sufficient for re-mobilization of the large volume of unconsolidated paraglacial sediments (Fig. 6). Below are few examples of catastrophic floods triggered from paraglacial zone in Uttarakhand Himalaya.

(i) The Birahi Ganga Flood: On 6th September 1893, a tributary of the Alaknanda River called Birahi Ganga was blocked by ~5000 million tons of rock mass that rolled from 900 m high valley flank. The debris blocked the river forming a lake which was around 270 m high, 3 km wide at the base and 600 m wide at the summit (Holland, 1894). The untiring efforts of Lt. Col. Pulford, the then superintending engineer meticulously estimated the magnitude of downstream inundation. An excellent telegraph system was installed between Birahi Ganga to Haridwar for real time monitoring and timely warning of the flood which predicted that the landslide dam would partially breach during August 1894. As predicted, on 25th August 1894, water began to trickle over the dam and at midnight the dam was partially collapsed, sending flood surges downstream. The flood lasted until the morning of 26th August causing unprecedented damage to the property around Srinagar town; however, there was no loss of life reported.

(ii) Alaknanda Flood: During July 1970, (after 76 years) Alaknanda valley witnessed the second major flood. The flood was triggered by a cloudburst on Kunwari Pass (PT-2) from the watershed proximal to the MCT in the Alaknanda valley. According to an estimate, flood transported about 15.9x106 tonnes of sediment in one day (Kumar and Shone, 1970). The catastrophe was so large that it filled the Gohna lake with the flood sediment and wiped out ~10 km stretches of Badrinath highway

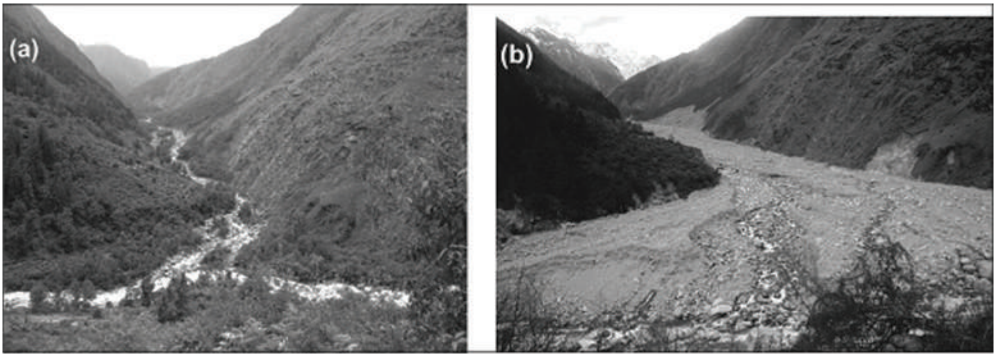


Figure 6. Khiro Ganga a river traversing through paraglacial zone (north of the PT-2). (A) Before June 2013 flood and (B) after the flood. Note the volume of sediment mobilized in overnight flood (after Sundriyal et al., 2015).

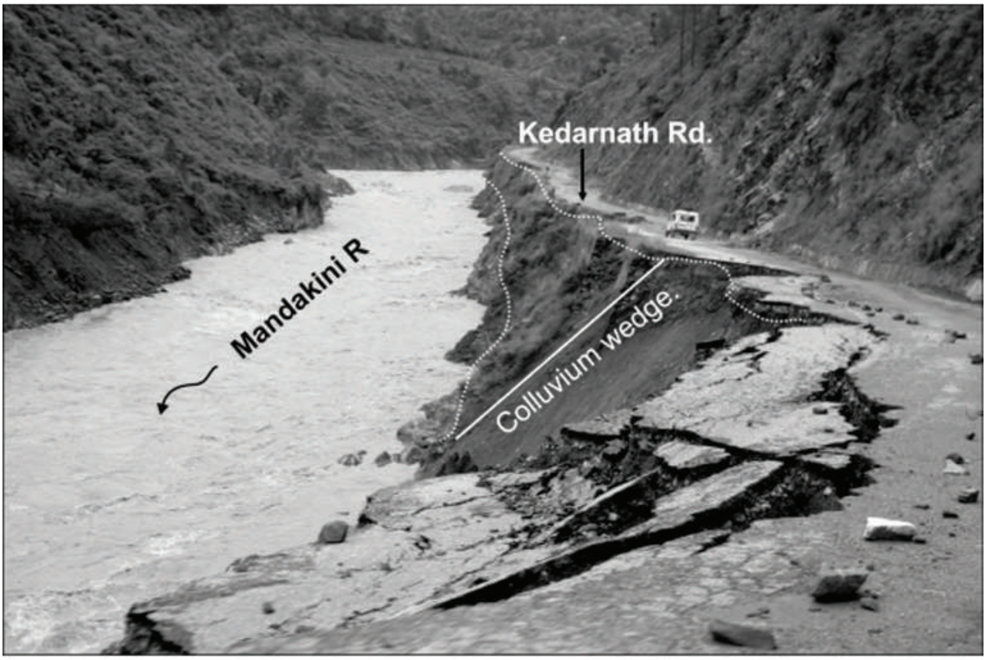


Figure 7. Roads proximal to the flood level in Himalaya are subjected to damage during extreme weather event. This is an example of Kedarnath road that was constructed on loose colluvium. During June 2013, flood water swept away many such stretches of the Kedarnath road.

along with a convoy of 30 buses and thirteen bridges were swept away in the torrent of the flood water. Further, downstream at Haridwar (located 300 km from Ghona lake), 10 km stretch of the Ganga canal was clogged with sediment and uprooted trees transported largely from the Higher Himalaya (Rana et al., 2013).

(iii) ***Kanodia Gad Flood (Bhagirathi Valley):*** On the midnight of 6th August 1978, a massive landslide in the MCT zone obstructed the Bhagirathi River. The landslide was triggered in the paraglacial zone of Kanodia Gad (rivulet) (around Gairaridhar; ~4000 m) and travelled ~4 km to the confluence of the Bhagirathi River where it blocked the river for about 14 hours. Around 175 m wide rampart of rocks and debris formed a lake 35 m deep, 45 m wide, and ~3 km in length. The water began to overtop the landslide dam on 10th August and the breaching occurred on 11th August 1978 that caused large-scale downstream destruction (Agarwal and Chak 1991).

(iv) ***Mandakini Flood:*** During the June 2013, majority of the rivers in Uttarakhand Himalaya were clogged by unprecedented sediment fluxes among which the Mandakini valley witnessed maximum loss of life. The flood was triggered by the extreme weather event caused by the interaction of the westerly disturbances

and ISM over the PT-2, which led to the mobilization of paraglacial sediments (moraines, alluvial fans, and landslide deposits). Although the flood was triggered by meteorological phenomena, the flood furry was amplified due to the proliferation of settlements and series of partially constructed barrages on the riverbed.

With the growing population, infrastructure demand has taken a quantum jump in Uttarakhand Himalaya. With paucity of safe accommodation space, many a times we are compelled to occupy the areas that are proximal to river bed. The projection based on 1000-year flood history from the upper Ganga catchment indicated that large floods generated by LLOFs, and heavy rainfall (similar to June 2013 Kedarnath disaster) will continue, and may increase in frequency (Wasson et al., 2013). If that happens, our infrastructures are going to become extremely vulnerable.

Recurrent Seismicity: During the last 100 years, earthquakes of magnitude >7.5 jolted Assam (1950), Bihar (1934) and Kangra valley (1905) in Himachal Pradesh. However, Uttarakhand Himalaya is yet to face high magnitude earthquakes (>7.5) hence is called the Central Himalayan seismic gap. The absence of large seismic events in this region for more than 200–500 year, despite Indo-Eurasian convergence of ~20 mm/yr (Bilham et al., 1997), has led many to suggest that this region is primed for a great earthquake. Although the vulnerability of this region to large earthquakes has been identified for quite some time, the active tectonic structures that could potentially host a large seismic event remain poorly understood. Although there is a suggestion that seismicity has progressed southward, studies suggest increasing evidence of seismic activity within the hinterland. In particular, there has been increasing evidence for significant active deformation along the base of the high Himalaya, ~100

Figure 8. Natural depression (Khal) on the saddle in Pinder River valley acts as spring recharge pond. Such depressions were extensively used by the villagers for recharging their springs. A tradition which is gradually decaying.

km north of the Main Frontal Thrust.

Rainfed and Meltwater Springs: The natural springs are considered as the life line of the people living in the Himalayan region for centuries. They are the source of around 60% freshwater for the majority of the mountain population and around 64% irrigation is done through these springs. According to an estimate, there are around 5 million springs in the Indian part of the Himalaya. Thus, the springs have a much broader role in the mountain ecosystem and socio-economic development. These springs are currently under threat due multifarious intervention in the catchment of the springs, particularly disruption of the subterranean water by disruption of slopes (natural and anthropogenic), increased surface runoff due to deforestation and poor maintenance of the recharge areas.

Since time immemorial, drinking water to the villages are supplied by the natural springs that are recharged in the upper reaches which were usually covered with good forests. This fact was well known to the local people hence they protected the saddles with shallow geomorphological depressions *(Khals)* (Fig. 8). These were natural rainwater harvesting bodies which were meticulously protected from undue tempering. We have the tradition of *Naulas* in Uttarakhand going back to 6-7th century and are still functional in some parts. They were considered scared so that they can be protected from undue tempering and pollution. With time this rich tradition of spring recharge methods which has a blending of traditional wisdom and religious belief has decayed consequently there is a severity of the crises for potable water in Uttarakhand villages. The concern of depleting village springs echoed in the 'Niti Ayog' report *"A Summary Report Contributing to Sustainable Development in the Indian Himalayan Region (2018)*. The report says that out of ~5 million springs in the Himalayas, one third are drying up and more than half have witnessed decline in water discharge. This is a matter of serious concern hence they have suggested that we must opt for a new paradigm that combines watersheds and aquifers to form a spring-shed. Himalayan ranges are intensely folded and faulted, thus the surface water flow direction (as defined by watershed boundaries), usually follow the sub-surface geological boundary conditions which determine the spring water movement. The earlier water conservation programs were largely based on the concept of watershed which predominantly accounts for surface water movement over the slopes. The movement of spring water (groundwater) is controlled by various factors (e.g., subsurface geology, nature and distribution of fractures, slope). Therefore, the conventional concept of watershed for spring recharge cannot account for water which flows beyond the watershed boundaries. Therefore, Niti Ayog is of the opinion that for Himalayan spring revival, we should adopt the spring-shed (often cover more than one watershed) approach implying that we must know the area of recharge area and the area of discharge.

In the higher and Trans Himalaya snow melt, and at places cirque glaciers feed the village streams. There are already indications that the discharge from glaciers fed streams is not only showing a declining trend but at times highly unpredictable. This has led to adverse impact on the food security in the Trans Himalayan villages because the local irrigation systems are failing due to erratic water contribution from these streams. The Trans Himalayan villages of

Uttarakhand require a different approach for the sustenance of their water supply by harvesting water for snow as demonstrated by Chewang Norphel- a local resident in Leh town. He suggested the noble idea of creating artificial glaciers by arresting the stream flows in the artificial ponds so that in winter it freezes and forms miniature ice sheets. This sheet provides irrigation water to the villagers during the summer. The results of this experiment are quite encouraging and must be replicated in the Trans Himalayan region of Uttarakhand.

Hydropower Projects: Hydropower comprises about 16% of electricity generation globally but close to 100%, in many mountainous countries (IHA, 2018). Under the climate change scenario, hydropower operations are expected to be affected by changes in runoff from glaciers and snow cover. In India, it is feared that the snow and glacier runoff to hydropower plants is projected to decline in several basins. According to the report of the Ravi Chopra Committee (2014) on hydropower projects in Uttarakhand Himalaya, the government plans to harness ~27,000 MW of potential hydropower from its rivers by constructing ~450 hydropower projects. Currently 92 projects with a total installed capacity of ~3624 MW have been commissioned and ~38 projects are under construction. If we investigate the nature of distribution of the proposed hydropower projects in Uttarakhand, nearly 22 are planned above 3000 m elevation in paraglacial zones (areas vacated by the glaciers), 44 are between 3000 and 2500 m (between paraglacial and winter snow line zone), whereas 54 are proposed between 2500 and 2000 m elevation (around the zone of winter snow line). This implies that the projects would largely populate the higher Himalayan region dominated by paraglacial process (discussed above). Considering that the paraglacial zones in Himalaya are experiencing increasing instability (discussed above), provision should be made to integrate the likely impact of paraglacial sediment mobilization on the hydropower projects.

Figure 9. Sarnul village in Yamuna valley still able to irrigate their field by rivulet which receives water from the upper catchment which is adequately covered with forest and well protected by the villagers.

Agricultural Productivity: High mountains have supported agricultural livelihoods for centuries. Rural communities are dependent on adequate levels of soil moisture at planting time, derived in part from irrigation water which includes rainwater fed streams (Fig. 9), glacier and snowmelt. Thus, the high-altitude mountain communities are extremely vulnerable to the impacts of climate change in the cryosphere (Rasul and Molden, 2019). These observations indicate that streamflow when required for irrigation is not there because of early melting of glaciers. This led to the reduction in agricultural yields in several mountain areas. In addition to the effects on agriculture of changing availability of irrigation water, it has been observed in Nepal Himalaya that reduction in snow cover have impacted the agriculture productivity through its direct effects on soil moisture. Rising air temperatures increase crop evapotranspiration, thus increasing water demand for crop production to maintain optimal yield.

To cope with the reduced water supplies, there is a steady decline in the agricultural area in Nepal. Adaptation responses within irrigation systems include the adoption of new irrigation technologies or upgrading existing technologies, water conservation measures, water rationing, constructing water storage infrastructure, and change in cropping patterns. In the prehistoric and historic times, climate change forced people to adapt new draught resistance crops- a classical example can be found in the Bronze Age Harappan civilization. Already people are experimenting with new crops and varieties as an adaptation response in several regions. Farmers in northwest India have increased production of lentils and vegetables, which provide important nutrients to the local diet, with support from government watershed improvement programs which help address decreased availability of irrigation water, though stringent requirements for participation in the programs have limited access by poor households to this assistance.

Summary:

Glaciers are the sensitive recorders of climate change and provide a direct indication of the warming climate. Although the response time in absolute term is still uncertain however, it is suggested that small glaciers (<5 km) compared to the large one responds too readily. Existing data point towards worldwide retreat of many glaciers during the past few decades. However, a more definite inference towards glacier health with respect to the global warming projection would require concerted efforts using multidisciplinary and multitemporal approach. Towards this, at least ten benchmark glaciers covering wider geographical and climatic domain in the Himalayan region should be selected for long-term monitoring and scientific investigation.

The limited studies on past and recent floods indicate that they are generated by two major processes viz. the mobilization of paraglacial sediment during extreme weather events and breaching of landslide impounded dams on the rivers. Under the climate change scenarios, it is being hypothesized that the sediment mobilization from paraglacial zone is likely to increase which may cause significant destruction in the lower valley as observed during the June 2013 Kedarnath disaster and more recently the 7th Feb 2021 Rishi Ganga flood. Therefore, considering the vulnerability of paraglacial environments, the effects of contemporary climate change is likely to be severe. There is explicit relationship between glacier retreat and paraglacial landscape relaxation, as measured by sediment movement and geomorphological change within mountain landscapes. However, there has been little consideration of how paraglacial environments in their totality will evolve under ongoing climate change and impact the lower valleys.

Mountain geohazards can be considered as one of the important high-magnitude end members of paraglacial responses to climate warming such as rockfalls, landslides and GLOFs. Changes in proglacial lake area are now being monitored in many areas of the Himalaya because of the danger of GLOFs, which can generate potentially devastating floods. The predictability of GLOFs events is although difficult however the fact remains that GLOFs are likely to be more frequent in future.

In the monsoon dominated Himalayan valleys, climate simulation model indicates increasing frequencies of extreme weather events. Such events are likely to cross over the PT-2 into the paraglacial zones consequently there would be large-scale mobilization of unstable paraglacial sediment and would inflict severe damage to the buildup structures as observed during June 2013 event in Mandakini valley and more recently the in the Rishi /Dhauli Ganga valley.

As a consequence of compressional tectonics, Himalaya in general, and Uttarakhand Himalaya in particular, is inherently vulnerable to the earthquake in which the central Himalaya (Uttarakhand) is due for a major earthquake. Regardless of whether earthquakes are or are not predicted, objectively a prediction does not change the risk factor instead it provides more information about the nature of the risk. Given the fact that there is a quantum jump in the population density in Uttarakhand Himalaya any future earthquake is likely to have a significantly large casualty. Therefore, it is essential that the mitigation planning should not wait for short- or long-term predictions. We can start right now with demarcating the terrain vulnerable to earthquake turmoil. The houses (individual and community) should be reinforced with the earthquake resistance technologies. In addition to this, we have reasonable idea about the response of slopes to earthquake turmoil, such valleys must be clearly demarcated particularly the streams that are likely to get impounded by earthquake triggered slope destabilization. People living in such valleys should be educated about the threat perception so that they desist from making houses in areas of potential landslide and flash flood threats. This is essentially a concept of not frightening but *"living with the earthquakes"* as our ancestors did for centuries.

Climate change is impacting the village water springs and coupled with poor understanding of the terrain, lack of scientific data on the carrying capacity, natural resource availability, land use landcover changes are accelerating the process of drying up of village springs. According to a recent study the scarcity may accelerate the already prevailing outmigration from the hills in regions and in the long term, and several conflicts among different classes, groups, and inhabitants may arise, although there is an ambitious plan of proving uninterrupted water supply to the villages through pipelines. Government of India has earmarked about Rs. 90,000 crores to provide drinking water to the rural population through the National Rural Drinking Water Programme (NRDWP). We fear that if we do not have the ecological and geological data base with clear demarcation of the spring shed recharge areas, we may vitiate the delicate balance between the recharge and discharge areas by engineering infrastructures such as making collection ponds, laying down pipes etc. Though it looked quite impressive that every household will have a water tap, but our experience shows that unless we understand both the recharge and the discharge areas, the desired results would be difficult to achieve. CAG report already pointed out some discrepancies in planning and execution, of this ambitious and extremely important initiative of the Government of India.

We require clean energy and must harness the hydropower potential of the Himalayan rivers for the economic growth of the nation. However, at the same time we cannot ignore the geological and geomorphological boundary condition along with the protection of unique biodiversity of the region. Most importantly for the viability and longevity of hydropower projects, long-term flood data is crucial to understand the behavior of a river and to devise a methodology to safeguard barrages, dams and related infrastructures. In the Himalayan region, there is a paucity of time-series flood records and therefore, to extend the instrumental archives, sedimentological evidence of past floods – slack water/palaeo-flood deposits are used. Climate change has become a reality and impulses of global warming are already being registered in the Himalayan cryosphere. A recent study published in Nature Geoscience by Li et al., (2022) warned that the stability of paraglacial zones both in terms of volume and timing of water delivery and unexpected sediment fluxes in the lower valleys. The study further cautions that large amounts of sediment being mobilized can fill up reservoirs, cause dam failure and degrade power turbines. Thus, a forward-looking design and maintenance measures and sustainable sediment management solutions are recommended that can help transition towards climate change-resilient dams and reservoirs in High Mountain Asia. The above suggestions are important considering the fact that Uttarakhand Himalaya was one of the worst sufferers in terms of the damage caused to the dams and barrages during the June 2013 and the February 2021 flash floods. Although the floods in Himalaya are triggered by high intensity rainfall event, but in the higher altitude (paraglacial areas) the GLOF is a potential threat posed in the recent times. The magnitude of flash floods gets significantly amplified if the rivers drain through sediment surplus zones (paraglacial).

Threat posed by climate change is looming over the Himalayan terrain. An assessment of the spatial and temporal changes in temperature and precipitation should be documented from various watersheds to evaluate the futuristic trend. The meteorological data would help in assessing the response of current cropping pattern and finding ways for a scientific intervention. For example, if there is a need for changing the existing cropping patterns from local consumption crop to the one which can create a steady cash flow such as pulses in areas of rain fed agriculture and vegetables in areas where water availability

Niti valley women council (Dhauliganga), gathered at community center for chalking out plan for a community festival exists. However, the prerequisite is the base line information on parameters influencing the crop patterns under present climatic condition and how they would respond if there were shift in temperature, humidity, precipitation and snow fall. These data should be evaluated with the traditional agricultural practices before proposing new interventions.

The phenomenon of climate change has emerged as a serious threat to the ecosystem service link of the Himalaya. Besides its role as climate regulator, increase in the frequency of extreme weather events, change in the rate of denudation, species migration, invasion of alien species and threat to endemic species have posed challenge to the role of the Himalaya as an ecosystem service provider. This has caused serious threat to the livelihood issues of the communities living in the Himalaya region particularly the women. This concern is eloquently echoed in the UPAPCC report (2014) showing great concern for the women in the hills as they are likely to be the hardest hit by climate change. In view of this, *Government policies and programs should have to be gender-responsive so that benefits flow to vulnerable women in the IHR.*

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G.B. Pant Memorial Lectures

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Dr. M.S. Swaminathan, Director, CRSARD, Madras - 1991

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Dr. T.N. Khoshoo, Jawaharlal Nehru Fellow, TERI, New Delhi – 1992

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Mr. V. Rajagopalan, Vice President, World Bank, Washington – 1993

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Prof. U.R. Rao, Member, Space Commission, New Delhi – 1994

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Dr. S.Z. Qasim, Member, Planning Commission, New Delhi – 1995

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Prof. S.K. Joshi, Vikram Sarabhai Professor, JNCASR, Bangalore – 1996

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Prof. V.K. Gaur, Distinguished Professor, IIA, Bangalore – 1998

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Prof. J.S. Singh, Emeritus Professor, BHU, Varanasi – 2004

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Prof. Madhav Gadgil, Centre for Ecological Sciences, IISc, Bangalore – 2005

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Dr. S.S. Handa, Ex-Director, PRL (CSIR), Jammu – 2006

XIII
Dr. Lalji Singh, Director, CCMB, Hyderabad – 2007

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Prof. Roddam Narasimha, Chairman, FMU, JNCASR, Bangalore – 2008

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Dr. R.S. Tolia, Chief Information Commissioner, Govt. of Uttarakhand, Dehradun – 2009

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Prof. Raghavendra Gadagkar, CES & CCS, IISC, Bangalore – 2010

XVII
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XIX
Prof. Jayanta Bandopadhyay, Former Prof. & Head, IIM, Calcutta – 2013

XX
Prof. T.S. Papola, Institute for Studies in Industrial Development, New Delhi - 2014

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Dr. David Moulden, Director General, ICIMOD, Nepal - 2015

XXII
Dr. Vijay Raghavan, Secretary, Department of Biotechnology, New Delhi - 2016

XXIII
Prof. S.P. Singh, Former Vice-Chancellor, HNB Garhwal University, Uttarakhand - 2017

XXIV
Prof. P.S. Roy, Former Director, Indian Institute of Remote Sensing, Dehradun – 2018

XXV
Prof. Raman Sukumar, Professor of Ecology, Indian Institute of Science, Bangalore – 2019

XXVI
Prof. Tej Pratap, Vice Chancellor, G.B. Pant University of Agriculture and Technology, Pantnagar – 2020

XXVII
Prof. R. Raghavendra Rao, Chairman, Karnataka State Environmental Appraisal Committee - 2021