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ISSUE BRIEF
IB/25/25

INTEGRATED UAVS AND GIS FOR ENVIRONMENTAL SECURITY OF GLACIATED REGIONS

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Introduction

The glaciated region is crucial for the climate as well as the security of India.[1] Glaciers are perennial features that temporarily store, freeze and hold freshwater as a thick mass of crystalline ice and snow on the land. Globally, mountain glaciers are losing ice mass in the early 21st century at double the rate of the end of the previous century.[2] Rising high temperatures are pushing glacier retreat badly, spawning unstable glacial lakes, and triggering many disasters that endanger villages, hydropower projects, and even the forward posts of the Indian Armed Forces.[3] However, climate change is rapidly transforming this high-altitude shield. Employing Unmanned Aerial Vehicles (UAVs) is an effective technique for real-time data collection with ultra-high resolution, and Geographic Information Systems (GIS) is a dynamic analytical tool for monitoring the ground and providing decision-making support.[4] In today's hyperconnected, advanced world, data and monitoring play a crucial role in every aspect, and collecting data at the appropriate time is more fruitful for initiatives & accomplishing any effective action. Collecting data at high altitudes above the snow line in glaciated regions is very difficult. Due to the complex and dynamic nature of glacier geology, data is obtained from multiple sources, as no single method can capture every feature.[5]

Glacier environmental security requires using GIS, UAVs and satellite imagery fusion to capture glacier movements, such as frost area, average elevation, ice volume and density over time.[6] This monitoring is essential for understanding the impacts of both slow and rapid climate change, managing water resources channels, assessing risks associated with melting glaciers, and generating new features. It is a fragile and unexplored frontier, where environmental risks align with strategic necessities, and technology is increasingly becoming a crucial ally. Integration of UAVs and Geographic Information Systems (GIS) for Climate Security of Glaciers enables ultra-high-resolution, real-time monitoring of glacial retreat, avalanches, lake expansion, movement and shifting terrain in areas where satellites lack details and ground surveys are perilous, as well as near impossible sometimes through a single model approach.[7] UAVs and drones for data collection offer ease of use, vertical take-off and landing capabilities, and the ability to operate in hard-to-reach and glaciated areas. These online connected methods of monitoring are not only scientific tools but also dynamic tactical assets for protecting critical infrastructure in the mountains, supporting military operations at high altitudes, calculating all possible routes, and strengthening disaster preparedness at the world's most geographically volatile, vulnerable, and risky landform on earth.[8]

GIS without UAVs and the Traditional Approach

Geographic Information Systems is an essential and powerful tool that performs on satellite data, ground features, digital mapping, and ground data to monitor fragile high-altitude ecosystems.[9] In a glaciated region, GIS works on multi-temporal data through satellites like Landsat (since 1972). It helps to provide a long-term record of glacier area and retreat in the form of Sentinel-1 and Sentinel-2, which supply moderate-resolution optical data of snow cover level, average ice flow, and glacial lakes. India's Cartosat satellite delivers detailed topographic features, enabling the study of high-altitude surface changes and moraine-dammed lakes in the Himalayas' glaciated region.[10] By processing this data, GIS can calculate glacier length and width, average volume loss, snowline level shifts, and even monitor risk-related hazards such as Glacial Lake Outburst Flood (GLOF) and other features at high altitudes. In fact, Landsat data represent how Himalayan glaciers have lost about forty per cent of their area since the Little Ice Age (LIA).[11]

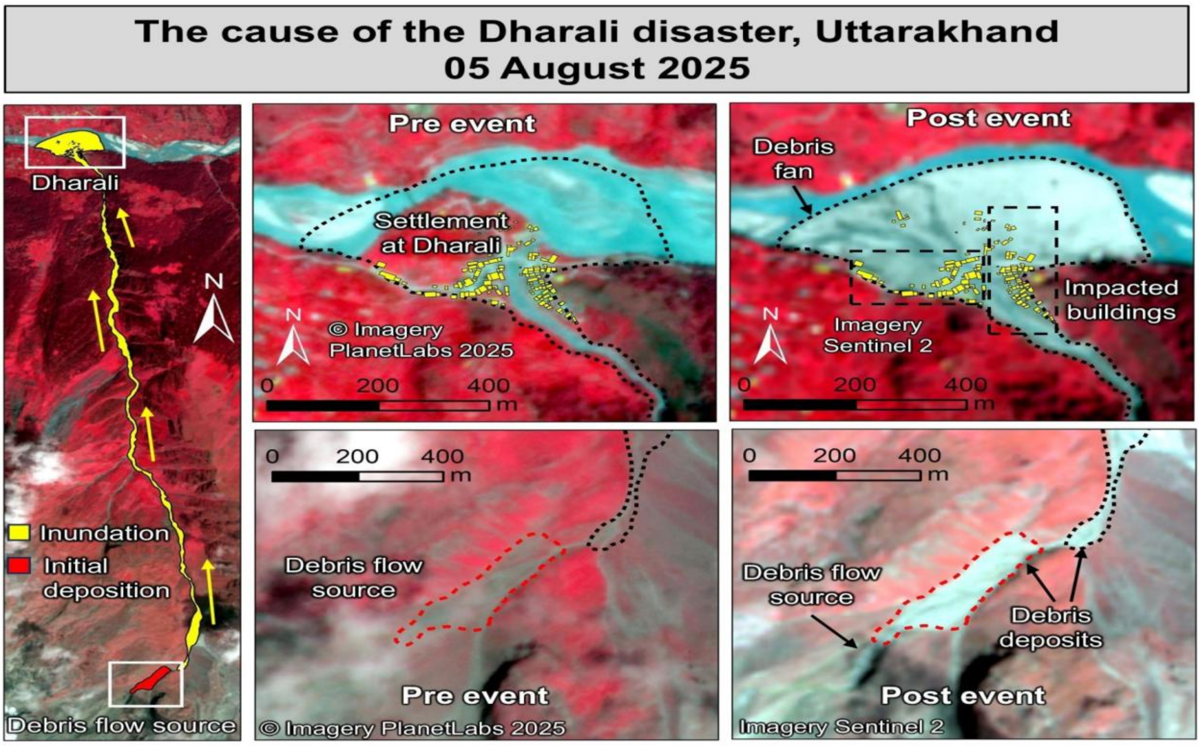

Image 1: Sentinel 1 and 2 images of the Dharali cloud burst and flash flood disaster 2025, Uttarakhand, India. Source: Dr. Ashim Sattar, IIT Bhubaneswar.

Satellite radar information is used to detect the movement, changes and structure of snow-covered crevasses. Cartosat imagery has been vital in mapping high-risk lakes, such as South Lhonak in Sikkim, which experienced an outburst in 2023.[12] This approach has its limitations due to cloud cover and disturbed weather conditions, as optical satellites cannot see through, leading to a data void and temporary gaps in satellite data due to revisit limitations. As can be easily seen in image 1, the Sentinel 1 and 2 datasets of the Dharali cloud burst and flash flood disaster of 2025 are not visible and have fewer features. Shuttle Radar Topography Mission (SRTM) and CartoSAT provide broader Digital Elevation Models (DEMs), but vertical errors (±10–30 m) make them unsuitable for fine glacier hazard mapping and monitoring.[13] Thus, even before UAVs added micro-level precision, GIS provided the strategic foundation layers for climate adaptation, disaster preparedness, and safeguarding national and regional security in the Himalayas.[14]

GIS with UAVs and the New Approach for Environmental Security

Unmanned Aerial Vehicles (UAVs) and Remote Sensing (RS) technology are gaining popularity among academicians, researchers, and scientists because they can be deployed at short notice, unlike waiting for the next satellite pass.[15] Additionally, UAVs are useful for avalanche rescue, GLOF warnings, and movement route planning because they can fly from very low to the ground and capture micro features. The challenges related to flying in high altitudes due to rugged terrains are hindering the progress of UAVs in glacier research, especially glaciers in high mountain regions such as the Himalayas.[16] The existing spaceborne RS platforms have many limitations for collecting individual glacier level accurate data at high resolutions, despite having numerous advantages for global-scale glacier monitoring. UAVs, as a remote sensing platform, can fly below the clouds and are easily portable, offering enormous potential to augment sparse and discontinuous field observations by providing ultra-high-resolution images at relatively low costs and gathering all essential features and information.[17] This potential has led to new facets in acquiring UAV-based remote sensing data, such as the availability of ultra-high-resolution data, comprehensive spectral and geometric data, and the fusion of multi-sensor data. The integration of UAVs into GIS has transformed glacier and Himalayan monitoring by adding near-real-time, high-resolution, and micro-scale insights to traditional satellite-based methods. Landsat, Sentinel, and Cartosat satellites provide large-scale trends and patterns, but due to clouds, there is some error. UAVs can fly at low altitudes and capture 1cm imagery, thermal data, moraine-dammed lakes, LiDAR scans of glaciers, and crevasse structures. This enables scientists to check rapid changes such as fresh cracks, sudden avalanches, or unstable glacial lakes, which helps in quick decision-making during emergencies, critical for preventing glacial risks. UAV-mounted sensors also allow continuous 3D mapping of glacier surfaces, snow accumulation, and ice melt, which feeds directly into GIS models for risk assessment, hydrological forecasting, and climate simulations. The thermal cameras can easily detect crevasse edges under snow. LiDAR penetrates canopy/loose snow for precise surface models.[18]

In recent years, UAV surveys in the Himalayas and Karakoram region have been used to identify hidden sub-surface water channels, monitor fast-changing lakes like Imja (Nepal), and provide local authorities with disaster early-warning data within hours instead of weeks. The combination of UAVs and GIS fusion helps in strengthening environmental security monitoring, ensuring quick disaster response, rapid recovery, and protection of downstream people who depend on glacier-melt streams. This combination supports national security by reducing vulnerabilities linked to climate change, water scarcity, and ecological instability through enhanced monitoring and surveillance. By fusing macro-scale satellite data along with micro-scale UAV mapping, GIS now offers a holistic and adaptive framework for safeguarding the fragile Himalayan environment.[19]

Make in India UAVs: High-Altitude Capabilities

India's emerging drone and UAV ecosystem is witnessing rapid growth under the 'Make in India' and Atmanirbhar Bharat initiatives for pushing toward 100% indigenisation of drone manufacturing.[20] At high altitude, UAVs face several challenges, including reduced lift, power, and endurance, as well as difficulties with extreme weather, navigation, and sensor issues, which complicate data collection operations. The Hindu Kush Himalaya (HKH) comprises many glaciers, covering 60,000 km^2, and contributes nearly forty per cent of the Indus River flow.[21] Climate change urgency adds new pressure to the Himalayas between 2011 and 2020 as glaciers in the HKH region melted sixty-five per cent faster than in the previous decade.[22] Drones, by flying low and frequently, are now critical for capturing near-real-time micro-changes, providing data vital for both scientific modelling and military preparedness. To enhance environmental security on glaciers, several projects are underway to design, improve, and build high-altitude drones and UAVs within the country, aiming to develop High Altitude Long-Endurance (HALE) systems successfully. They are becoming increasingly crucial for monitoring terrain, gathering real-time data, and aiding disaster relief efforts in challenging mountainous regions. Under the Make in India programme, the SWITCH VTOL UAV, developed by IdeaForge, has been inducted by the Indian Army for glacier operations. It has two hours of endurance, fifteen km of line-of-sight range, and is engineered to withstand freezing winds and sub-zero conditions.[23]

As highlighted in the report "Indigenisation of Critical Components Currently Being Imported from Foreign OEMs in UAVs & C-UAS*"* by HQ IDS[24], in collaboration with the Centre for Joint Warfare Studies (CENJOWS)*,* India's focus is on building 100% self-reliance in UAV and drone technology. It's an outstanding flagship achievement for TAPAS MALE UAV, an advanced indigenous surveillance platform for tri-services use. The TAPAS is carrying payloads such as Electro-Optical Pods, Synthetic Aperture Radar/Maritime Patrol Radar, Automatic Identification System, Electronic Support Measures, and SATCOM. It can fly at 225 kmph, reach 30,000 ft, and has a range of 250 km and 1000 km (SATCOM).[25] The capabilities of indigenous developed UAVs are as follows:

UAVs Names	Type	Altitude Capability	Endurance	Special Features	Developer
TAPAS-BH[26]	MALE UAV	28,000 ft	18–24 hrs	EO & SAR, ISR, capable of operating in varied terrains	DRDO-ADE
Archer NG[27]	MALE Combat UAV	30,000 ft	24 hrs	Ground data terminal and weaponised with precision strike ability	DRDO+HAL
CATS Warrior (loyal wingman)[28]	UCAV	30,000–35,000 ft	8 hrs	Fifth-generation unmanned wingman drone.	HAL
High-Altitude Pseudo Satellite(HAPS)[29] **DRDO**	Solar-powered UAV	65,000 ft and above	Weeks to months	Persistent surveillance, communication relay	ADE (concept under development)
SWiFT Ghatak[30]	UCAV	30,000 ft	2–5 hrs	Stealth tech, Autonomous Unmanned Research Aircraft (AURA)	DRDO

UAVs Names	Type	Altitude Capability	Endurance	Special Features	Developer
Private Startups (ideaForge, NewSpace, Garuda Aerospace)[31]	Mini & Tactical UAVs	15,000–20,000 ft	2–8 hrs	Lightweight, portable, high-altitude optimised	Startups with defence orders

Table 01: India's drone capabilities developed and under development data set. Compiled by Author

GIS Fusion with UAVs and Satellite Data for Glacier Security

Glaciers are in critical condition due to global warming and monitoring is a crucial factor for understanding the behaviour of climate change. At a very high pace, upper glacier surface moments are visible due to high temperature, low ice density and other geological factors. Analysing water flow, air pressure changes, moments, and natural hazards to identify new exposures.[32] Conventional patterns or methods, such as field-based monitoring, are often limited by the remoteness and hazardous nature of high altitude, making them more expensive and potentially high-risk.[33] The combination of moderate-resolution satellite imagery and high-resolution UAV imagery offers a comprehensive solution for analysing the glacier ecosystem. This is achieved through strong data analysis, which generates integrated layers of both datasets and yields a variety of outcomes and possibilities. It is beneficial for a deep understanding of micro-level objects.

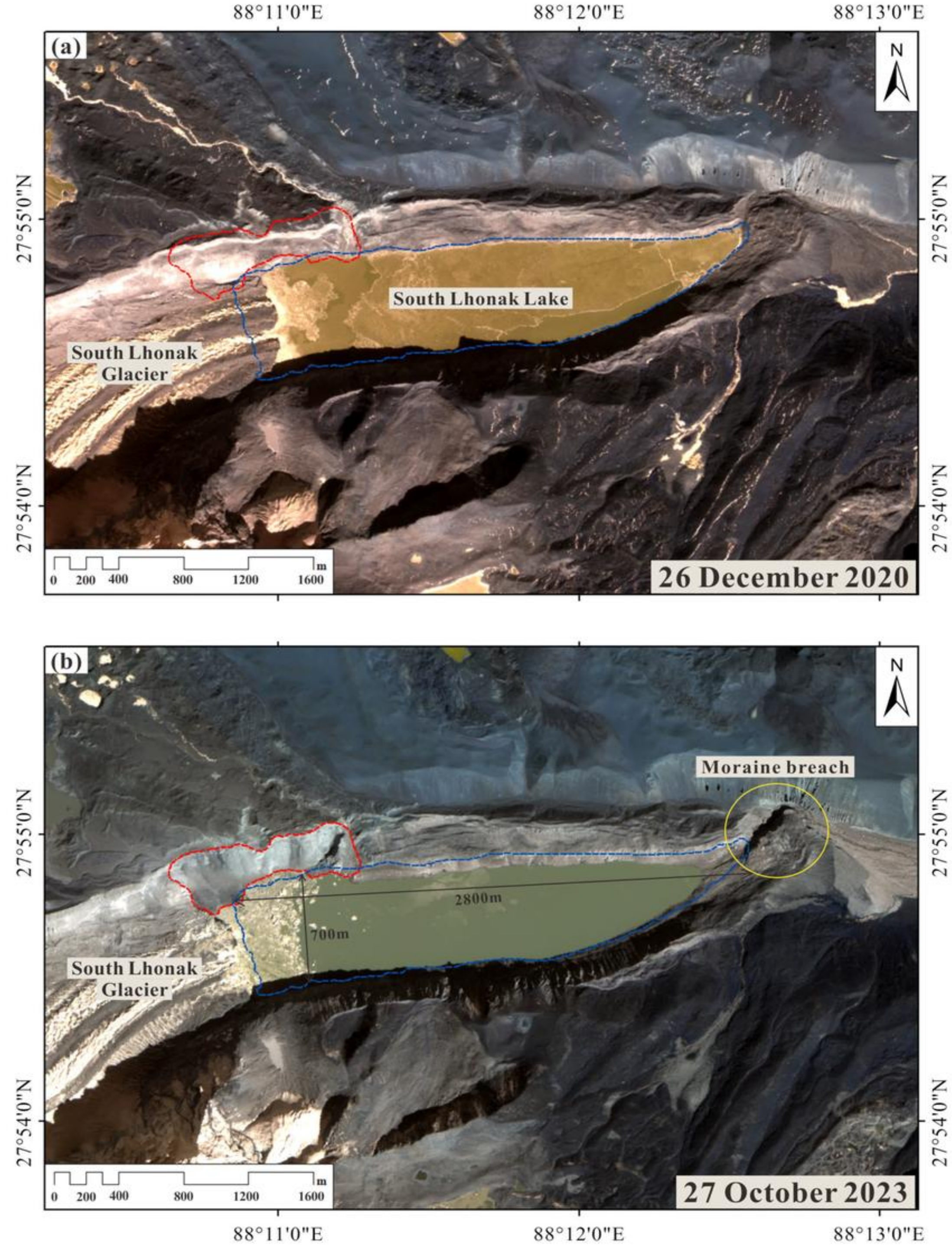

Image 2: Retrospective Analysis of Glacial Lake Outburst Flood (GLOF) Using AI Earth InSAR and Optical Images: A Case Study of South Lhonak Lake, Sikkim.
Source: Scientific Figure on ResearchGate

As above image 2 represent the retrospective analysis of Glacial Lake Outburst Flood (GLOF) by Using AI Earth InSAR and Optical Images and combination of both techniques, a Study area of South Lhonak Lake, Sikkim, India, which helps to determine the most effective tools, inputs, and management strategies for enhancing the productivity and resilience of a critical, volatile and unexplored frontier system in response to significant weather or environmental disturbances.

The GIS platform's fusion tool for satellite and UAV datasets also creates multi-scale ecological intelligence.[34] Drones can provide Ortho mosaics with 0.1 to 0.2 m accuracy[35], while Cartosat-3, Sentinel-2, Landsat-9, and Sentinel-1 SAR supply repeatable, region-wide inputs. Himalayan surveys using UAVs have measured elevation changes with <10 cm vertical accuracy when combined with GIS modelling, which aids in detecting glacial lake expansion and surface lowering, an essential early warning for Glacial Lake Outburst Floods (GLOFs) and other glaciated disasters. The latest Harsil-Dharali Cloudburst on 5 August 2025 was a predictable disaster, causing significant damage and displacement in the region. The South Lhonak Lake flood (Sikkim, 2023) as shown in image 2, which caused devastating damage to the region's ecosystem, highlighted the need for real-time monitoring and rapid recovery. Image 2 demonstrates that UAVs and AI-based image processing features performed accordingly.[36] GIS fusion and multiple layers also help policymakers assess patterns and trade-offs between tourism, hydropower, and environmental safety, ensuring that glaciated regions are managed without compromising ecosystem balance, along with fast rescue from any glaciated hazards through mapping the region. Table 02 below compares the UAVs and satellite data in terms of highlighting UAVs' superior performance coverage, revisit time and resolution.

Parameter	**UAVs**	**Sentinel-2**	**Landsat-9**	**Cartosat-3**	**Sentinel-1 (SAR)**
Resolution	cm-level (1–5 cm)	10–60m	15–30 m	0.25 m	5×20 m (IW mode)
Coverage	Few–tens km²/flight	290km swath	185 km swath	16 km swath	250 km swath
Revisit	On demand	5 days	16 days (8 combined)	talkable	6–12 days
Weather Impact	Cloud, wind sensitive	Cloud-limited	Cloud-limited	Cloud-limited	All-weather

Table 02: UAVs and Satellite capabilities comparison. Source: Compiled by Author

Benefits of GIS fusion.

- A combination of both helps in enhancing accuracy and detail. Combining the broad perspective of satellite data with the high-resolution information from drones' results in more accurate and detailed mapping. Easy in modelling and analysis of glacier characteristics patterns. For example, UAVs can improve the accuracy and constrain the results obtained from satellite process images.[37]
- To overcome terrain limitations, as drones can access areas difficult for satellites, such as deep inside valleys, satellite data provides context and covers areas inaccessible to drones due to weather conditions or terrain.[38]
- Data from GIS fusion can be used to calibrate and verify numerical ice-sheet models for improving modelling, leading to more robust predictions of glacier evolution.[39]
- To create informed sustainable stewardship by providing crucial data for climate change analysis and pattern detection, water channel resource management, and help in an early warning system to predict glacial hazards like outburst floods.[40]
- Ultra-High-resolution satellite imagery can be expensive, but equally important, drone technology offers a more affordable option for localised and frequent data collection over time.[41]
- Analysing high-resolution data on ice flow velocities, new surface elevation changes, and the impact of debris cover, helps understand the complex dynamics of glacier systems and their response to climate change for monitoring moments.[42]

Challenges and future directions:

- Integrating data from multiple sources with varying accuracy and formats remains a challenge for standardisation on time, but it can be compiled by using AI (Artificial Intelligence), which requires the development of a specific model.[43]
- To identify take-off/landing locations for conducting efficient UAV surveys using fixed-wing UAVs. Handling the large data set is challenging. From the acquired UAV geotagged images, data products such as ortho-mosaicked images and DEMs were generated using the Pix4D Mapper software version 4.4.9, which

uses the Structure from Motion (SfM) technique. Applying advanced techniques such as Structure from Motion (SfM) for three-dimensional advanced modelling requires expertise and robust software.[44]

- UAV images of Himalayan glaciers pose additional challenges, such as low air pressure and poor GNSS reception for UAVs with automatic navigation at high altitude. Automating the mapping and analysis of glaciers, including debris-covered areas, is crucial for efficiency, as there is a need to improve and develop an automated process system.
- Within mountainous regions, studies demonstrating the UAV applications in Himalayan glaciers remain sparse. Broadening GIS education in glaciology and fostering multidisciplinary collaborations are vital for maximising the potential of GIS fusion, which needs to be enhanced through education and collaboration.
- Improving drone endurance, payload capacity, and navigating challenges in high-altitude environments. Remote and debris-covered terrain are important areas for future research in extreme weather conditions, but drones are not capable of operating in such environments.

Indian Armed Forces in Environmental Security

Global warming and Climate change are rapidly being recognised as a security concern in India (Bharat), and the Indian armed forces are continuously addressing environmental and climate security challenges.[45] In 2017, the Joint Doctrine of the Indian Armed Forces (JDIAF) was released by the Integrated Defence Staff (IDS) to recognise the security implications of environmental disasters and climate change.[46] Indian Armed Forces have many bases on glaciers, such as Siachen Glacier in Ladakh, India, which is home to the world's highest battlefield and features the Indian Army's Siachen Base Camp, located at around 12,000 feet. 102nd Infantry Brigade (Siachen Brigade) is situated on base camp, a unit that is central to both security and environmental stewardship in the glaciated region.[47] Operational experience of dealing with such disruptions on the ground and the consequent strategic thinking on 'non-traditional security threats'. The troops are responsible not only for defending the area but also for implementing environmental protection measures to build a strong ecosystem, including waste management, sustainable development, and conservation efforts. They have advanced technology and ground-based monitoring due to significant technical and physical advancements.

In the Hindu Kush Himalaya (HKH), climate vulnerabilities have doubled in recent years, with implications for military strategy.[48] These severe changes have gradually led to initiatives dealing with mitigating change-related impacts as well as promoting climate-friendly measures within the military. India is known for setting up one of the world's first ecological battalions for the restoration of ecologically degraded regions.[49] More recently, with the worsening effects of climate change and the gaining momentum of climate change narratives and policies, the Indian armed forces have gradually integrated climate concerns into planning and strategy. For planning purposes, these steps are not necessarily tied solely to climate goals but are more seriously targeted at a broader gamut of security objectives, including enhancing resilience in military readiness and preparedness from disasters. Despite the apparent need for more institutional and policy mechanisms targeted at climate security challenges within the Indian Government, there is a lack of effective measures

The Defence Geoinformatics Research Establishment (DGRE) provides an early warning system for avalanches and hazard mapping, and the Indian Meteorological Department delivers six-hourly weather updates for troops.[50] The Indian Armed Forces deploys UAVs for detection, patrol route mapping, avalanche detection, supply drops, and integrating data with GIS to help in better understanding model avalanche corridors.[51] Advanced tactical programs save lives and strengthen terrain readiness. For example, in the Chamoli disaster (2021), nearly 200 people lost their lives, and the Indian Armed Forces utilised UAVs mapping and satellite tasking to coordinate rescue efforts as well as recovery. Through integration of UAVs and satellite data in GIS enables faster decision-making, reduces soldier risk, enhances disaster response capability, and provides environmental security. Thus, the Indian Armed Forces are not only defenders of frontiers but also caretakers of ecological protection in the glaciated region of the Himalayas.[52]

Conclusion

India's glaciers are shrinking rapidly, with a 65% faster melt rate over the last decade and increasing GLOF risks threaten both ecosystems and down valley populations. At the same time, 100+ dams in the Himalayan states are flagged as vulnerable to outburst floods. Satellites for long-term, synoptic coverage: Sentinel-2, Landsat-9, Cartosat-3, Sentinel-1. UAVs for fine-scale, repeatable, and rapid-deployment monitoring. Geographical information systems play the role of an integrator that translates raw imagery into actionable outcomes for early-warning and planning tools.

Investing in cold-resistant batteries, lightweight sensors, and RTK standardisation will enhance the versatility and effectiveness of UAVs & Drones. Meanwhile, integrating GIS alerts with community early-warning systems and decision patterns can directly save lives during GLOFs and avalanches. Which study achieved the highest vertical (horizontal) accuracy, with a range of 0.1–0.25 m (0.03–0.09 m)? Other glacier studies have also used GCPs (varying between seven and seventeen) to generate DEMs at centimetre and decimetre level accuracies. The Indian Armed Forces' decades of experience in dealing with environmental degradation problems and disruptions provide it with a head start on climate action and a deeper understanding of ecological security. Now that it is gradually integrating climate security risks into its planning and strategy, it could set an example for the rest of the world with a more coordinated and institutionalised response. India, by leveraging Make in India UAVs alongside global satellite assets, is well placed to lead in climate-security innovation for high-altitude regions.

Disclaimer

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