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GEO-HAZARD MONITORING, MODELING AND MITIGATION

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From the Desk of Special Editor

Defence Geoinformatics Research Establishment (DGRE) under Soldier Support System (SSS) has been raised on 15 November 2020. DGRE imbibes the responsibilities of erstwhile Snow & Avalanche Study Establishment (SASE), Chandigarh and Defence Terrain Research Laboratory (DTRL), Delhi. With its Headquarter at Chandigarh, DGRE has four Research & Development Centres (RDCs) and five Mountain Meteorological Centres (MMCs) spread over Northwest, Central, and Northeast regions of Indian Himalayas for in-depth geo-hazard research and management.

DGRE is working towards the development of broad spectrum of technologies for mountain geo-hazard mapping, monitoring, prediction, and mitigation. For the management of avalanche hazard in the Indian Himalayan snowbound regions, DGRE has developed technologies and models for weather & avalanche forecasting; snow & meteorological sensors; instrumentation for snow cover monitoring; communication network; and data links for near real-time dissemination of hazard information and critical alerts to the users.

To mitigate the avalanche hazard of strategic areas, DGRE has developed various control measures that includes implementation of avalanche control structures and artificial triggering of avalanches etc. The development & implementation of geospatial tools and techniques for geo-hazard mapping, monitoring and geo-inst generation is another technology domain of DGRE. DGRE is extensively employing multi-source remote sensing data (optical, thermal and microwave) for mapping, detection and monitoring of avalanches and landslides.

Physical and statistical modelling of the snow, avalanches and landslides is another important research domain of DGRE. These models provide the better insight to avalanche and landslide problems, which leads to effective implementation of geo-hazard mitigation measures.

Previous issue of Technology Focus on "Mountain Geo-hazard Mapping and Geo-Intelligence" highlights the technologies for mapping and monitoring of mountain geo-hazards. The current edition of technology focus entitled, "Geo-hazard Monitoring, Modeling and Mitigation" reveals the key enabling technologies developed by DGRE in recent years towards mountain geo-hazards management and prevention and are expected to serve the reference for future developments.

I'm extremely delighted with the dedicated efforts that are continuously being put by DGRE team in developing technologies & products and services for geo-hazard management to fulfil the crucial operational requirements of the Users and exhort DGRE to continue the excellent work towards the complete safety from geo-hazards in Indian Himalaya.

Dr Upendra Kumar Singh
Distinguished Scientist & Director General
Soldier Support System (SSS)

From the Desk of Guest Editor

DGRE is the only establishment of its kind working on the technologies for geo-hazard management with a focus on avalanches and landslides for safe movement of the Armed Forces. DGRE is striving to ensure safe mobility of troops in inhospitable terrains with a focus on enhancing military potential and combat effectiveness in various types of terrains based on niche techniques. DGRE has its Area of Responsibility (AOR) along all major land border areas in states/UTs including Jammu & Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh. Major users of DGRE are Armed Forces, Para-Military Forces, MoRTH, BRO and other Central and State Government Departments.

Snow avalanches are prominent natural hazards in mountainous regions of Indian Himalaya. DGRE has developed the technologies for identification, mapping, control of the mountain geo-hazards and it provides operational weather and avalanche forecasting services to the users. These technologies and services play a critical role in planning and decision-making by defence establishments as well as civil authorities in their operations.

Accurate observations of snow, meteorological and avalanche parameters are important inputs in the process of geo-hazard estimation, forecasting, and mitigation. To achieve this, DGRE has developed a network of manual snow-met observatories as well as Automatic Weather Stations (AWS) in the Himalayan region to collect data on a wide range of atmospheric and snow parameters. Further, DGRE has designed the network of 348 AWS keeping the geo-hazards in mind along with important road networks and community settlements.

Different kinds of avalanche control structures have been designed, developed and implemented by DGRE to mitigate avalanche hazards. DGRE has also provided technical consultancies to infrastructure development agencies for implantation of various avalanche mitigation measures.

The extensive analysis and susceptibility mapping of landslide prone regions and control release of weak zones prone to landslides has been demonstrated to the Users to achieve safe mobility in North-East regions.

Development of geospatial technologies and generation of geo-intelligence is another research domain of DGRE. To address the requirements of Indian Armed Forces, DGRE generates exhaustive terrain topographic and thematic database of Indian Himalayan regions and developed various GIS applications for geo-hazard analysis, mapping and monitoring. DGRE has also generated various GeoInt products such as DEMs (5 m resolution) of AOI, contour maps for high resolution data to be used for navigation.

The previous issue of *Technology Focus*, "Mountain Geo-hazard Mapping and Geo-Intelligence", highlighted the glimpse of new technologies developed by DGRE in the ambit of geo-hazards Management. The current issue, "Geo-hazard Monitoring, Modeling and Mitigation" highlights the DGRE R&D efforts towards geo-hazard mitigation, control and deterrence. It is anticipated that this issue of *Technology Focus* will provide a cursory insight into the preparedness of DGRE to develop futuristic geo-hazard technologies for Indian Himalayan region.

Dr Pramod Kumar Satyawali
Outstanding Scientist & Director
DGRE

Snow-Metrological Data Networks for Geohazard Monitoring

DGRE operates a network of manual snow-met observatories as well as Automatic Weather Stations (AWS) in the Himalayan region to collect data on a wide range of atmospheric and snow parameters. DGRE data observation/AWS sites are distributed throughout the Himalaya and across altitude zones between 2000 m and 6000 m.

Manual Reference Observations Stations

The laboratory has set up a network of manual observatories spread across different regions in UT of Ladakh, J&K, Uttarakhand, Himachal Pradesh, Sikkim, Arunachal Pradesh & also at HQrs DGRE, Chandigarh. The aim of setting up of observatories as under:

- Continuous monitoring of snow and meteorological conditions.
- Develop numerical, statistical and AI based models for prediction of weather and avalanches.
- Climate change studies.

DGRE also collects information on avalanche occurrence to generate data archive of avalanche activities in the Indian Himalaya. This data is used to develop models for avalanche forecasting and generation of avalanche hazard maps. DGRE personnel are deployed at field locations to collect snow and meteorological data, snow profile data, snow stability tests and to conduct field experiments during the winter period. These data are used to run various avalanche and weather forecasting models and generate daily avalanche and weather forecasts for the North-West Himalaya, Central Himalaya and North-East Himalaya. Various types of data collected at field observatories of DGRE (Fig. 1) is archived HQrs DGRE, Chandigarh.

Figure 1: Photographs of DGRE-Field Observatories.

Automatic Weather Station Network

Automatic Weather Station (AWS) is an autonomous snow meteorological data acquisition system designed for inaccessible and remote locations having geo-hazard problems. AWS data is essentially required for situational awareness and hazard analysis. AWS data is received directly at HQrs DGRE through an earth receiving station in near real-time. DGRE has designed the geo-special network of 348 AWS @ PAN Himlaya keeping the geo-hazards in focus along with important road networks and community settlements (Fig. 2). The data received from AWS network is used as a input in various physical/statistical models for hazard assessment and also for operational purposes for risk minimization due to geo-hazards. The AWS consists of the following snow and meteorological sensors:

- Ambient temperature
- Relative humidity
- Wind direction and wind speed
- Atmospheric pressure
- Albedometer
- Pyrgeometer
- IR surface temperature
- Snow depth
- Snow precipitation gauge/rain gauge

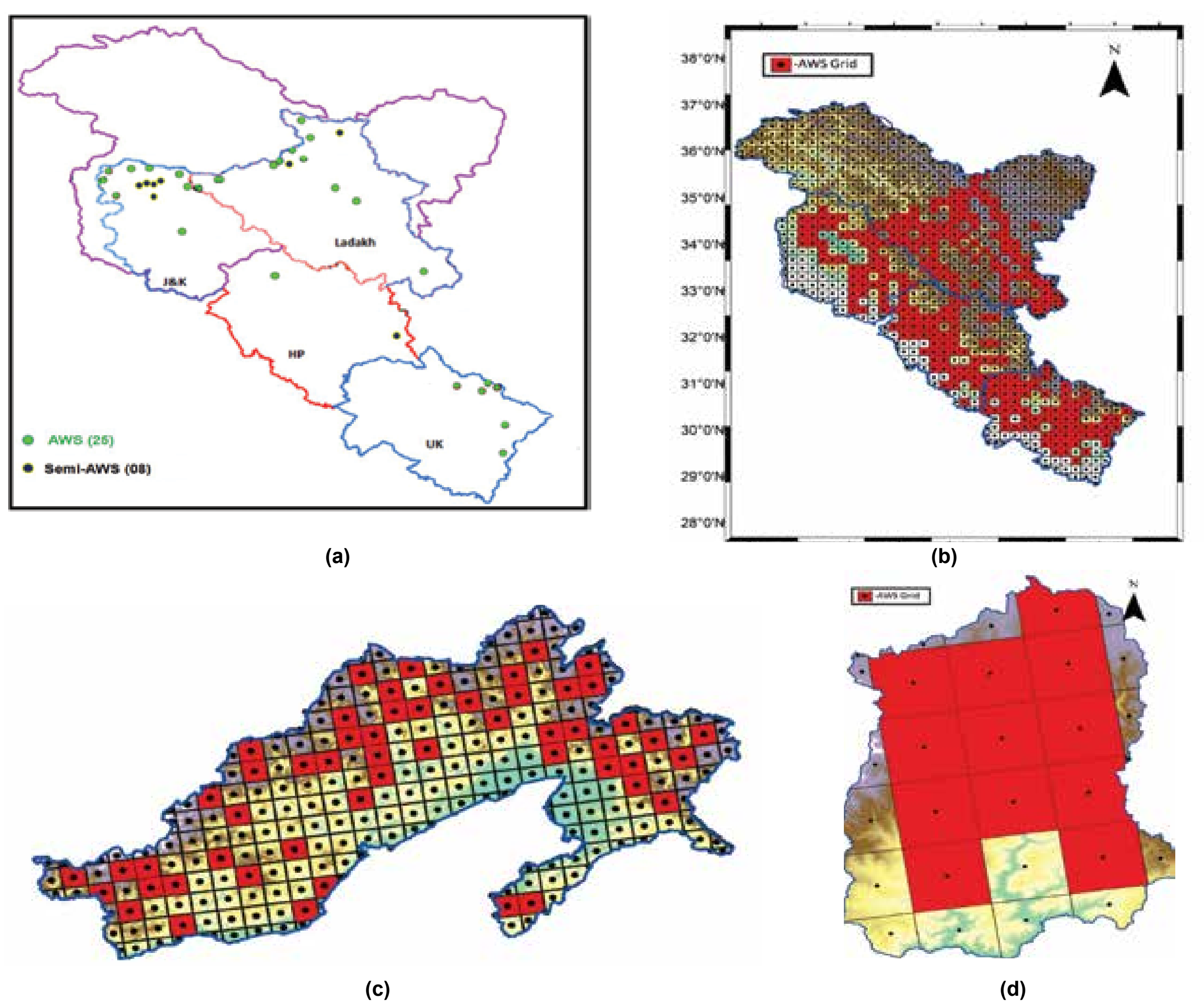


Figure 2: Existing (a) and Proposed (b, c & d) Automatic Weather Station Network.

DGRE Participation in Indian Scientific Expedition to Antarctica

In the polar regions, energy fluxes directly affect the accumulation and ablation processes at the ice/snow surface and are helpful in monitoring the evolution of glaciers and ice sheets. Polar ice sheets are highly dynamic and are continuously exposed to changing climatic conditions. DGRE has experience of working on energy exchange processes of snow/ice-atmospheric interaction in Antarctica. The laboratory has been participating in the Indian Scientific Expedition to Antarctica (ISEA) programme since 1995. It is presently working on a project "Study of Antarctic Climate Change and Its Effect on Various Cryospheric Feature", duly approved by National Committee on Polar Program (NCPP) for 2023-2028. The main focus is to study energy exchange processes and mass balance over Antarctic snow/ice sheet. In addition, various cryospheric phenomenon such as crevasse opening/closing, calving, ice quakes are also being monitored by using satellite and ground-based measurements (Figs. 3, 4, 5).

Figure 3: AWS Installation Process.

Figure 4: AWS at Sankalp: 10 Km from Maitri.

Figure 5: AWS Location~90 Km from Maitri.

Weather and Avalanche Forecast

To address the user requirement of precise and high-resolution mountain weather forecast (01 km x 01 km spatial 03 days in advance) and also to bridge the grey areas, such as inadequate observational network, biases in the forecast and now-casting of mountain weather for operational activities, two new technologies namely doppler weather radar and microwave radiometer have been ingested in avalanche forecast process. To achieve this, a Doppler Weather Radar (DWR) is installed in Sikkim and data assimilation methods were developed for ingestion of DWR data into the WRF model for improved mountain weather forecast. One microwave Radiometer is also installed for collecting upper air profile data for now-casting of mountain weather events. Necessary infrastructure has been created to keep the DWR and Microwave radiometer functional round-the-clock.

Doppler Weather Radar

The Doppler Weather Radar operates continuously to supply information relating to rainfall position and as well as capturing WD (Western Disturbance) features. The DWR data is being used for advance data assimilation (4D-VAR) in WRF model for generating 03 days forecast at 1 km spatial resolution. The developed forecast model has been implemented for operational mountain weather forecasting and generated forecast is being disseminated to users on regular basis.

The important technical specifications of the DWR are given in the Table 1.

Table 1: Technical Specification of Doppler Weather Radar

General Specification	Value
Operating frequency range (Tuneable)	9200 MHz – 9700 MHz
Max range resolution	75 m or better
Max range	125 km or better
Operating temperature	-10 °C to +40 °C
Scan speed	Up to 6 rpm or better
Wind load	
Scan strategy	Volume scan in 10 minutes
Noise figure	≤ 40 dB
Power	Capable of operating at 220 ±10% V, 50 ±2% Hz in Single Phase or 440 ±10% V, 50 ±2% Hz in Three Phase
Online UPS	Suitable 10 KVA online UPAS to run whole radar system for at least 30 minutes
Diesel generator	At least 25 KVA suitable diesel generator set with AMF panel for automatic turn ON when main fails and capable to take up the load of all the essential components and accessories.

The DWR generates products such as reflectivity, rainfall rate, radial velocity, spectrum width, differential reflectivity, differential phase, and correlation coefficient at zero lag, which are being used for forecast generation (Fig. 6, 7).

Figure 6: DWR Facility in Sikkim

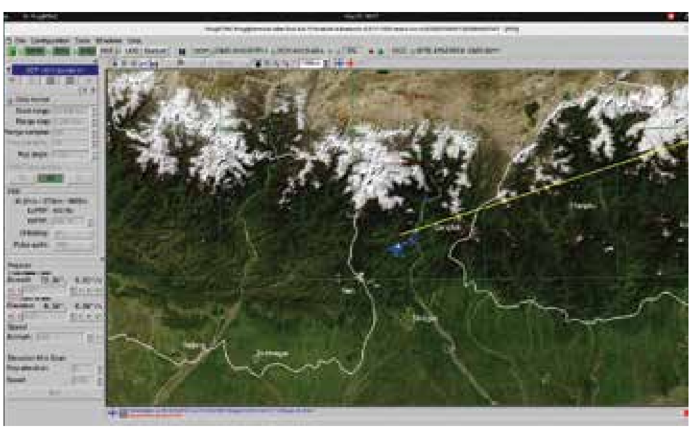


Figure 7: Interface for DWR Data Reception

The meteograms are also being generated for location specific detailed weather analysis. The weather meteograms contains parameters such as precipitation (rain/snow), temperature, relative humidity, wind speed and wind direction (Fig. 8).

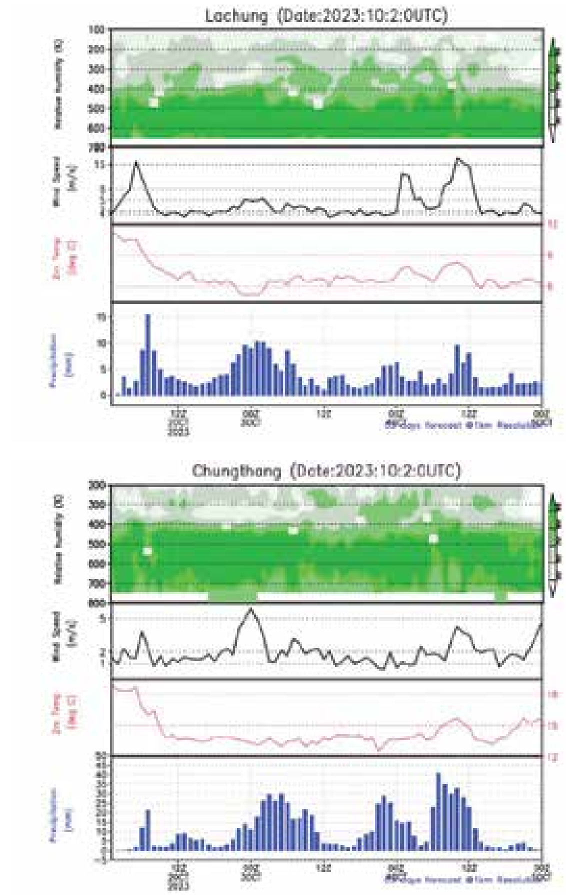


Figure 8: Location Specific Meteograms.

Microwave Radiometer

This is a multi-channel microwave radiometer with azimuth positioner and IRR elevation-scanner. Radiometer is protected by the radome sheet and can collect data in the vertical level upto 10 km height. Microwave radiometer profiler is operational in Sikkim to collect upper air thermodynamic profiles of the atmosphere and is being used for developing algorithm for now-casting of weather over the region (Fig. 9).

Figure 9: Microwave Radiometer in Sikkim

The radiometer collects data such as temperature, water vapor, relative humidity and liquid water profile up to 10 km height in the atmosphere. The interface of Radiometer data reception is shown (Fig. 10) . The data received through the radiometer is being used to develop an algorithm for now-casting (less than 12 hr) of mountain weather over the region.

Avalanche Forecasting Framework

The laboratory is committed to provide daily avalanche forecast for regions of UT of Jammu and Kashmir, UT of Ladakh, Himachal Pradesh, Uttarakhand and Sikkim. Avalanche forecasting services provided to the users under the following avalanche danger categories.

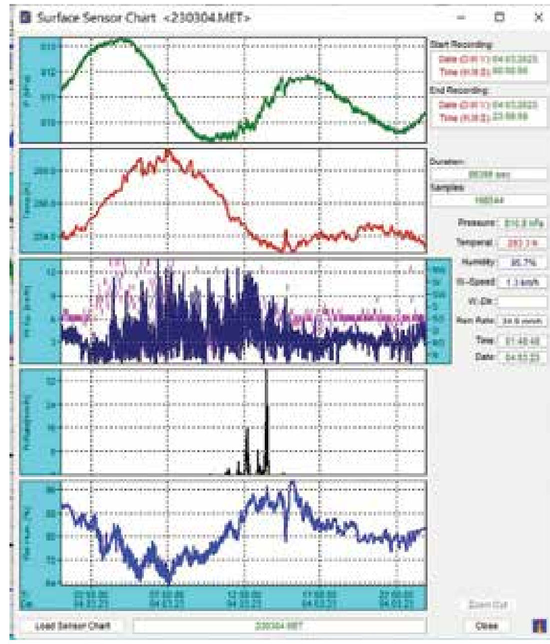


Figure 10: Interface for Various Parameter from Radiometer Skew-T Diagram, Relative Humidity and surface Meteogram.

Table 2: Avalanche Forecasting Framework

Danger Category (Alert)	Description/Interpretation		
	Snow Condition	**Avalanche Likelihood**	**Preferred Action**
Unlikely	Generally safe conditions. Snowpack on slopes, if any, is generally stable with isolated instability	Avalanche activity is possible with external loading e.g. tremors, explosives or movement in formation zones.	Valley movement is generally safe. Movement on snow-loaded slopes with care.
Low danger	Partly unsafe conditions	Small size triggering is possible on few extreme slopes.	Valley movements with care. Avoid movement on snow-loaded slopes.
Medium danger	Unsafe conditions	Triggering is possible from the most avalanche prone slope and may reach the valley in medium size.	Restrict movements to only carefully selected safer routes with extreme care. Evacuate from unprotected settlements on/near the avalanche paths.
High danger	Highly unsafe condition	Triggering is possible from all avalanche prone slopes and may reach the valley in large size. Airborne avalanches likely.	Suspend all movements. Evacuate from all settlements on/near the avalanche paths.
All round danger	Extremely unsafe condition	Numerous large avalanches are likely from all possible avalanche slopes even on moderately steep terrain. Avalanches may follow unexpected paths.	Evacuate from avalanche prone areas.

Statistical and AI-based models have been developed as a guidance tool for operational avalanche forecasting in the Indian Himalaya. Some of these are Random Forest (RF), Support Vector Machine (SVM), Nearest Neighbors, Expert System, etc.

Site-specific Avalanche Detection and Monitoring

There are still uncertainties in accurate stability assessment of snowpack leading to the snow avalanche formation at slope scale, due to unavailability of the true information pertaining to the avalanche process occurring in remote and inaccessible avalanche formation zones. However, for passive mitigation of the avalanche hazard, avalanche forecasting is employed which is based on statistical, deterministic and heuristic approaches. This forecasting is of generic nature; limited only for the larger areas and road axes. Therefore, there is a need of slope scale snow stability assessment techniques for precise and accurate warning and alert generation.

Acoustic Emission-based Snow Cover Stability Estimation

Acoustic Emissions (AE) are vital acoustical signatures produced by the materials or structures from several physical processes including the failure process, therefore a continuous watch can be kept over the AE vis-à-vis avalanche process ranging from microscopic to macroscopic scales of the failure activity, and thus helpful for predictive modelling of the avalanches.

AE-based Site-specific Avalanche Monitoring and Warning System

The AE Technology is a state-of-the-art and cutting-edge technology for direct monitoring of the avalanche slope instability and site-specific avalanche warnings. It primarily involves the detection of AE's with respect to snow avalanche processes and interpretation of the true information from AE for avalanche warnings. For this purpose, the AE sensors are deployed in avalanche starting zone (Fig. 11). The initial microscopic failure activities within the weak layer of the snowpack, built over the formation zone, lead towards the persistent growth of snow failure (crack) process which, in turn, produces the AE signals. These AE signals are vital in monitoring the entire failure process of the snowpack prior to the avalanche occurrence.

Figure 11: Site-specific AE Sensor Networking in Avalanche Formation Zone

This AE-based monitoring system is comprising of the following subsystems:

Indigenously Developed AE Sensors 'Sensing Unit and Signal Arrestors

The frequency range of the indigenous AE sensor is 20 kHz to 80 kHz with central frequency near 50 kHz. The peak sensitivity of the AE sensor as used in present case is 98 dB ref 1V/m/s with inbuilt pre-amp of gain 26 dB which is powered by 5 VDC through phantom circuit (Fig. 12).

Figure 12: Indigenously Developed AE Sensing Unit (left) Based on 1-3 piezo Composite Material (right).

The AE signal arrestor is a metallic (aluminium) interface having larger surface sensing area and it remains in the contact of sensor unit at one point and in contact of snow (or submerged) at other point (Fig. 13).

(a)

(b)

Figure 13: AE Arrestors installed in Avalanche Slope, (a) Static (OD-AR) types of AE Arrestor (left) and Sensor Housing (right), (d) Dynamic (WS-AR) types of AE arrestor.

AE Data Acquisition and Communication System

The AE data acquisition system is a large distributed network comprising of AE Node, AE Hub and AE Base station controller.

AE Node

AE Node is a System on Chip (SoC)-based digital device used for acquisition of analog AE waveforms detected by AE sensor. The AE sensor is connected to AE Node via a co-axial cable with SMA and BNC terminals (Fig. 14).

Figure 14: AE Node Installed in Avalanche Formation zone.

AE Hub

AE Hub is a junction between two different strings of the AE node line installed in slope where each string is connected through different Nodes in daisy-chain design as input to AE Hub, and the OFC based AE data communication system to base station as an output. The purpose of AE Hub is first to transfer digital AE data packet received from each sensor to the base station controller and to inject DC electric power supply to the serially connected AE Nodes through PoE (Fig. 15).

Figure 15: AE Hub with OFC Data Interface, Housed Inside Shelter Installed Near Avalanche Formation Zone.

The AE-base Station Controller

To communicate & send commands to the devices such as AE Hub & Nodes installed in avalanche slope, and further it acquires the AE data detected by each AE sensor station controller is installed (Fig. 16).

(a) (b)

Figure 16: (a) AE Base Station controller with display & AE data server storage system installed at Dhundi in HP state, (b) 100 TB capacity server-based AE data storage system (NL-SAS).

A rule-based Decision Support System and Information Dissemination Platform

Decision Support System (DSS) is developed for near real-time decision making of the slope instability and the possible failure of the snowpack on avalanche slope. These outcomes used to assess the danger level and the generate the projected avalanche warnings. The DSS controller is an embedded system that sends the commands and power to different output dissemination modules. The control commands are generated through data processing and rule-based decisions. This device, at the same time, feed and controls the electric power supplies to different interface modules (outdoor display system, traffic signal indicator system and avalanche hooter) (Fig. 17).

(a) (b)

Figure 17: (a) DSS Server for Data Processing to Generate Information & Commands, (b) DSS Controller to Power and Control Output Dissemination Devices.

To pass the near real-time avalanche slope condition and site-specific warnings generated by DSS system, a dissemination platform and GUI have been developed to disseminate the information through audio-visual (graphical) and parametric alert messages modes (Fig. 18).

Figure 18: Avalanche Information Dissemination through Outdoor Display Signboard (top), GSM Message Alerts (bottom left side) and Traffic signal Danger Level Indicator (bottom right).

Doppler Radar-based Avalanche Detection

Although there are different techniques for avalanche detection, active methods using FMCW/ Pulse Doppler Radar in C/X Band provides most accurate and promising solution for automatic detection and tracking of avalanches.

The radar can permanently scan the targeted slope for avalanche release and track the avalanche path and size in case of detection of avalanche. C/X band Radar can see through snow, fog day, and night making it an all-weather solution. In addition, radar operates at distance, and thus, permits large areas to be monitored without the need to install instruments in dangerous zones. Available COTS Avalanche Radars can work up-to a maximum range of 5 km with coverage of slopes up to 10 km^2 using single radar. Integrated cameras can record images/videos of the event and the avalanche radar can be linked to an alarm system enabling automatic traffic control measures, for example road closures.

Pulse Doppler Radar Provides a promising method for acquisition of avalanche velocity data, which is required for qualitative and quantitative estimates of macroscopic avalanche behaviour. The radars operate at X Band (10.425 GHz). The signal is pulse modulated using a high frequency switch, amplified to an output power of about 1 W and radiated from a parabolic antenna to the detection area. DGRE has installed a state-of-the-art Doppler Avalanche Detection Radar in Sikkim to improve the safe mobility in this region during winter.

The Key Features of Avalanche Radar are:

- The Avalanche Radar (FMCW/Pulse Doppler) is a mast mounted device for automatic detection and tracking of avalanches.
- The Radar permanently scans the targeted slope for avalanche release.
- Radar sees through snow and fog day and night.
- In addition, Radar operates at distance and thus permits large areas to be monitored without the

need to install instruments in dangerous zones (such as geophones).

- With a maximum range of 5 km, slopes of up to 10 km^2 can be monitored with a single Radar.
- Once the Radar detects an avalanche, it tracks the avalanche's path and size.
- Integrated cameras record videos of the event.
- The avalanche radar linked to an alarm system enabling automatic traffic control measures, for example road closures.

Deployment Scenario

Avalanche Radar is mounted on a fixed mast on a safe location with direct line of sight and at a range of 500 m – 5000 m from the avalanche zone has Antenna, RF trans-receiver and radar processing unit as a single unit and run on solar power with the help of solar panels and low maintenance battery. Optional data storage and visualization device can be used to store and post analysis of raw time domain data. Audio/visual alarm can be used for localized alert generation in case of successful detection of avalanche along with GSM/SATCOM communication module for sending alert messages to concern authorities/ rescue teams (Fig. 19, 20 a, 20 b).

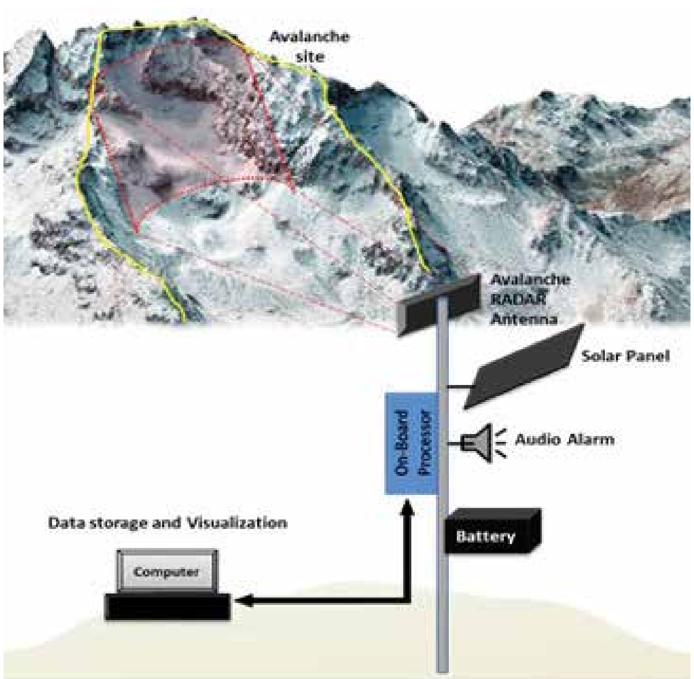


Figure 19: Avalanche Radar Deployment Scenario.

Figure 20: Installed Avalanche Radar, (b) Avalanche Zones Covered by Avalanche Radar.

Avalanche events were detected by the radar during winter of 2023-24 and same were verified by visual confirmation.

Geohazard Mitigation, Control and Deterrence

Improved Avalanche Control Structures

An effective way to mitigate the risk of the avalanche is to prevent the release of avalanche from the formation zone by putting snow or avalanche barrier. There are two types of conventional formation zone avalanche control structures (a) rigid structures such as snow bridge, snow rake and (b) flexible structures such as snow net.

There are several challenges with the conventional avalanche control structures, for example snow bridge and snow rakes, such as heavy weights of the components which leads to difficulty in manual transportation of structure to the formation zone; labour intensive and time-consuming construction work and difficulty in installation in uneven terrain.

An improved avalanche control structure, which is Semi-Flexible Snow Supporting (SFSS) type has been conceptualised, designed and developed by DGRE. It addresses the limitations of conventional structures by incorporating innovative design approach. It has high strength to weight ratio, light weight, fast installation mechanism, having single ground anchor as foundation and is suitable for almost all types of topographies.

The SFSS steel structure as shown in (Fig. 21), resting vertically on the ground, has four transverse cross members rigidly connected to a central joint. The central assembly consists of top and bottom plates, ball for connecting the upslope central tube through a ball-and-socket arrangement, stiffening plates for connecting the transversal cross members, and a small circular pipe for connecting the downslope central tube. The ball and socket arrangement allows the relative rotation between the transverse supporting plane and the upslope central tube. The central tube is attached to the ground anchor by anchor plates. Further these anchor plates are connected with the bi-podal ground anchors. Self-drilling bipodal ground anchor system is adopted for foundations. Ground anchors of 4 m and 6 m length each (micro-piles) are provided as support/foundation for intermediate and end structures respectively. Micro-piles are especially suited for foundations with difficult access and poor ground conditions, wherein minimal ground modifications are done. Hexagonal wire mesh is provided to support the snow cover. Cable mesh profile in the SFSS structure form the main snow pressure bearing plane.

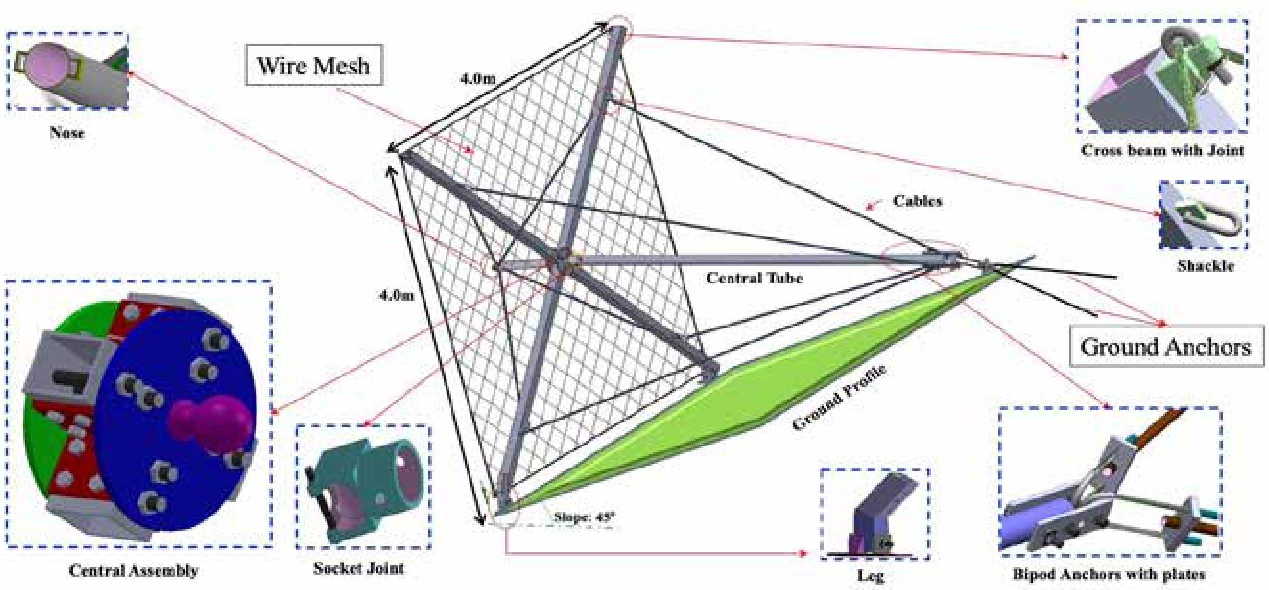


Figure 21: 3D View of the Semi Flexible Snow Supporting Structure.

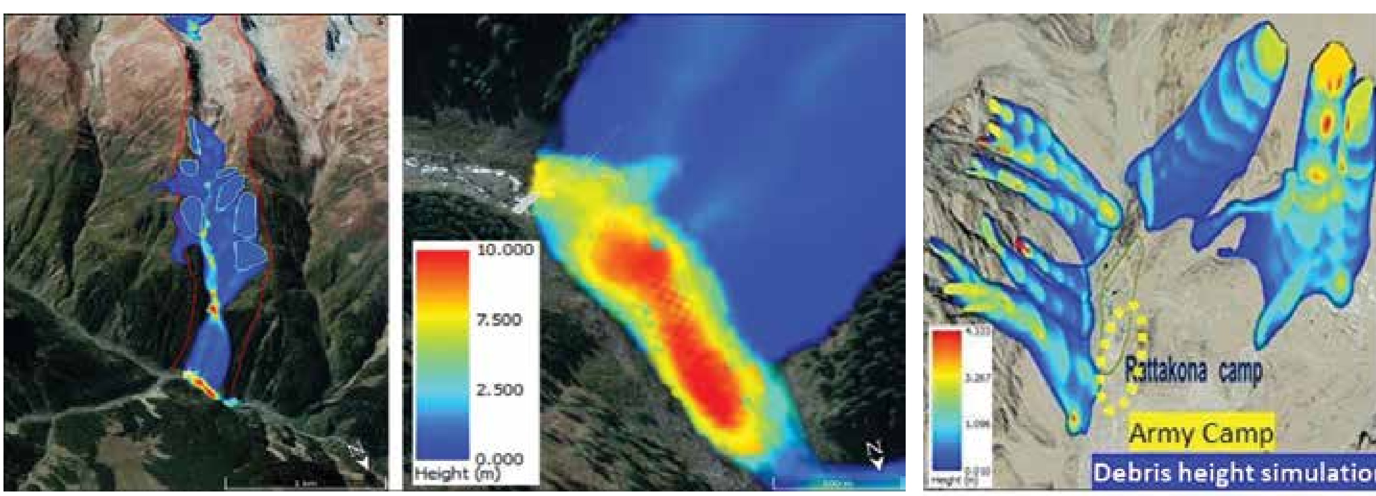
The construction and installation work on steep slopes is a strenuous task. All the structural components are to be transported to mounting locations. To get a good working space across the contour line for fixing machineries for drilling, grouting and erection (of structures) work along with manpower deployment is very challenging task at such a steep slope condition. Major activities of ground anchoring and installation work can be seen in (Fig. 22).

Assembling of Structure on ground | Chain Pulley system for erection of structure | Installed structure at MSP-04 site | First row of structures at MSP-04 site

Figure 22: SFSS Installation work at Test Avalanche Site

Avalanche Flow Modelling

Among many methods, avalanche hazard mapping is an effective and low-cost tool used to mitigate avalanche hazards just by proper land use planning. Avalanche hazard maps consist of information about probable extreme avalanche event extent along with zonation information based on impact pressure and event frequency. Avalanche dynamics models, developed based on understanding of dynamics of avalanche flow are used for generation of avalanche hazard maps. With this motivation, DGRE developed a hazard assessment and mapping software named as “Avalanche Flow simulation software (AFS)”. This software is quasi-3D in nature and based on the solution of depth averaged shallow water equations. This model is being used extensively for avalanche hazard assessment for a large number of tasks received from Users. This model has been proved very helpful in understanding probable avalanche



(a) (b)

Figure 23: Avalanche Hazard Assessment Tasks Carried for different Users sites in Himachal Pradesh and Uttarakhand

situation. However, this model applicable only for dense flow avalanches. A few hazard assessments carried out using SAFS are shown in Fig. 23 (a-b).

Small Scale Avalanche Flow Modeling on Snow Chute

It is quite hazardous and cumbersome to carry out the avalanche dynamics experiments at the real avalanche sites. Hence, a state-of-the-art, 61 m long and 2 m wide experimental facility 'Snow Chute' made of mild steel was developed at Dhundhi field research station of DGRE to study avalanche flow parameters like velocity, impact pressure, flow depth, etc. Snow Chute has 5.5 m long snow feeding hopper, having maximum filling capacity of 11 m^3 and inclination angle of 35°. It has 13.5 m long diverging-converging trapezoidal section inclined at 35°; a 22 m long flow accelerating section inclined at 30° and an 8 m long flow retarding section inclined at 12°, and lastly, a 12 m long test bed inclined at -1.8°. The complete geometry of the Snow Chute is depicted in (Fig. 24). Currently, avalanche impact pressure, snow dynamic friction coefficient, debris deposition profile, flow depth, run-out distance and velocity parameters are being measured on the above Snow Chute. The locally developed system Avalanche Impact Force Measurement System (AIFMS) for measurement of avalanche impact pressures is shown in Fig. 25.

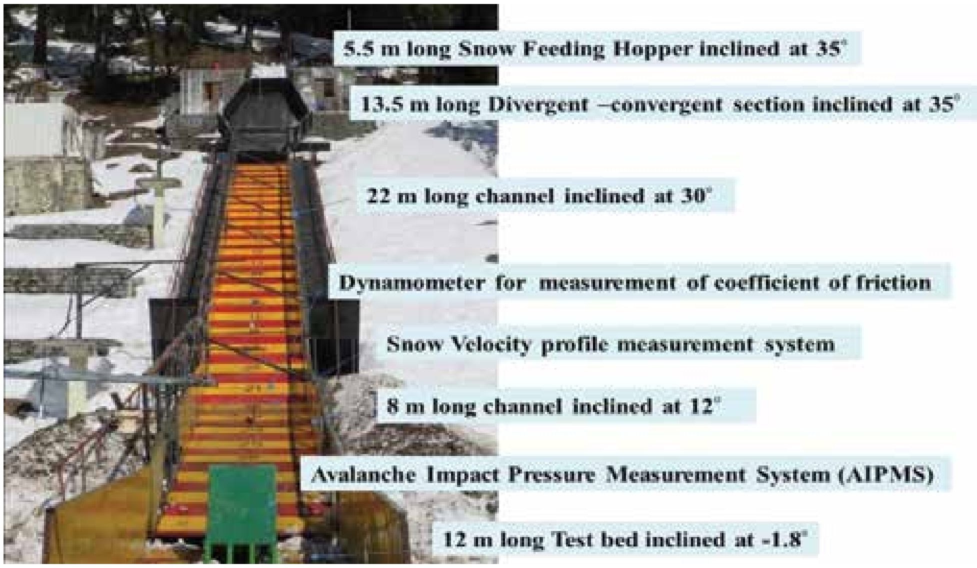


Figure 24: Geometric Details of the Experimental Facility, Dhundhi, Himachal Pradesh

Figure 25: AIFMS system installed in avlanche chute and interaction results

Avalanche Flow Interaction with Structures

In an avalanche dynamics model, besides other parameters, simulation of impact pressure on the structures is most crucial. Currently, this is obtained from the empirical guidelines only. To improve the assessment of this parameter, modelling of avalanche flow interaction with the obstacles, based on the solution of Navier-Stokes equations, has been attempted at DGRE using 2D and 3D CFD Modelling in ANSYS Fluent. Snow is modelled as bi-viscous Bingham fluid. A customized wall shear stress model is proposed at the snow chute ground-snow interface to model wall-slip. The simulated model results agree well with the experimental observations on the Snow Chute, Dhundhi (Fig. 26). For the simulation of avalanche flow interaction, a 2-D CFD model is developed for a 12 m high Instrumented tower erected in the path of a natural avalanche site (MSP-10) at Dhundhi. The preliminary results obtained are shown in Fig. 27.

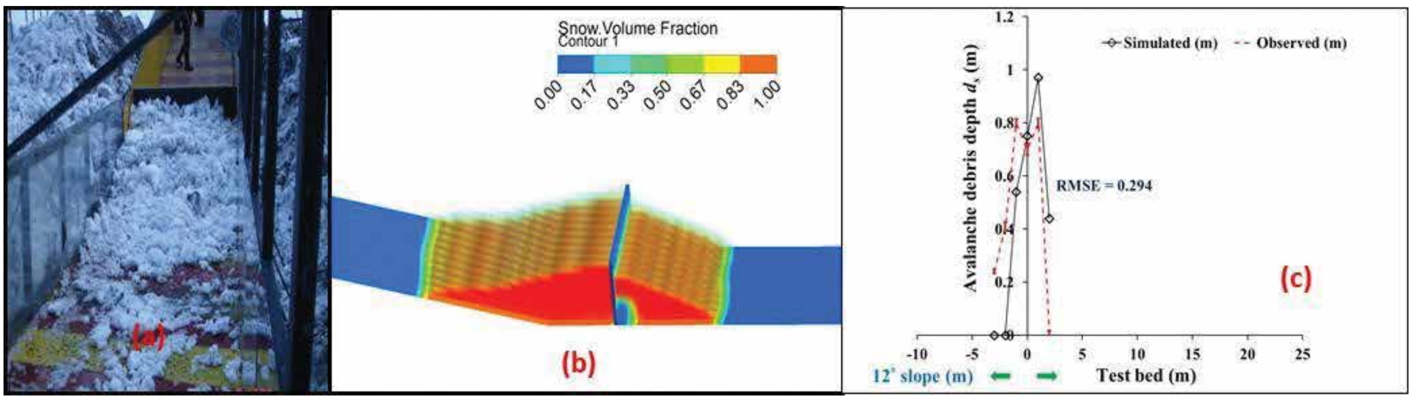


Figure 26: Avalanche Flow Interaction with a Catch Dam Type Obstacle (a) Experimentally Observed Snow Debris Profile (b) Simulated Snow Debris Profile (c) Comparison between the simulated and Observed Snow Debris Profile.

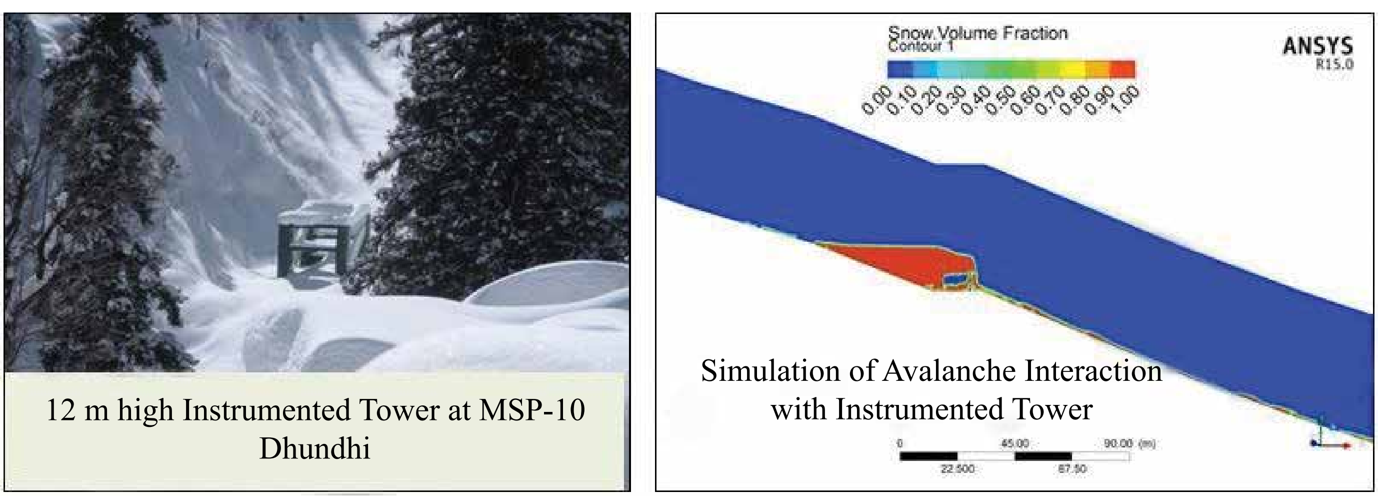


Figure 27: Simulation of Avalanche Flow Interaction with a 12 m High Instrumented Tower at MSP-10 Avalanche Site.

Artificial Triggering of Avalanches

Artificial Triggering is an active measure to mitigate the hazard of snow avalanches. This technology helps in controlled release of avalanches, thereby minimising the potential damage to the infrastructure present in the avalanche path and also enhances the operational readiness of Armed Forces by ensuring safe transportation on roads and foot-routes during winter months. Following two explosive delivery systems are under various stages of development (Fig. 28):

Figure 28: Artificial Triggering of Avalanches

Using 84 mm RL Gun

The new ammunition, specialized for avalanche triggering along with a database of target points and safe firing points has been developed for control release of avalanches.

After successful completion of development trials at sea level and high altitude, the new ammunition has been evaluated to release an avalanche during artificial triggering trials in J&K. During the course of trials, 15 HE rounds were fired at four target points in the avalanche zone and three minor sluffs and two small avalanches were triggered. These trials demonstrated the efficacy of explosive blast overloading in triggering a snow avalanche. Pictures from the trials are presented below (Fig. 29, 30, 31, 32):

Figure 29: Targets were monitored for snow cover buildup.

Figure 30: Firing during Avalanche Triggering Trials.

Figure 31: Blast at Target End.

UAV-based Avalanche Triggering

To meet the requirement of Artificial triggering of avalanches of inaccessible avalanche sites, a feasibility study for avalanche triggering using unmanned aerial system is conducted. Further development is underway.

As the Himalayan terrain is very rugged with steep slopes and venturing in the avalanche formation zones is a hazardous operation. Also to overcome the limitations of ground-based triggering methods, unmanned aerial system based avalanche triggering is under development (Fig. 33).

Figure 33: UAV System.

To achieve this UAV system to have following features:

- Autonomous operations in beyond line-of-sight avalanche zones.
- Obstacle detection, avoidance and navigation in unchartered territories.
- Accurate delivery and Height of Burst (HoB) of explosive device.
- Simultaneous delivery of explosive devices at all the targets in an avalanche zones.

A feasibility study and system evaluation trials were conducted to assess the performance and identify the shortcomings of the presently available systems for avalanche triggering (Fig. 34, 35).

Following are the salient features of system tested during trials:

Table 3: System Tested During Trials

Parameter	Value	Parameter	Value
UAV type	Octacopter	UAV class	Mini
Altitude ceiling	5000 m AMSL	Propulsion	Battery powered
Max. range	≈ 2000m	Fuze	Electronic timer based
Explosive content in payload	≈ 1.6 kg	Explosive composition	TNT

Following tests were conducted during the trials:

- Flight stability assessment and endurance trials.
- UAV positioning accuracy over snow surface.
- Range and Ceiling trials of UAV system.
- Trials for accuracy in HoB.
- Evaluate the performance of all the sub-systems in avalanche triggering trials with explosive payload.

Figure 34: Trials in Progress at 3800 m AMSL

Figure 35: HoB Trials in Progress

Geohazard Process Modelling

Snowcover 3D Modelling

Knowledge of current state of snowpack structure and it's mechanical stability (in space and time) is very important for avalanche forecasting. Conventional method to assess the state of the snowpack is manual snow pit profiling, which is subjective, destructive in nature and time and labour intensive. In order to overcome these limitations, a process-based approach is developed, where simulated snow-profiles are generated by modelling energy exchange, heat and mass transfer processes, etc. occurring inside the snowpack. Such a snow cover evolution model-SNOWPACK 1D has been operationally implemented at DGRE, which can simulate hourly snow-profiles from snow-met data from a network of automatic weather stations. However, site-specific avalanche forecasting and artificial triggering of avalanches require estimation of snowpack layer structure and stability information at formation zones of individual avalanche site, for which presently snow-met data is not readily available. Therefore, there is a need to set up a process chain, by which meteorological field as well as information about snowpack and its properties could be generated at formation zones. To establish process-chain Alpine 3D libraries have been used. (Fig. 36, 37) shows the overall process chain to implement spatially distributed SNOWPACK model. To compare the performance of the model, data of three Automatic Weather Stations AWSs were taken.

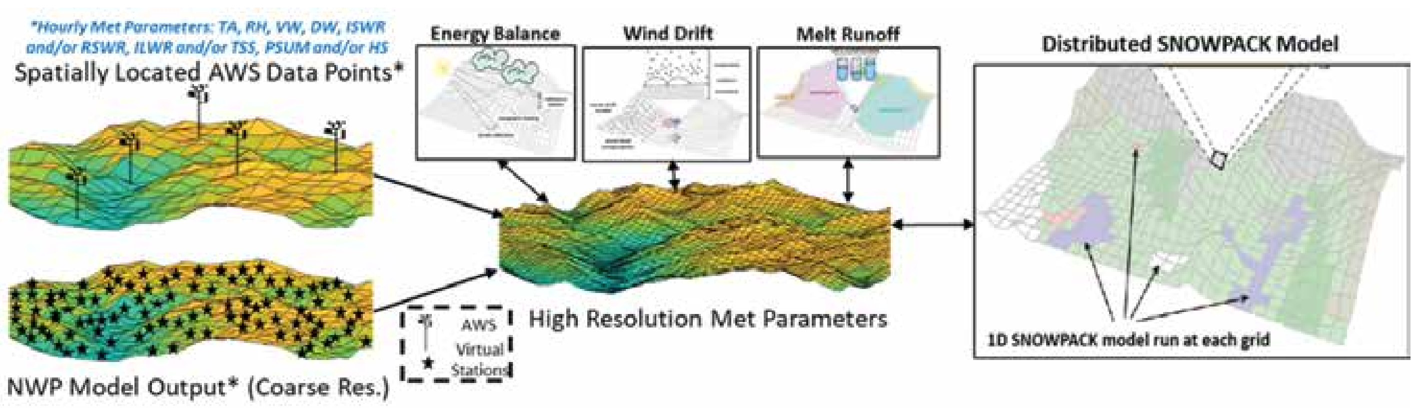


Figure 36: The Overall Process Chain for Spatially Distributed SNOWPACK Model.

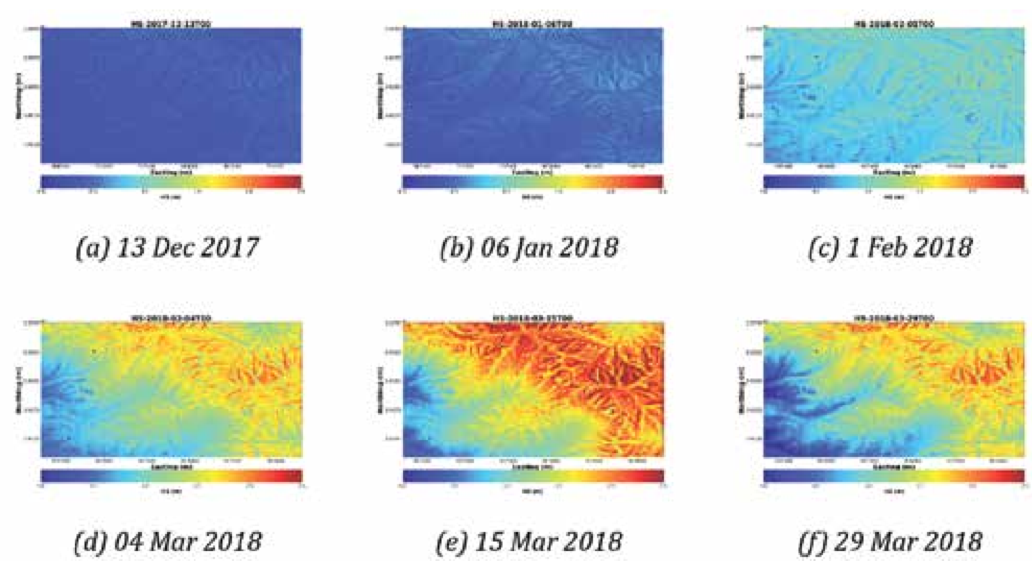


Figure 37: Simulated Snow Depth Maps. Figures (a) to (e) Shows Increase in Snow Heights, Whereas (f) Shows Ablation Period.

Figure 38 (a-c) shows the comparison of height of snow generated by model for three different inputs datasets IMDAA data (NCMRWF), ERA-Interim Data and AWS data. Though, all three are matching in trend, but a clear throughout offset can be seen in all. As observed in gridded outputs, here also ERA-Interim data driven model is generating more snow heights. Comparatively, IMDAA data is better than ERA-Interim data for estimating precipitations. Overall, it can be noted that, distributed SNOWPACK simulations have potential to be used for generating site specific avalanche danger assessment, as it provides not only meteorological parameters but also snowpack parameters at formation zones of avalanche sites.

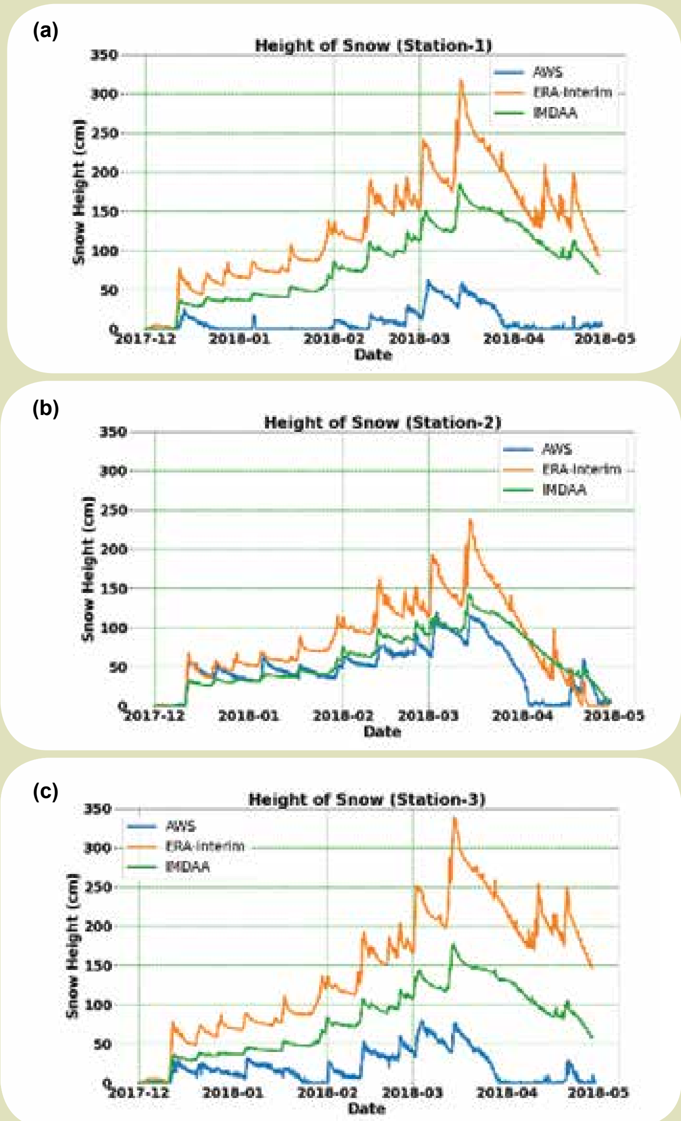


Figure 38: Figures Show the Comparison of Model Generated Height of Snow by Considering IMDAA Data, ERA-Interim Data and AWS Data for all Stations.

Landslide Modelling

Landslide Susceptibility Maps (LSMs) are critical tools used to identify areas prone to landslides, aiding in risk management and land-use planning. By leveraging satellite data and Digital Elevation Model (DEM)-derived themes, these maps provide detailed spatial information on landslide hazards. Use of Analytical Hierarchy Process (AHP) and Machine Learning (ML) models in a GIS environment enhances the accuracy and reliability of these maps.

At DGRE, Landslide Hazard Zonation maps for Sikkim Himalayas & North Eastern States Jammu & Kashmir, Himachal Pradesh and Uttarakhand has been prepared at 1:50000 scale. Recently, Bilinear Logistic regression model has been applied on high resolution satellite imageries and DEM. The overall methodology for landslide susceptibility mapping is given in Fig. 39.

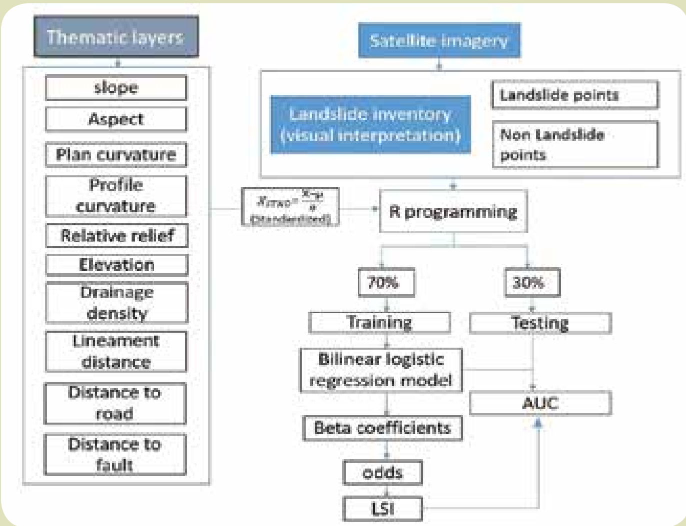


Figure 39: Methodology for Landslide Susceptibility Mapping.