DEVELOPING THE NATIONAL AVALANCHE FORECASTING SYSTEM FOR FINLAND USING IOT WEATHER STATION DATA AND SNOW MODELS

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ABSTRACT: This project aims to advance avalanche forecasting in Finland towards closer alignment with European Avalanche Warning Services (EAWS) standards.

At present, forecast regions are large and observational data is sparse, reflecting the practical challenges of monitoring vast and remote fell areas. While avalanche terrain in Northern Finland is limited in scale and the risk to recreationists is generally low, improved forecasting would strengthen both safety communication and the scientific foundation underlying it. This pilot project develops a semi-automated avalanche forecasting system based on real-time IoT measurement data and snow modelling. In the project Snower IoT weather stations form an observation network across the fell areas of Northern Finland, and the continuous data they collect is integrated into the Finnish Meteorological Institute's snow models. Model outputs are combined with regular manual snow profiles conducted by avalanche technicians, enabling risk assessment at finer spatial and temporal resolution than is currently possible. The project progresses in four phases between 2026 and 2030, expanding from a pilot in the Pyhä–Luosto area to ultimately cover the entire fell region of Lapland. The long-term goal is an operational forecasting system that progressively moves towards EAWS standards, supported by a citizen science observation application for backcountry users. Scientific outputs will include peer-reviewed publications on snow model forecast accuracy and the optimal design of IoT observation networks in Arctic continental snowpack conditions.

KEYWORDS: avalanche forecasting; IoT weather stations; snow modelling; SnowModel; SNOWPACK

1. INTRODUCTION AND BACKGROUND

Finland has limited extent of avalanche-prone terrain and lacks high mountain ranges compared with most European avalanche forecasting regions.

Avalanche terrain exists in the fell areas of northern Finland. The exposure to avalanches is only for recreationalists or professional search and rescue teams. There is very little infrastructure exposed to avalanche paths. Under normal winter conditions, recreational backcountry users constitute the primary group exposed to avalanche hazard in Finland. However, following an avalanche accident, professional rescue personnel become exposed as well. Avalanche forecasting is an important safety communication tool for backcountry users.

Finland does not currently operate a national avalanche forecast aligned with the danger-scale and terminology used by the European Avalanche Warning Services (EAWS). There are currently two separate forecasting operations that follow the EAWS forecasting standards: one in the Pyhä-Luosto area and another in the Pallas–Ylläs area. The weather observation stations network in Northern Finland is sparse and includes only about 26 weather stations equipped with snow depth sensors.

The Finnish Meteorological Institute (FMI) has issued avalanche forecasts since 2003 for six avalanche-prone areas in Northern Finland. The forecast is based on weather forecasting models and automatic weather station data. The FMI forecast currently conveys only the EAWS danger level, which is a comparatively coarse description for the typically small avalanches found in Finnish terrain (Landon and Mäkelä, 2024). A recent analysis of Finnish weather-station data suggests that, under typical winter conditions, manual field visits to avalanche terrain need to be made only about three times per week to track changes in snowpack stability, but wind redistribution of snow can add more than 500 kg/m2 of

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loading to the snowpack within a few hours, i.e. far faster than a weekly observation cycle can capture (Landon, 2024).

This paper describes a pilot project that develops a semi-automated avalanche forecasting system for northern Finland, combining data from a network of small IoT weather stations with the Finnish Meteorological Institute's (FMI) snow models, SnowModel and SNOWPACK. The project is a collaboration between Snower Oy (the IoT station manufacturer and applicant), FMI, the Pyhä Avalanche Centre (Suomen lumiturvallisuuskeskus), Ylläs Ski Resort, and FINLAV, the Finnish avalanche training organization. The project area is administered by Metsähallitus (Parks & Wildlife Finland).

1.1 International context

Neighboring countries have made substantial progress on similar problems in recent years. Norway faces a similar challenge with sparse weather and snowpack observations in big forecasting areas. They have recently begun running gridded, semi-distributed SNOWPACK simulations across its 23 avalanche forecast regions using the open-source AWSOME framework (Herla et al., 2024). In Switzerland, machine-learning models driven by an automated weather-station network have been shown to discriminate between stable and unstable conditions about as well as a team of professional forecasters, and are increasingly used as an operational "second opinion" alongside expert judgement (Techel et al., 2024). In Finland, FMI and FINLAV have already identified the need to combine automated data streams with professional avalanche expertise (Landon and Mäkelä, 2024). This project aims to provide an observation network capable of capturing the spatial variability of meteorological and snowpack conditions across the principal avalanche-prone regions of northern Finland.

This paper presents the motivation, methods and phased implementation plan for the project, which runs from October 2026 to September 2030. As the actual project has not started at the time of writing, the paper focuses on system design, methodology and expected outcomes rather than on forecast verification results. Quantitative results will be reported yearly to stakeholders and after the whole project has ended.

2. STUDY AREA

The pilot phase of the project is located in Pyhä–Luosto National Park in northern Finland, an area of moderate fell terrain (summit elevations of 400–560 m a.s.l.) with a continental Arctic snowpack climate. The current observation network provides limited information on the spatial variability of snowpack conditions across Lapland. Large fetch areas for wind redistribution and strong temperature gradients that result in wind slabs and depth-hoar formation are problematic to understand in large areas without observations.

Pyhä–Luosto National Park is characterised by steep, glacially carved gorges and fell slopes, including the Isokuru gorge. Pallas–Ylläs National Park is another area that is popular amongst winter enthusiasts. The latest fatal avalanche accident occurred in the Pyhäkuru gorge in January 2024 (Landon and Mäkelä, 2024). Wind conditions on the exposed fell tops are severe: hourly-average wind speeds at existing FMI stations in comparable Lapland fell terrain average 3.5–7.6 m/s over a winter season, with daily maximum gusts regularly exceeding 20 m/s (Landon, 2024).

In subsequent phases, the network is replicated in the Pallas–Ylläs fell area and then extended across the wider fell region of Finnish Lapland. All station sites are located on land administered by Metsähallitus. Site selection is carried out jointly with Metsähallitus to avoid any sensitive natural areas.

3. METHODS

3.1 IoT weather stations

The observation network uses Snower One + Wind devices. Each unit is mounted on a separate vertical pole without any need for groundwork or other invasive actions. The devices weigh approximately 2 kg total and run on batteries that last about 5 years. Each station measures air temperature, relative humidity, air pressure, wind speed and direction, snow depth, surface-height change, and surface temperature. Data is sent continuously over NB-IoT/LPWAN to a cloud service. FMI's models pull their input data from this service automatically.

3.2 Manual snow profiles

Avalanche technicians from the Avalanche Center and FMI field researchers collect regular manual snow profiles near the IoT stations during the first two phases. They record the snowpack according to the Canadian Avalanche Associations Observation Guidelines and Recording Standards (OGRS) (Canadian Avalanche Association, 2024). From phase 3 onward, Ylläs Ski Resort's forecasting team will collect equivalent snow profiles in the Pallas–Ylläs area. These profiles are shared with FMI to validate and calibrate the model output.

3.3 Snow model integration

IoT station observations are assimilated into two snow models operated by FMI: SnowModel, a spatially distributed snow-evolution model (Liston and Elder, 2006), and SNOWPACK, a one-dimensional snow-layer model (Lehning et al., 2002). Model output is checked against the manual snow profiles and independent reference stations, and the models are recalibrated each season. A key research question is the observation-network density required to achieve operationally useful snowpack simulations. Norway runs semi-distributed SNOWPACK simulations at a larger scale across its forecast regions (Herla et al., 2024). This project's station-density results will feed into similar scaling decisions for Finnish terrain.

3.4 Data management and quality control

All the IoT device data is timestamped, quality-flagged and stored in a European, GDPR-compliant cloud database. Automated checks catch sensor drop-out, physically impossible measurement values, and low battery voltage. Both raw and quality-controlled data are kept, so quality-control choices can be checked against model performance later. FMI, the Avalanche Center and Metsähallitus can access the data under a shared data-sharing agreement.

3.5 Station density and placement optimisation

Device locations are chosen to cover the combinations of elevation, aspect and wind exposure that drive avalanche-prone snowpack development. Norway uses a similar topographic-class logic for its gridded snowpack modelling (Herla et al., 2024), but with simulated grid cells rather than physical stations. Manual field visits to Finnish avalanche terrain are usually only needed about three times a week, while wind loading can add more than 500 kg/m2 to the snowpack within a few hours (Landon, 2024). Device placement favors wind-exposed start zones and lee-side deposition areas, where conditions change fastest and manual observation cannot keep up. Placement is reviewed at the end of each phase (Section 4) once the first season's data show which sites are most useful for model calibration.

4. IMPLEMENTATION PLAN AND TIMELINE

The project runs in four phases, each covering one snow year (1 October–30 September), from 2026 to 2030. Table 1 summarizes the station count, area and key milestones for each phase.

Table 1: Summary of the phased implementation plan (2026–2030).

Phase	***Period***	***Stations (cumulative)***	***Key focus***
1	2026–2027	10–20	Pilot in Pyhä–Luosto; establish IoT–model data pipeline
2	2027–2028	20–30	Expand Pyhä–Luosto; parallel evaluation of SNOWPACK and SnowModel; first citizen-science courses
3	2028–2029	20–30 (Pallas–Ylläs)	Replicate network in Pallas–Ylläs; first integrated forecast prototype
4	2029–2030	130+	Scale to all Finnish Lapland; transition to operational use

Phase 1 builds the technical and organisational groundwork in a single, well-known pilot area that is easily accessible.

4.1 *Phase 1 (2026–2027): Pilot, Pyhä–Luosto*

- Install 10–20 Snower devices in Pyhä–Luosto National Park
- Test and optimise device placement
- Establish and document the data pipeline linking IoT data, manual field profiles, and the SNOWPACK and SnowModel models
- Record a full snow season and analyse the resulting dataset
- Begin automatic ingestion of IoT data directly into FMI's models

Phase 2 uses the pilot's results to add more devices in Pyhä–Luosto. Start the Citizen-science observer course groundwork in collaboration with FINLAV.

4.2 *Phase 2 (2027–2028): Expansion and parallel model evaluation*

- Expand the Pyhä–Luosto network (20–30 devices) following placement optimisation
- Run SNOWPACK and SnowModel in parallel to identify the relative strengths of each model
- Deliver the first citizen-science observer training courses (2 h and 4 h field courses)

Phase 3 tests whether the Pyhä–Luosto methodology can be copied to a second fell area with similar terrain and produces the first integrated forecast prototype.

4.3 *Phase 3 (2028–2029): Replication, Pallas–Ylläs*

- Replicate the network in the Pallas–Ylläs fell area (20–30 devices)
- Use Ylläs Ski Resort's resources to cross-validate the Pyhä–Luosto results across two fell areas
- Combine the snow model output with avalanche forecasting logic in a first forecasting-system prototype
- Extend citizen-science training to an 8 h course
- Develop a citizen-science observation mobile application for avalanche-relevant reports

Phase 4 scales the validated methodology from two pilot areas to the whole fell region of Finnish Lapland and turns the system from a research pilot into an operational service.

4.4 *Phase 4 (2029–2030): Scale-up across Lapland*

- Extend the network to cover the entire fell region of Finnish Lapland (total 130+ stations)
- Bring the avalanche forecasting system into operational use
- Release the citizen-science observation system to the general public
- Publish scientific articles and a final project report

5. EXPECTED OUTCOMES AND BENEFICIARIES

5.1 *Scientific outcomes*

The project seeks to evaluate the feasibility of a semi-automated avalanche-forecasting framework based on distributed IoT observations and process-based snow models in Arctic terrain. The results may also be relevant to other Arctic regions with sparse observation networks, including those considering approaches similar to the gridded snowpack-modelling framework currently used in Norway (Herla et al., 2024).

5.2 *Beneficiaries*

The denser device network also benefits Metsähallitus management of hiking infrastructure and visitor safety in national parks and wilderness areas:

- Near real-time information on snow quantity and conditions along hiking trails, especially during autumn and spring
- Near real-time local weather and condition data to support field-work planning and safety
- Water-level monitoring data at known problem sites (bridges, trail structures)
- Improved safety information for hikers

6. DISCUSSION

6.1 *Finland in an international context*

Avalanche risk to recreationists and professionals in Finland is small compared with alpine regions of Europe or North America. On the other hand, backcountry use of the fells is growing, and the terrain and snowpack processes involved are the same kind that other EAWS member countries deal with. The goal of the project is to build a weather and avalanche forecasting capability that fits the Nordic conditions. Finland's existing national avalanche forecast shares many of the same weaknesses observed elsewhere, including sparse manual observations, limited public reach, and uncertain long-term funding (Landon and Mäkelä, 2024). In the Alps, fully data- and model-driven forecasts have reached a quality comparable to experienced human forecasters (Techel et al., 2024). That result supports the long-term goal of this project. At the outset, automated model output will support expert judgement and manual field observations, not replace them.

6.2 *Practical and organizational challenges*

The four-year implementation period brings several practical challenges. Battery-powered stations must keep working through Arctic winters with limited access for maintenance. Device locations need to balance between scientific value, installation cost and land-use limits. Combining automated IoT data, manual snow profiles and model output into one dataset needs a robust, repeatable method. The citizen-science component depends on how reliable non-specialist observations turn out to be, so training and quality control are needed before that data can be used operationally. Funding and institutional commitment also need to hold across the full 2026–2030 period. After the project there also needs to be a clear plan how and who will keep the system operationally running.

6.3 *Funding and long-term sustainability*

A cost-benefit analysis using Finnish value-of-a-statistical-life estimates suggests that avalanche-safety spending of a few hundred thousand euros a year is justified if it prevents even one fatality over a decade (Landon, 2024). This makes the case for long-term funding of the project.

7. CONCLUSION

This paper has presented the design and phased plan for a pilot project that combines a network of small IoT weather stations with FMI's snow models, to build Finland's first automated, data-supported avalanche forecasting system. The project runs from 2026 to 2030, expanding from a pilot in Pyhä–Luosto to the whole fell region of Lapland. It should strengthen avalanche safety communication in Finland and add scientific knowledge on snow-model performance and observation-network design in Arctic conditions. Land managers such as Metsähallitus get practical benefits too. Results from the first pilot season will follow in later publications.

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