A ROUTING ALGORITHM FOR SKI TOURING IN NORWAY

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ABSTRACT: An increasing number of Norwegians engage in ski touring in winter mountains. With growing traffic in avalanche terrain, there is a need for tools that can support safer travel and help reduce avalanche accidents. In the Alps, Skitourenguru uses terrain data to automatically generate routes between two locations. Inspired by this approach, this study investigates how a similar routing algorithm can be adapted to Norwegian conditions. An important challenge in developing such tools is the risk of unintended negative effects. While routing algorithms aim to support better decisions, they may also encourage uncritical reliance on suggested routes or create a false sense of safety. By simplifying complex decision-making processes, they can reduce users' active engagement and understanding of avalanche terrain. This study therefore emphasizes the design of a tool that supports rather than replaces user judgment. The algorithm is based on a raster cost surface representing avalanche exposure and terrain preferences for ski touring, derived from parameters such as slope angle, potential release areas, trails, and forest cover. Routing is performed using least-cost path analysis, and the study explores the use of track data to better reflect realistic travel patterns. To avoid overly prescriptive guidance, particular emphasis is placed on how results are presented, introducing a route corridor that represents a range of near-optimal routes rather than a single path. This approach aims to support flexible route planning while maintaining active user involvement. A user interface has been developed to enable intuitive interaction and allow user-defined routing preferences. The algorithm has been tested across six study areas in Norway representing diverse terrain types and touring contexts. Results show that the generated routes generally correspond well with expert-defined routes, while also revealing limitations in certain terrain settings, particularly in steep and complex mountain terrain. The study highlights both the potential and limitations of automated routing approaches, and underscores the importance of designing decision-support tools that maintain user engagement and critical thinking in avalanche terrain.

KEYWORDS: routefinding, GIS, terrain, ski touring, decision making

1. INTRODUCTION

Ski touring has become increasingly popular in Norway, creating a growing need for tools that support safer travel and help reduce avalanche accidents. Terrain is the only spatially consistent and relatively stable factor influencing avalanche conditions, making it particularly suitable for route-planning tools (Statham and Campbell, 2025).

In the Alps, Skitourenguru has demonstrated how terrain data can be used to automatically generate ski touring routes between two locations (Schmudlach and Eisenhut, 2024). Inspired by their approach, this study investigates how a similar routing algorithm can be adapted to Norwegian terrain, conditions and available data.

The routing method transforms terrain characteristics into a raster cost surface representing the relative avalanche exposure and terrain preferences of each location for ski touring. A least-cost algorithm then identifies the route with the lowest accumulated cost between a start and end destination (Etherington, 2016).

An important challenge in developing such tools is the risk of unintended negative effects. While routing algorithms aim to support better decisions, they may also encourage uncritical reliance on suggested routes or create a false sense of safety (McCammon, 2004; Zweifel and Haegeli, 2014). By simplifying complex decision-making processes, they can reduce users' active engagement and understanding of avalanche terrain (Haegeli et al., 2010). This study therefore emphasizes the design of a tool that supports rather than replaces user judgment.

2. DATA

Several nationwide spatial datasets are available in Norway for terrain-based route planning. The routing algorithm used data describing terrain geometry, avalanche exposure, vegetation, infrastructure, barriers and recorded ski-touring activity (see Table 1).

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Table 1: Terrain data used in the algorithm.

Dataset	***Description***
Digital terrain model (DTM)	Terrain elevation (10 m resolution) (Kartverket, 2026).
Slope	Steepness derived from DTM.
Wind shelter	Related to curvature, where positive values indicate sheltered depressions and negative values indicate exposed ridges (Toft et al. 2024; Mannberg et al., 2026).
PRA	Potential release areas, with values between 0 and 1 indicating increasing likelihood of avalanche release (Toft et al. 2024; Mannberg et al., 2026).
Travel distance	Horizontal distance [m] from release areas to runout endpoints (D'Amboise et al. 2022; Mannberg et al., 2026).
Forest density *(Forest attribute maps)*	Number of trees per hectare with diameter greater than 8 cm (Schumacher et al., 2022).
Water bodies *(FKB-Vann)*	Including oceans, lakes, rivers and glaciers (Kartverket, 2026).
Road *(NVDB Vegnett)*	Drivable roads longer than 50 m (Kartverket, 2026).
Tractor road and trail *(FKB-TraktorvegSti)*	Tractor roads and trails (Kartverket, 2026).
Track data	Recorded track data retrieved from UiT/CARE, N = 55 954 (Mannberg et al., 2026).

All datasets were reprojected to EUREF89 UTM zone 33, clipped, and aligned to a common 10 m grid. Vector datasets were rasterized before inclusion in the cost surface. Dataset-specific preprocessing included filtering minor rivers, identifying bridge locations and retaining only roads and trails relevant for ski touring.

3. METHODS

3.1 Study areas

The routing algorithm was developed and evaluated in six study areas: Hemsedal (800 km^2), Isfjorden (400 km$^{2)}$, Jotunheimen (1600 km^2), Kattfjordeiedet (400 km^2), Sogndal (400 km$^{2)}$ and Svolvær (400 km^2). The regions were selected to represent different types of terrain and complexity, and because they include popular ski-touring mountains and available track data. The study areas (Figure x) were organized into ten 20 x 20 km processing units totaling 4 000 km^2, allowing a standardized workflow to be applied across all regions.

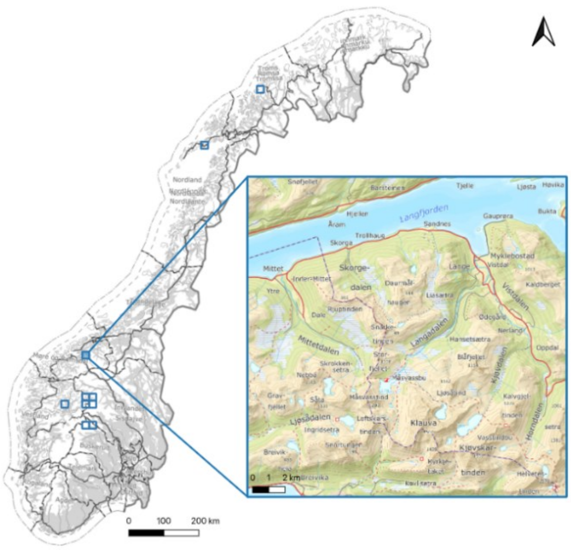

Figure 1: Location of the six study areas and ten 20 × 20 km processing units across Norway. The inset provides a detailed view of the Isfjorden study area.

3.2 Cost surface

The input datasets were transformed into raster cost layers representing relative avalanche exposure and terrain preferences for ascent-oriented ski touring. Cost values represent relative terrain preference rather than a physical quantity such as travel time or avalanche risk. Values primarily ranged from 1 to 100, with increasing values representing less suitable terrain and values above this range used for barriers. Detailed transformations, parameter values, and source code are available in the project repository (Undheim, 2026). Figure 2 summarizes the workflow used to combine the input datasets into the final cost surface. The workflow consisted of four stages:

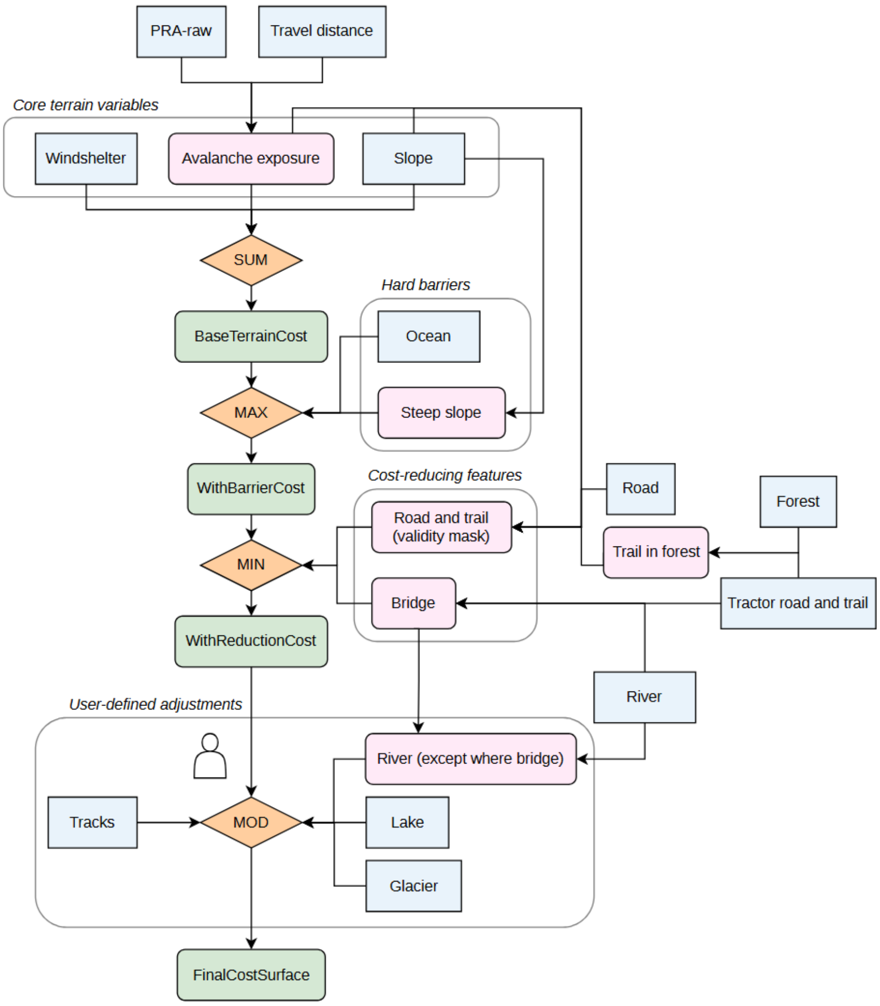

Figure 2: Simplified workflow showing how input datasets (blue) are combined and modified in four stages to produce the final cost surface.

Combination of core terrain variables:

The base terrain cost combined three terrain variables: avalanche exposure, slope, and wind shelter. The avalanche exposure cost layer combined potential release areas and modeled travel distance, following the approach of Mannberg et al. (2026). The three layers were combined using weighted summation with the following relative weights:

$$C_{avalanche} = 0.35, C_{slope} = 0.53, C_{wind} = 0.12 \quad (1)$$

The weights were selected through iterative testing of routing performance using expert knowledge.

Hard barriers:

Features that should be avoided while ski touring were subsequently applied as hard barriers. The ocean and very steep terrain (over 45°) received very high costs using a maximum operator.

Cost-reducing features:

Roads, trails, and bridges were included as cost-reducing features where they could facilitate movement using a minimum operator. The reductions were suppressed in steep or avalanche-exposed terrain.

User-defined adjustments:

To account for different seasonal and geographical conditions and individual preferences, user-defined adjustments were applied as the final step. Users could additionally choose whether rivers, lakes and glaciers should be treated as barriers or not.

Recorded ski-touring track density was also optionally included as a cost modifier. A total of 55,954 recorded ski-touring tracks were rasterized, with each raster cell representing the number of tracks intersecting that cell. The resulting track-density raster was used to modify the movement cost, with frequently travelled cells receiving a cost reduction. Track density was allowed to have a greater influence in forested terrain, where recorded tracks may provide particularly useful information on preferred travel corridors. Different modes allowed users to control the influence of track density on the final cost surface.

3.3 Routing

Routes were generated using raster-based least-cost analysis in GRASS GIS (GRASS Development Team, 2026). Accumulated movement cost was calculated using *r.walk*, which combines the terrain cost surface with elevation-dependent walking costs and accounts for differences between uphill and downhill movement. The least-cost route was extracted using *r.path*, before simplified and smoothed (*v.generalize*).

3.4 Route corridor

A single least-cost route may give misleading impression of precision, as several alternative routes may have similar accumulated costs. A route corridor was therefore generated to represent the area of near-optimal route choices (Etherington, 2016; Schmudlach and Eisenhut, 2024). Accumulated cost surfaces were calculated from both the start and end locations using *r.cost* (GRASS Development Team, 2026) and added together. The cost of the optimal least-cost connection was then subtracted:

$$C_{additional}(x) = C_{start}(x) + C_{end}(x) - C_{opt}(x) \quad (2)$$

The resulting value represents the additional cost of routing through each cell relative to the least-cost solution. Cells with values close to the minimum represent near-optimal route alternatives (Lechner et al., 2017). Corridor thresholds of 10%, 20%, and 30% of the total least-cost route cost were tested. The balanced 20% threshold was selected for presentation as a compromise between route flexibility and corridor extent. As illustrated in Figure 3, the corridor widens where several near-optimal choices are available and narrows where movement is constrained by the terrain. In this example, the corridor identifies two comparable route alternatives.

3.5 Evaluation

The routing outputs were evaluated against 55 reference routes delineated by experts across the six study areas. Routes were generated using four track-based cost reduction modes, resulting in 220 route-mode cases. Geometric agreement was assessed using symmetric point-to-line deviation, reference-route coverage within 25, 50, and 100 m, and route-length ratio. The metrics were combined using predefined thresholds to classify each generated route as having low, moderate, high, or very high geometric similarity to its reference route. Corridor performance was measured as the proportion of each reference route contained within the corridor. Because geometric similarity does not necessarily indicate route quality, routes generated without and with track influence were also visually classified as good, acceptable, problematic, or clear failures. The evaluation therefore focused on whether the outputs represented realistic ski touring routes rather than exact reproductions of a single reference route.

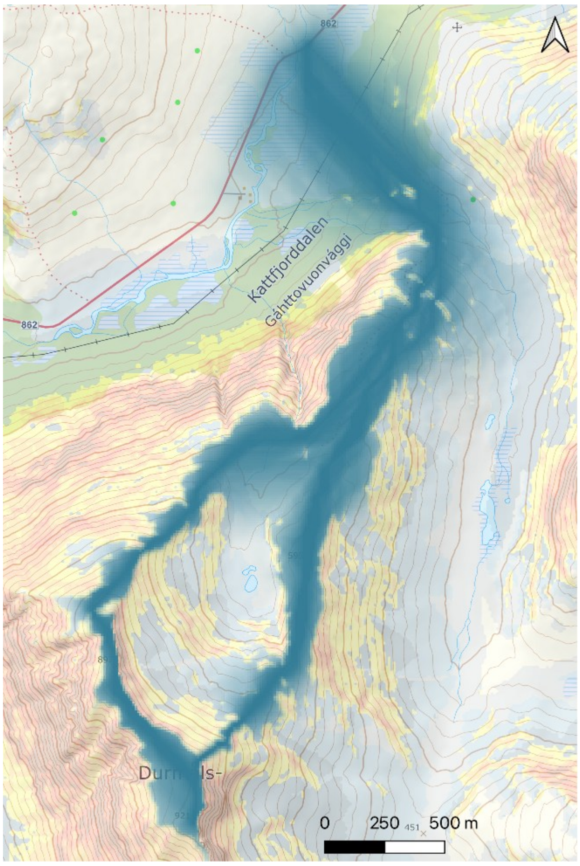

Figure 3: Example of a route corridor where two comparable route alternatives were found. Darker blue indicates lower additional cost relative to the least-cost solution.

4. RESULTS

The resulting cost surface represented relative avalanche exposure and terrain preferences for ski touring ascents (Figure 4).

Table 2 summarizes the geometric agreement between the 55 routes generated without track-based cost reduction and their corresponding reference routes.

Manual visual inspection classified 51 of the 55 routes (92.7%) generated without track-based cost reduction as good or acceptable. With track-based cost reduction, this increased to 54 of 55 routes (98.2%), while the number of routes classified as good increased from 37 to 41. Figure 5 shows the relationship between geometric similarity and manually assessed route quality. Without track-based cost reduction, 27 of the 30 routes with moderate or low geometric similarity were nevertheless assessed as good or acceptable. With track-based cost reduction, the number of routes with high or very high geometric similarity increased from 25 to 37. No routes were classified as problematic with track-based cost reduction, although one failure remained.

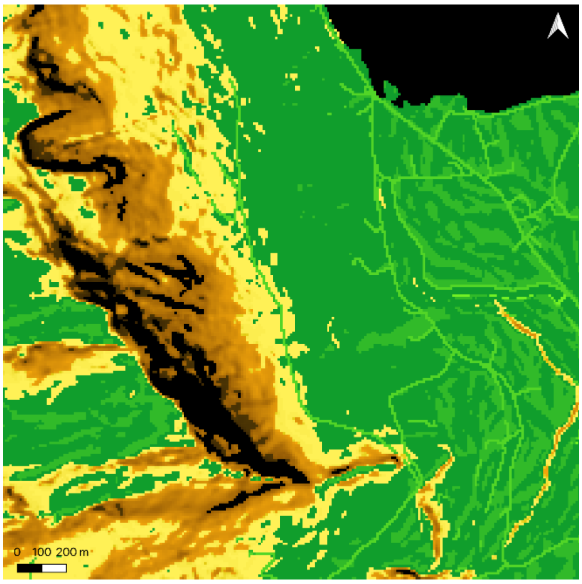

Figure 4: Example of the final cost surface. Green indicates low-cost terrain, yellow and brown indicate increasing cost, and black represents barriers such as the ocean and very steep terrain. Light-green linear features show local cost reductions along roads and trails.

Table 2: Geometric route-comparison and corridor metrics for 55 routes generated without track influence.

Metric	*Value*
Median symmetric deviation [m]	35.0
P95 symmetric deviation [m]	167.6
Reference route within 50 m buffer [%]	58.1
Reference route within 100 m buffer [%]	82.3
Generated-/reference route length ratio	0.964
Mean corridor coverage of reference route [%]	98.1

Two examples of generated routing outputs compared with reference routes are shown in Figure 6. In the first example, both generated routes were assessed as good, although the route without track-based cost reduction differed from the reference route in the upper section. Track-based cost reduction shifted the generated route closer to the reference. In the second example, the generated routes differed more substantially from the reference route and included potentially more problematic route choices.

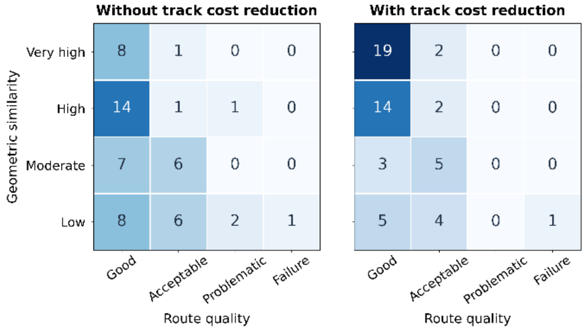

Figure 5: Relationship between geometric similarity and manually assessed route quality for routes generated without track-based cost reduction (left) and with track-based cost reduction (right). Cell values show the number of routes in each category.

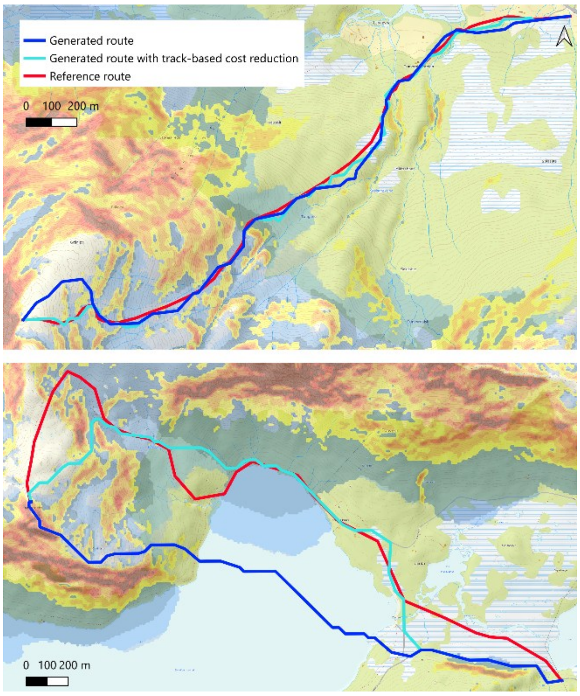

Figure 6: Two examples of generated routes with (light blue) and without (dark blue) track-based cost reduction compared to the reference route (red).

5. DISCUSSION

The cost surface is the most important and challenging component of the framework, as all generated routes and corridors depend on how avalanche exposure and terrain preferences are represented. Combining avalanche exposure, slope, and wind shelter provided information that could not be represented by slope alone, but also introduced trade-offs when the layers favored different terrain choices. Determining which component should dominate is not straightforward and may depend on the terrain and conditions. The selected weights performed well overall and were developed through iterative testing and expert review, but they may not be equally suitable across all terrain types. The model is also primarily designed for ascent and does not necessarily represent desirable downhill terrain.

Track data improved routing, particularly in forests and lower-elevation terrain where suitable travel corridors may be missing from mapped trails and terrain data. However, recorded movement reflects accessibility, popularity, and previous user behavior rather than the underlying avalanche exposure and terrain characteristics represented by the cost surface.

The generated routes generally performed well, but visual inspection showed that geometric similarity to a single reference route is an incomplete measure of route quality. Several geometrically different routes represented reasonable alternatives, meaning that reference routes should be treated as expert-informed examples rather than absolute ground truth. Conversely, a geometrically similar route may still contain undesirable local terrain choices. Evaluation should therefore combine quantitative route-comparison metrics with expert assessment.

Route corridors represent route flexibility and near-optimal alternatives more appropriately than a single precise route, as movement in avalanche terrain is rarely restricted to one route. Rather than providing a definite route, a corridor can function as soft decision support by highlighting favorable terrain while preserving the user's responsibility for assessing and selecting the final route (Dahl et al., 2026). However, whether corridors actually promote active terrain assessment remains unknown. Corridors are also derived from the same cost surface as the least-cost route and therefore share the same assumptions and limitations. They represent near-optimal terrain according to the model, not terrain that is necessarily safe under current avalanche conditions.

Several limitations should be considered when interpreting the results. The framework is based on static terrain data and does not account for current snowpack, weather, or avalanche conditions. Individual preferences, skiing style, experience, and technical ability are also not represented. Furthermore, the 10 m resolution limits the representation of small cliffs, narrow passages, and other micro-terrain features. The algorithm will also always generate a least-cost route whenever a connection exists, even when no suitable ski-touring route exists between the selected locations. The generated routes and corridors should therefore be interpreted as planning support, not as safe or recommended routes.

Future work should focus on refining the cost surface through more systematic calibration. A broader validation involving several independent experts and user testing is also needed. In addition, expert-defined route corridors may provide a more appropriate basis for evaluation than single reference routes.

Although the algorithm can be used for user generated routes, a more promising application may be a new nationwide ski-touring map based on route corridors as proposed by Bachmann (2020). The algorithm could generate corridors representing suitable movement spaces for ski-touring mountains across Norway, including mountains not covered by existing route maps. These corridors could then be reviewed, adjusted, and quality-controlled by avalanche professionals or experienced route planners before publication. This approach would combine the scalability of automated routing with expert knowledge, while presenting an area for further assessment rather than a single recommended route.

6. CONCLUSIONS

This study demonstrates that terrain-based least-cost routing can generate realistic routes across varied Norwegian ski-touring terrain. Most generated routes were assessed as good or acceptable, and use of recorded track data generally improved route quality. The evaluation also showed that geometric similarity to a single reference route is not sufficient to determine route quality, as several geometrically different routes represented reasonable alternatives.

A key reflection from this study is that route corridors may be more suitable than single generated routes in decision-support tools, because they encourage active route planning and support rather than replace user judgment. However, both routes and corridors depend on the assumptions of the underlying cost surface and do not account for current snowpack, weather, or avalanche conditions. The output should therefore support terrain assessment and route planning and not be interpreted as safe route alternatives. With further calibration, expert validation, and user testing, the scalable framework could provide a basis for expert-reviewed, corridor-based ski-touring maps across Norway.

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REFERENCES

Bachmann, A., 2020. Der Computer als Skitourenautor: Automatisch generierte Skitourenkarte, Die Alpen, 2, Schweizer Alpen-Club SAC, available at: https://www.sac-cas.ch/de/die-alpen/der-computer-als-skitourenautor-21914/ (last access: 13 August 2026).

Dahl, T. I., Dassler, T., Fjellaksel, R., Hetland, A., Pfuhl, G., Street, K., Toft, H. B., and Schulze, C., 2026. It's fun … until it isn't: Boosting and nudging for safer decisions in hazardous backcountry winter mountains, J. Outdoor Recreat. Tour., 53, 100996, https://doi.org/10.1016/j.jort.2025.100996.

D'Amboise, C. J. L., Neuhauser, M., Teich, M., Huber, A., Kofler, A., Perzl, F., Fromm, R., Kleemayr, K., and Fischer, J.-T., 2022. Flow-Py v1.0: A customizable, open-source simulation tool to estimate runout and intensity of gravitational mass flows, Geoscientific Model Development, 15, 2423–2439, https://doi.org/10.5194/gmd-15-2423-2022.

Etherington, T. R., 2016. Least-cost modelling and landscape ecology: Concepts, applications, and opportunities, Curr. Landsc. Ecol. Rep., 1, 40–53, https://doi.org/10.1007/s40823-016-0006-9.

GRASS Development Team, 2026. Geographic Resources Analysis Support System (GRASS GIS), Open Source Geospatial Foundation, available at: https://grass.osgeo.org/ (last access: 21 April 2026).

Haegeli, P., Haider, W., Longland, M., and Beardmore, B., 2010. Amateur decision-making in avalanche terrain with and without a decision aid: A stated choice survey, Nat. Hazards, 52, 185–209, https://doi.org/10.1007/s11069-009-9365-4.

Kartverket, 2026. Geonorge: The national website for geographic information in Norway, available at: https://www.geonorge.no/.

Lechner, A. M., Devi, B., Schleger, A., Brown, G., McKenna, P., Ali, S. H., Rachmat, S., Syukril, M., and Rogers, P., 2017. A socio-ecological approach to GIS least-cost modelling for regional mining infrastructure planning: A case study from South-East Sulawesi, Indonesia, Resources, 6, 7, https://doi.org/10.3390/resources6010007.

Mannberg, A., Toft, H. B., Stefan, M. A., Aase, M. J., and Hetland, A., 2026. Do backcountry skiers react to the avalanche forecast? Measuring avalanche terrain exposure using a continuous score, Cold Reg. Sci. Technol., 251, 105039, https://doi.org/10.1016/j.coldregions.2026.105039.

McCammon, I., 2004. Heuristic traps in recreational avalanche accidents: Evidence and implications, Avalanche News, 68, 19–24.

Schmudlach, G. and Eisenhut, A., 2024. A routing algorithm for backcountry ski tours, in: Proceedings of the International Snow Science Workshop, Tromsø, Norway, 2024, 1489–1495, available at: https://arc.lib.montana.edu/snow-science/item/3341.

Schumacher, J., Toft, H. B., McLean, J. P., Hauglin, M., Astrup, R., and Breidenbach, J., 2022. The utility of forest attribute maps for automated Avalanche Terrain Exposure Scale (ATES) modelling, *Scand. J. For. Res.*, 37, 264–275, https://doi.org/10.1080/02827581.2022.2096921.

Statham, G. and Campbell, C., 2025. The Avalanche Terrain Exposure Scale (ATES) v.2, Nat. Hazards Earth Syst. Sci., 25, 1113–1137, https://doi.org/10.5194/nhess-25-1113-2025.

Toft, H. B., Sykes, J., Schauer, A., Hendrikx, J., and Hetland, A., 2024. AutoATES v2.0: Automated Avalanche Terrain Exposure Scale mapping, Nat. Hazards Earth Syst. Sci., 24, 1779–1793, https://doi.org/10.5194/nhess-24-1779-2024.

Undheim, P., 2026. A Routing Algorithm for Ski Touring in Norwegian Avalanche Terrain: Source code and documentation, GitHub repository, available at: https://github.com/PederUndheim/routing-algorithm.

Zweifel, B. and Haegeli, P., 2014. A qualitative analysis of group formation, leadership and decision making in recreation groups traveling in avalanche terrain, J. Outdoor Recreat. Tour., 5–6, 17–26, https://doi.org/10.1016/j.jort.2014.03.001.