

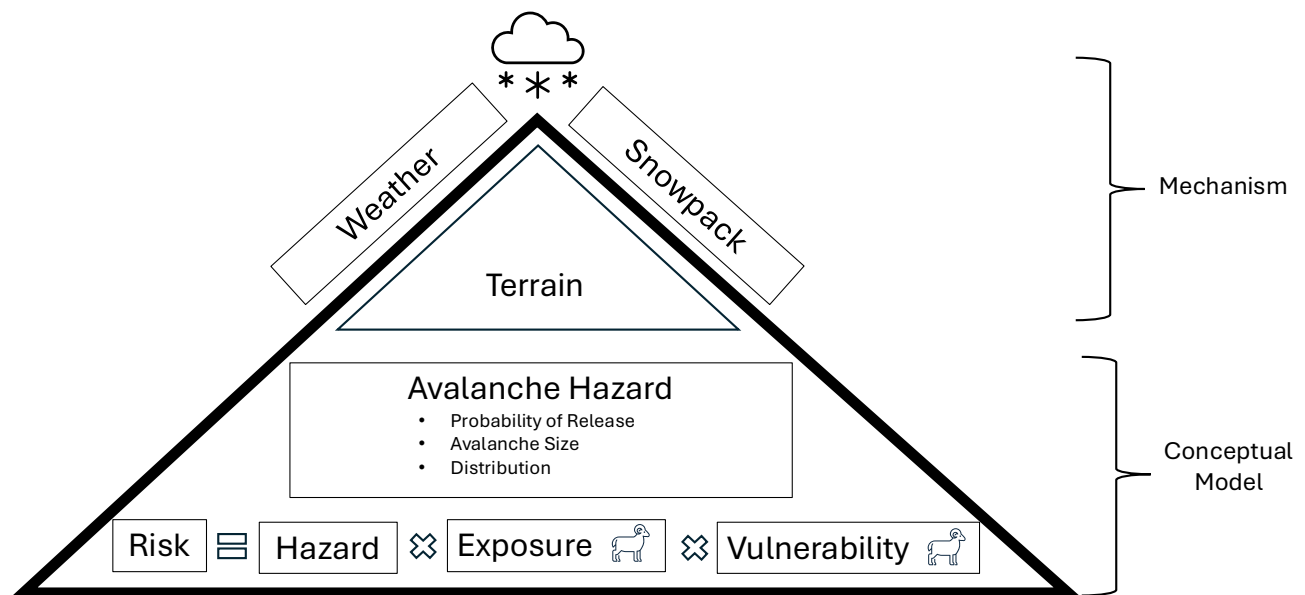
Avalanche Risk Framework for Alpine Ungulate Research

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Understanding avalanche risk is inherently complex, requiring knowledge of the interacting mechanisms that drive avalanche release, including terrain, snowpack structure and weather. These processes operate across multiple spatial and temporal scales, and their combined effects determine when and where avalanches occur. As a result, avalanche risk is often represented using conceptual models that synthesize these mechanisms into a usable framework.

For researchers without a background in snow science, translating these processes into ecological questions can be challenging. However, an avalanche risk framework can provide a structured way to link physical drivers (e.g., snow accumulation, temperature, terrain attributes) with biological outcomes, such as ungulate movement, habitat use, and survival.

The Conceptual Model of Avalanche Hazard (Statham et al. 2017) is widely used as a forecasting framework for communicating avalanche risk. While primarily qualitative for assigning a danger rating, it provides a structure that can be applied to ecological questions, and serves as the basis for the conceptual model presented here:



Weather drives the loading and evolution of the snowpack through precipitation, wind, and temperature. Storm intensity, wind redistribution of snow, and rapid warming events can all increase instability by adding stress or weakening bonds within the snowpack.

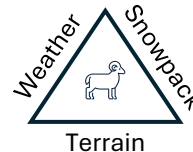
Snowpack structure consists of layered snow with varying strength and stability, influenced by past and present weather conditions. In slab avalanche conditions, a stronger, cohesive layer of snow sits over a weaker layer; when that buried weakness fails, the overlying slab can produce an avalanche.

Terrain determines where avalanches are most likely to occur, with slope angle, aspect, and surface characteristics influencing release. Slopes between ~30–45° are most prone to avalanche initiation, and terrain features such as convexities and gullies can further increase susceptibility.

Trigger
A trigger is the force that initiates failure in an unstable snowpack, such as a skier, wildlife, or natural loading from new snow, wind, rain or solar radiation. Even when conditions are primed for instability, a trigger is often required to release the avalanche.

Adapted for a Wildlife Application: $\text{Avalanche Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}$

- Hazard = environmental conditions (snow, weather, terrain)
- Exposure = animal movement (space use, habitat selection)
- Vulnerability = individual and population-level susceptibility (consequences)



Each component represents a different aspect of how avalanches influence wildlife, where each can be quantified independently relative to study objectives, design and available data.

<p>Hazard: The probability and potential magnitude of avalanche occurrence, driven by weather, snowpack, and terrain.</p> <ul style="list-style-type: none"> • Represents when and where avalanches are likely • Often the most difficult component to quantify directly • Approximated using: <p>Weather proxies (Snow water equivalent, temperature, precipitation) Snow models (e.g., SNOWPACK, SnowModel)</p> <p>Avalanche observations & forecasts</p> <p>Historical weather records</p>	<p>Exposure: The degree to which animals use or occupy avalanche-prone terrain.</p> <ul style="list-style-type: none"> • Represents how animals use avalanche-prone terrain • Directly measurable from telemetry data • Common approaches: <p>Terrain classification (e.g., ATEs, slope 30–45°, aspect, ruggedness index)</p> <p>Potential Release Areas (starting zones)</p> <p>Flow accumulation (runout zones)</p>	<p>Vulnerability: The likelihood that an animal is affected given exposure to an avalanche.</p> <ul style="list-style-type: none"> • Represents susceptibility to mortality or injury • Inferred from outcomes (e.g. mortality) or approximated from ecological or behavioral factors • Influenced by: <p>Group size, behavior, movement</p> <p>Seasonal conditions (e.g., snow depth, hardness, density)</p> <p>Demographic traits (e.g., sex, age)</p>
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Field Monitoring Considerations:

1. Cause-specific mortality monitoring (investing cause of death)
2. GPS Telemetry collars (links movement and mortality events to short-term weather and exposure in terrain)
3. Field Observations (seasonal weather history, snow conditions, avalanche size, type & distribution across region, **PHOTOS** of avalanche(s))
4. Risk management (avalanche training, gear & emergency protocols for working in avalanche terrain)

Data Sources and Tools:

Avalanche Canada & Avalanche.org (USA)

- Daily avalanche forecasts for regions with avalanche centers
- Mountain weather station data specific to forecast regions

Avalanche Terrain Analysis Tools

- Automated Avalanche Terrain Exposure Scale (**AutoATESv2.0**)
- Rapid Mass Movement Simulation (RAMMS)
- Digital Elevation Models (elevation, aspect, slope angle)

Weather Data and Snow models (commonly used)

- Natural Resources Conservation Service (SNOTEL network)
- State transportation (DOT) weather stations
- Satellite Products: MODIS, Sentinel-2, Landsat, AMSR2
- Reanalysis Products: ERA5, MERRA-2, CFSR
- Modeled Snow Data: SNOWPACK (AWSOME), SnowModel (Liston & Elder et al 2006)

Storm Tracker: Compare current storms to historical data for any SNOTEL site

avystormtracker.com

The Starting Zone: At the interface between avalanche science and practice

by Karl Birkland