# Systematic Avalanche Runout Path Delineation for Mountain Hazard Communication


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## OBJECTIVE

Since 1950, avalanches have been the deadliest geohazard in Colorado, and the state accounts for one-third of avalanche fatalities in the United States. Reliable maps of avalanche extent provides the basis for safety operations, public warnings, and recreational route-finding. Previous runout maps were digitized by hand for varied purposes, from highway operations to land-use planning, leaving inconsistencies between contributors and likely overestimated the extent of the paths. The result is a patchwork of inventories with no shared, repeatable criteria for defining avalanche terrain.

The Colorado Avalanche Information Center (CAIC) used a systematic, repeatable process mapping the runout of avalanches that are large relative to their path on the Relative Size scale[2] (R-size 4), utilizing forest and terrain data.. The product is a single standardized statewide layer of paths along Colorado transportation corridors, extending to all CAIC forecast areas by Fall 2026. We see this tool as a step toward connecting avalanche hazard information more directly to the terrain where that hazard exists, ultimately improving decision-making in mountainous terrain.

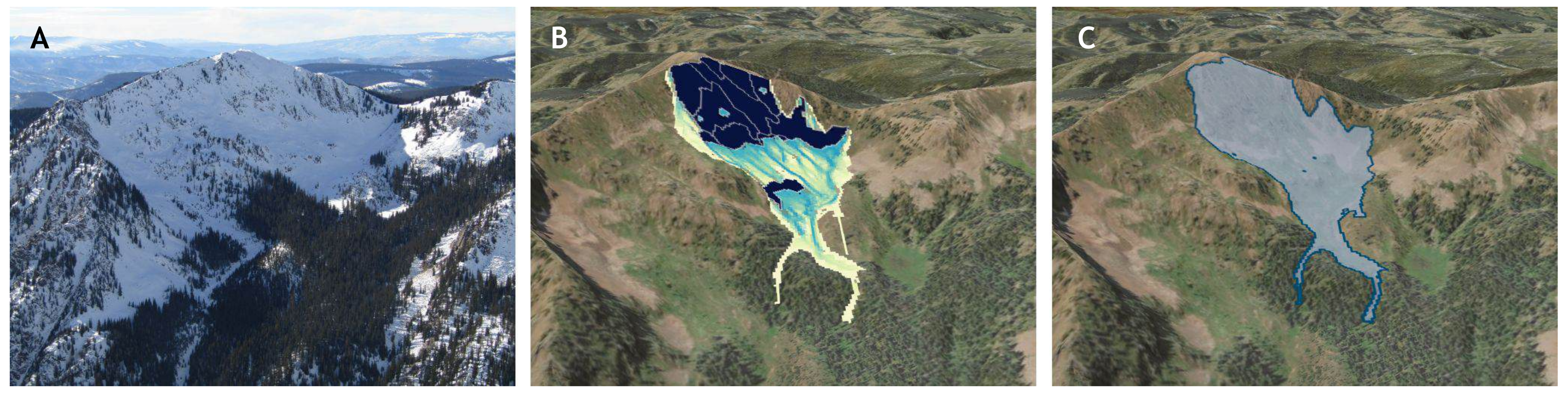
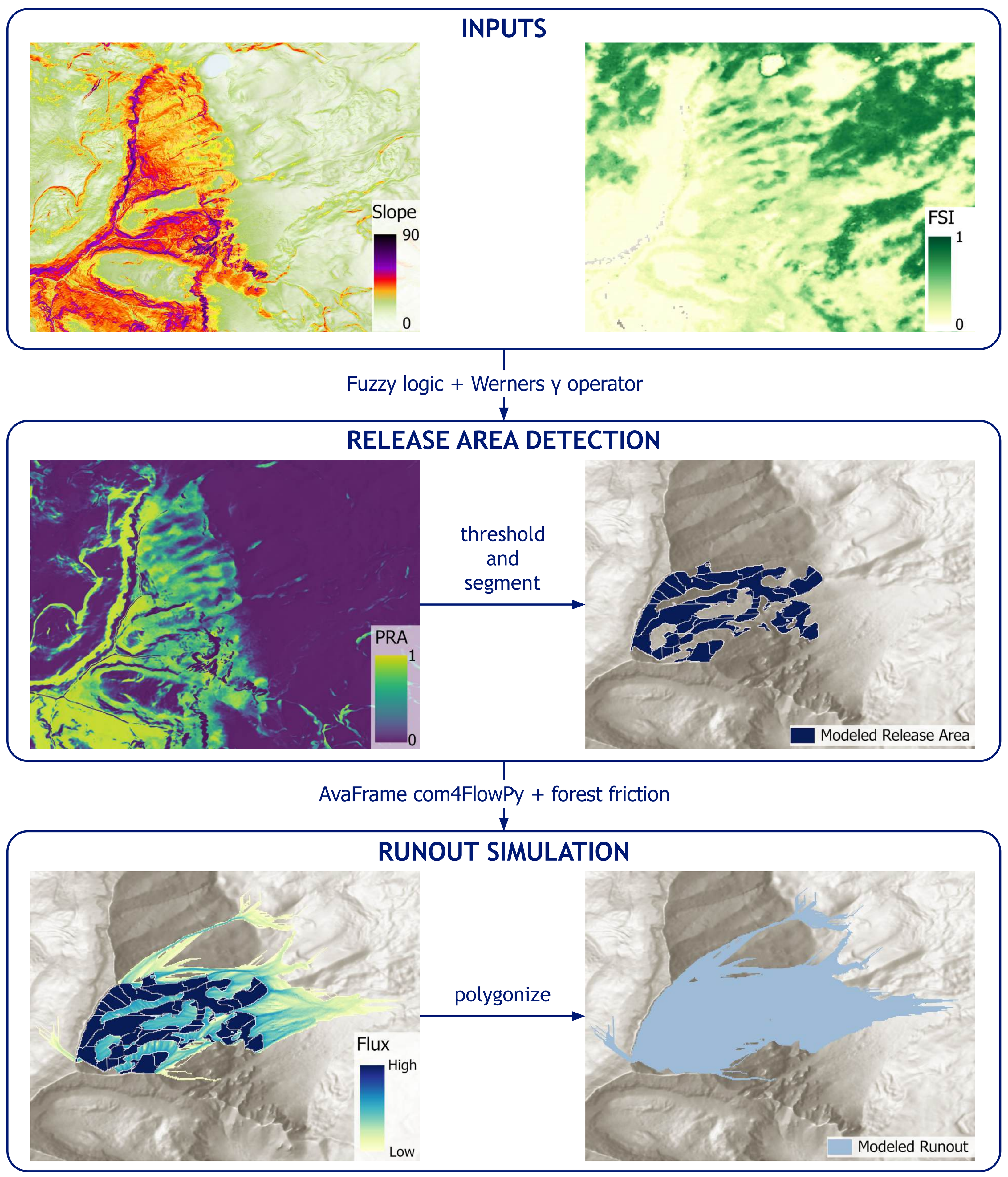



*Figure 1: Modeling workflow for the east face of Bald Mountain, Gore Range: (a) oblique aerial photo captured 11/29/2023, (b) modeled energy flux over the path, (c) modeled runout polygon.*

## METHODS




- **Inputs:** A 1m LiDAR DEM gives slope and terrain. A 10m canopy raster (XGBoost on Sentinel-2, anchored to the 20m Colorado State Forest Service canopy[3]) gives the Forest Structure Index (FSI).
- **Release Area Detection:** Slope and FSI combine through fuzzy logic and a Werners γ operator[4, 5]. The resulting PRA raster is thresholded at 0.55 to keep release surfaces capable of very large avalanches and to absorb canopy-density bias. Watershed and aspect segmentation yield individual release polygons.
- **Runout Simulation:** Release polygons, DEM, and FSI are input to com4FlowPy[6, 7]. The flux output is polygonized at its boundary to produce one runout per release area.
- **Validation:** Modeled polygons are compared against forecaster-drawn paths and checked against oblique imagery of historical cycles and disturbance signatures in satellite imagery.

## RESULTS

The workflow has been applied across varying Colorado terrain. Modeled runouts were compared against forecaster-drawn extents for 41 paths using area-overlap statistics (intersection-over-union, IoU, and Sørensen–Dice), and checked visually against disturbance signatures in satellite imagery and historical photographs.

Agreement was moderate to strong, with a median IoU of 0.77 and a median Dice coefficient of 0.81. Across most paths the model rarely stopped short of the forecaster-drawn extent (median underprediction of 9% of reference area), indicating the workflow captured the downslope reach of very-large avalanche runout.

Where the model exceeded the reference, the difference was mostly attributable to additional start zones and flow routed into secondary channels. Modeled and reference boundaries showed close alignment along the primary runout corridor, with the largest divergences occurring where additional release areas and lateral spread were present.

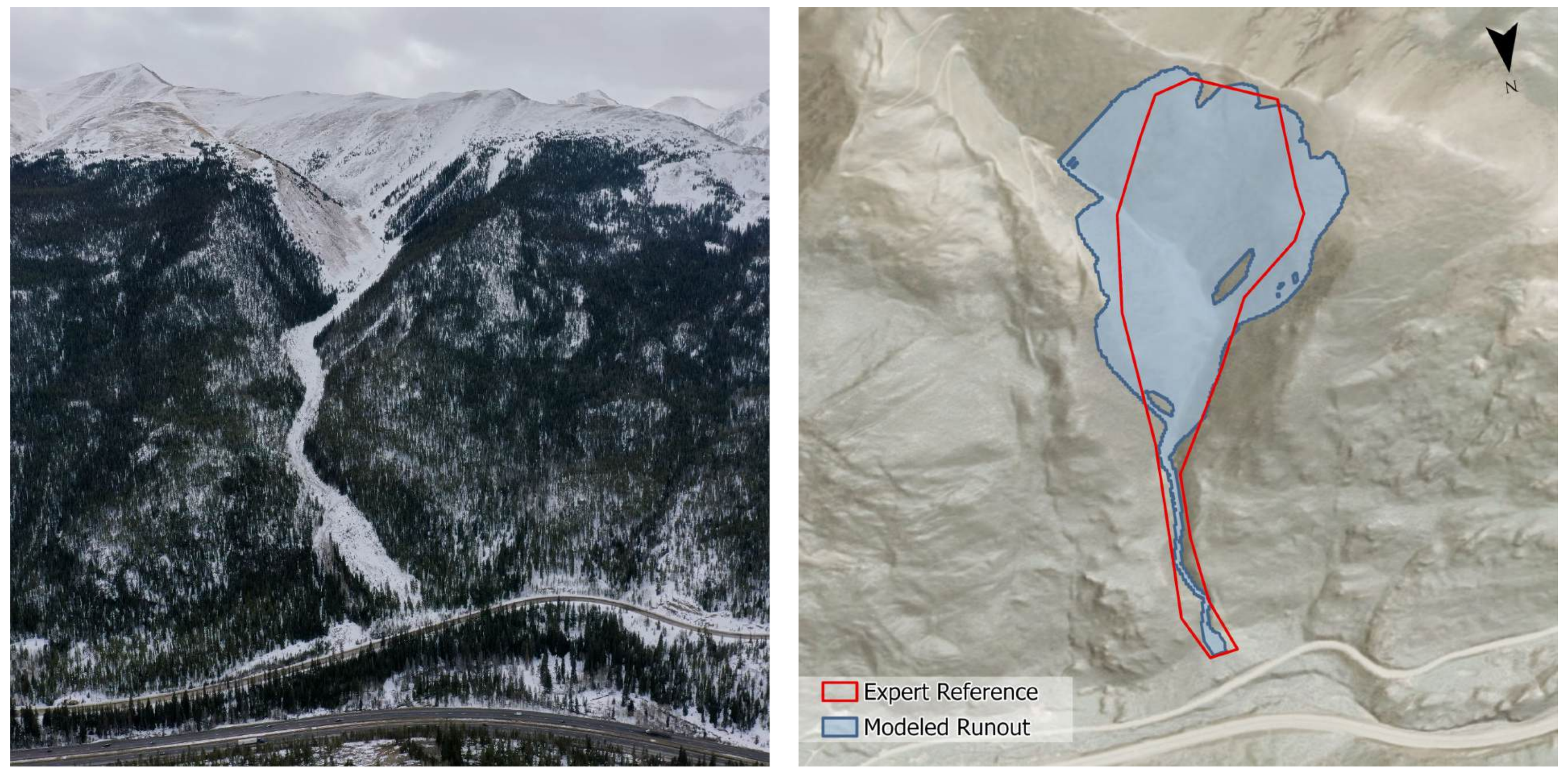



*Figure 3: Ganley Gulch Avalanche Path, I-70. Left: oblique aerial view of the path above the highway. Right: the modeled runout boundary (blue) closely matches the expert-drawn reference (red).*

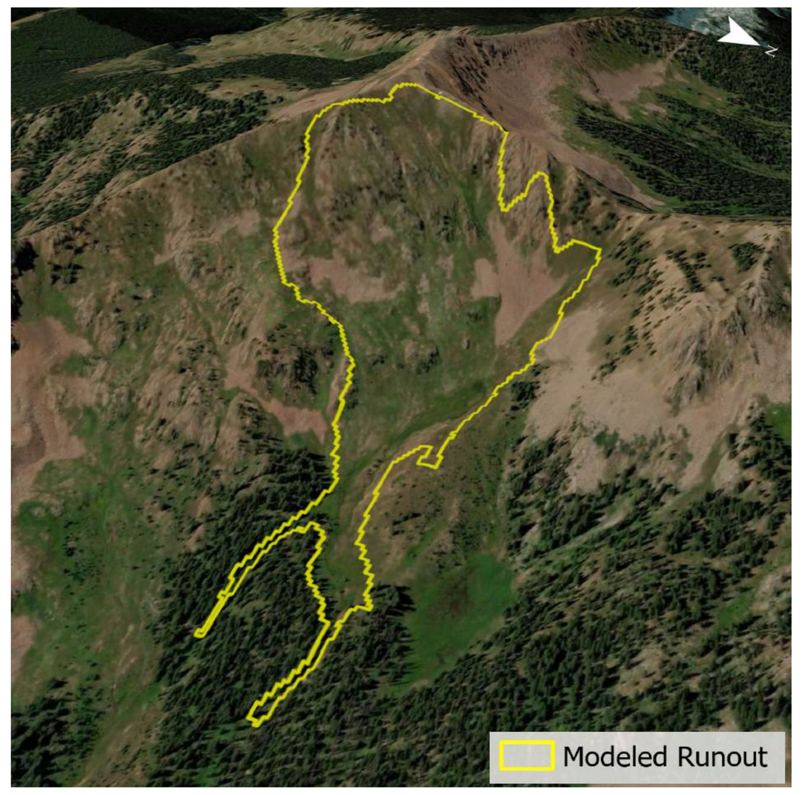



*Figure 4: The modeled runout slows at dense forests and correctly continues through narrow hallways through the trees (East face of Bald Mountain, Gore Range).*

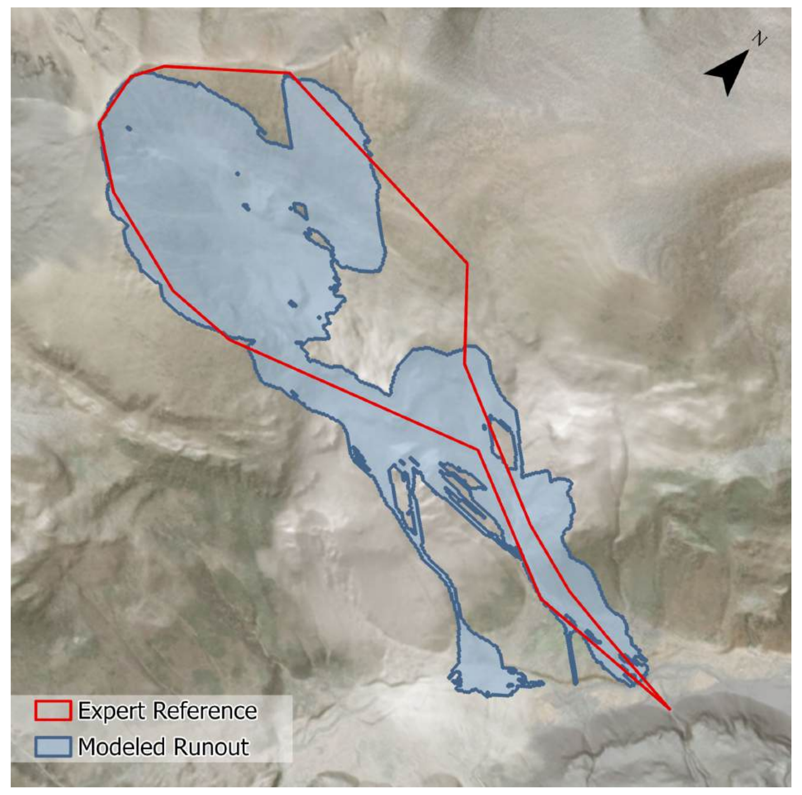



*Figure 5: The modeled runout (blue) broadly agrees with the expert-drawn reference (red). Additional lower start zones in the model account for the extra lateral spread and secondary runouts (East face of Beautiful Mountain, Southern San Juans).*

## LIMITATIONS

- **Disturbed forests:** Canopy data underestimates the density of disturbed stands (fire, drought, disease). The model overruns areas where standing dead trees still buffer flow.
- **Canopy data limits:** No canopy dataset captures forest perfectly. Forest diversity, disturbance, terrain, and acquisition conditions all limit what remote sensors capture, and deriving canopy metrics from imperfect data adds further error.
- **Reference outlines vary:** The expert-drawn paths are estimates with some variability. They can represent the boundary of a single event, typical large events, or historic runs for specific paths rather than a single fixed boundary.
- **Simple model:** FlowPy is a gravitational flow model that does not consider snow properties or physical exchanges like detrainment/entrainment. It is best for regional mapping but does not capture the many nuances of avalanches for individual paths.

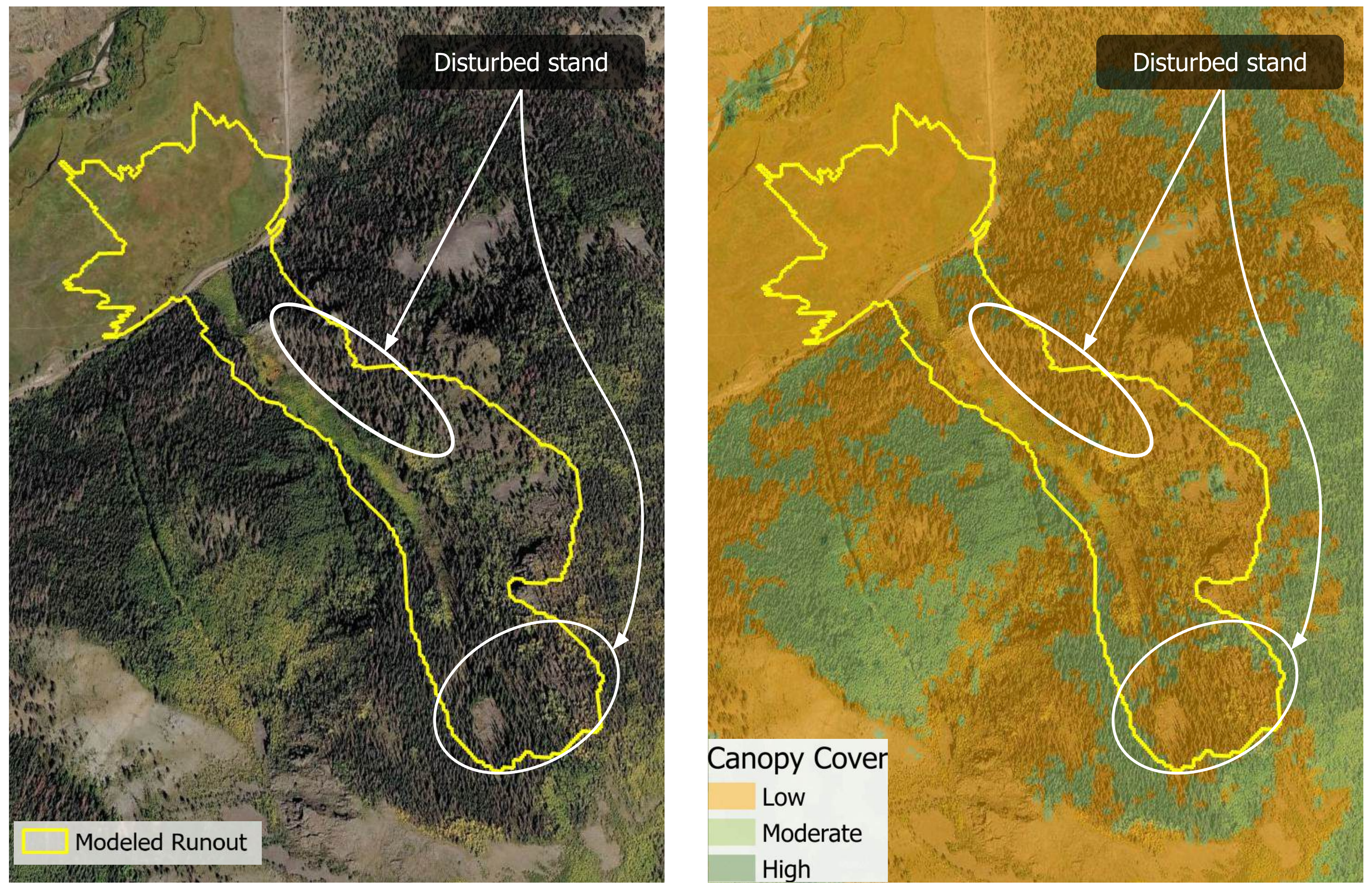



*Figure 6: The same avalanche path above Road 30 near Lake City, CO, shown in aerial imagery (left) and the modeled canopy product (right), with the runout outlined in yellow. Standing dead trees (circled in white) line the path perimeter and the slopes above the start zone, yet the canopy product maps this disturbed forest as Low cover (orange), so the model treats it as open and over-runs the true path.*

## APPLICATIONS

- **Repeatable and standardized:** Combining fuzzy logic terrain analysis with FlowPy and a Colorado-specific canopy product produces a single set of runout polygons that can be consistently regenerated. Moving away from expert-based digitized mapping to a terrain-based modeling approach reduces analyst-to-analyst variability
- **Public-facing hazard communication:** A shared geographic reference for backcountry travelers, recreation planning, and CAIC staff available on the CAIC website and mobile application.
- **Statewide expansion:** By Fall 2026, the regional avalanche runout layer will be expanded to all CAIC forecast areas, the first internally consistent statewide avalanche path dataset for Colorado.

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