ANALYZING AUTOMATED AND METEOROLOGIST-DERIVED QUANTITATIVE PRECIPITATION FORECASTS: OPERATIONAL APPLICATIONS IN HIGHWAY AVALANCHE FORECASTING PROGRAMS

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ABSTRACT: Mountain weather significantly influences avalanche activity in maritime snow climates. The rapid accumulation of precipitation from snow or rain-on-snow events can quickly meet the critical loading threshold of the snowpack. Quantitative Precipitation Forecasts (QPF) play a critical role in predicting the timing of such events, provided they deliver reasonable volume and temporally dependable accuracy. A comparative analysis of two QPF forecast products, presenting water volume in 6-hour intervals, sheds light on their accuracy over 72 hours.

Avalanche forecasting programs often establish operational thresholds for avalanche activity. By examining the time scale and loading volume necessary to reach these thresholds, forecasters can assess the applicability of various accuracy levels in operational settings. Reliable multi-day precipitation forecasts, with acceptable accuracy, contribute significantly to operational decision-making, planning, and avalanche safety. Analyzing forecast evolution, comparing these forecasts with actual water accumulation, and correlating meteorological inputs with observed avalanche activity from highway corridor avalanche paths form the foundation for this analysis and its associated outcomes.

KEYWORDS: Avalanche Forecasting, Weather Forecasting, Weather Data, Forecast Accuracy, Highways, Precipitation.

1. INTRODUCTION

Meteorological factors influence avalanche formation, especially in maritime snow climates, where most avalanches occur in combination with new snow or rain-on-snow events. Therefore, accurate and timely weather forecasts provide critical information to avalanche forecasters. In the Pacific Northwest region of the United States, meteorological information is essential when forecasting avalanche hazards and risks. Accurate meteorological information is especially pertinent in the Cascade Mountains of Washington State. Snoqualmie Pass (921m), in the central region of the WA State Cascades, provides a prime example of the maritime snow climate where abundant snowfall and fluctuating snow levels combine to create a perplexing challenge for avalanche forecasters (Figure 1). Each year, the area receives 1100 cm average snowfall and 2500 mm precipitation.

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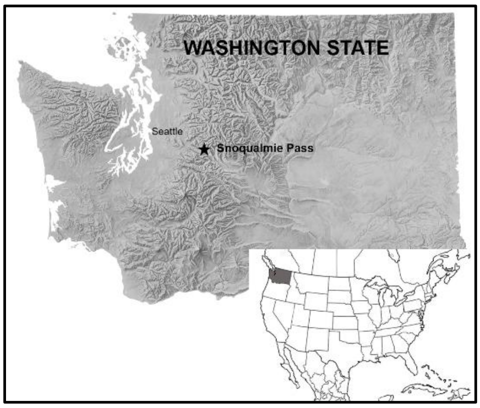

Fig. 1 Location Map

Snoqualmie Pass lies within the Stampede Gap, an area of relatively lower elevation within the Cascades. Here, the shifting air flow between the cooler inland air mass and the warmer maritime conditions to the west results in significant and rapid snow level fluctuations. These transitions, often from heavy snow to rain-on-snow events, are frequent and lead to a rapid increase in snowpack instability, thereby increasing the likelihood of avalanches.
Interstate 90 crosses the Cascade Mountains at Snoqualmie Pass, WA's primary east-west transportation corridor connecting the Puget Sound Region and Seattle to the northern tier of the US. In addition to the transportation corridor,

Snoqualmie Pass and the surrounding area are the site of four ski areas, joined under The Summit at Snoqualmie brand, and multiple access points to backcountry recreation. Avalanche forecasters for the Washington State Department of Transportation (WSDOT) and Northwest Avalanche Center (NWAC), plus snow safety teams from The Summit at Snoqualmie, face constant challenges predicting avalanche hazards.

The WSDOT avalanche forecasting program encounters challenges due to steep terrain, transitional snow zones, and the operational demands of a busy mountain pass highway. Interstate 90 experiences an average daily traffic (ADT) count exceeding 30,000 vehicles, with a significant percentage as commercial heavy vehicles. Although freight transport decreases on the weekends, the highway sees an increase in recreation traffic, often approaching 50,000 ADT. The rapidly developing snow instability combined with near-constant exposure creates a need for timely and accurate weather and snow conditions forecasting. This paper focuses on avalanche forecasting, though weather conditions significantly impact travel from deteriorating road conditions. Thus, accurate weather forecasts benefit highway operations in many ways.

WSDOT Avalanche Forecasters on Snoqualmie Pass rely on multiple data sources to inform their daily decision-making workflow. Two primary weather forecast entities produce quantitative precipitation forecasts (QPF), including wind and freezing level projections, while an array of automated weather stations provides local meteorological values. Forecasters collect snowpack information and integrate recent avalanche observations into their hazard outlook. Avalanche forecasters strongly consider avalanche path and terrain conditions, snow coverage, and, more importantly, snow structure and anticipated avalanche problem. The accuracy of the weather forecasts is an essential link in the workflow and is weighted heavily in planning avalanche operations over the following 12-72 hours. Therefore, evaluating the overall accuracy of data input such as a QPF is critical to worker and highway safety.

2. METHODS

WSDOT forecasters on Snoqualmie Pass utilize two QPF products in their daily avalanche hazard assessment workflow. One forecast, compiled by avalanche meteorologists, comes from NWAC, while the other is an automated product from the National Weather Service (NWS). The automated forecast maintains a fixed geographic location centered over the WSDOT Snoqualmie Pass study plot for day-to-day consistency. Both forecasts include, at a minimum, precipitation, freezing level, and wind variables. The NWAC forecast covers eight 6-hour intervals totaling 48 hours, while the NWS forecast utilizes the same 6-hour intervals extending to seven days. The 6-hour intervals align with global forecasts based on GMT; locally, these intervals correspond to 0400-1000, 1000-1600, 1600-2200, and 2200-0400 PST.
For this study, WSDOT forecasters recorded twelve 6-hour intervals covering 72 hours. WSDOT prioritizes the first four intervals, or 24 hours, for avalanche forecasting and direct operational impacts. The following four 6-hour intervals extend from 24 to 48 hours, which factors into avalanche forecasting and operational planning, while the final group, covering the 48–72-hour period, primarily informs planning and scheduling. The study examined three winter seasons from 2020 to 2023 and included 1361 forecast intervals.

One of the key objectives of this analysis is to determine the accuracy of the forecasts by comparing the QPF to the actual precipitation received within the forecast zone. The meteorological data for this comparison arrived from the WSDOT Snoqualmie Pass Snow Study Plot (921m) (Figure 4). Study plot data include direct observations and automated weather data, such as precipitation quantities from a heated tipping bucket rain gauge, manual snow water equivalent observations, and a full complement of meteorological readings. The data from the heated tipping bucket serves as the comparative values for the precipitation received.

The analysis compared NWAC and NWS forecasts to precipitation received during the comparative 6-hour intervals using the Diebold-Mariano test. The QPF comparison led to further questioning how to define accuracy, particularly in an operational context; does accuracy imply an absolute, or is there an acceptable range comprising accuracy?

Weather conditions often directly impact avalanche formation in maritime climates; therefore, the accuracy of a forecast may depend on a certain QPF threshold to forecast the likelihood of avalanche release. Determining the QPF threshold led to a secondary analysis that added observed avalanche activity and examined two components: How does an increase in precipitation affect the probability of an avalanche, and what is the variation within that precipitation threshold? The analysis then established a precipitation range for the probability of avalanche activity, and the original QPF evaluation was again compared to that range.

Aggregating avalanche paths into zones based on geographical proximity provides a better indicator of overall avalanche activity. Avalanche data arrive from the Denny Mountain, West Shed, and Airplane Curve areas located 1-2 km west and southwest of the Snoqualmie Pass study plot (fig). Denny Mountain 1-6 (DM 1-6) paths have minimal impact on the highway and received no avalanche control during the study period, while the DM 9-10 (DM 9-10), West Shed 1-5 (WS 1-5), and Airplane Curve 1-5 (AC 1-5) paths provided some concern to the highway and received mitigation efforts (Figure 4). Observations were filtered to consider three direct action avalanche types: loose, wet loose, and soft slab, resulting in 330 observed avalanches during the study period.

3. DISCUSSION

Avalanche formation is unique and highly variable, and one or two factors do not easily predict the conditions leading to avalanche release. However, in a maritime climate, meteorological conditions heavily influence avalanche release. Additionally, weather conditions significantly impact travel for highway operations. Therefore, accurate weather forecasts, particularly precipitation quantities, are essential to operations. An analysis of their accuracy and impact on avalanche formation is vital to the success of a highway program.

The analysis used recorded forecasts and observed precipitation from 6-hour intervals over three winter seasons (n=1361). Figure 2 shows the forecast error by year, and considerable variation exists. In 2022, all forecasts were correct more often, while in 2021 and 2023, there was increased variation in forecast accuracy, with NWAC providing more accurate predictions.

The aggregate data shows that the NWAC and NWS 1-day forecasts are similar in accuracy, with NWAC having a slight edge over NWS. Meanwhile, the NWS 2-day and 3-day forecasts are progressively less accurate. The 1-day forecasts, involving the first four 6-hour intervals, provide the highest value to forecasters for programmatic success on I-90, both for avalanche and highway operations.

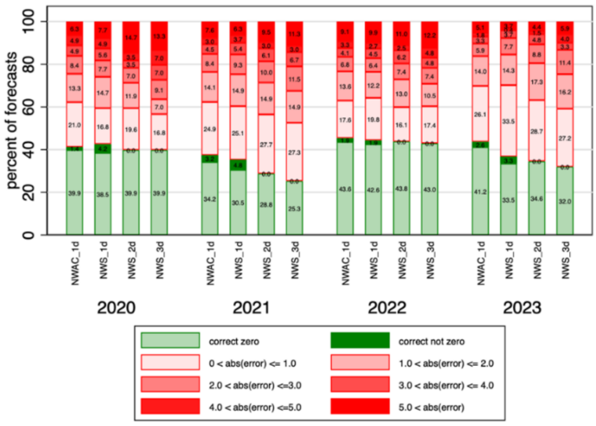

Fig. 2 QPF Error by Season

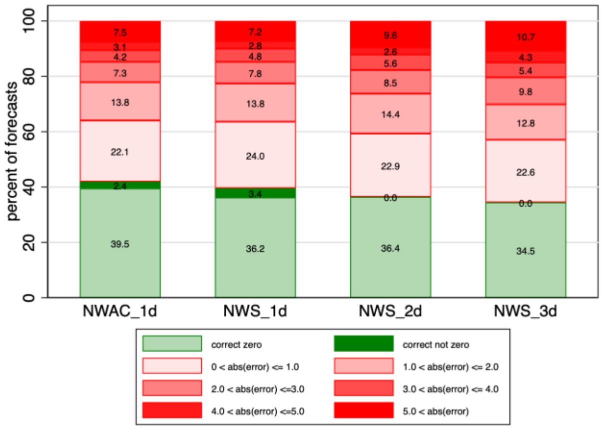

Fig. 3 Aggregate QPF Error by Forecast Interval

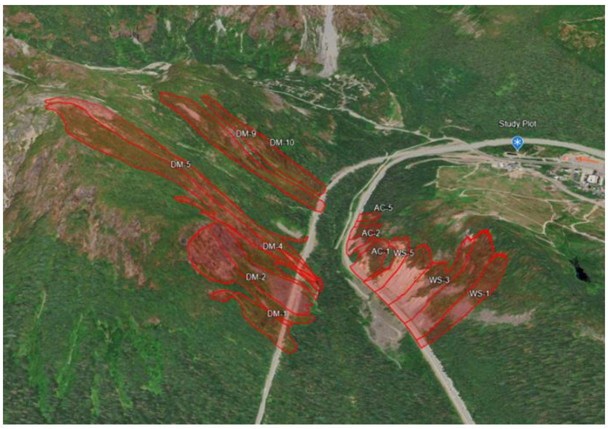

Fig. 4 US Interstate 90 at Snoqualmie Pass Overlayed with the roadway, study plot and Denny Mountain, Airplane Curve and West Snow Shed avalanche paths.

The avalanche analysis, based on three winter seasons, 2020-2023, and focusing on direct-action avalanche types of loose, wet loose, and soft slab, has practical implications for the analysis. The observations included data from DM 1-6, DM 9-10, WS 1-5, and AC 1-5 avalanche paths (n=330). We estimate a statistical model that describes how variation in precipitation is associated with the occurrence of an avalanche. Data from DM 1-6 only included naturally triggered avalanches and informed the model to consider how well the precipitation forecasts predicted the occurrence of an avalanche on the other group of paths: DM 9-10, AC 1-5, and WS 1-5. It is difficult to estimate the impact of precipitation on the occurrence of avalanches in these areas because these paths include artificially triggered avalanches.

4. RESULTS

4.1 *Statistical Model*

Using a logistic model, the model estimates the probability of an avalanche during a 6-hour interval. Let p denote the probability of an avalanche and X the amount of precipitation.

The logit model we estimate is of the form:

$$\log\left(\frac{p}{1-p}\right) = \alpha + \beta X + e^{1} \qquad (1)$$

The model considers the probability of an avalanche over the past 24 hours using the 6-hour intervals (t = 0400-1000, t-1 = 1000-1600, t-2 = 1600-2200, t-3 = 2200-0400) and only considers precipitation since the last avalanche occurrence.

$$\log\left(\frac{p}{1-p}\right)_t = \alpha + \beta_1 X_1 + \beta_2 X_{t-1} + \beta_3 X_{t-2} + \beta_4 X_{t-3} + e \qquad (2)$$

In testing, the coefficients on (t-2) and (t-3) proved not to be statistically different from zero, suggesting that precipitation received more than two intervals ago (12-24 hours) does not significantly affect the probability of an avalanche.

What is the appropriate probability tolerance for an avalanche? Plotting the predictions from the model shows the predicted probability of an avalanche at any precipitation value (t+t-1) or in (t) if there was an avalanche in (t-1). The figures show the predicted probability of an avalanche (vertical axis) with the amount of precipitation (horizontal axis). The dotted lines are confidence intervals. The slope of this line tells us how additional precipitation affects the probability of an avalanche.

For example:

With 0 mm precipitation in the previous interval (t-1) and no avalanche, the addition of 6 mm of precipitation in the current interval produces a 1% probability of an avalanche, while 24 mm of precipitation in the current interval produces a 5% probability of an avalanche (Figure 5).

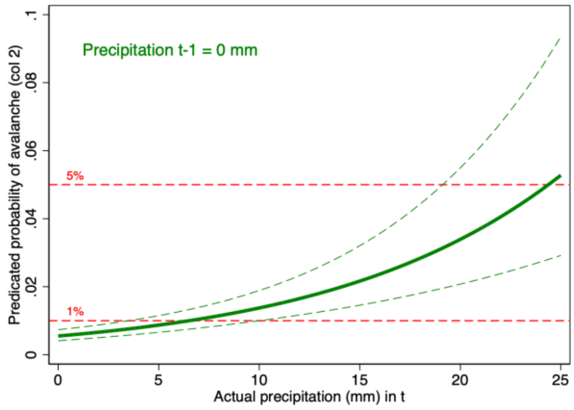

Fig. 5

Meanwhile, 20 mm of precipitation in the previous interval (t-1) with no avalanche saw the probability of an avalanche increase to 2.5% with 3 mm of additional precipitation and 5% with the addition of 11 mm (Figure 6).

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[1] The interpretation of the estimated coefficient $\hat{\beta}$ is that an increase in precipitation of 1 unit (1mm) will result in a $\hat{\beta}$ increase in log(p/1 − p), the log-odds ratio. When log(p/1–p) increases by $\hat{\beta}$, that means that p/(1|p) increases by exp($\hat{\beta}$). So exp($\hat{\beta}$)% is the increase in the odds of an avalanche where there is 1 unit more precipitation. For example, if we estimate $\hat{\beta}$ = 0.1309 this implies exp($\hat{\beta}$) = 1.14, so an increase in precipitation increases the odds of an avalanche by 14%.

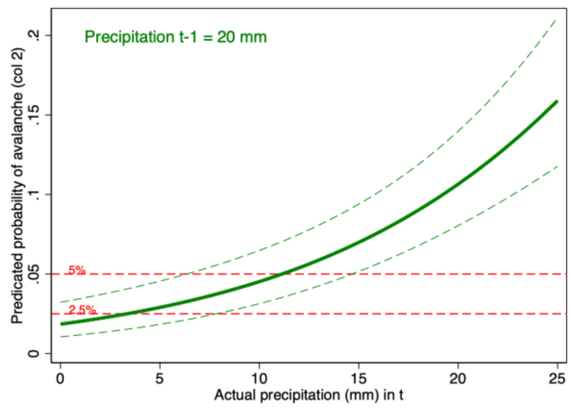

Fig. 6

Compiling results for different precipitation values in t and t-1 is summarized in the following table.

Precipitation Received in Interval t-1	Precipitation Received in Interval t		
0mm	6mm		24mm
5mm	3mm		21mm
10mm	1mm		18mm
15mm		7mm	14mm
20mm		3mm	11mm
25mm		0mm	3mm
Probability of Avalanche	1%	2.5%	5%

4.2 *Combining the Statistical Model with Forecast Predictions*

The next step looks to understand avalanche predictability by combining the precipitation forecasts. The red dots are the predicted probability of an avalanche based on the different precipitation forecasts. The QPF correctly predicts an avalanche where the red dot lies within the confidence interval. Where the red dot lies above the green line, the QPF overestimates the probability of an avalanche; where it lies below the green line, it underestimates precipitation.

The model only considers precipitation since the last avalanche and does not include avalanches in (t-1). The forecasts underestimate the probability of an avalanche during periods receiving more precipitation than forecasted, with the 2- and 3-day forecasts doing so to a greater extent (Figures 7, 8).

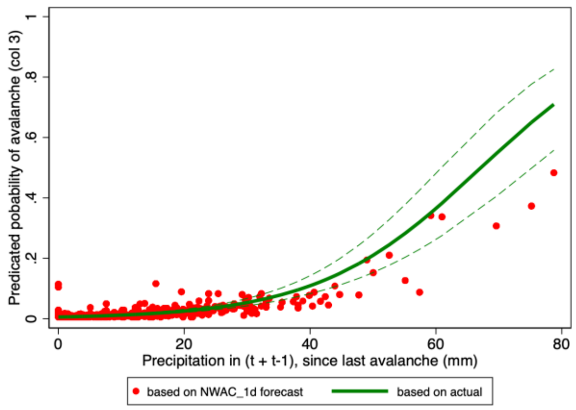

Fig. 7

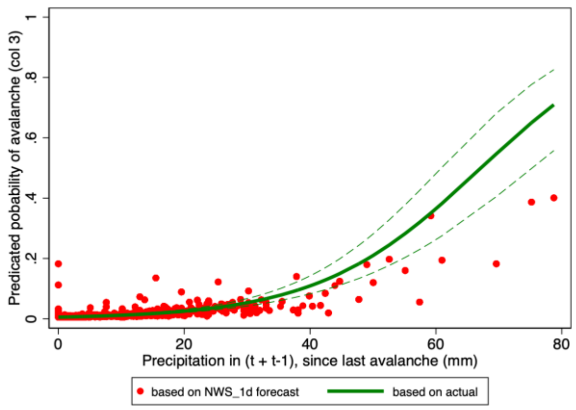

Fig. 8

5. CONCLUSIONS

The results suggest critical loading events for Loose, Wet Loose, and Soft Slab avalanches occur in short periods (≤12-hour). The model output gives insight into the precipitation ranges that result in those critical loading events.

The precision of QPF is more than adequate to predict these events within a typical operational time scale, instilling confidence in forecast products.

QPF products tend to underpredict significant precipitation events (>20 mm in a 6-hour interval). However, this is already a critically high water-level, and avalanche forecasters will likely be alerted to rapidly increasing avalanche danger.

Future research related to this paper includes continued tracking of QPF forecasts and comparative results, improved detection using automated sensors to analyze avalanche occurrence timing better, and combining avalanche size into the analysis and how it relates to precipitation totals.

Overall, the logistic model proved insightful. However, the application of hazard-based duration models, which have enjoyed widespread use in several fields (e.g., economics, biostatistics, transportation), may be better suited for modeling these phenomena. Further discussion on avalanche probability and how it applies to an operational scale is also needed.

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