Prophet-driven AI Modeling for Flood Prediction in the Bow River, Canada

Adya Aiswarya Dash[1] and Edward McBean[2]
PhD Student, College of Engineering, University of Guelph, Guelph, Canada, ON N1G 2W1[1]
E-mail: adash@uoguelph.ca

University Professor Emeritus, College of Engineering, University of Guelph, Guelph, Canada, ON N1G 2W1[2]
E-mail: emcbean@uoguelph.ca

ABSTRACT

Flooding remains one of the most damaging natural hazards in Canada, with the June 2013 Bow River flood causing widespread disruption in southern Alberta and highlighting the critical need for reliable early warning systems. This study presents an artificial intelligence-based flood forecasting approach using the Prophet time-series model to predict streamflow in the Bow River at Banff, a snowmelt-dominated mountainous watershed. Prophet is particularly suited for hydrological applications due to its ability to capture nonlinear trends, strong seasonal patterns, and abrupt changes in time-series data while remaining computationally efficient and robust to missing values.

Historical daily streamflow, precipitation, snowfall, and temperature data were used to develop the forecasting framework. The model was evaluated for multiple lead times, including 15-day, 10-day, 5-day, and 1-day ahead predictions, with a specific focus on the extreme flood event of June 21, 2013. Results demonstrate that Prophet performs exceptionally well at short lead times, accurately reproducing both the timing and magnitude of peak flows during the extreme event. Forecast accuracy decreases with increasing lead time; however, the model retains useful predictive skill for advance warning purposes.

The findings indicate that Prophet-based forecasting can provide valuable lead time for flood preparedness and emergency response in cold-region river basins. The approach offers a practical and interpretable tool for supporting operational flood forecasting and risk management, particularly in watersheds where snowmelt and seasonal variability play a dominant role.

KEYWORDS: Flood forecasting; Bow River; Prophet model; Early warning systems; AI in hydrology; Extreme events

1 INTRODUCTION

Flooding remains one of the most damaging natural hazards worldwide, with increasing impacts on communities, infrastructure, and economies. In Canada, floods are the most frequent natural disaster, and recent extreme events have highlighted the growing need for reliable and timely flood forecasting systems. Mountainous, snowmelt-dominated river basins are particularly vulnerable, as rapid snowmelt combined with intense precipitation can lead to sudden and severe flooding with limited warning time.

The Bow River in southern Alberta exemplifies these challenges. The June 2013 flood caused widespread damage across the region, including large scale evacuations and significant economic losses, emphasizing the importance of early warning and preparedness. Accurate short to medium-term streamflow forecasting is therefore essential to support emergency response, operational decision making, and risk mitigation in such basins.

Traditional flood forecasting approaches often rely on physically based hydrological models, which can be computationally intensive and require extensive data and calibration. In contrast, data driven and artificial intelligence (AI) approaches have gained increasing attention due to their ability to learn complex patterns directly from historical data. However, many machine learning models are difficult to interpret and require substantial tuning, which can limit their adoption in operational settings.

This study investigates the use of the Prophet time-series forecasting model for flood prediction in the Bow River at Banff. Prophet is an additive forecasting framework designed to capture nonlinear trends, strong seasonality, and abrupt changes in time-series data, while remaining computationally efficient and robust to missing values. Using historical hydrometeorological data, Prophet is applied to generate streamflow forecasts at multiple lead times, ranging from 15-days to 1-day ahead, with a specific focus on the June 2013 extreme flood event.

The objective of this work is to evaluate the suitability of Prophet as a practical flood forecasting tool for snowmelt dominated river basins. By assessing forecast performance across multiple lead times, this study demonstrates the potential of Prophet to support early warning systems and improve flood preparedness in cold region watersheds.

2 STUDY AREA AND DATA

The Bow River is a major river system in southern Alberta, Canada, originating in the Canadian Rocky Mountains and flowing eastward through Banff National Park toward the city of Calgary. The study area focuses on the Bow River at Banff hydrometric station, located in a mountainous, snowmelt-dominated watershed characterized by glaciers, icefields, and steep topography. The surrounding landscape consists primarily of montane, subalpine, and alpine ecosystems, with forested areas concentrated in valley bottoms and lower slopes.

The hydrology of the Bow River basin is strongly influenced by climatic conditions typical of cold regions, including long winters and short summers. Annual precipitation in the upper basin ranges from approximately 500 to 700 mm, with nearly half falling as snow. Peak streamflow typically occurs between May and June due to the combined effects of seasonal snowmelt and spring rainfall. These conditions make the basin particularly susceptible to rapid increases in discharge and extreme flooding.

The Bow River at Banff station has been operational since 1909, providing one of the longest continuous streamflow records in western Canada. For this study, daily streamflow data were obtained from Environment and Climate Change Canada (ECCC), complemented by historical records compiled by Alberta Environment and Parks. In addition, daily precipitation (rainfall and snowfall) and temperature data were used to support the forecasting framework. The analysis focuses on the extreme flood event of June 2013, with model training based exclusively on data available prior to the forecast dates in order to replicate realistic forecasting conditions.

Figure 1 illustrates the location of the Bow River basin, highlighting the study reach and the monitoring station used in this analysis.

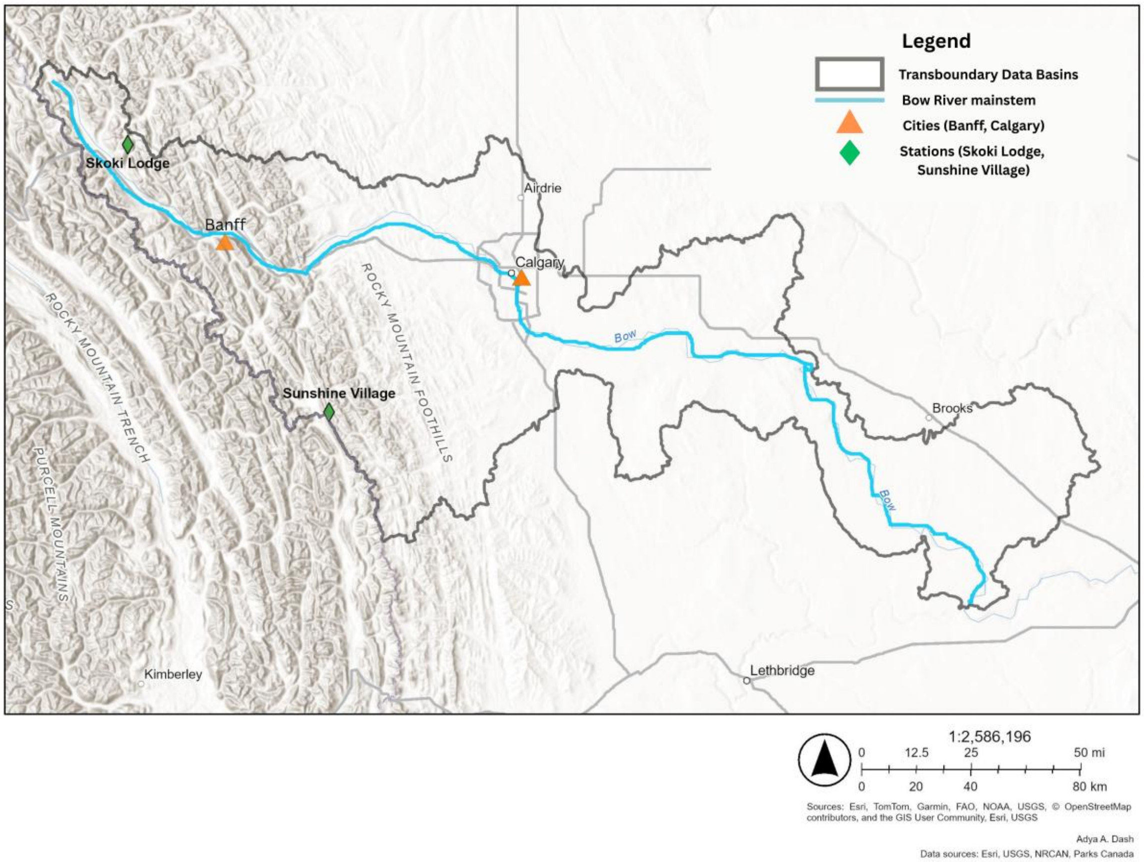


Figure 1: Map of the Bow River Basin, highlighting the study area and the hydrometric station at Banff used for flood forecasting. Adapted from Dash and McBean (2025).

3 METHODOLOGY

This study employs the Prophet time-series forecasting model to predict streamflow in the Bow River at Banff for multiple lead times relevant to flood early warning. Prophet is a decomposable, additive forecasting framework designed to model complex temporal patterns while remaining computationally efficient and interpretable (Taylor and Letham, 2018), making it suitable for operational hydrological applications.

Prophet represents the observed streamflow time series as the sum of trend, seasonal, and external components, expressed as:

$$y(t) = g(t) + s(t) + h(t) + \varepsilon_t \tag{1}$$

where $y(t)$ is the streamflow at time t, $g(t)$ denotes the non-periodic trend component, $s(t)$ represents seasonal variations (e.g., annual and weekly cycles), $h(t)$ captures the effects of external regressors, and ε_t is the residual error term.

The trend component allows for gradual or abrupt changes in river flow behavior, which are common in snowmelt-dominated basins. Seasonal components enable the model to capture strong annual hydrological cycles associated with winter snow accumulation and spring melt. External regressors, including precipitation and temperature, were incorporated to enhance predictive skill during extreme hydrometeorological conditions.

To replicate realistic forecasting conditions, the Prophet model was trained exclusively using historical data available prior to each forecast date. Forecasts were generated for multiple lead times, including 15-day, 10-day, 5-day, and 1-day ahead predictions. Particular emphasis was placed on evaluating model performance during the extreme flood event of June 2013, allowing assessment of the model's ability to capture rapid increases in discharge and peak flood magnitude (Dash and Mcbean, 2025).

Model performance was evaluated using standard statistical indicators, including the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). These metrics were selected to assess both the accuracy and reliability of the forecasts across different lead times, with a focus on their suitability for flood preparedness and early warning applications.

4 RESULTS AND DISCUSSION

4.1 Forecast Performance during the June 2013 Flood Event

The Prophet model was evaluated for its ability to reproduce streamflow dynamics during the extreme flood event of 21 June 2013 at the Bow River, Banff station. Forecasts were generated at multiple lead times, including 15-day, 10-day, 5-day, and 1-day ahead, using only information available prior to each forecast date to replicate realistic early-warning conditions.

Figure 2 presents the 1-day-ahead forecast, demonstrating close agreement between predicted and observed streamflow. The model successfully captured both the timing and magnitude of the peak discharge, indicating strong short-term predictive skill during extreme hydrological conditions.

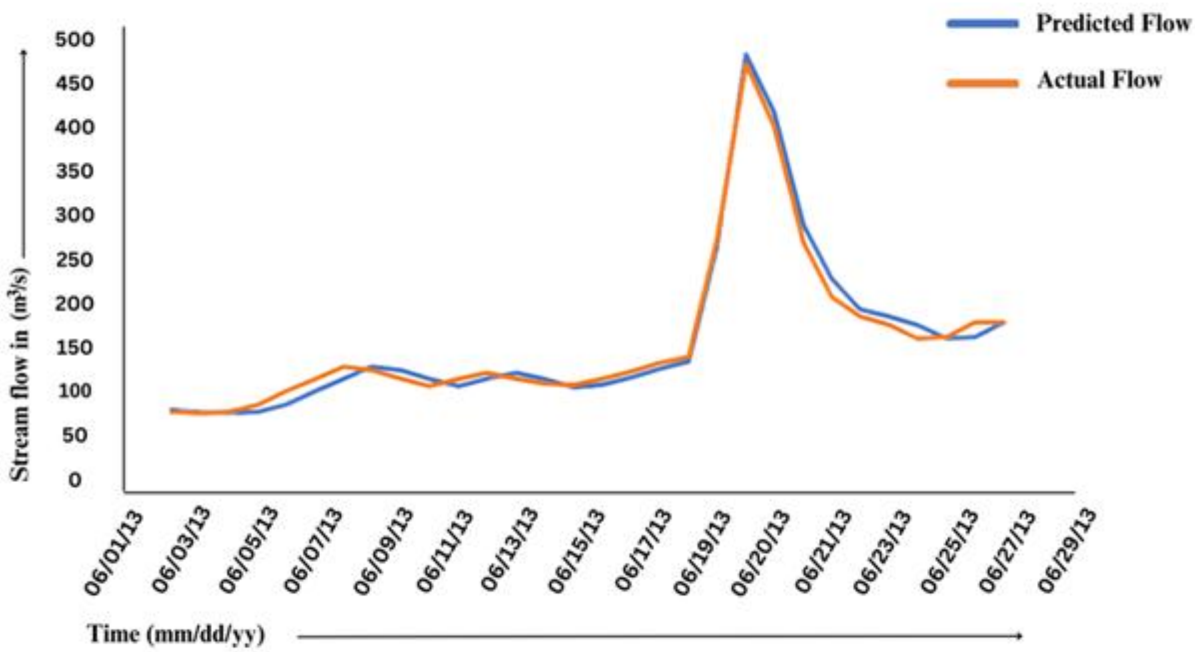
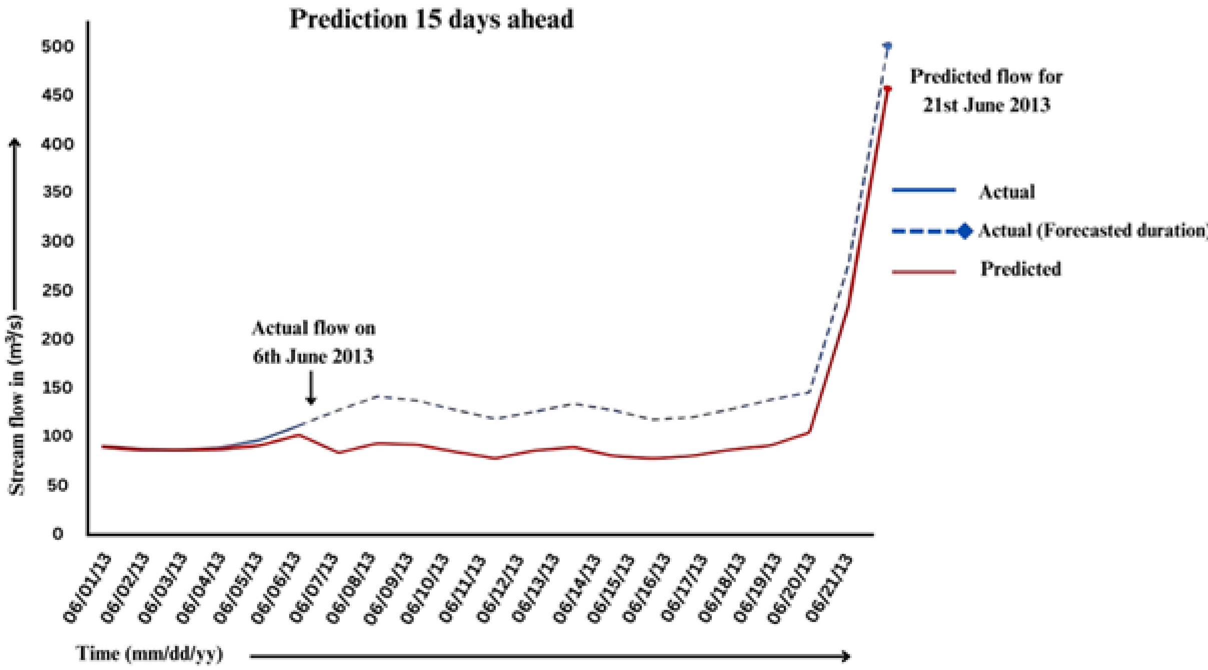


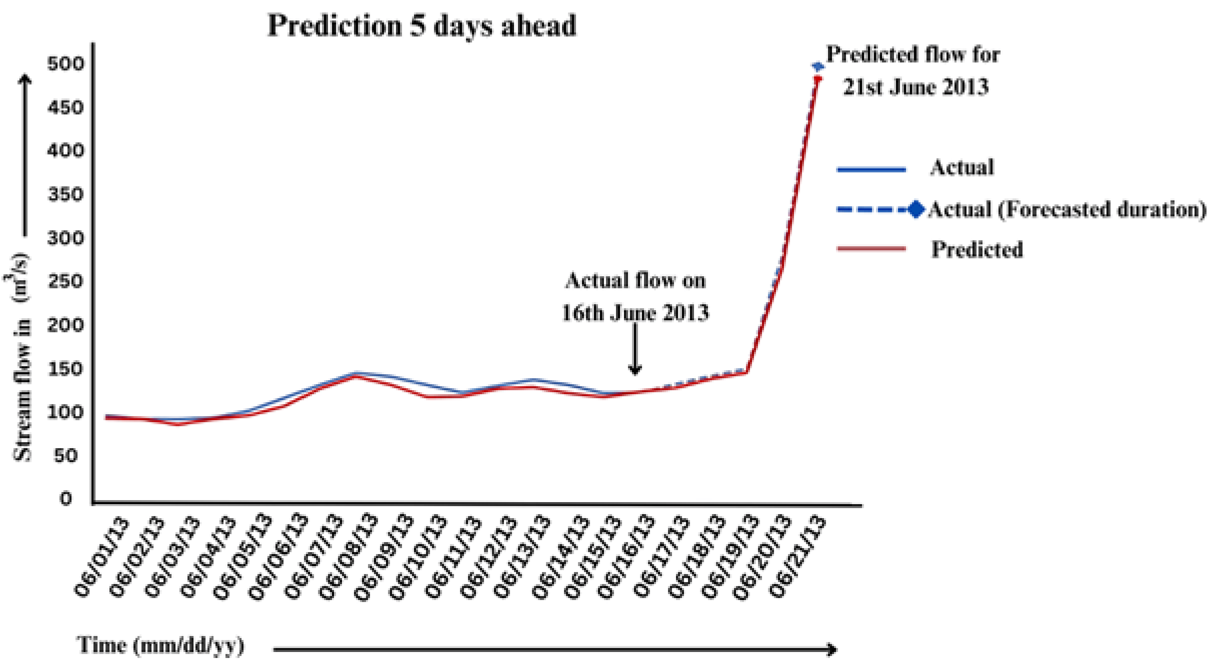
Figure 2: Observed and predicted streamflow for the Bow River at Banff during the June 2013 flood event using a 1-day-ahead Prophet forecast. Adapted from Dash et al. (2024).

4.2 Multi Lead Time Forecast Evaluation

To assess the robustness of Prophet across longer forecasting horizons, predictions were generated for 15-day, 10-day, and 5-day lead times. Figure 3 compares observed streamflow with Prophet forecasts across these horizons for the 2013 flood event.



(a)



(b)

Figure 3: Comparison of observed and Prophet-predicted streamflow for the Bow River at Banff during the 2013 flood event across multiple forecast horizons (15,and 5-day ahead). Adapted from Dash et al. (2024).

The results show a progressive reduction in accuracy with increasing lead time, which is expected given the compounding uncertainty in hydrometeorological drivers. Nevertheless, the Prophet model retained useful predictive skill at medium lead times, particularly in identifying the onset and general magnitude of flooding, which is critical for preparedness and emergency planning.

4.3 Quantitative Performance Metrics

Model performance was evaluated using standard statistical indicators, including the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE), to assess agreement between predicted and observed streamflow during the June 2013 flood event.

The Prophet model demonstrated high predictive accuracy at short forecast horizons, with R^2 values exceeding 0.95, indicating strong correspondence between predicted and observed discharge. Very low error magnitudes further confirmed the model's ability to reproduce rapid increases in streamflow and peak flood conditions. As forecast lead time increased, a gradual reduction in accuracy was observed, consistent with increasing uncertainty in hydrometeorological drivers and basin response.

Despite this decline, the model retained useful predictive skill at longer lead times, successfully capturing the timing and overall magnitude of flooding. This performance is particularly valuable for flood early warning and preparedness, where advance notice despite higher uncertainty supports operational decision-making and risk mitigation.

Overall, the quantitative assessment confirms that Prophet is most effective for short-term flood forecasting, while still providing meaningful information for short to medium term early warning applications in snowmelt-dominated river basins.

4.4 Implications for Flood Early Warning

The results indicate that Prophet is particularly effective for short lead time flood forecasting, where accurate prediction of peak timing and magnitude is essential for evacuation planning and operational decision-making. While longer lead-time forecasts exhibit increased uncertainty, they still provide valuable situational awareness for emergency preparedness in snowmelt-dominated river basins.

Overall, the findings highlight Prophet's potential as a practical and interpretable forecasting tool that balances accuracy, computational efficiency, and operational applicability for flood risk management.

5 CONCLUSION

This study evaluated the applicability of the Prophet time-series forecasting model for flood prediction in the Bow River at Banff, with a particular focus on the extreme June 2013 flood event. Using historical hydrometeorological data, the model was tested across multiple forecast lead times relevant to operational flood early warning.

Results demonstrate that Prophet performs exceptionally well for short lead times, accurately capturing both the timing and magnitude of peak streamflow during the extreme event. While forecast accuracy decreases with increasing lead time, the model retains useful predictive skill at medium horizons, providing valuable situational awareness for flood preparedness and emergency response. These findings are particularly relevant for snowmelt-dominated, cold-region watersheds, where rapid changes in discharge can occur with limited warning.

A key advantage of the proposed approach is its balance between predictive accuracy, interpretability, and computational efficiency, making it suitable for operational deployment. Unlike more complex machine-learning models, Prophet requires limited tuning and can be readily updated as new data become available, which is advantageous for real-time flood forecasting applications.

Overall, the results highlight the potential of Prophet-based forecasting as a practical tool to support early warning systems and flood risk management in mountainous river basins. Future work will explore the integration of additional climate drivers and the application of the framework to other flood-prone regions to further enhance forecasting reliability.

6 ACKNOWLEDGEMENTS

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