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Investigating the Behavior of Hail, Wind, and Extreme Rainfall Events and Their Impact on Urban Flooding in Alberta

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ABSTRACT
Flooding is a major natural hazard that poses serious threats to lives and property safety, which is increasingly driven by compound weather extremes rather than isolated hazards. In regions such as Alberta's "hail alley," intense rainfall is often accompanied by hail accumulation and strong winds, which together may reduce urban drainage capacity, increase surface runoff, and amplify flood- related damages. Hailstones can clog stormwater inlets and conveyance systems, while strong winds enhance rainfall-driven runoff and debris transport, jointly exacerbating urban flooding impacts. Therefore, understanding the inter-dependencies and joint behaviour of these hazards in both historical and future periods is crucial for developing effective flood risk mitigation strategies. In this study, we conduct a multivariate probabilistic assessment of concurrent hail, wind, and rainfall extremes over Alberta's "hail alley" using radar and ground-based observations to investigate the joint occurrence of these extreme events in the historical period. Moreover, the changes in the behaviour of these compound events are investigated under future global changes.

KEYWORDS: compound weather extremes, hail and rainfall and wind, urban flooding, probabilistic analysis, copula, joint return period.

1 INTRODUCTION

Flooding is one of the most devastating natural disasters worldwide, resulting in more than half a million deaths over the past 30 years (Liu et al., 2022) and annual damage of around US$50 billion worldwide (Jalili Pirani and Najafi, 2023). Multiple interacting drivers may jointly influence flood magnitude and impacts rather than individual drivers alone. Recent studies have shown that the concurrence of extreme climate events can exacerbate the consequences of urban flooding, resulting in significant damage and human fatality due to the potential associated (non)linear interactions (Zhong et al., 2021, Jalili Pirani and Najafi, 2023, AghaKouchak et al., 2014; Chang et al., 2016). For example, hailstorms, can be significantly more hazardous when accompanied by extreme rainfall and wind, leading to increased risks of urban flooding. The accumulation of large hailstones can potentially clog rain drains, reducing their capacity to manage runoff effectively. This, combined with intense rainfall, may increases surface runoff, which overwhelms drainage systems, exacerbating urban flooding and causing damage to infrastructure, property, and public safety (Mohamed et al., 2024).

The June 13, 2020's flood in Alberta, Canada, which cost at least $1.2 billion in insured damages, was caused by the concurrence of large hailstones, intense short-duration rainfall, and strong wind gusts. Observations and post-event assessments indicated that hail accumulation obstructed stormwater inlets and reduced drainage efficiency, while strong winds and heavy rainfall enhanced surface runoff. This event highlights the critical role of compound climate extreme events analysis in flood risk management (Mohamed et al., 2024).

This study conducts a multivariate probabilistic assessment of concurrent hail, wind and extreme rainfall events in Alberta's 'hail alley' Using radar data and data from Western University's Northern Hail

Project (NHP), including ground surveys, drone observations, and hail pad data. We analyse individual and joint hazard scenarios through a copula-based approach for the historical period. The study quantifies individual and joint return periods to evaluate the compound risk of hail and extreme rainfall during 2008-2020. Moreover, projected changes in the characteristics of concurrent rainfall, wind and hail extremes are investigated using CMIP6 RCMs. Furthermore, a copula-based approach is applied to assess the interdependence between these extremes and to estimate the joint return periods of theses compound events in the future and under different global warming levels.

2 METHODOLOGY

A comprehensive multivariate statistical framework is developed to quantify risk of compound urban flooding events. For each variable (hail, wind, and rainfall), extreme events are identified using the Peaks-Over-Threshold (POT) method, with the 90th percentile threshold selected to isolate the most impactful events. Suitable marginal distributions are fitted individually for each variable using maximum likelihood estimation, and the optimal distributions are selected based on the Akaike Information Criterion (AIC) and Kolmogorov–Smirnov goodness-of-fit tests.

Dependence between hazard components is first explored using rank-based measures, including Kendall's τ and Spearman's ρ, confirming statistically significant positive dependence among hail, wind, and rainfall extremes. To capture nonlinear and potentially asymmetric dependence structures, a copula-based modeling approach is adopted. Multiple copula families—Gaussian, Student-t, Clayton, Gumbel, Frank, and Joe—are evaluated, and the best-fitting copulas are identified through likelihood-based criteria and goodness-of-fit diagnostics.

The analysis is conducted at both bivariate and trivariate levels. While bivariate copulas are used to model paired combinations of hazards, a vine copula construction is implemented for the trivariate case to flexibly represent complex interdependencies that cannot be adequately captured by standard multivariate copulas. Using the fitted copula models, joint probabilities and joint return periods are calculated under both "AND" (simultaneous exceedance of all variables) and "OR" (exceedance of at least one variable) definitions.

3 RESULTS

The analysis of various return periods during the historical period has highlighted the importance of quantifying the trivariate return periods of compound hailstorm variables to accurately assess the projected risks of urban flooding and the potential impact if they occur simultaneously. According to Table 1, Joint return periods for trivariate and bivariate OR and AND cases are smaller than those of the independent cases for all scenarios, indicating a high correlation between variables and a higher likelihood of simultaneous occurrence of such extreme events.

The trivariate analysis indicates that although the concurrent occurrence of extreme hail, wind gust, and rainfall events is less frequent than univariate and bivariate extremes, it represents substantially higher risk when such events occur. Using a trivariate C-vine copula framework applied to peak-over-threshold samples (90th percentile), the nonlinear dependence structure among hail intensity (max_VIL), maximum wind gust (WGust), and rainfall rate (PRate) is explicitly quantified.

Table 1 demonstrates that the trivariate AND return periods during the historical period derived from the copula-based framework are markedly shorter than those obtained under the assumption of independence. This nearly 80% reduction in return period relative to the independence assumption demonstrates that neglecting dependence among the three drivers leads to a substantial underestimation of compound flood risk. Therefore, the trivariate return period provides a more realistic estimate of how often urban drainage systems may be exposed to simultaneous extreme rainfall, reduced drainage capacity due to hail accumulation, and wind-enhanced runoff conditions that are critical for urban flooding management.

Table 1 Univariate, bivariate and tri-variate joint return periods estimated for quantile 90 using the tri-variate sample of observations

Hazard quantiles estimated using the inverse of the best fitted marginal cumulative distribution functions (CDFs)			Univariate joint return periods (Years)			Bivariate joint return periods (Years)				Tri-variate joint return Periods		Independent cases		
max_VIL (X) (kg/m2)	Prate (Y) (mm/hr)	WGust (Z) (km/hr)	Tx	Ty	Tz	T_{XY}^{OR}	T_{XY}^{AND}	T_{XZ}^{OR}	T_{XZ}^{AND}	T_{XYZ}^{OR}	T_{XYZ}^{AND}	T_{XY}^{IND}	T_{XZ}^{IND}	T_{XYZ}^{IND}
96.19	19.59	89.97	3.6	3.3	4.10	1.16	4.8	1.0	10	1.7	55.4	16.32	12.59	285

4 CONCLUSION

The results demonstrate that ignoring dependence among hail, wind, and rainfall extremes leads to a substantial underestimation of return periods of compound urban floods. Joint return periods derived under an independence assumption are underestimated by up to approximately 70% compared to copula-based estimates during the historical period. In the trivariate case, the joint AND return period of concurrent hail–wind–rainfall extremes is approximately 55 years, compared to about 285 years under the assumption of independence.

These findings highlight the importance of trivariate dependence analysis for flood risk assessment and emphasize the need to consider compound-event analysis into stormwater infrastructure design and urban flood management, particularly in regions such as Alberta where severe convective storms are common.

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