

Multivariate Comparative Analysis of Weather-Related Disasters: A Case Study of Huye, Ngororero, and Bugesera Districts, Rwanda (2020–2025)

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Abstract

Rwanda's hilly terrain and increasingly erratic rainfall expose its districts to recurrent weather-related disasters, including floods, landslides, and windstorms. National agencies report disaster effects annually but rarely test whether observed differences among districts are jointly statistically significant across multiple impact indicators. This study evaluates whether weather disaster-impact profiles differ significantly among three districts representing contrasting agro-ecological zones. In this comparative multivariate study, district-year disaster-effects records for Bugesera, Huye, and Ngororero districts (2020–2025) were analyzed using one-way multivariate analysis of variance (MANOVA) across six indicators: deaths, injuries, houses damaged, damaged crops, lost cattle, and other livestock losses. The number of observations for each district is over five ($g = 3$ districts, $p = 6$ variables). The Wilks' Lambda test was computed from the within-group and between-group sum-of-squares and cross-products matrices. Significant multivariate results were followed by Tukey's Honestly significant post hoc test for the pairwise comparisons of difference of means. Wilks' Lambda was found equal to 0.0455. This value, which is close to zero, indicates a statistically significant multivariate difference among the three districts. At 5% significance level, the Tukey post-hoc tests showed that Ngororero differed significantly from Bugesera and Huye in deaths with small p -values of 0.005 and 0.010 respectively. Bugesera differs from Bugesera in injuries (p -value = 0.047) and in lost cattle (p -value = 0.031). Differences in houses damaged, damaged crops, and other livestock were not statistically significant as the corresponding p -values are greater than the 5% significance level in use. Weather-related disaster impacts differ significantly among Bugesera, Huye, and Ngororero districts. Ngororero District, part of Rwanda's north-western landslide- and flood-prone belt bearing a disproportionate share of deaths, injuries, and livestock losses. Findings support continued targeted disaster risk reduction investment in high-risk north-western districts.

Key Words: Multivariate Analysis of Variance (MANOVA); disaster risk management; Rwanda; climate variability;

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I. Introduction

Rwanda is a small, hilly, landlocked country in East Africa's Great lakes region highly affected by weather-related disasters. Among them floods, landslides, windstorms, hailstorms, and lightning are the most recurring threats to human life, infrastructure, and livelihoods.

Rwanda's steep topography, high population density, and reliance on rain-fed agriculture make many districts structurally vulnerable to hydro-meteorological hazards. The Ministry in Charge of Emergency Management (MINEMA) is the government institution mandated to coordinate disaster preparedness, response, and recovery, and it maintains a Disaster Communication System that records annual district-level disaster effects, including deaths, injuries, and damage to housing, agriculture, and livestock^{1,2}.

National-level reporting shows that disaster impacts are not evenly distributed across the country. MINEMA's contingency planning documents identify the north-western districts including Nyabihu, Ngororero, Rubavu, Musanze, Burera, and Gakenke as the area's most vulnerable to landslides and floods, owing to their volcanic, mountainous terrain and high-intensity rainfall exposure³. Nationally reported events reinforce this pattern: the May 2023 floods and landslides affected 14 districts and killed 137 people, concentrated in the western, northern, and southern provinces⁴, while annual MINEMA disaster effects reports for 2018, 2023, 2024, and 2025 consistently show lightning, floods, landslides, and windstorms as leading causes of death, injury, crop

loss and livestock together and structural damage, with substantial year-to-year and district-to-district variation^{1,2,5,6}.

Despite this well-documented spatial unevenness, much of Rwanda's disaster-effects reporting remains descriptive rather than formally tested for statistical significance across districts and across multiple impact indicators simultaneously. Treating each indicator separately, as is common in administrative reporting, obscures whether observed differences in disaster severities are statistically significant or attributable to normal year-to-year variability.

This study addresses that gap by applying one-way multivariate analysis of variance (MANOVA) to compare weather-related disaster-impact profiles across three purposively selected districts, representing contrasting agro-ecological zones: Bugesera (Eastern Province, semi-arid), Huye (Southern Province, moderate hilly terrain), and Ngororero (Western Province, mountainous, landslide-prone). The specific objectives were (i) to construct district-level mean impact profiles across six disaster-effect indicators; (ii) to test, using Wilks' Lambda, whether the three districts equally suffered from weather-related disasters from 2020 up to 2025; and (iii) to formulate some recommendations for further planning of policies and preventive measures.

II. Material and Methods

This comparative multivariate study analyzed secondary data related to weather disasters for three Rwandan districts over a five-year period from 2020 up to 2025.

Study Design:

The design for this study is a retrospective comparative multivariate (one-way MANOVA) analysis of district-year disaster-effects records.

Study Area:

Three districts were purposively selected to represent contrasting agro-ecological and hazard-exposure profiles within Rwanda. **Bugesera District**, in the Eastern Province, has a relatively flat, semi-arid landscape with lower and more erratic rainfall, more commonly associated with dry-spell and localized flooding risk than with landslides. **Huye District**, in the Southern Province, has a moderate, hilly topography placing it at intermediate exposure to both flooding and landslide hazards. **Ngororero District**, in the Western Province, lies within Rwanda's mountainous north-western belt, identified by national risk assessments as the area of highest landslide and flood susceptibility in the country^{3,7}.

Study Duration:

The current study covers the period from 2020 up to 2025.

Data Source and Sample Size:

The used data is from January 2020 to December 2024 from MINEMA Reports.

Statistical analysis:

A one-way multivariate analysis of variance was used to test whether the mean vectors of six disaster-effect indicators differed significantly among the three districts: Bugesera, Huye and Ngororero. The null hypothesis was stated as:

$$H_0: \mu_{Bugesera} = \mu_{Ngororero} = \mu_{Huye}$$

Indicating the three districts have the same mean vector of disaster impacts. The alternative hypothesis was

$$H_0: \text{At least one district has a different mean vector}$$

To decide whether the districts under consideration are equally affected by weather related disasters, the between group sum of squares and cross product matrix H and within between group sum of squares and cross product matrix E were computed from the secondary data. These matrices were then used to calculate Wilks' Lambda⁸ given by

$$\Lambda = \frac{|E|}{|E + H|}$$

A statistically significant result was interpreted as evidence that the mean vectors of the disaster-effect indicators differed across the districts. Following a significant MANOVA results, pairwise comparisons were conducted in order to identify which specific district differs from one another and, consequently to determine which districts experienced significantly greater effects. Tukey's Honestly significance (HSD) post hoc test was used for the pairwise comparisons of difference of means at the 5% significant level. All statistical analyses were performed in Python using pandas, numpy, scipy.stats and statsmodels.

III. Results

Table 1 shows the mean value of each disaster-effect indicator by district over 2020–2025. Ngororero recorded substantially higher mean values than Bugesera and Huye on nearly every indicator most outstandingly for deaths (17.8 versus 1.8 and 3.4), houses damaged (417.2 versus 80.8 and 104.2), and lost cattle (10.0 versus 0.2 and 1.4).

Table 1: Mean disaster-effect indicators by district, 2020–2025.

District	Deaths	Injured	Houses Damaged	Damaged Crops (Ha)	Lost Cattle	Other Livestock
Bugesera	1.8	6.0	80.8	10.70	0.2	8.2
Huye	3.4	7.8	104.2	73.54	1.4	0.2
Ngororero	17.8	17.6	417.2	172.35	10.0	44.8
Overall Mean	7.67	10.47	200.73	85.53	3.87	17.73

The one-way MANOVA yielded Wilks' Lambda $\Lambda = 0.0455$ which is close to zero. Therefore, the null hypothesis of equal mean vectors across the three districts is rejected in favor of the alternative hypothesis stating that at least one district has a different mean vector.

To identify which district significantly experienced greater weather-related disasters, effect the Tukey's HSD pairwise comparisons of difference between means was conducted. The results in Table 3 revealed that Ngororero differed significantly from both Bugesera and Huye in Deaths (P-values 0.005 and 0.010 respectively less than the significance level), and Bugesera in Injuries (p-value=0.047) and lost cattle (P-value=0.031). The Huye-Ngororero difference in cattle was not statistically significant as the related p-value of 0.059 is greater than the significance level of 0.05. No pairwise comparison reached a statistically significant difference for Houses damaged, damaged crops, or other livestock across the districts under consideration despite Ngororero's substantially higher raw means on these indicators.

Table 2: Tukey HSD pairwise comparisons by disaster-effect variable.

Variable	Comparison	Mean Diff.	p-adj	Sig.
Deaths	Bugesera - Huye	1.6	0.919	No
	Bugesera - Ngororero	16.0	0.005	Yes
	Huye - Ngororero	14.4	0.010	Yes
Injured	Bugesera - Huye	1.8	0.908	No
	Bugesera - Ngororero	11.6	0.047	Yes
	Huye - Ngororero	9.8	0.096	No
Houses Damaged	Bugesera - Huye	23.4	0.995	No
	Bugesera - Ngororero	336.4	0.416	No
	Huye - Ngororero	313.0	0.465	No
Damaged Crops (Ha)	Bugesera - Huye	62.84	0.879	No
	Bugesera - Ngororero	161.65	0.447	No
	Huye - Ngororero	98.81	0.731	No
Lost Cattle	Bugesera - Huye	1.2	0.932	No
	Bugesera - Ngororero	9.8	0.031	Yes
	Huye - Ngororero	8.6	0.059	No
Other Livestock	Bugesera - Huye	-8.0	0.952	No
	Bugesera - Ngororero	36.6	0.386	No
	Huye - Ngororero	44.6	0.256	No

IV. Discussion

The significant multivariate result confirms, with formal statistical support, a pattern long documented descriptively in Rwanda's disaster-management literature: north-western, mountainous districts face materially higher disaster impact than eastern and central districts. Ngororero's elevated death toll and injury rate align with its designation, alongside Nyabihu, Rubavu, Musanze, Burera, and Gakenke, as part of the landslide and flood hotspot belt identified in MINEMA's contingency planning and the National Risk Atlas of Rwanda. According to a disaster assessment by the Ministry in Charge of Emergency Management, as reported by Nkurunziza (2025), four people died, and at least 70 hectares of crops were damaged between 10 and 13 April 2025¹⁰, and the May 2023 floods and landslides that killed 137 people across 14 districts concentrated in the western, northern, and southern provinces⁴, both implicate Ngororero as a recurrent hotspot rather than a one-off outlier year.

The absence of statistically significant differences in Houses Damaged, Damaged Crops, and Other Livestock, despite Ngororero's higher raw averages, is likely attributable to the small number of years sampled relative to the high year-to-year variability characteristic of hydro-meteorological hazards a single severe event, such as the 2023 disaster season, can dominate a five-year average and inflate within-group variance, making district means statistically harder to distinguish with only five annual observations per group.

A recent evaluation of Rwanda's disaster risk management system, using the May 2023 floods and landslides as a case study, found that despite functioning early-warning infrastructure operated by Meteo Rwanda and MINEMA, gaps remained in translating warnings into localized, risk-specific preparedness, particularly in areas not previously classified as high-risk zones. This is consistent with the present findings that structural risk (captured here through significant multivariate differences) persists despite national early-warning coverage, underscoring a continued need for geographically targeted, rather than uniform, disaster risk reduction investment.

From a policy standpoint, the significant and consistent excess in deaths, injuries, and livestock losses in Ngororero supports continued prioritisation of this district, and its neighbouring north-western districts, for early-warning system investment, household relocation from identified hotspots, and livestock-protection measures. At the same time, the non-significant findings for housing and crop damage caution against assuming Bugesera and Huye are low-risk on all dimensions; both districts recorded non-trivial impacts that may reflect distinct hazard types, such as dry-spell or localized flood risk in Bugesera, not fully captured by a landslide-weighted comparison.

V. Conclusion and Recommendations

This study applied one-way MANOVA to compare weather-related disaster-impact profiles across Bugesera, Huye, and Ngororero districts in Rwanda over 2020–2025. The analysis found a statistically significant multivariate difference among the three districts (Wilks' $\Lambda = 0.0455$ close to zero), driven primarily by significantly higher deaths, injuries, and cattle losses in Ngororero relative to Bugesera, and higher deaths in Ngororero relative to Huye. These findings provide formal statistical confirmation of a pattern long recognized in Rwanda's disaster risk management literature: north-western, mountainous districts bear a disproportionate share of weather-related disaster impact, supporting sustained, geographically targeted disaster risk reduction investment and pointing toward an expanded panel more districts, a longer time series, and climate covariates as the next stage of this research.

Based on these findings, disaster risk reduction efforts should give greater priority to highly affected districts such as Ngororero by strengthening early warning systems, community preparedness, resilient infrastructure, and protection of livestock and livelihoods. Local communities should be actively involved in disaster preparedness, environmental conservation, and awareness activities to reduce their vulnerability. NGOs and other development partners should support vulnerable communities through financial assistance, technical expertise, emergency response, and community-based resilience programs. Stronger collaboration among government institutions, local authorities, communities, and NGOs is also recommended to improve disaster preparedness and response. Finally, future research should include more districts, a longer time series, and climate-related variables to provide a broader understanding of weather-related disaster impacts in Rwanda.

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