

Risk-Informed Assessment of Airport Operational Resilience Under Weather-Related Hazards: A Case Study of Djalaluddin Gorontalo

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Abstract: Weather-related hazards can affect airport operations, particularly through heavy rainfall and strong winds that may increase pressure on airside infrastructure and operational management. This study assesses the operational resilience of Djalaluddin Gorontalo Airport under weather-related hazards using a risk-informed and data-proportionate approach. Historical meteorological observations from the Meteorology, Climatology, and Geophysics Agency for 2021–2025 were analyzed descriptively, covering rainfall, relative humidity, average wind speed, and wind direction corresponding to the maximum recorded wind speed. The results show substantial variability in rainfall, with the highest annual total of 2,287 mm in 2021 and the highest monthly rainfall of 405 mm in November 2021. The highest recorded monthly wind speed reached 30 knots in April 2022, while wind directions corresponding to the maximum recorded wind speed were predominantly from the north (37.5%) and south (25.0%) during 2022–2025, indicating potential relevance to crosswind exposure for the east–west oriented Runway 09/27. Relative humidity remained generally high but was considered a supporting environmental condition rather than an independent operational hazard. Overall, rainfall and wind represent the principal weather-related exposure pathways, while airport resilience depends on the interaction between weather exposure, infrastructure vulnerability, and adaptive capacity. The findings provide an engineering basis for strengthening weather monitoring, drainage and surface-condition management, wind-aware operational planning, and preparedness at regional airports.

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INTRODUCTION

Airports are critical transportation infrastructure whose operations can be affected by weather-related hazards such as heavy rainfall, strong winds, thunderstorms, and reduced visibility. These conditions may constrain runway and airside operations and contribute to flight disruption. Previous studies have demonstrated significant relationships between weather conditions and airport operational performance, while recent research has increasingly examined airport resilience under severe weather using data-driven approaches (de Oliveira et al., 2021; Song et al., 2024; Zhang et al., 2025). The broader literature on airport climate risk also emphasizes that weather and climate hazards can affect airport infrastructure, operations, and continuity, requiring systematic consideration of exposure and risk mitigation (National Academies of Sciences, Engineering, and Medicine [NASEM], 2018; Voskaki et al., 2023).

Airport resilience, however, depends not only on hazard exposure but also on infrastructure vulnerability and the capacity to prepare for and manage disruptive conditions. Poo et al. (2021)

emphasized the importance of integrating exposure, vulnerability, and adaptive capacity in assessing airport climate resilience. This perspective is also consistent with ICAO's risk-management principles, which emphasize systematic hazard identification, risk assessment, monitoring, and mitigation (ICAO, 2018, 2020, 2022). Recent aviation climate-adaptation guidance further emphasizes the need to understand climate-related risks and strengthen resilience through appropriate adaptation measures (ICAO, 2024). Airport climate-resilience assessments likewise highlight the importance of considering infrastructure vulnerability and management capacity when responding to changing climate and weather risks (NASEM, 2019).

Despite these developments, many recent airport resilience studies rely on detailed operational datasets, including high-frequency weather observations, flight movement records, and delay or cancellation data (de Oliveira et al., 2021; Song et al., 2024; Zhang et al., 2025). Such data are not always available for regional airports. This creates a methodological need for practical and data-proportionate approaches that can assess weather-related operational resilience without making unsupported assumptions about actual flight disruption. Climate-risk management studies have similarly emphasized the value of using existing airport management and operational information to support risk assessment where comprehensive datasets are unavailable (NASEM, 2018).

The Djalaluddin Gorontalo Airport provides a relevant case for addressing this gap. Previous studies at the airport have examined runway ACN-PCN compatibility (Dukalang, 2025), night-flight readiness (Dukalang, 2026b), and airside operational resilience during infrastructure expansion (Dukalang, 2026c). However, the interaction between historical weather exposure, airport infrastructure vulnerability, and operational resilience has not been specifically examined. In contrast to studies that evaluate airport resilience using detailed operational performance or high-frequency disruption data, this study develops and applies a data-proportionate assessment that integrates observed weather exposure with airport-specific vulnerability and adaptive capacity. The approach is intended to provide a structured resilience assessment while explicitly avoiding unsupported claims about actual flight disruption when such operational records are unavailable.

Therefore, this study applies a risk-informed, data-proportionate framework to assess the operational resilience of Djalaluddin Gorontalo Airport under weather-related hazards. Historical rainfall, relative humidity, average wind speed, and maximum-wind direction are analyzed using BMKG observations and interpreted in relation to runway orientation, movement-area infrastructure, drainage requirements, and operational preparedness. The selection and interpretation of meteorological variables are also consistent with the broader role of aviation meteorological observations in supporting the assessment of weather conditions relevant to aviation operations (Gultepe & Feltz, 2020). The scientific contribution of this study lies in integrating historical weather exposure, airport-specific infrastructure vulnerability, and adaptive capacity within a transparent, data-proportionate assessment framework for a regional airport with limited operational disruption records. Rather than estimating actual probabilities of delays, cancellations, or other disruptions, the framework identifies relative weather-exposure pathways, potential vulnerability, and resilience priorities that can be evaluated using available evidence. This approach provides a reproducible engineering basis for weather-related resilience assessment in regional airports where comprehensive operational datasets are not available.

RESEARCH METHOD

This study employs a quantitative retrospective case-study approach to assess the operational resilience of Djalaluddin Gorontalo Airport under weather-related hazards. The analysis uses historical meteorological observations and airport-specific secondary information to characterize weather exposure, examine potential infrastructure and operational vulnerability, and assess adaptive capacity. The retrospective design examines historical weather conditions during 2021–2025 and their potential implications for airport operations. Previous studies have demonstrated that weather conditions can influence airport operational performance and resilience (Borsky & Unterberger, 2019; de Oliveira et al., 2021; Lui et al., 2022; Song et al., 2024; Zhang et al., 2025). Because detailed airline operational records are unavailable, the study adopts a risk-informed and data-proportionate approach, consistent with the exposure–vulnerability–adaptive-capacity framework of Poo et al. (2021), the hazard identification and risk-management principles of ICAO (2018), and airport climate-risk management approaches that emphasize the use of available airport information to support climate-risk assessment (NASEM, 2018).

The study was conducted at Djalaluddin Gorontalo Airport, Gorontalo, Indonesia, a regional airport with relatively low scheduled commercial flight activity. Under normal operating conditions, the airport has approximately three scheduled passenger flights per day. The airport provides an appropriate case for examining weather-related resilience because its operational environment combines relatively low routine demand with changing infrastructure requirements following infrastructure expansion in 2026. Previous airport-specific studies have examined runway ACN-PCN compatibility, night-flight readiness, and airside capacity at Djalaluddin Gorontalo Airport (Dukalang, 2025, 2026b, 2026c). These studies provide supporting contextual evidence for interpreting airport vulnerability and operational characteristics, while established airport engineering principles and applicable ICAO aerodrome standards provide the technical basis for interpretation (Ashford et al., 2011; de Neufville & Odoni, 2003; Dukalang, 2026a, 2026d; ICAO, 2020, 2022). The interpretation of climate-related vulnerability and resilience also considers established approaches to airport climate adaptation and infrastructure risk management (NASEM, 2019; ICAO, 2024).

The principal meteorological dataset was obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) for 2021–2025. Four variables were analyzed: monthly rainfall (mm), monthly relative humidity (%), monthly average wind speed (knots), and wind direction corresponding to the maximum recorded wind speed (degrees). The observations were organized chronologically by year and month. Usable wind-direction observations were consistently available only for 2022–2025 ($n = 48$) because the 2021 records contained no usable directional observations. Rainfall, relative humidity, and average wind-speed observations for November and December 2025 were unavailable; these missing values were retained and were not estimated through interpolation or statistical imputation. Additional airport-specific secondary information was obtained from technical documents, official airport information, aviation standards, engineering references, and previous studies concerning runway and airside characteristics, drainage and surface-water management, operational configuration, infrastructure capacity, and preparedness. The selection of rainfall, wind speed, and wind direction is consistent with aviation-meteorological practice, in which meteorological observations provide important information for understanding weather conditions affecting aviation operations (Gultepe & Feltz, 2020).

The analytical framework consists of three interconnected dimensions: weather exposure, airport vulnerability, and adaptive capacity. Weather exposure represents the magnitude and temporal distribution of the observed meteorological conditions. Rainfall is considered the principal precipitation-related exposure because prolonged or intense precipitation may contribute to surface-water accumulation and increase demands on runway, taxiway, and drainage systems. Relative humidity is interpreted as an environmental condition associated with wet-weather conditions rather than as an independent direct cause of disruption. Average wind speed represents the magnitude of wind exposure, while wind direction is examined separately because its operational significance depends on its relationship with runway orientation. This framework follows Poo et al. (2021), while hazard identification and risk interpretation are supported by ICAO safety-management principles (ICAO, 2018) and broader airport climate-resilience approaches (NASEM, 2019; Voskaki et al., 2023). To support a transparent and reproducible assessment, the three dimensions were integrated to classify the level of concern associated with each weather-related condition. The classification considers the relative level of weather exposure, the potential vulnerability of airport infrastructure and operations, and the available adaptive capacity. The resulting categories are interpreted as areas of low, moderate, or high concern rather than as probabilistic estimates of operational disruption.

Before analysis, the BMKG data were checked for completeness, consistency, measurement units, and chronological organization. Descriptive statistics were used to characterize the historical distribution and temporal variability of the meteorological variables. Rainfall was examined through monthly values, annual totals, and temporal patterns, while relative humidity and average wind speed were summarized using the minimum, maximum, mean, and standard deviation. The arithmetic mean was calculated as :

$$\bar{X} = \frac{\sum X_i}{n} \quad (1)$$

where $\bar{X}$ is the mean, X_i is the observed value, and n is the number of available observations. Standard deviation was calculated as:

$$SD = \sqrt{[\sum (X_i - \bar{X})^2 / (n - 1)]} \quad (2)$$

where SD is the standard deviation, X_i is the observed value, $\bar{X}$ is the mean, and n is the number of available observations. These descriptive measures were used to characterize temporal variability and weather exposure rather than to establish causal relationships between weather conditions and flight disruption. Because rainfall, relative humidity, and wind speed have different measurement units and numerical ranges, min-max normalization was applied when a composite comparison of relative weather exposure was required. The normalized value was calculated as:

$$X' = (X - X_{min}) / (X_{max} - X_{min}) \quad (3)$$

where X' is the normalized value, X is the observed value, and X_{min} and X_{max} are the minimum and maximum observed values in the study dataset. The resulting value ranges from 0 to 1, with higher values indicating a relatively higher position within the observed range of the corresponding weather variable. The normalized values are interpreted only as relative exposure indicators, not as probabilities

of accidents, delays, cancellations, or other operational events. Wind direction was analyzed separately as a circular variable. The 48 available observations for 2022–2025 were grouped into directional sectors, and their frequencies were examined and interpreted in relation to runway orientation rather than through an ordinary arithmetic mean. The analysis was used to identify potential crosswind exposure based on the angular relationship between the observed wind directions and the east–west orientation of Runway 09/27. A numerical crosswind component was not calculated because the available dataset did not provide sufficiently high-frequency, time-matched wind-speed and wind-direction observations together with aircraft-specific operational limits. Therefore, the wind-direction findings are interpreted as potential crosswind exposure rather than evidence that aircraft-specific crosswind limits were exceeded.

The meteorological findings were subsequently used to identify weather-related hazards relevant to airport infrastructure and operations, principally rainfall-related exposure, wind-related exposure, and persistent humid conditions. The presence of a weather condition was not assumed to automatically produce operational disruption; rather, weather observations represent exposure whose potential consequences depend on airport infrastructure, operational characteristics, and mitigation capacity. Airport vulnerability was assessed by examining runway and airside infrastructure, drainage and surface-water management, runway and taxiway operating conditions, operational configuration, and infrastructure capacity. Previous findings on ACN-PCN compatibility, night-flight readiness, and airside capacity (Dukalang, 2025, 2026b, 2026c) were incorporated as airport-specific contextual evidence. Adaptive capacity was assessed as the airport's ability to prepare for, respond to, manage, and reduce the potential consequences of weather-related hazards, considering infrastructure and facilities, drainage management, operational preparedness, weather monitoring, operational procedures, and mitigation measures.

Because detailed internal emergency procedures, airline operational records, and comprehensive real-time response data were unavailable, the adaptive-capacity assessment was restricted to capabilities supported by technical documents, standards, previous research, and observable airport characteristics. The final assessment integrated weather exposure, vulnerability, and adaptive capacity. Conceptually, the combination of weather exposure and airport vulnerability may increase weather-related operational risk, whereas stronger adaptive capacity may reduce such risk and contribute to greater operational resilience. Methodological validity was supported through source triangulation, integrating BMKG observations for weather exposure, ICAO standards and safety-management guidance for hazard and risk interpretation, and airport-specific technical information and previous research for vulnerability and adaptive capacity. Conventional internal-consistency measures such as Cronbach's alpha were not applied because the study does not use questionnaire-based constructs. Missing observations were transparently reported without imputation, and the same analytical criteria were applied consistently to the available data.

The analysis followed a sequential process from BMKG data preparation, descriptive statistical analysis, wind-direction analysis, weather-exposure characterization, hazard identification, vulnerability assessment, adaptive-capacity assessment, and risk-informed operational resilience assessment to the identification of resilience priorities. The identified conditions were classified using a three-level, study-specific concern classification based on the combined interpretation of weather exposure, potential vulnerability, and available adaptive capacity. Exposure was interpreted from the observed meteorological range and normalized exposure values, where applicable, with higher

normalized values indicating relatively greater exposure. Potential vulnerability was assessed according to the presence of plausible pathways through which the identified weather condition could affect airport infrastructure or operations. Adaptive capacity was assessed according to the availability of infrastructure, monitoring, preparedness, operational procedures, and mitigation measures that could reduce the potential consequences. A condition was classified as high concern when relatively high exposure was accompanied by a plausible vulnerability pathway and limited or insufficiently documented adaptive capacity; moderate concern when exposure and vulnerability were evident but available infrastructure or preparedness could reasonably reduce the potential consequences; and low-moderate concern when the condition was relevant or persistent but the available evidence indicated comparatively lower exposure, lower potential vulnerability, or greater adaptive capacity. These classifications are study-specific analytical categories and do not represent official ICAO or FAA safety-risk categories. The overall methodological framework began with BMKG meteorological data preparation and descriptive analysis, followed by the development of a weather exposure profile, hazard identification, airport vulnerability assessment, adaptive-capacity assessment, and risk-informed operational resilience assessment, ultimately leading to the identification of resilience and preparedness priorities. The methodology thus provides a practical and data-proportionate framework for assessing weather-related operational resilience at a regional, low-traffic airport where detailed operational disruption data are limited.

RESULTS AND DISCUSSION

Historical meteorological observations from Djalaluddin Gorontalo Airport for 2021–2025 indicate substantial temporal variability in rainfall, relative humidity, and wind speed. As summarized in Table 1, annual rainfall totals for complete years were 2,287 mm in 2021, 1,973 mm in 2022, 1,473 mm in 2023, and 1,835 mm in 2024, while the available January–October 2025 observations recorded 1,675 mm. The corresponding annual mean rainfall ranged from 122.8 to 190.6 mm/month. Relative humidity varied between 80.5% and 85.6% in annual averages, whereas annual mean wind speed ranged from 14.7 to 17.6 knots. Monthly rainfall also showed pronounced variability, with high values including 405 mm in November 2021, 397 mm in May 2021, 285 mm in October 2022, 317 mm in July 2024, and 295 mm in October 2025. Monthly average wind speed reached 30 knots in April 2022, while relative humidity reached 89% in January 2021. These findings demonstrate that weather exposure at the airport is multidimensional rather than represented by a single climatic variable.

Table 1. Descriptive Statistics of Meteorological Variables at Djalaluddin Gorontalo Airport, 2021–2025

Year	Rainfall (mm), total*	Rainfall mean (mm/month)	Humidity mean (%)	Wind speed mean (knots)
2021	2,287	190.6	85.6	15.8
2022	1,973	164.4	85.1	17.6
2023	1,473	122.8	80.5	17.0
2024	1,835	152.9	82.8	17.3
2025 (Jan-Oct)**	1,675	167.5	81.3	14.7

*Annual rainfall total based on available monthly observations.

**November and December 2025 were unavailable in the BMKG dataset; therefore, the 2025 values are based on January–October observations.

The monthly rainfall observations provide further detail on the temporal variability identified in Table 1, particularly the occurrence of pronounced rainfall peaks across different months and years. Figure 1 illustrates the monthly rainfall distribution from 2021 to 2025 and provides a clearer visualization of these temporal patterns.

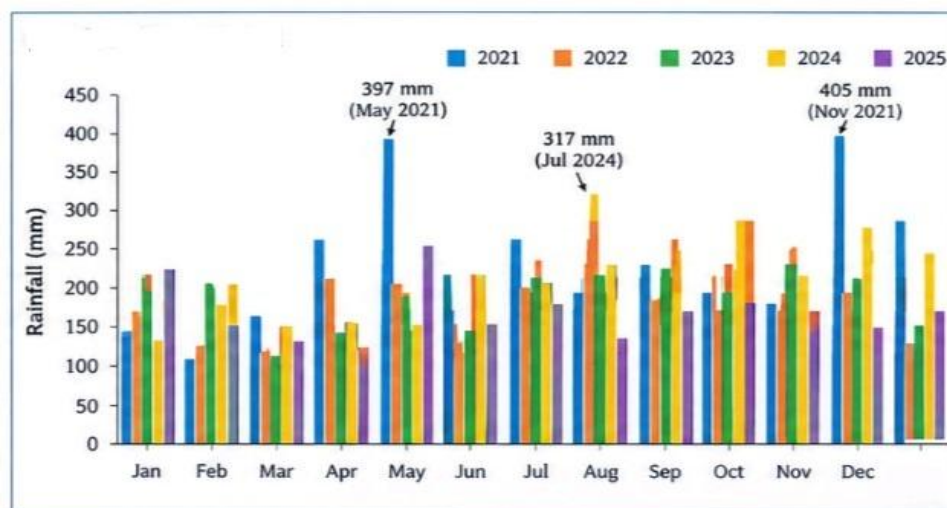


Figure 1. Monthly Rainfall Pattern at Djalaluddin Gorontalo Airport, 2021–2025 (Source: BMKG meteorological observations, processed by the author)

Rainfall represents the most directly infrastructure-related weather exposure because intense or sustained precipitation can increase demands on runway, taxiway, apron, and drainage systems. The observed rainfall peaks occurred in different months and years, indicating that exposure cannot be adequately represented by assuming a single fixed wet season. The highest complete-year rainfall occurred in 2021 at 2,287 mm, while several individual months exceeded 280 mm, including November 2021 (405 mm), May 2021 (397 mm), July 2024 (317 mm), October 2025 (295 mm), and October 2022 (285 mm). Consistent with the climate-resilience perspective of Poo et al. (2021), these observations are best interpreted as evidence of weather exposure that may interact with infrastructure vulnerability and adaptive capacity. In particular, the principal potential vulnerability pathway is the rainfall–surface-water interaction, through which intense precipitation may increase the demand for effective drainage and pavement-surface management. However, the meteorological observations alone do not demonstrate actual flooding, runway closure, aircraft delay, or cancellation; therefore, the results identify potential sensitivity rather than measured operational disruption.

Wind exposure is relevant not only because of wind magnitude but also because of its direction relative to runway orientation. The highest monthly average wind speed was 30 knots in April 2022, followed by 24 knots in December 2022 and 22 knots in March 2023 and March 2024, while annual mean wind speed ranged from 14.7 to 17.6 knots. A total of 48 monthly maximum-wind-direction observations from 2022–2025 were analyzed, as presented in Table 2. Northerly winds (360°) occurred most frequently at 37.5% (18 observations), followed by southerly winds (180°) at 25.0% (12 observations). The airport operates Runway 09/27, approximately 2,500 m × 45 m and oriented broadly east–west. Consequently, the predominance of northerly and southerly winds indicates a potential crosswind interaction with the runway orientation. Because wind direction is a circular

variable, directional frequency is more appropriate than a simple arithmetic mean for describing the observed pattern. Nevertheless, these results do not establish that aircraft-specific crosswind limits were exceeded, since such an assessment would require higher-frequency wind observations and aircraft-specific operational criteria.

Table 2. Distribution of Recorded Maximum-Wind Directions, 2022–2025

Direction	Occurrences	Relative frequency
360° (N)	18	37.5%
180° (S)	12	25.0%
135°	5	10.4%
270° (W)	4	8.3%
90° (E)	3	6.3%
225°	2	4.2%
315°	2	4.2%
145°	2	4.2%
Total	48	100%

Figure 2 provides a visual representation of the directional frequency distribution presented in Table 2, highlighting the predominance of northerly (360°) and southerly (180°) wind directions during 2022–2025.

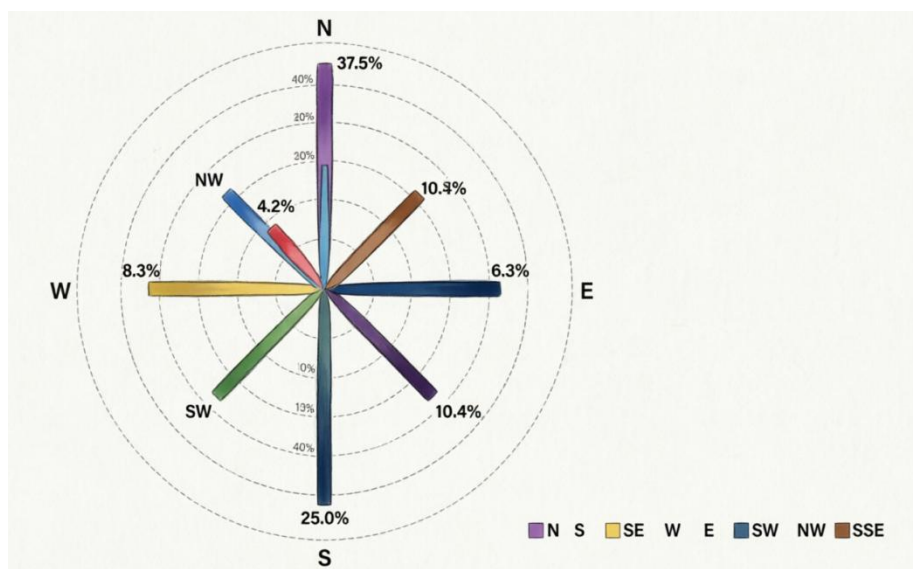


Figure 2. Distribution of Recorded Maximum-Wind Directions, 2022–2025 (Source: BMKG meteorological observations, processed by the author)

To compare meteorological variables with different units and scales, the min–max normalization procedure specified in the methods was applied to the observed ranges. Rainfall values ranged from 12 to 405 mm, relative humidity from 71% to 89%, and wind-speed observations from approximately 10 to 30 knots. The normalized results provide a relative indication of the position of each observation within the study dataset, rather than a probability of operational disruption. Rainfall showed the greatest temporal variability, while humidity exhibited a comparatively narrower range. Therefore, a high normalized value should not be interpreted as equivalent to high operational risk or a 100% probability of disruption. Instead, the normalized values function as relative exposure indicators that

must be interpreted together with infrastructure and operational sensitivity and the airport's adaptive capacity, consistent with the resilience framework proposed by Poo et al. (2021).

The combined results indicate two principal potential vulnerability pathways: the rainfall-surface-water interaction and the wind-runway interaction. The physical airport context includes a 2,500 m × 45 m runway, three taxiways, two aprons, and Apron Bravo measuring approximately 291 m × 130 m. These infrastructure characteristics provide the physical basis for interpreting how weather exposure may interact with airport operations. Previous airport-specific studies by Dukalang (2025, 2026b, 2026c) examined runway ACN-PCN compatibility, night-flight readiness, and airside capacity, respectively, providing complementary evidence concerning infrastructure and operational capability. In this study, rainfall is therefore interpreted primarily as an infrastructure and surface-management exposure, whereas wind is interpreted as an operational exposure influenced by both magnitude and direction. Following the risk-informed approach of ICAO (2018), the identification of these pathways does not imply that disruption has occurred; rather, it identifies conditions under which weather exposure may generate operational consequences.

The airport's adaptive capacity should be understood as its ability to use infrastructure, monitoring systems, maintenance practices, procedures, and available resources to anticipate and manage weather-related consequences. The existing runway, taxiway, apron, and expanded airport infrastructure provide opportunities to strengthen resilience, but infrastructure expansion alone does not guarantee resilient operations. Effective resilience depends on how physical capacity is supported by drainage inspection and maintenance, pavement and surface-condition management, weather monitoring, preparedness, and operational response procedures. The findings therefore support a system perspective in which infrastructure development must be accompanied by resilience-oriented operational management. However, detailed internal emergency procedures, real-time operational responses, and airport decision-making records were not available for this study. Consequently, adaptive capacity is assessed only from available technical evidence, observable infrastructure characteristics, previous airport-specific studies, and relevant standards, thereby avoiding unsupported conclusions regarding actual response performance.

Table 3 integrates the observed weather exposure, potential vulnerability pathways, and available adaptive-capacity evidence into a study-specific risk-informed assessment. High rainfall exposure associated with 405 mm in November 2021 and 2,287 mm in 2021 is classified as Moderate, primarily because of its potential implications for drainage and surface-water management. Other elevated rainfall events are classified as Moderate, while elevated wind exposure and predominant crosswind-direction exposure are also classified as Moderate. Persistent humidity is classified as Low-Moderate because it represents a supporting environmental condition rather than an independent direct operational hazard. These classifications are analytical interpretations developed specifically for this study and are not official ICAO, FAA, or regulatory safety-risk categories. The integrated assessment considers that weather exposure, when interacting with infrastructure and operational sensitivity, may increase the potential for weather-related operational risk, whereas adequate adaptive capacity may reduce the potential consequences of such exposure and support operational resilience. The resulting assessment is data-proportionate because it combines available meteorological observations with airport-specific engineering and operational evidence without assigning unsupported causal probabilities.

Table 3. Risk-Informed Assessment of Weather-Related Operational Resilience

Weather-related exposure	Evidence from BMKG	Potential airport vulnerability	Adaptive-capacity consideration	Resilience concern
High rainfall	Maximum monthly rainfall of 405 mm (Nov. 2021)	Potential surface-water accumulation and increased drainage demand	Drainage, pavement and surface-condition management	Moderate
Elevated rainfall	Several months >280 mm	Increased pressure on airside drainage and movement areas	Monitoring and maintenance of drainage systems	Moderate
High wind speed	Maximum monthly average of 30 knots (Apr. 2022)	Potential effect on aircraft operations and airside activities	Weather monitoring and operational preparedness	Moderate
Predominant N-S wind direction	360° and 180° were the most frequent directions	Potential crosswind relevance to runway 09/27	Wind-aware runway operational planning	Moderate
Persistent high humidity	Monthly values generally >70%	Environmental condition accompanying wet-weather exposure	Routine monitoring and maintenance	Low-Moderate

The concern classifications in Table 3 represent an integrated interpretation of relative weather exposure, potential airport vulnerability, and available adaptive capacity. The moderate concern assigned to rainfall and wind-related conditions reflects the presence of relevant exposure and plausible vulnerability pathways, while available monitoring, maintenance, and operational preparedness may reduce their potential consequences. The low-moderate concern assigned to persistent high humidity reflects its role primarily as a supporting environmental condition rather than a direct operational disruption mechanism. These classifications should therefore be interpreted as resilience-priority indicators rather than as measured probabilities of operational disruption. The findings have several practical implications for Djalaluddin Gorontalo Airport. First, rainfall monitoring should be integrated with drainage inspection, pavement-surface monitoring, and preventive maintenance because rainfall represents the most prominent weather exposure identified in the study. Second, wind monitoring should consider both speed and direction because the observed predominance of northerly and southerly winds may create operational relevance for the east-west-oriented runway. Third, infrastructure development should be accompanied by operational resilience planning rather than being considered sufficient by itself. A practical monitoring framework could integrate rainfall intensity or accumulation, wind speed and direction, runway surface condition, drainage condition, and operational status. Such integration would allow weather observations to function not merely as climatological records but as inputs to airport preparedness and risk-management processes. This approach is consistent with the system-oriented resilience perspective of Poo et al. (2021) and the risk-informed safety-management principles of ICAO (2018).

Several limitations should be recognized. The use of monthly climatological observations restricts the analysis of short-duration thunderstorms, intense hourly rainfall, and rapid changes in wind conditions; moreover, November–December 2025 observations were unavailable, making the 2025 record incomplete. The study also lacks flight-level records of delays, cancellations, diversions, runway closures, and other operational disruptions, preventing statistical estimation of causal disruption probabilities. Wind-direction analysis was based on monthly maximum-direction observations and therefore provides an historical exposure indicator rather than a complete representation of short-term crosswind conditions. Future research should combine higher-frequency meteorological observations with flight movement records, delay and cancellation data, runway surface conditions, drainage performance, and aircraft-specific crosswind limits. Overall, the results show that rainfall and wind are the principal weather exposures requiring attention at Djalaluddin Gorontalo Airport, while humidity functions mainly as a supporting environmental condition. More importantly, the study demonstrates that airport resilience under weather-related hazards should be evaluated as a system interaction among external weather exposure, infrastructure and operational sensitivity, and adaptive capacity. By integrating meteorological observations with engineering and operational evidence from previous airport-specific studies, the research provides a data-proportionate approach for assessing weather-related operational resilience in a regional airport where detailed disruption records may be limited.

CONCLUSION

This study assessed the operational resilience of Djalaluddin Gorontalo Airport under weather-related hazards using a risk-informed, data-proportionate approach based on historical meteorological observations and airport-specific technical information. The results demonstrate that rainfall and wind represent the principal weather-related exposure pathways, while persistent high humidity functions primarily as a supporting environmental condition rather than an independent operational hazard. Rainfall exposure was characterized by substantial temporal variability, which may increase potential vulnerability through surface-water accumulation and additional demands on runway, taxiway, apron, and drainage conditions. Wind exposure was also operationally relevant, particularly when wind magnitude occurred in directions potentially unfavorable to the east–west orientation of Runway 09/27. The integrated assessment further indicates that weather exposure alone does not determine airport resilience; rather, resilience depends on the interaction between hazard exposure, infrastructure and operational vulnerability, and the airport's adaptive capacity to monitor, prepare for, and manage weather-related conditions. Infrastructure development can strengthen the airport's capacity, but physical expansion alone does not guarantee operational resilience without corresponding improvements in drainage and surface-condition management, weather monitoring, wind-aware operational planning, maintenance, and preparedness procedures. The main contribution of this study is the development and application of a practical, data-proportionate framework for assessing weather-related operational resilience at a regional airport where detailed flight disruption records are limited. The findings provide an engineering basis for informing priorities in weather monitoring and infrastructure management while supporting more systematic risk-informed resilience planning. Future research should strengthen this assessment by integrating high-frequency meteorological observations, aircraft movement and flight disruption records, runway surface

conditions, drainage performance, and aircraft-specific operational limits to enable quantitative estimation of weather-related disruption probabilities and more detailed resilience evaluation.

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