

ORIGINAL RESEARCH ARTICLE

Century-long rainfall structure in Macao:
Implications for urban governanceQixiang Geng^{ID}, Shufang Zhao, Xi Wang*^{ID}, and Kan Chen

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Abstract

Long-term climate records provide a historical evidence base for governing urban weather-related hazards. This study uses monthly total rainfall and monthly rainy-day records for Macao from 1901 to 2000 to construct a structured monthly panel. It descriptively examines annual totals, annual rainy days, rainfall per rainy day, the April–September wet-season share, monthly and seasonal patterns, 20-year subperiods, extreme years, and the data-quality boundaries of the published historical compilation. Among 97 years with complete monthly records, the mean annual rainfall was 1,879.3 mm (standard deviation: 454.3 mm). Annual rainfall showed a significant positive trend (ordinary least-squares slope, 6.24 mm/year; Theil–Sen slope, 6.61 mm/year), and annual rainy days also increased (0.36 days/year). Heteroscedasticity- and autocorrelation-consistent inference did not alter these substantive conclusions. By contrast, the linear trend in annual rainfall per rainy day was not statistically significant. Rainfall remained concentrated in late spring, summer, and early autumn: based on monthly climatology, April–September accounted for 82.9% of annual rainfall, while summer and spring accounted for 47.5% and 28.8%, respectively. For the shared 1961–2000 period, annual rainfall covaried strongly with the published Hong Kong Observatory record (Pearson $r = 0.859$; $p < 0.001$). These results support a seasonally differentiated maintenance calendar, tail-year scenario preparation, and a staged data architecture linking historical rainfall with real-time hydrometeorological, water-system, and service-impact records.

Keywords: Macao; Century-long climate records; Urban governance; Climate adaptation***Corresponding author:**Xi Wang
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1. Introduction

Rainfall governance in coastal cities requires both emergency responses to acute events and long-term records that define the basic hydrological conditions under which urban systems operate. Annual totals, numbers of rainy days, monthly distributions, and anomalous years cannot be equated directly with disaster losses. Nevertheless, they shape the temporal windows and operational burdens associated with drainage maintenance, road management, construction scheduling, and emergency preparedness. Macao, on the western side of the Pearl River Estuary, has a subtropical maritime monsoon climate. Frontal rainfall strengthens in late spring; monsoon and tropical weather systems influence summer rainfall; and relatively high rainfall may persist into early autumn.¹ In a setting characterised by limited land resources, concentrated urban functions, and high coastal exposure, a systematic account of Macao's long-term rainfall structure has

clear historical and urban-governance value.

Research on climate adaptation and urban resilience shows that risk is jointly shaped by hazards, exposure, vulnerability, and response capacity. A single meteorological indicator cannot adequately explain specific disaster outcomes.² Urban resilience is also more than just post-disaster recovery. It requires risks to be identified before a shock, critical functions to be maintained during it, and institutional arrangements to be revised afterwards.^{3,4} Climate-adaptation planning likewise needs to embed climate information in infrastructure, spatial planning, and routine management rather than merely add measures after major events.⁵⁻⁷ In this process, data updating, interdepartmental coordination, and institutional learning are integral to adaptive governance.^{8,9}

Existing research on Macao has recognised the compound risks associated with hazardous weather events, including typhoons, storm surges, and urban flooding. However, the natural characteristics of Macao's century-long rainfall record have received less systematic attention. Monthly data can address several foundational questions: whether annual rainfall has changed directionally over the long term; whether rainy days and rainfall per rainy day have changed together; in which months and seasons rainfall is concentrated; whether average levels differ across periods; and where extremely wet and dry years lie within the century-long series. A systematic descriptive analysis of these questions is a prerequisite for subsequent risk modelling or policy evaluation. It also provides the rainfall-baseline layer required for a fuller urban-systems analysis. Recent water-management research shows that precipitation becomes operationally meaningful only when matched with water-demand, pumping, energy-use, and infrastructure-performance data at comparable temporal scales.^{10,11} Historical evidence is most valuable when it informs the timing and scope of preparation, rather than replacing these more specific decision processes.

Accordingly, this article addresses four research questions. First, what long-term trends and interannual variability characterised annual rainfall, annual rainy days, and rainfall per rainy day in Macao between 1901 and 2000? Second, how was rainfall distributed across months, seasons, and 20-year periods, and how concentrated was the April–September wet-season window? Third, what implications do extreme years and high monthly accumulations have for routine urban maintenance and pre-season preparedness? Fourth, how should the published single-station record be interpreted in relation to data provenance, time-series diagnostics, and the wider Pearl River Estuary context? The study documents the basic structure of century-long rainfall in Macao

and derives bounded governance implications from the historical record. In doing so, it provides an evidence base for subsequent policy research that integrates real-time observations, urban-exposure data, water-system operations, and disaster-loss data.

2. Materials and methods

2.1. Study design and analytical scope

This study used a descriptive analytical design based on historical climate data. It examined monthly total rainfall and monthly rainy days in Macao from 1901 to 2000, with the statistical analysis focused on the temporal structure of rainfall. The published compilation provides a traceable historical record for descriptive long-term analysis, but it is not a formally homogenised climate series. Statistical findings and governance interpretation are deliberately separated: Section 3 (Results) describes patterns in the published rainfall record, whereas Section 4 (Discussion) considers their implications for routine governance arrangements and specifies the further data required to evaluate urban-system effects.

The units of analysis were months and years. The monthly analysis identified seasonality and the distribution of high-value months. The annual analysis calculated the annual total rainfall, annual rainy days, rainfall per rainy day, and the April–September wet-season share. The study also compared 20-year periods to describe long-term change while reducing the influence of anomalous single years on period-level interpretation. Analysis of extreme years was used to illustrate tail differences beyond the mean.

2.2. Data source and data structuring

The source data were obtained from *Macao Century-Long Climate Data* (2nd ed.),¹ compiled by the Macao Meteorological and Geophysical Bureau (please refer to Table 1 for a descriptive introduction). The source documentation reports that meteorological observations in Macao began in 1882, that an observation station was established in 1900, and that the 1901–2000 climate compilation was organised from daily observations, including daily total precipitation. The extracted variables included monthly rainfall, annual total rainfall, monthly rainy days, and annual rainy days. The source defines a rainy day as a day with daily rainfall of at least 0.1 mm. The data were read in Python and reconstructed as a panel organised by year, month, and annual fields. The use of historical climate series should retain source information, missing-data indicators, and interpretative boundaries, consistent with the World Meteorological Organization's basic requirements for climate-data management and

traceability.¹²

2.2.1. Source characteristics, station history, and homogeneity boundary

The published source provides several historical metadata elements relevant to interpreting the series. It reports that the observation location was Penha Hill from 1901 to 1903 (22°11'20" N, 113°31'56" E; 55 m), Guia Hill from 1904 to 1966 (22°11'45" N, 113°32'39" E; 65 m), Monte Fort from 1966 until the relocation in 1996 (22°12' N, 113°32' E; 57 m), and Taipa Grande Hill from 1996 onward (22°10' N, 113°34' E; 110 m). The source further records changes in the observing routine: five observations per day (04:00, 10:00, 13:00, 16:00, and 22:00) in the early historical period, three observations per day (09:00, 15:00, and 21:00) from the 1920s to the early 1950s, and 24-hour observations from the 1950s onward. It also documents daily precipitation coverage and explicitly lists missing daily precipitation periods: February 1901, all of 1905, and January–March 1906. These details make potential non-climatic discontinuities identifiable in principle, although they do not quantify or correct any such effect.¹

However, the published compilation does not contain a complete technical archive for each site, including rain-gauge model and orifice characteristics, site-exposure records, calibration procedures, maintenance logs, data-processing adjustments, and overlapping measurements across relocations. Such information is central to formal homogeneity assessment under World Meteorological Organization guidance.¹² Accordingly, the present study does not claim climate-series certification, formal homogenisation, or climate attribution. The documented station relocations and observing-routine changes are treated as explicit interpretative constraints, not as proof

that the series is either homogeneous or invalid. The 0.1 mm value is treated only as the source-defined rule for counting a rainy day. It is not interpreted as evidence of gauge sensitivity, instrumental precision, or historical calibration quality. The findings are therefore framed throughout as descriptive trends and structures in the available published historical compilation.

Data processing preserved original values, explicitly marked missing observations, and did not replace missing values with zeroes. Monthly rainfall was missing for February 1901, all months of 1905, and January–March 1906. Monthly rainy days had the same pattern of missingness. Although the source retained annual fields for 1901 and 1906, these years were excluded from the main statistical analyses because their monthly records are incomplete. No annual record is available for 1905. The remaining 97 years contain complete 12-month records of rainfall and rainy days, constituting the core annual sample.

The source also reports multi-year monthly and seasonal averages. The source-reported official averages were used for monthly and seasonal climatology, whereas the 97 complete-record years were used for annual trends, period comparisons, and extreme-year analysis. These two statistical bases serve different purposes. Official averages present the source's overall monthly and seasonal structure of the century-long climate record, whereas the complete-record sample avoids distortion of annual comparisons by missing data. They are not pooled or treated as interchangeable data products.

A consistency check showed that, among the 97 complete-record years, the summed monthly rainfall matched the source Annual field in 96 years. In 1941, the

Table 1. Data sources, coverage, and completeness

Variable	Coverage	Unit	Data note
Monthly total rainfall	1901–2000	mm	February 1901; all months of 1905; January–March 1906
Monthly number of rainy days	1901–2000	days (rainfall ≥ 0.1 mm)	February 1901; all months of 1905; January–March 1906
Complete-record annual sample	97 years	years	Excludes 1901, 1905, and 1906 from the main annual analysis
Station-location history	1901–2000	–	Penha Hill (1901–1903; 55 m); Guia Hill (1904–1966; 65 m); Monte Fort (1966–1995; 57 m); Taipa Grande Hill (1996–2000; 110 m).
Observing-routine history	Historical coverage	–	Five observations/day in the early period; three/day from the 1920s to the early 1950s; 24-hour observations from the 1950s onward.
Technical metadata boundary	1901–2000 compilation	–	No complete archive of gauge model, exposure, calibration, maintenance, processing adjustments, or overlap observations; no formal homogenisation claimed.

sum of the 12 monthly values was 2,488.5 mm, whereas the source Annual field reported 2,481.3 mm, a difference of 7.2 mm (0.29% of the annual value). The published compilation provides no erratum, station-history note, or parallel record that permits the origin of this discrepancy to be resolved or attributed to a documented relocation or observing-routine change. It was therefore neither silently corrected nor attributed to a particular cause. The source Annual field was retained for the annual indicators, trends, period comparisons, and extreme-year rankings, while original monthly values were retained for monthly, seasonal, and wet-season calculations. A sensitivity analysis excluding 1941 was added to verify whether this isolated discrepancy changes the trend interpretation. In addition, the 12 source-reported monthly climatological averages summed to 1,870.4 mm, and the four source-reported seasonal averages summed to 1,869.0 mm; both differ from the source-reported annual mean of 1,849.5 mm. Because the source provides no further explanation for reconciling these bases, the relevant within-table totals were used as denominators for monthly and seasonal shares and are disclosed in the tables.

2.3. Indicators

Six groups of indicators were used. First, annual rainfall, measured in millimetres, was directly extracted from the Annual field in the main sample and verified against the sum of monthly values. Second, annual rainy days, measured in days, were extracted from the Annual field in the rainy-day table. The source-defined threshold of daily rainfall ≥ 0.1 mm was used solely to count rainy days; it is not a measure of instrument sensitivity. Third, rainfall per rainy day was calculated by dividing annual rainfall by annual rainy days. This measure distinguishes between more frequent rainfall and a higher average rainfall amount per rainy day. It is an

annual-level proxy and should not be interpreted as hourly rainfall intensity or short-duration rainstorm intensity. Fourth, monthly climatology was represented by the multi-year monthly average rainfall and rainy days reported by the source. Fifth, seasonal climatology followed the source definition: winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). Sixth, the wet-season share was calculated as rainfall from April to September divided by annual rainfall. This six-month window encompasses Macao's principal rainfall months in late spring, summer, and early autumn and is appropriate for examining the timing of pre-season preparation and wet-season maintenance. The resulting indicator definitions and their interpretative boundaries are set out in Table 2.

In addition, the 90th percentile of annual rainfall was used as a descriptive threshold for extremely wet years, and the 10th percentile for extremely dry years. These are within-sample descriptive thresholds, not meteorological warning criteria, and do not imply that reaching a given value necessarily produces an urban disaster. Their purpose is to identify years at the two ends of the century-long distribution.

2.4. Analytical procedures

The statistical analysis proceeded in six steps. First, means, standard deviations, medians, ranges, and percentiles were calculated for annual indicators to describe the dispersion of the century-long series. Second, ordinary least-squares (OLS) regression was used to estimate linear slopes over time, and the Theil–Sen method was used to provide slope estimates more robust to anomalous years. The Theil–Sen slope is the median of the slopes estimated from pairs of observations and is appropriate for long records

Table 2. Indicators and interpretative boundaries

Indicator	Calculation	Unit	Interpretation boundary
Annual rainfall	Annual field in Monthly Total Rainfall	mm	Describes annual water input
Annual rainy days	Annual field in Monthly Total Rainfall Days	days	Describes rainfall frequency
Rainfall per rainy day	Annual rainfall/Annual rainy days	mm/day	Annual average proxy, not short-duration intensity
Wet-season share	Rainfall from April to September/Annual rainfall	%	Describes seasonal concentration
Extreme wet-year threshold	90th percentile of annual rainfall	mm	Sample-based descriptive threshold
Extreme dry-year threshold	10th percentile of annual rainfall	mm	Sample-based descriptive threshold
Rainy-day counting threshold	Daily rainfall ≥ 0.1 mm (source definition)	mm	Counting rule only; not documentation of gauge sensitivity, calibration, or climate-series certification

containing outlying years. Third, Kendall rank-correlation tests were used to assess monotonic relationships between time and each indicator. This non-parametric test does not require normality and complements linear regression. Fourth, OLS residuals were assessed using the Durbin–Watson statistic and Ljung–Box tests at lag 5. To verify whether serial dependence affected statistical inference, OLS p -values were re-estimated using heteroscedasticity- and autocorrelation-consistent (HAC) Newey–West standard errors with a maximum lag of 1. Fifth, averages for 1901–1950 and 1951–2000 were compared, and the series was further divided into five 20-year periods to examine whether changes were driven by a few years. Sixth, monthly and seasonal averages, April–September wet-season shares, the wettest and driest years, and high monthly accumulations were examined. The analysis remains descriptive: a linear slope indicates direction in the historical record rather than a future annual rate of change; a monthly accumulation identifies a high-value month rather than a single rainstorm event; and annual rainfall per rainy day supplements understanding of frequency and total amount but does not replace hourly or daily heavy-rainfall indicators. Data extraction and statistical processing were performed in Python, principally using PyMuPDF, pandas, NumPy, SciPy, statsmodels, and Matplotlib. Statistical significance was defined as a $p < 0.05$. Figures and tables were generated directly from structured data without imputing missing months. For 1901, 1905, and 1906, figures retain blank spaces or indicate incomplete records.

To maintain transparency between the source record and the derived statistics, all annual indicators were calculated only for years with complete monthly observations. Analyses of official monthly and seasonal climatology were retained on their source-reported basis rather than reconstructed from incomplete early years. This distinction is important because a single historical source can contain internally different aggregation bases. The 1941 sensitivity analysis retained the original data architecture while testing whether the isolated annual-monthly discrepancy affects trend inference. In addition, a limited regional comparison was undertaken using the published annual-rainfall record of the Hong Kong Observatory Headquarters for the shared 1961–2000 period.¹³ The comparison reports paired descriptive statistics, concurrent trend estimates, and interannual correlation without pooling or adjusting the two series. It therefore tests regional covariability rather than formal regional homogeneity or climate attribution.

3. Results

3.1. Data completeness and analytical sample

The source covers 100 years, from 1901 to 2000. After structuring, missing observations were concentrated at the beginning of the record: February 1901 is missing at the monthly level, all of 1905 is missing, and January–March 1906 are missing. Apart from these gaps, 1902–1904 and 1907–2000 contain complete 12-month records of rainfall and rainy days. The main annual statistics therefore use 97 complete-record years. The proportion of missing data is low and concentrated at the start of the series. Excluding incomplete years from the main annual analysis avoids underestimating annual totals and distorting the ranking of extremely dry years. The source's documentation of daily precipitation coverage, missing periods, station relocations, and broad changes in observing routine enables transparent reconstruction and a limited historical audit of the record. Nevertheless, the absence of a continuous technical archive means that observation conditions cannot be assumed to be fully consistent across all years. More rigorous climate attribution would require original daily data, full station metadata, and formal homogenisation procedures.

3.2. Annual rainfall: Positive trend alongside marked variability

Across the 97 complete-record years, mean annual rainfall in Macao was 1,879.3 mm (SD: 454.3 mm), with a median of 1,911.5 mm. The maximum, 3,041.4 mm, occurred in 1982, and the minimum, 981.4 mm, occurred in 1963. Rainfall in the wettest year was approximately 3.1 times that in the driest year. The 90th and 10th percentiles were 2,466.2 mm and 1,299.6 mm, respectively. These values show that annual rainfall did not fluctuate within a narrow range, but exhibited pronounced interannual differences.

Figure 1 presents annual rainfall for complete-record years, the 10-year moving average, the complete-record mean, and the 10th- and 90th-percentile lines. Two features are evident. First, annual values fluctuated markedly, with high and low years occurring in multiple periods. Second, the moving average increased overall and was especially high in the second half of the 20th century. OLS regression estimated an increase of 6.24 mm/year ($p < 0.001$); the Theil–Sen robust slope was 6.61 mm/year (95% confidence interval [CI]: 3.37–9.69); and Kendall's tau was 0.271 ($p < 0.001$). The three methods point in the same direction, indicating a statistically significant positive change in annual rainfall over the complete-record period. Residual diagnostics did not indicate significant serial dependence

for this model at lag 5 (Ljung-Box $p = 0.607$), and the HAC-adjusted result remained statistically significant ($p < 0.001$; Table 3).

This result requires cautious interpretation. The regression coefficient of determination was 0.150, meaning that calendar year explained only a limited share of annual variation. Annual rainfall remained strongly affected by interannual variability. The record therefore contains both a long-term trend and substantial uncertainty; the estimated slope should not be interpreted as a deterministic year-to-year trajectory or as a forecast of future annual rainfall. Excluding 1941, the one complete-record year with a documented 7.2 mm annual-monthly discrepancy, changed the OLS slope only from 6.24 to 6.33 mm/year and did not alter the HAC-based inference (Table 3). For

urban governance, this duality is more consequential than the trend estimate alone. Infrastructure maintenance and emergency arrangements should account for changes in the long-term baseline while retaining capacity for years that depart markedly from the mean.

3.3. Rainy days and rainfall per rainy day

Changes in annual rainfall may arise from two sources: more rainy days or more rainfall on the average rainy day. Separating these indicators avoids treating all change as generic rainfall intensification. Summary statistics and conventional trend diagnostics are provided in Tables 4 and 5, respectively. Across the 97 complete-record years, annual rainy days averaged 146.8 days (SD: 24.5), ranging from 93 days in 1904 to 212 days in 1998. OLS regression

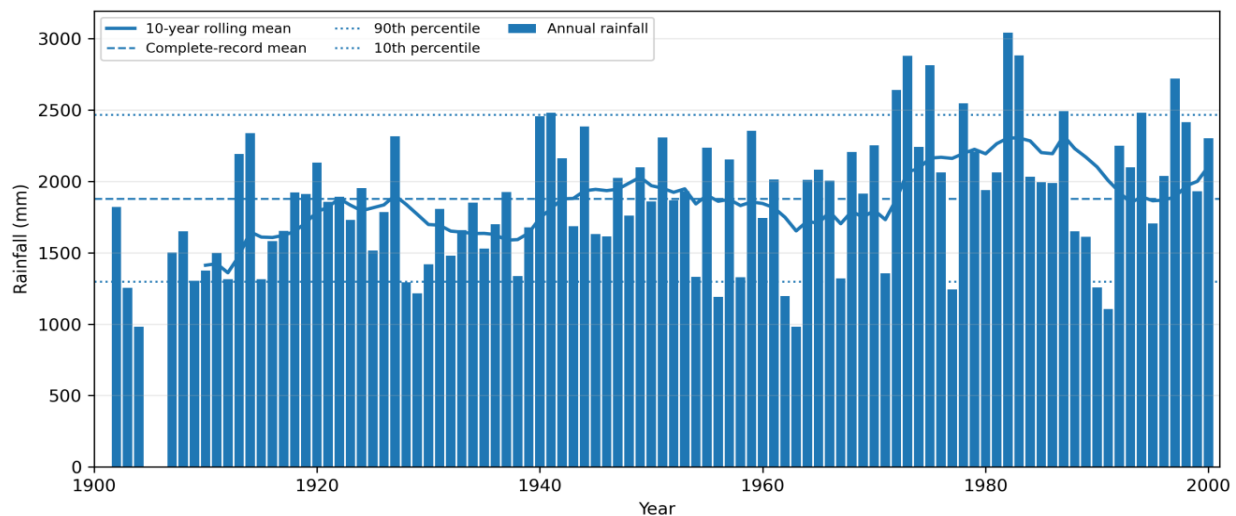


Figure 1. Annual rainfall and long-run variability in Macao, 1901–2000

Table 3. Time-series diagnostics and robustness checks for annual indicators

Indicator	Durbin-Watson	Ljung-Box p (lag 5)	HAC p (lag 1)	Slope excluding 1941	HAC p excluding 1941	Interpretation
Annual rainfall	1.745	0.607	<0.001	6.333 mm/year	<0.001	No lag-5 residual autocorrelation; positive trend retained.
Annual rainy days	1.144	<0.001	0.001	0.362 days/year	0.001	Serial dependence present; positive trend retained after HAC adjustment.
Rainfall per rainy day	1.126	<0.001	0.294	0.015 mm/day/year	0.268	No significant linear trend.
Wet-season share	2.177	0.303	0.444	0.022 percentage points/year	0.471	No significant linear trend.

Notes: Ljung-Box tests use residuals from the corresponding ordinary least-squares (OLS) model. HAC denotes Newey-West heteroscedasticity- and autocorrelation-consistent standard errors with maximum lag 1. The sensitivity analysis excludes 1941, the only complete-record year with a documented difference between the source annual field and the sum of monthly rainfall values.

estimated a linear increase of 0.36 days/year ($p < 0.001$); the Theil–Sen slope was 0.33 days/year; and Kendall rank correlation also indicated a positive association ($\tau = 0.236$, $p = 0.001$). Figure 2 shows that annual rainy days were generally high in the 1990s. The rainy-day residuals showed serial dependence (Ljung–Box $p < 0.001$ at lag 5), but the trend remained significant after HAC adjustment ($p = 0.001$; Table 3).

The mean rainfall per rainy day across the century-long record was 12.93 mm/day (SD: 2.95 mm/day). The maximum was 22.20 mm/day in 1982, and the minimum was 6.47 mm/day in 1991. Figure 3 shows marked fluctuation but a weak linear trend. The OLS slope was 0.014 mm/day per year ($p = 0.185$); the Theil–Sen slope was 0.019 mm/day per year, and its 95% CI crossed zero. The residuals were serially correlated (Ljung–Box $p <$

Table 4. Summary statistics for annual rainfall indicators (N = 97)

Indicator	Mean	SD	Median	Range	P10–P90
Annual rainfall (mm)	1,879.35	454.31	1,911.50	981.40–3,041.40	1,299.56–2,466.16
Annual rainy days (days)	146.85	24.49	145.00	93.00–212.00	117.60–178.80
Rainfall per rainy day (mm/day)	12.93	2.95	12.66	6.47–22.20	9.19–17.19
Wet-season share (%)	82.95	7.66	83.57	58.66–97.00	72.49–91.50

Table 5. Trend diagnostics for annual indicators

Indicator	OLS slope	OLS p -value	Theil–Sen slope	95% CI lower	95% CI upper	Kendall tau	Kendall p -value
Annual rainfall (mm)	6.236	<0.001	6.612	3.374	9.694	0.271	<0.001
Annual rainy days (days)	0.362	<0.001	0.333	0.140	0.500	0.236	0.001
Rainfall per rainy day (mm/day)	0.014	0.185	0.019	–0.004	0.040	0.114	0.097
Wet-season share (%)	0.023	0.407	0.028	–0.027	0.088	0.061	0.379

Abbreviation: OLS: Ordinary least squares.

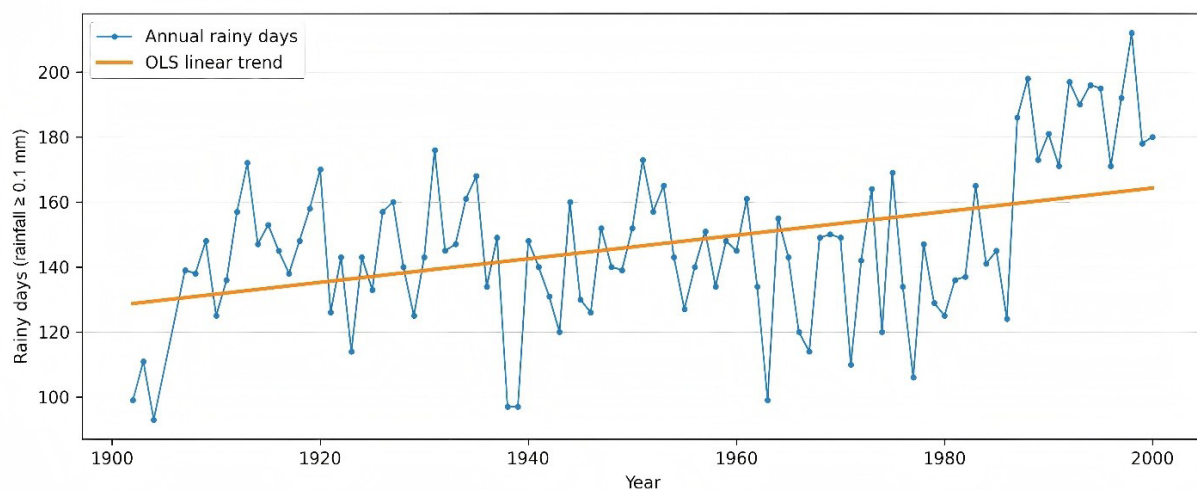


Figure 2. Annual number of rainy days in Macao, 1901–2000

Abbreviation: OLS: Ordinary least squares.

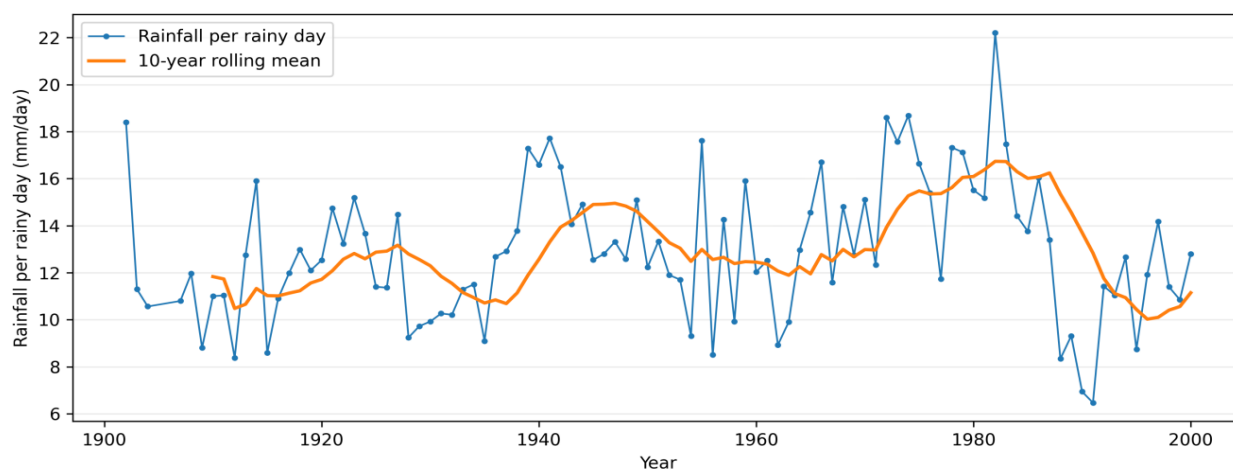


Figure 3. Annual rainfall per rainy day in Macao, 1901–2000

0.001 at lag 5), and HAC adjustment likewise did not support a significant linear trend ($p = 0.294$; Table 3). Thus, the increase in century-long annual rainfall cannot be interpreted simply as a continuing increase in average rainfall per rainy day. At the annual aggregation level, the increase in rainy-day frequency warrants separate attention.

This result also demonstrates the limitations of monthly data. Rainfall per rainy day cannot capture the peak intensity of heavy rainfall over one or several hours. A year with a lower value may still contain localised short-duration rainstorms, while a year with a higher value does not imply that all rainy days had the same intensity. The measure is therefore used as a supplementary descriptive indicator rather than a direct measure of rainstorm risk.

3.4. Monthly distribution: Rainfall pressure concentrated in late spring, summer, and early autumn

Monthly climatology describes the usual temporal structure within a year. The source-reported monthly climatology is presented in Table 6. According to the multi-year averages reported by the source, average monthly rainfall in Macao rose from 28.8 mm in January to 326.4 mm in June. August (293.5 mm) and May (292.0 mm) were also high. Average rainfall declined progressively after September. Rainy days showed a similar seasonal pattern: June averaged 19.6 days, July 17.7 days, August 17.0 days, and May 16.2 days, whereas winter months were much lower.

Figure 4 displays average monthly rainfall and average monthly rainy days together. The two series are complementary. From May to August, both total rainfall and rainy-day frequency were high, indicating that urban drainage maintenance and routine operations faced

sustained rainfall pressure during this period. April and September also retained relatively high average rainfall. This pattern shows that pre-season preparation should not wait until summer and that maintenance should not be reduced too early after the wet season.

Table 6. Monthly climatology of rainfall and rainy days

Month	Average rainfall (mm)	Average rainy days (days)	Rainfall per rainy day (mm)	Share of annual rainfall (%)
Jan	28.8	7.0	4.11	1.54
Feb	52.0	10.0	5.20	2.78
Mar	77.1	13.0	5.93	4.12
Apr	171.1	13.3	12.86	9.15
May	292.0	16.2	18.02	15.61
Jun	326.4	19.6	16.65	17.45
Jul	267.8	17.7	15.13	14.32
Aug	293.5	17.0	17.26	15.69
Sep	199.6	13.7	14.57	10.67
Oct	91.7	7.4	12.39	4.90
Nov	42.6	5.9	7.22	2.28
Dec	27.8	5.4	5.15	1.49

Note: Monthly shares are calculated using the sum of the 12 source-reported monthly climatological averages (1,870.4 mm).

Monthly averages do not represent every year. Figure 5 presents a year-by-month heatmap of rainfall from 1901 to 2000. High values are concentrated mainly between April and September, but the peak month differs across years. For example, high monthly accumulations occurred in May 1972, June 1966, July 1942, August 1940, and September 1964. This variation shows that seasonality can identify

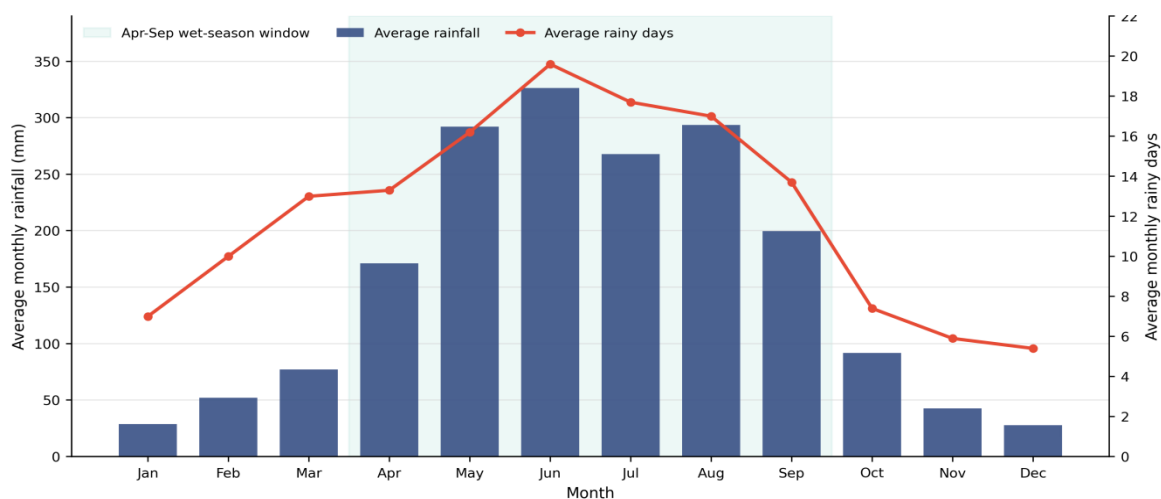


Figure 4. Monthly climatology of rainfall and rainy days in Macao

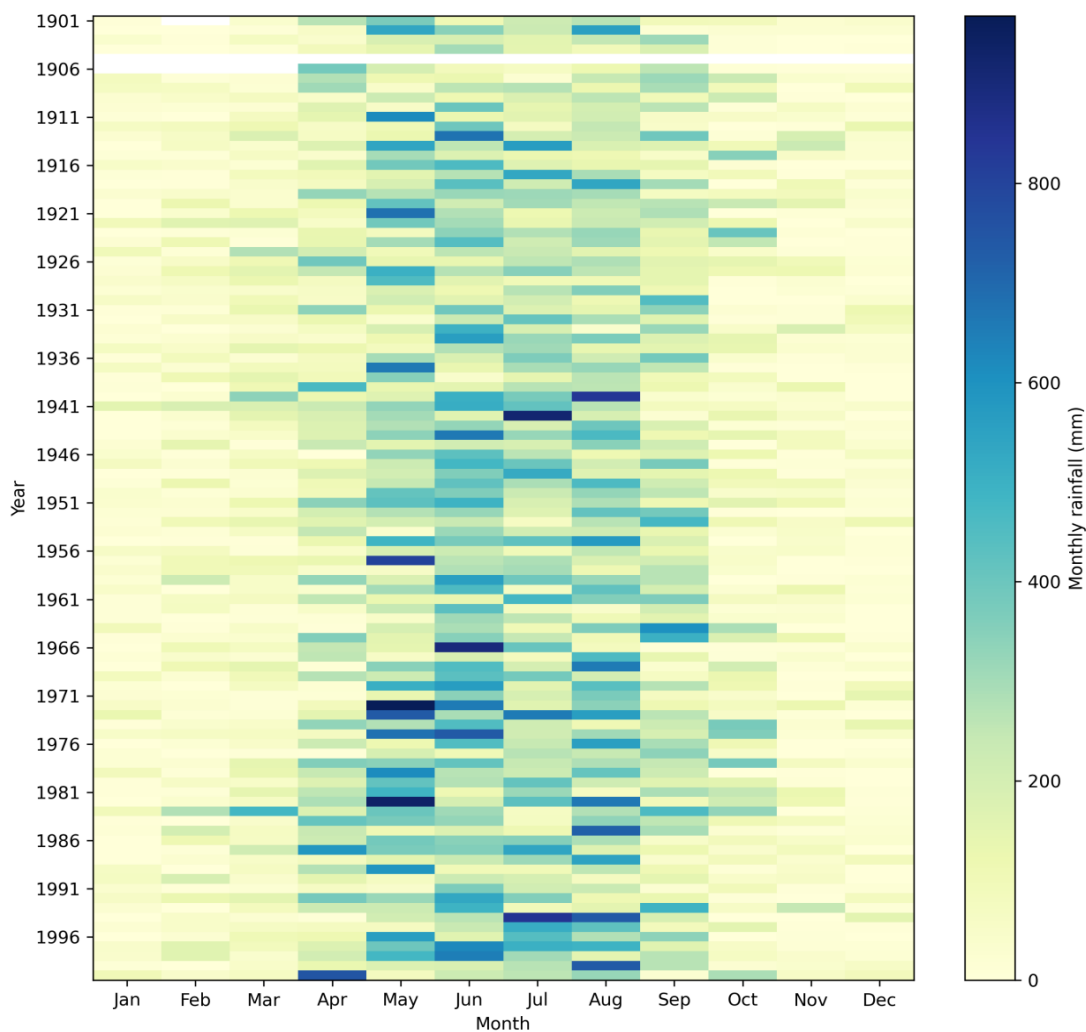


Figure 5. Temporal heatmap of monthly rainfall in Macao, 1901–2000

a preparation window but should not be mistaken for a fixed operational timetable. Urban governance should still integrate historical climatology with short-term forecasts, real-time monitoring, and context-specific conditions.

3.5. Seasonal structure and wet-season concentration

Source-reported seasonal averages further show the pronounced concentration of rainfall in Macao. Table 7 reports the corresponding seasonal climatology. Winter rainfall averaged 108.4 mm, accounting for 5.8% of the seasonal total; spring averaged 539.0 mm (28.8%); summer averaged 887.7 mm (47.5%); and autumn averaged 333.9 mm (17.9%). Summer had both the highest rainfall total and the greatest number of rainy days, averaging 54.4 days. The corresponding values were 42.5 days in spring, 26.9 in autumn, and 22.5 in winter.

Figure 6 shows why rainfall governance in Macao should not be framed as a summer-only window. Summer

rainfall is the largest and is clearly the principal period; however, rainfall has already risen substantially in spring and remains relatively high in autumn. The source notes that frontal rainfall strengthens in late spring, summer rainfall is influenced by tropical weather systems and monsoons, and rainfall recedes gradually in autumn.¹ In spring, attention should focus on prolonged wet spells, ground saturation, slopes, and ageing buildings; in summer, on convective storms, outer rainbands of tropical cyclones, drainage peaks, and transport disruption; and in autumn, on the latter stages of typhoon events, compounded storm-surge effects, and the resumption of tourism activity. A more appropriate governance rhythm therefore brings preparation forward into spring and retains necessary monitoring and maintenance capacity in autumn.

Across individual years, the April–September share of annual rainfall averaged 82.9%, with an SD of 7.7%. Its linear trend was not statistically significant (OLS slope, 0.023 percentage points/year; $p = 0.407$). Residual

Table 7. Seasonal climatology of rainfall and rainy days

Season	Months	Average rainfall (mm)	Average rainy days (days)	Share of annual rainfall (%)	Rainfall per rainy day (mm)
Winter	Dec, Jan, Feb	108.4	22.5	5.80	4.82
Spring	Mar, Apr, May	539.0	42.5	28.84	12.68
Summer	Jun, Jul, Aug	887.7	54.4	47.50	16.32
Autumn	Sep, Oct, Nov	333.9	26.9	17.87	12.41

Note: Seasonal shares are calculated using the sum of the four source-reported seasonal climatological averages (1,869.0 mm).

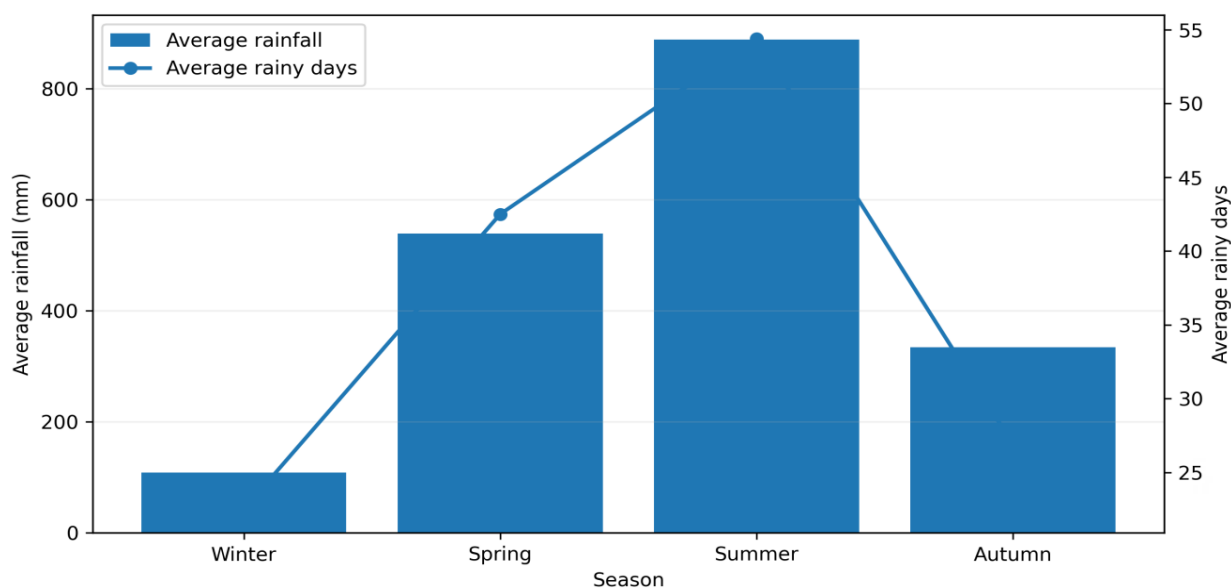


Figure 6. Seasonal distribution of rainfall and rainy days in Macao

diagnostics showed no significant lag-5 autocorrelation (Ljung–Box $p = 0.303$), and HAC adjustment retained the non-significant result ($p = 0.444$; Table 3). Wet-season concentration was therefore a stable feature of the century-long record, with no evidence that the proportion increased monotonically. The implication is not that the wet season is becoming increasingly concentrated, but that most annual rainfall has long been concentrated within a limited set of months.

3.6. Period comparisons: higher mean annual rainfall and rainy days in the second half of the century

Dividing complete-record years into the first and second halves of the century provides a more intuitive view of long-term differences. There were 47 complete years between 1901 and 1950, with a mean annual rainfall of 1,741.7 mm. There were 50 complete years between 1951 and 2000, with a mean of 2,008.7 mm. This represents an increase of 267.0 mm, or 15.3%. Over the same period, the mean annual rainy days rose from 139.9 to 153.4 days, an increase of 13.5 days.

Comparison across 20-year periods provides a more detailed view. Figure 7 and Table 8 show mean annual rainfall of 1,632.3 mm in 1901–1920, 1,720.3 mm in 1921–1940, 1,907.7 mm in 1941–1960, 1,995.9 mm in 1961–1980, and 2,103.4 mm in 1981–2000. The overall trend was upward, although not every indicator changed in parallel. Rainfall per rainy day was higher in 1961–1980, whereas annual rainy days increased markedly in 1981–2000. This pattern suggests that higher annual rainfall in the later period may be associated with both rainy-day frequency and the annual structure of rainfall.

Period comparisons should be treated as descriptive rather than mechanistic evidence. Considerable variability remained within each 20-year period, and multiple natural and observational factors may have affected different periods. Their policy value lies in helping managers avoid decisions based solely on a single year. Updates to drainage-maintenance standards, pre-season preparation, and assessments of redundancy capacity should consider long-term averages, period-level change, and anomalous years together.

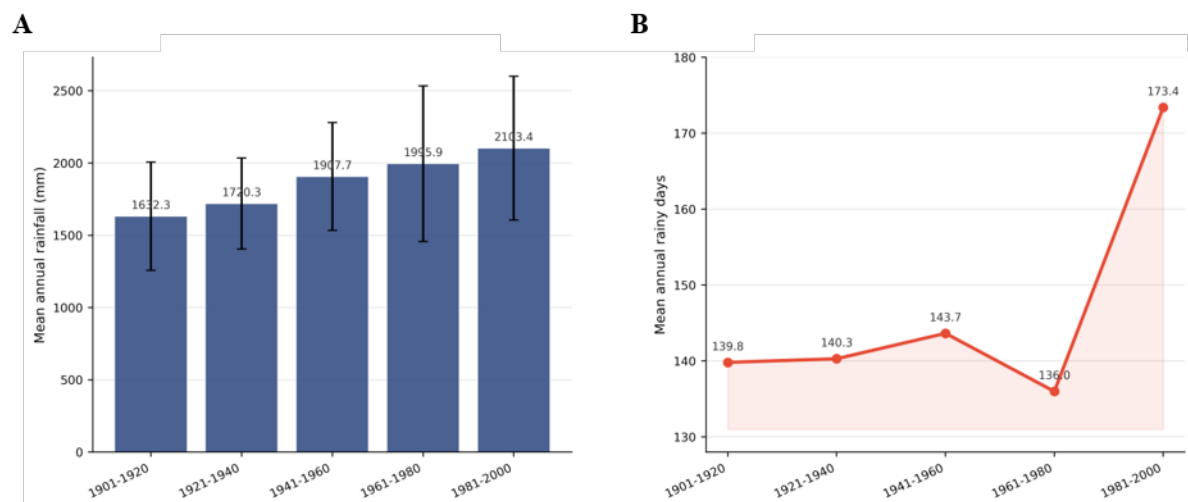


Figure 7. Twenty-year comparison of annual rainfall and rainy days. (A) Mean annual rainfall. (B) Mean annual rainy days by 20-year period.

Table 8. Twenty-year summary of annual rainfall indicators

Period	Valid years	Mean annual rainfall (mm)	SD annual rainfall (mm)	Mean annual rainy days (days)	Rainfall per rainy day (mm)	Wet-season share (%)
1901–1920	17	1,632.3	374.1	139.8	11.76	82.16
1921–1940	20	1,720.3	315.1	140.3	12.43	80.61
1941–1960	20	1,907.7	373.0	143.7	13.31	84.96
1961–1980	20	1,995.9	538.3	136.0	14.54	84.80
1981–2000	20	2,103.4	497.6	173.4	12.43	82.08

3.7. Regional context: Comparative analysis with the Hong Kong Observatory record

To examine whether the observed interannual changes were confined to Macao, annual rainfall in the published Hong Kong Observatory Headquarters record was extracted for the shared 1961–2000 period.¹³ Table 9 reports the paired comparison and its interpretative boundary. This post-war window contains 40 paired annual observations and avoids the 1940–1946 gap in the Hong Kong record. The two annual series covaried strongly: the Pearson correlation was 0.859 ($p < 0.001$), and the Spearman rank correlation was 0.829 ($p < 0.001$). The correspondence is also visible in several high- and low-rainfall years, including 1963, 1982, and 1997.

Over the same 1961–2000 interval, both records had positive OLS slopes, although neither slope reached the conventional 0.05 threshold in this shorter comparison window: 7.50 mm/year in Macao ($p = 0.293$) and 12.31 mm/year in Hong Kong ($p = 0.078$). The corresponding Theil–Sen slopes were 4.55 and 10.09 mm/year, respectively. These results support the interpretation that annual rainfall variability in Macao shared a substantial regional component during the common period. They do not establish that the full-century trend in Macao was caused by regional climate change.

This comparison remains deliberately bounded.

The Macao and Hong Kong records differ in source compilation, station history, observation environment, and temporal coverage, and neither series was homogenised or adjusted for a pooled regional analysis. The results are therefore used as evidence of regional covariability, not as a formal regional homogeneity test or a climate-attribution result. To complete the regional picture, future research plans to incorporate at least one adjacent mainland station, such as Zhuhai, which will serve as a crucial step toward conducting a formal regional homogenisation test.

3.8. Extreme years and high monthly accumulations

Means and trends do not replace examination of years in the tails of the distribution. Tables 10–12 report the wettest years, driest years, and highest monthly accumulations, respectively. For complete-record years, the 90th percentile was 2,466.2 mm, and the 10th percentile was 1,299.6 mm. The 10 wettest years were 1982, 1983, 1973, 1975, 1997, 1972, 1978, 1987, 1941, and 1994. The 10 driest years were 1963, 1904, 1991, 1956, 1962, 1929, 1977, 1903, 1990, and 1928. Figure 8 visualises the gap between these two groups.

Extremely wet years did not have an identical internal structure. Annual rainfall reached 3,041.4 mm in 1982, with 137 rainy days and rainfall per rainy day of 22.20 mm. In 1997, annual rainfall was 2,720.9 mm, with 192 rainy days and rainfall per rainy day of 14.17 mm. Both were high-rainfall years, but the former was more strongly

Table 9. Comparative annual rainfall results for Macao and Hong Kong, 1961–2000

Statistic	Macao	Hong Kong Observatory Headquarters	Paired interpretation
Number of paired years	40	40	1961–2000 is the longest continuous common post-war window in the published records.
Mean annual rainfall (mm)	2,049.7	2,290.2	Average level differs by station and should not be interpreted as an exposure-adjusted regional mean.
Standard deviation (mm)	514.6	511.3	Both series exhibit substantial year-to-year variability.
OLS slope (mm/year); p -value	7.50; 0.293	12.31; 0.078	Both slopes are positive but not statistically significant within the 40-year comparison window.
Theil–Sen slope (mm/year)	4.55	10.09	Robust slopes retain the same positive direction.
Pearson correlation	0.859; $p < 0.001$	0.859; $p < 0.001$	Strong common interannual variation.
Spearman correlation	0.829; $p < 0.001$	0.829; $p < 0.001$	Rank-order association supports the same conclusion.
Interpretative boundary	Published single-station compilation	Published single-station record ¹³	Comparison tests regional covariability only; it is not a pooled or homogenised regional climate series.

Notes: Hong Kong annual totals were taken from the Hong Kong Observatory's published annual-data table. The 1940–1946 Hong Kong gap precludes a full-century paired analysis. Differences in station setting, observation history, and data processing mean that the comparison does not establish formal regional homogeneity or climate attribution.

Abbreviation: OLS: Ordinary least squares.

characterised by rainfall per rainy day, whereas the latter involved more rainy days. This distinction has practical significance: years with similar total rainfall, or years that fall within a similar high-value range, may require different emphases in maintenance and emergency response.

Table 10. The 10 wettest complete-record years

Year	Annual rainfall (mm)	Rainy days (days)	Rainfall per rainy day (mm)	Wet-season share (%)
1982	3,041.4	137	22.20	85.59
1983	2,883.0	165	17.47	58.66
1973	2,880.2	164	17.56	92.29
1975	2,813.0	169	16.64	78.21
1997	2,720.9	192	14.17	86.35
1972	2,641.8	142	18.60	88.27
1978	2,547.0	147	17.33	73.71
1987	2,493.1	186	13.40	85.95
1941	2,481.3	140	17.72	73.93
1994	2,481.1	196	12.66	91.02

Table 11. The 10 driest complete-record years

Year	Annual rainfall (mm)	Rainy days (days)	Rainfall per rainy day (mm)	Wet-season share (%)
1963	981.4	99	9.91	90.80
1904	982.5	93	10.56	97.00
1991	1,106.5	171	6.47	84.76
1956	1,191.4	140	8.51	79.27
1962	1,196.3	134	8.93	88.68
1929	1,216.2	125	9.73	89.71
1977	1,243.6	106	11.73	92.57
1903	1,254.0	111	11.30	90.21
1990	1,256.9	181	6.94	67.61
1928	1,294.4	140	9.25	80.20

High monthly values further illustrate differences within annual totals. The highest monthly accumulation in the century-long record was 968.0 mm in May 1972, followed by 935.4 mm in May 1982, 917.9 mm in July 1942, 894.6 mm in June 1966, 848.8 mm in July 1994, and 836.4 mm in August 1940. April 2000 reached 749.8

mm, showing that high monthly accumulations are not confined to midsummer. Because the source is monthly, these values cannot directly identify the duration or peak of an individual rainfall event. However, they demonstrate the importance of high-accumulation months for drainage maintenance, construction scheduling, and emergency duty arrangements.

Table 12. The 15 highest monthly rainfall accumulations

Year	Month	Monthly rainfall (mm)
1972	May	968.0
1982	May	935.4
1942	Jul	917.9
1966	Jun	894.6
1994	Jul	848.8
1940	Aug	836.4
1957	May	803.2
2000	Apr	749.8
1994	Aug	736.9
1973	May	736.2
1975	Jun	734.0
1999	Aug	730.8
1985	Aug	719.0
1921	May	682.4
1975	May	677.8

4. Discussion

4.1. Principal findings

This study establishes a historical baseline for Macao's 20th-century rainfall structure. Four findings are particularly relevant to rainfall governance: annual rainfall increased overall but retained marked interannual variability; annual rainy days increased, whereas rainfall per rainy day did not show an equally clear linear trend; most rainfall remained concentrated between April and September, although the peak month varied across years; and extremely wet years had different internal structures, expressed either through higher rainfall per rainy day or through a greater number of rainy days. The time-series checks qualify rather than overturn these findings. HAC-based inference confirmed the annual-rainfall and rainy-day conclusions, while also confirming the absence of statistically significant linear trends in rainfall per rainy day and wet-season share.

Taken together, these patterns suggest that the

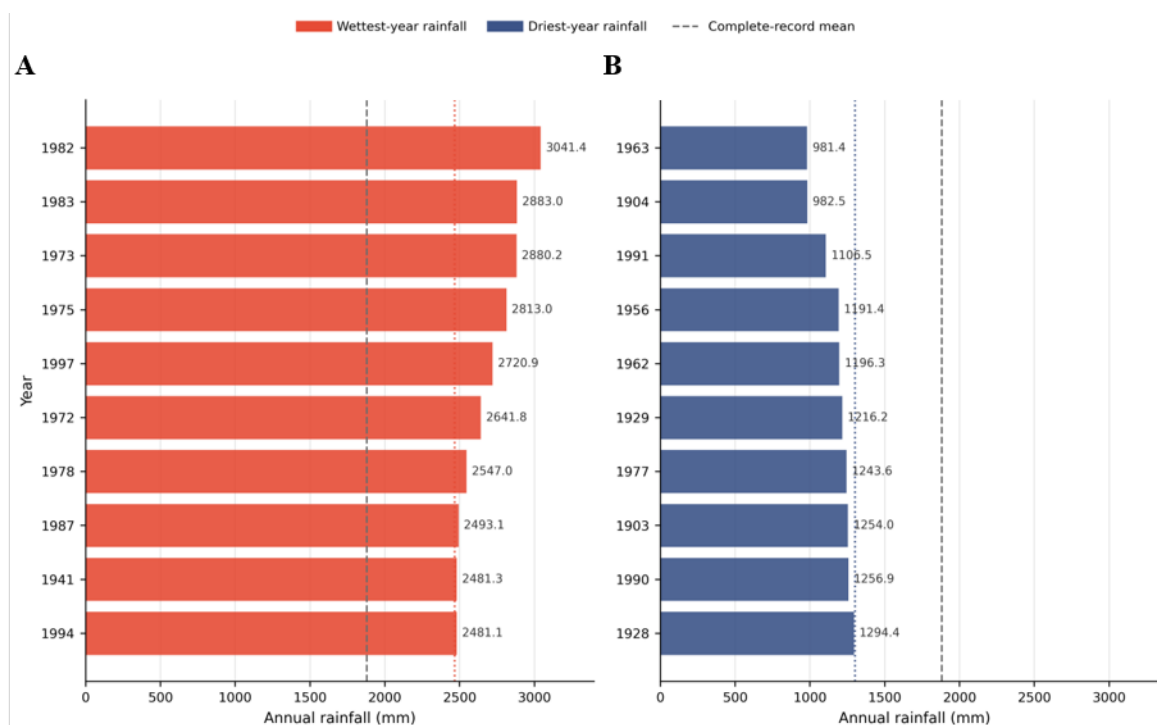


Figure 8. The (A) 10 wettest and (B) 10 driest complete-record years

management implications of rainfall cannot be reduced to a single annual total. A year with many rainy days may create repeated operational demands, such as prolonged inspection cycles, more frequent construction disruptions, and cumulative wear on drainage and transport systems. A year with a high amount of rainfall per rainy day may instead place a more concentrated burden on local response capacity. The month and season in which rainfall occurs also matter because maintenance, tourism, construction, and public-service activities follow different schedules. A rainfall baseline is therefore most useful when translated into a differentiated governance calendar and combined with event-scale information.

This contribution complements existing research. Urban-flood studies commonly use hydrodynamic models, spatial-exposure indicators, complex networks, or disaster-loss data to identify high-risk areas, critical facilities, and system consequences in particular contexts. For example, a stress test of extreme rainstorms in Hong Kong identified interdependencies within urban systems,¹⁴ while research on storm-surge flooding during Typhoon Hato in Macao demonstrates the need to account for compound risk in coastal cities.¹⁵ The present study instead provides a historical natural-data analysis that can support such work. Urban resilience emphasises sustained adjustment before, during, and after disturbances,^{4,16} while urban-adaptation planning requires stable data foundations and management

mechanisms that can be updated.^{5,7} The Sendai Framework similarly identifies understanding disaster risk, risk governance, resilience investment, and preparedness as priorities.¹⁷ From this perspective, century-long records remain useful for identifying long-term baselines, regular seasonal windows, and tail scenarios that should be incorporated into contingency planning. They are not, however, a substitute for models of water demand, pumping energy, drainage performance, or service continuity. Such models require matched operational data at much finer temporal resolution.^{10,11}

4.2. Practical implications

First, historical baselines should be transformed from archived material into a mechanism for periodic updating. Long-term changes in annual rainfall and rainy days show that maintenance arrangements based only on recent experience are insufficient. Management departments can update multi-year averages, period means, anomalous years, and high monthly accumulations at regular intervals and use them in drainage inspection, budget allocation, and infrastructure review. Second, the annual governance calendar should cover late spring to early autumn rather than focusing only on midsummer. Monthly climatology and seasonal structure show that rainfall increases markedly after April, reaches high levels in summer, and remains relatively high in September. Desilting,

pumping-station inspection, underground-space checks, construction-risk management, and interdepartmental liaison should therefore be completed before the high-risk window and accompanied by necessary monitoring and maintenance capacity into early autumn. Seasonality offers a preparation window rather than a mechanical timetable; specific action must remain linked to short-term forecasts and real-time monitoring. Table 13 translates the historical evidence into defined operational uses and specifies the decisions it cannot determine.

These implications are intended as a layered governance approach rather than a single engineering prescription. At the baseline level, historical climatology can guide the seasonal timing of inspections, desilting, equipment checks, and resource preparation. At the operational level, forecasts, hourly rainfall observations, tide information, and facility monitoring can determine whether particular weeks or events require staff redeployment, precautionary service adjustments, or public communication. At the learning level, records of individual events can reveal whether observed impacts were associated with rainfall duration, short-duration peaks, tidal coincidence, drainage failure, water demand, pumping load, or exposure at

particular locations. Linking these levels helps avoid both underreaction to gradual baseline changes and overreliance on a single extreme year. It also allows resources to be allocated according to the type of stress anticipated: recurrent wet-day exposure, high monthly accumulation, or short-lived but intense rainfall.

Third, management indicators should distinguish total amount, frequency, and intensity proxies. An increase in annual rainy days may increase the burden of continuous facility operation, construction coordination, and routine inspection. Years with higher rainfall per rainy day may signal a more concentrated response burden. Because the intensity measure in this study is an annual average, it cannot replace hourly rainstorm indicators. In practice, it should be used alongside short-duration rainfall, waterlogging locations, tidal conditions, and facility-operation data. Fourth, tail years should be incorporated into routine scenario preparation. Both 1982 and 1997 were high-rainfall years, yet the former had higher rainfall per rainy day, and the latter had more rainy days. These patterns do not impose identical management requirements. Historical monthly data can therefore inform the timing of maintenance, the selection of anomalous-

Table 13. From historical rainfall baseline to urban water-system decision support

Evidence layer	Variables and indicators	Operational use	Additional data required	What the historical monthly record cannot determine
Historical baseline	Annual totals, rainy days, monthly and seasonal climatology, wet-season share.	Set pre-season inspection window; schedule desilting, equipment checks, and staffing preparation.	Periodic update of rainfall baseline.	Event warning threshold or engineering design storm.
Tail-year scenario	Wet/dry percentiles; high monthly accumulations; frequency-versus-amount profile.	Select anomalous-year scenarios; plan standby equipment, budget reserves, and continuity arrangements.	Historical impacts and post-event review records.	Probability or consequence of a specific flood event.
Event operations	Hourly intensity, duration, antecedent rainfall, tide, typhoon conditions, waterlogging locations.	Issue event-level warnings and redeploy personnel or assets.	Matched high-resolution meteorological, hydraulic, and location-specific impact records.	Hourly flood prediction from annual or monthly indicators alone.
Utility and service response	Water demand, pumping schedules, electricity use, pressure, storage, leakage, service interruptions.	Test precipitation-to-operation-to-energy pathways; optimise utility response.	Time-matched utility-operation and energy records.	Water consumption, energy cost, or pump performance without operational outcome data.
System modelling	Linked climate, infrastructure, exposure, and service data.	Use regression, time-series, clustering, or machine learning after valid outcomes are available.	Integrated post-2000 database and validation data.	Causal policy-effect evaluation from the historical rainfall compilation alone.

Note: Historical rainfall information is used here as the baseline layer of a staged evidence architecture, not as a direct substitute for hydraulic design analysis, operational telemetry, or outcome-based decision models.

year scenarios, the scale of standby arrangements, and the design of post-event review records. They cannot directly revise drainage design storms, engineering return periods, or warning thresholds, which require high-resolution intensity-duration-frequency information, hydraulic capacity data, and local exposure analysis. Fifth, historical baselines, real-time monitoring, and event records should form a continuous evidence chain. After high-rainfall years, reviews should record not only annual totals and losses but also the monthly accumulation process, short-duration peaks, warning lead times, facility failures, road impacts, public-service interruptions, water-supply demand, pumping energy use, and recovery times. This would progressively convert descriptive evidence into more specific governance improvements.

4.3. Limitations and directions for future research

First, the record ends in 2000 and can provide only a 20th-century historical baseline; it cannot directly represent current climatic conditions. Second, the source mainly contains monthly total rainfall and monthly rainy days and therefore cannot identify hourly peaks, continuous-rainfall processes, or short-duration rainstorms. Third, this study does not include tide levels, typhoon tracks, topography, land use, drainage infrastructure, population exposure, road networks, water consumption, pumping energy, and disaster losses. High-rainfall years therefore cannot be equated directly with high-loss years, and the effects of particular policies cannot be evaluated. Fourth, the source documents several important station relocations and broad changes in observing routine, but it does not provide a complete technical archive of rain-gauge models, exposure conditions at each location, calibration and maintenance records, or adjustment procedures. The documented relocations involve different sites and elevations and may have affected the homogeneity of the compiled series. Because no adjustment parameters can be derived from the available source, no formal homogenisation was attempted. The reported trends should therefore be read as descriptive properties of the published record, with the station-history information used to define rather than eliminate this uncertainty. Consequently, it is essential to reiterate that the observed statistical trends strictly describe the properties of the published historical series and do not necessarily represent absolute climatic reality, as they may embed undocumented observational artifacts.

Future research can proceed along four paths. First, monthly, daily, and hourly data since 2001 should be added to compare the 20th-century baseline with recent change. Second, event-based analysis should link hourly rainfall intensity, rainfall duration, antecedent rainfall, tide levels, typhoon information, topography, drainage networks, and

waterlogging locations to identify compound-risk settings. Third, matched facility-operation records should be added, including water demand, pumping schedules, electricity use, pressure, storage, emergency dispatch, and service interruption, so that the precipitation-to-operation-to-energy pathway can be tested using appropriate regression, time-series, clustering, or machine-learning methods. Fourth, formal homogenisation should assemble original daily station data, documented relocation and observing-routine history, gauge metadata, calibration records, overlap information, and harmonised multi-station records from Macao, Hong Kong, Zhuhai, and other Pearl River Estuary locations. Such a staged approach can build a progressive research programme from a historical rainfall baseline toward regionally comparable climate analysis and operational decision support. Finally, the present results address the climate-baseline layer of a broader urban water-system decision problem. In future studies, the chain of precipitation, water consumption, and energy cost is conceptually important because meteorological conditions affect utilities through multiple intermediate processes. Studies of urban water supply have shown that precipitation, temperature, calendar effects, demand patterns, and pumping operations can be integrated where high-frequency operational records are available.¹⁰ Broader water-resource resilience research similarly demonstrates the value of linking hydrological conditions with system-level indicators for decision support.¹¹

5. Conclusion

Using Macao's century-long climate data, this study descriptively analysed rainfall structure between 1901 and 2000. The 97 complete-record years indicate a statistically significant positive change in annual rainfall alongside pronounced interannual variability. Annual rainy days also increased, whereas the linear trend in rainfall per rainy day was not statistically significant. Residual diagnostics and HAC-based inference did not alter these substantive conclusions. Rainfall was highly concentrated in time: based on monthly climatology, April–September accounted for 82.9% of annual rainfall. However, the peak month was not fixed across years, and extremely wet years had different internal structures. The paired 1961–2000 comparison with the published Hong Kong Observatory record shows strong interannual covariability, but it does not establish regional attribution because the two station records were not homogenised or pooled. Historical data should be used as a continuously updated management baseline rather than as a complete model of disaster risk. Rainfall governance in Macao should integrate pre-season maintenance, in-season monitoring, indicator differentiation, tail-scenario preparation, and post-event

review. At the same time, 20th-century records cannot substitute for post-2000 updates, and monthly single-station data cannot establish climate attribution, meaning the trends described herein reflect the published series rather than a reconstructed climatic reality, nor can they directly infer disaster losses, water-system operation, energy costs, or policy effects.

The principal contribution of this analysis is therefore not a claim that a historical trend alone determines present-day risk. Instead, it provides an explicit and reproducible starting point for interpreting how rainfall pressure is distributed across time and for structuring the data required to move from climatological description to operational decision support. This starting point can support periodic reassessment of maintenance calendars, the timing of pre-season preparation, anomalous-year scenarios, and the design of event-review records. It can also improve communication between meteorological services, infrastructure managers, emergency-response agencies, utilities, and departments responsible for transport, construction, and public services. As new data are incorporated, the historical baseline should be recalculated rather than treated as fixed, while engineering standards and warning thresholds should continue to rely on high-resolution hydrometeorological and hydraulic evidence.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Further disclosure

During the preparation of this manuscript, the authors used ChatGPT 5.5 (OpenAI) to support data cleaning, Python-assisted visualisation, methodological documentation, and language refinement. The generative AI tool was not used to create independent empirical data.

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