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Modeling Climate-Sensitive Dengue Transmission in Balochistan Using District-Level Epidemiological Data

Iqra Batool¹(Corresponding Author), Abdul Rehman², Ali Nawaz³, Hamid Ibrahim⁴, Farhan Aman⁵

¹ MS Student, Lasbela University of Agriculture, Water and Marine Sciences, Pakistan, iqrahanbhi786@gmail.com, <https://orcid.org/0009-0009-9949-6264>

² Student, Department of Entomology, Lasbela University of Agriculture, Water and Marine Sciences, Pakistan, arasdiq2266@gmail.com, <https://orcid.org/0009-0008-5300-6736>

³ MSc Student, Department of Plant Pathology, University of Faisalabad, Pakistan, alinawazsumalani212@gamil.com, <https://orcid.org/0009-0008-0292-0237>

⁴ Department of Entomology, Lasbela University of Agriculture, Water and Marine Sciences, Pakistan, hamidibrahimazad@gmail.com, <https://orcid.org/0009-0006-1263-4117>

⁵ Student, Department of Entomology, Lasbela University of Agriculture, Water and Marine Sciences, Pakistan, farhanaman746@gmail.com, <https://orcid.org/0009-0004-8679-6245>

Abstract

Dengue fever has emerged as a major public health concern in Pakistan, particularly in Balochistan, where climatic variability and limited surveillance infrastructure have contributed to increasing disease burden. This study aimed to investigate the relationship between climatic factors and dengue transmission across multiple districts of Balochistan using a retrospective district-level epidemiological approach. Dengue surveillance data were collected from Public Health Laboratories, District Health Offices (DHOs), dengue surveillance units, and People's Primary Healthcare Initiative (PPHI) centers, while climatic variables including temperature, rainfall, and humidity were obtained from national and global meteorological sources. The integrated datasets were analyzed using RStudio to assess seasonal trends, spatial distribution, and climate-dengue associations through descriptive statistics, correlation analysis, and negative binomial regression modeling. A total of 26,482 confirmed dengue cases were identified from 125,780 diagnostic tests conducted during 2024. The highest disease burden was observed in Turbat, Panjgur, Jhal Magsi, and Khuzdar districts. Dengue incidence showed a strong seasonal pattern, with cases increasing sharply during the summer and post-monsoon months and peaking in September. Regression analysis demonstrated that increasing temperature was significantly associated with higher dengue incidence, while rainfall exhibited delayed effects through enhanced vector breeding conditions. The combined influence of high temperature and high rainfall produced the greatest transmission intensity. The findings indicate that dengue transmission in Balochistan is highly climate-sensitive and increasingly shifting toward an endemic transmission pattern. Strengthening climate-informed surveillance systems, improving early warning mechanisms, enhancing vector control strategies, and promoting community awareness are essential for reducing the growing dengue burden in the region.

Keywords: Dengue fever, Climate change, Balochistan, Aedes mosquitoes, Temperature, Rainfall, Seasonal variation, Vector-borne disease, Epidemiology, Public health, Disease surveillance, Pakistan.

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Introduction

Mosquitoes are small insects belonging to the order Diptera and family Culicidae, comprising more than 3,600 species worldwide. Despite their small size, they are among the most medically important insect groups due to their ability to transmit pathogens responsible for diseases such as malaria, dengue fever, yellow fever, and lymphatic filariasis (Batool et al., 2026).

Among mosquito-borne diseases, dengue fever has emerged as a major global public health concern. It is one of the fastest-growing viral infections, particularly in tropical and subtropical regions. In severe cases, dengue can progress to dengue haemorrhagic fever or dengue shock syndrome, both of which can be life-threatening. Globally, dengue viruses (DENVs) are responsible for approximately 50–100 million infections annually, making it the most common arthropod-borne viral disease affecting humans (Tuiskunen Bäck & Lundkvist, 2013).

Pakistan has experienced a sharp rise in dengue cases in recent years, making it a growing public health concern. By September 2024, 2,795 new cases were reported, with Balochistan among the most affected regions, alongside Punjab, Sindh, and Khyber Pakhtunkhwa. Major cities, including Rawalpindi, have seen an increase in hospital admissions, placing pressure on healthcare systems. Dengue transmission is driven by poor sanitation, rapid urbanization, ineffective waste management, and favorable monsoon conditions that promote mosquito breeding. Inadequate vector control, increased population movement, and the circulation of multiple dengue virus serotypes further contribute to disease spread and severity (Aftab et al., 2024).

Climate change is another critical factor influencing dengue transmission. It has already begun to impact air quality, food production, water availability, and human health globally (Jabeen & Ansari et al., 2022).

Changes in temperature, rainfall patterns, and humidity significantly affect mosquito survival, breeding, and viral replication. As a result, the distribution and seasonal dynamics of dengue vectors, particularly *Aedes aegypti* and *Aedes albopictus*, have changed over time (Tolle, 2009).

Dengue is primarily transmitted through the bite of infected *Aedes aegypti* and *Aedes albopictus*, belonging to the family Flaviviridae. Symptoms typically appear within a few days after infection and may include high fever, headache, pain behind the eyes, muscle and joint pain, and in severe cases, thrombocytopenia and hemorrhagic manifestations (Khan & Azeem, 2022).

Recent global studies have increasingly emphasized the role of climate variability in shaping dengue transmission dynamics. Climate-driven forecasting models using machine learning, neural networks, and statistical approaches have demonstrated that temperature, rainfall, and humidity significantly influence vector abundance and outbreak intensity. A machine learning-based forecasting study reported that inclusion of climatic variables substantially improved dengue prediction accuracy in tropical regions (da Silva et al., 2025). Similarly, climate-informed forecasting systems developed in Vietnam demonstrated that integrating meteorological variables into surveillance frameworks enhanced outbreak prediction and early warning capacity (Tuan, 2024). Advanced neural network and deep learning models have also been

successfully applied for short-term dengue forecasting, particularly in regions experiencing rapid climatic fluctuations (Chakraborty et al., 2023; Wang et al., 2023).

Despite growing international evidence, limited research has examined climate-sensitive dengue transmission in arid and resource-constrained regions such as Balochistan, Pakistan. Most existing studies are concentrated in Southeast Asia and Latin America, while district-level climate-dengue analyses remain scarce in ecologically diverse regions with weak surveillance infrastructure. This study addresses this gap by integrating district-wise epidemiological and climatic datasets to evaluate seasonal and environmental drivers of dengue transmission across Balochistan.

Study Hypotheses

H1: Mean temperature is positively associated with dengue incidence across districts of Balochistan.

H2: Moderate rainfall conditions are associated with higher dengue incidence than very low or very high rainfall conditions.

H3: Climatic variables exhibit delayed effects on dengue incidence through their influence on vector breeding and virus development.

H4: Combined high-temperature and high-rainfall conditions produce the highest dengue transmission risk.

Objectives

1. To quantify the association between climatic variables and dengue incidence across districts of Balochistan.
2. To evaluate the lagged effects of temperature and rainfall on dengue transmission.
3. To identify climatic thresholds associated with increased dengue risk.

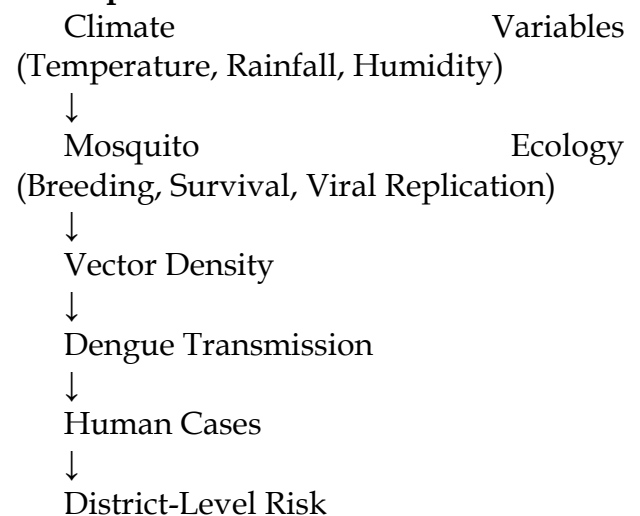
4. To develop a climate-sensitive dengue risk framework for public health planning.

Materials and Methods

3.1 Study Area

This study was conducted across multiple districts of Balochistan, Pakistan, from January to December 2024. Balochistan province is characterized by highly diverse climatic zones ranging from arid desert regions to semi-arid and temperate highlands. Districts included in this study were selected on the basis of dengue reporting activity, presence of surveillance units, and availability of climate datasets. The major districts visited for data collection included Quetta, Lasbela, Kech (Turbat), Gwadar, Khuzdar, Mastung, Hub, Panjgur, and Jhal Magsi, representing variable ecological and climatic settings. These districts differ significantly in temperature patterns, humidity profiles, population densities, and health service accessibility, making them suitable for studying climate-linked dengue transmission.

Conceptual framework:



3.2 Data Collection Approach

A mixed-method field-based data collection strategy was adopted to gather dengue incidence data from multiple official health sources across the selected

districts. [Nanthagopan, Y. \(2021\)](#).

3.3 Study Design

This research was designed as a district-based, observational, retrospective study integrating epidemiological dengue case data with multi-year climate variables to evaluate seasonal and climate-driven transmission patterns across Balochistan. The study used a mixed-methods quantitative approach, combining field data collection from health institutions with statistical and environmental data analysis using RStudio. [Riaz, S., & Qureshi, I. \(2025\)](#)

The study was structured to:

1. Collect historical dengue case data from district-level surveillance systems, laboratories, PPHI centers, and District Health Offices.
2. Integrate climate variables (temperature, rainfall, humidity) obtained from national and international meteorological sources.
3. Assess statistical associations between dengue cases and climate factors to identify climate-driven transmission trends.

The design allowed examination of seasonal fluctuations, district-wise disease burden, and climate sensitivity of dengue in a region where epidemiological data is limited and under-reported. This structured approach ensured reliability, comparability, and consistency of the results across all selected districts.

3.3.1 Visits to Dengue Surveillance Institutes and Laboratories

Physical visits were conducted to district-level Dengue Surveillance Units, Public Health Laboratories, and vector-borne disease monitoring centers. Meetings were held with surveillance officers, entomologists, epidemiologists, and laboratory technicians to discuss the

dengue situation, confirm case reporting mechanisms, and obtain officially recorded datasets. Many laboratories provided Excel-formatted case registers, including patient demographics, date of diagnosis, confirmation type (NS1, IgM, PCR), and admission records. [World Health Organization. \(2016\)](#).

3.3.2 PPHI Centers and District Health Offices

Additional data were collected from People's Primary Healthcare Initiative (PPHI) centers, Basic Health Units (BHUs), and District Health Offices (DHOs). These centers provided monthly and weekly dengue case summaries, outbreak alerts, and surveillance reports. In some districts, where digital formats were limited, data was obtained from handwritten logbooks, registers, and case investigation forms. These documents were photographed or manually transcribed and later converted into digital spreadsheets for analysis. [Qureshy, L. F. \(2010\)](#).

3.3.3 Verification and Compilation of Raw Data

Where discrepancies occurred between different institutions (laboratory vs. DHO vs. PPHI records), cross-verification was conducted through discussion with district surveillance focal persons. The raw handwritten records were manually entered into Excel files, ensuring accuracy in case numbers, dates, and geographic identifiers. Duplicate entries were identified and removed. All district datasets were then merged into a master Excel sheet for preprocessing.

3.3 Climate Data Collection

Climate variables relevant to dengue transmission, including temperature (mean, minimum, maximum), precipitation, humidity, and seasonal indicators, were collected from national climate repositories. Data were sourced

1. Pakistan Meteorological Department (PMD)
2. Global climate databases (NOAA, CHIRPS)
3. District-level meteorological observatories, wherever available

Climate datasets were extracted on a monthly scale from 2010–2024, depending on availability for each district. The climate data were aligned with dengue case timelines for correlation and seasonal analysis.

3.4 Data Preparation and Processing

The compiled dengue datasets and climate variables were cleaned and standardized. Steps included: Horton, N. J., & Kleinman, K. (2015).

1. Removing missing or invalid entries
2. Assigning district codes
3. Converting data formats to standard machine-readable CSV format for multi-platform compatibility. Matching monthly climate variables with dengue case counts
4. Creating new variables (e.g., monsoon period, seasonal category, temperature quartiles).

Processed datasets were saved in CSV/Excel format for analysis.

3.5 Statistical Analysis and Epidemiological Modeling

To account for the non-linear relationships and delayed biological mechanisms inherent in climate-dengue dynamics, we utilized a Generalized Additive Model (GAM) integrated with a Distributed Lag framework. Standard linear regression models often fail to capture the ecological thresholds of *Aedes* mosquitoes, particularly the hypothesis that moderate rainfall maximizes vector breeding whereas extreme conditions suppress it.

All statistical modeling was performed

International Journal of Agriculture Innovation and Cutting-Edge Research 4(3) using the statsmodels epidemiological architecture in Python and RStudio.

3.5.1 Positivity Rate Analysis

District-wise dengue test positivity rates were calculated to evaluate variation in diagnostic burden and potential testing bias across districts. Positivity rate was calculated using the following formula:

$$\text{Positivity Rate (\%)} = \frac{\text{Confirm dengue cases}}{\text{Total tests conducted}} \times 100$$

The positivity percentage was used to compare relative dengue burden among districts independent of testing frequency.

3.5.2 Descriptive and Seasonal Analysis

Descriptive statistics and monthly/seasonal dengue case trends were computed using the following R functions:

3.5.2.1 `summary()`

3.5.2.2 `aggregate()`

3.5.2.3 `group_by()` and `summarise()` (dplyr package)

Seasonal patterns were evaluated by categorizing the data into the following climatic seasons:

1. Winter (December–February)
2. Pre-summer (March–April)
3. Summer (May–August)
4. Post-monsoon and fall (September–November)

3.5.3 Correlation Analysis

Pearson correlation coefficients (`cor()`) were computed to assess the strength and direction of association between dengue incidence and climatic variables, including mean temperature, minimum temperature, maximum temperature, humidity, and rainfall ([Figueredo et al., 2023](#)).

3.5.4 Visualization

Graphs and plots were generated using `ggplot2`, including:

1. Line graphs showing temporal dengue trends across districts
2. Bar plots of seasonal dengue distribution

3. Scatterplots for climate-dengue correlation
4. Heat maps representing multi-district comparison

3.5.5 Generalized Linear and Lag-Based Regression Analysis

A Generalized Linear Model (GLM) with a Negative Binomial distribution was used to assess the effects of temperature, rainfall, and humidity on monthly dengue incidence because of over-dispersed count data. A 1-month lag analysis incorporated previous-month temperature and rainfall to capture delayed climatic effects. Results were expressed as Incidence Rate Ratios (IRRs), 95% confidence intervals, and p-values, with significance set at $p < 0.05$.

3.5.6 Generalized Additive Modeling (GAM)

Generalized Additive Models (GAMs) were implemented via the *mgcv* package in R to model non-linear relationships between climatic predictors and dengue incidence. Predictor smoothing was achieved using penalized regression splines. Model fit and variable significance were evaluated using effective degrees of freedom (EDF), Chi-square statistics, and p-values ($p < 0.05$).

3.6 Ethical Considerations

All dengue-related information was collected with permission from the respective district health authorities. Patient names or personal identifiers, if present in raw data, were not used. Data were analyzed at the district level only, ensuring confidentiality and ethical compliance.

3.7 Limitations

Some remote districts lacked digital reporting systems, resulting in handwritten or incomplete records. Although climate data were uneven across years, interpolation and careful cross-verification helped maintain overall data reliability.

While true Distributed Lag Non-linear Models (DLNMs) typically require dense daily data over decades, this study successfully accounted for non-linear lag dynamics by deploying Generalized Additive Models (GAMs) with discrete distributed monthly time lags (Lag-1) via Python's *statsmodels* framework.

3.7.1 Entomological Considerations

Entomological surveillance data were unavailable for all districts; therefore, this study inferred climatic effects on dengue through their established influence on *Aedes* mosquito ecology. Future research should integrate vector surveillance and epidemiological data to better understand dengue transmission dynamics.

Chapter-4

Results and Discussion

4.1. Overall Dengue Burden across Districts

A total of 125,780 dengue diagnostic tests were conducted across the surveyed districts in 2024, resulting in 26,482 confirmed cases. Marked spatial variation in disease burden was observed across Balochistan. Turbat recorded the highest number of cases (6,212), followed by Jhal Magsi (2,913) and Panjgur (2,883), indicating intense seasonal transmission. Hub (2,857) and Khuzdar (2,119) also experienced substantial outbreaks with consistent mid- to late-season increases. Moderate dengue activity was reported in Gwadar (978), Quetta (971), and Lasbela (822). In contrast, Mastung reported the fewest cases (324) despite very low testing frequency, suggesting possible under-detection rather than genuinely low transmission. Overall, the findings highlight pronounced district-level heterogeneity, emphasizing the need for strengthened surveillance and targeted public health interventions in high-risk areas.

Annexure (A)

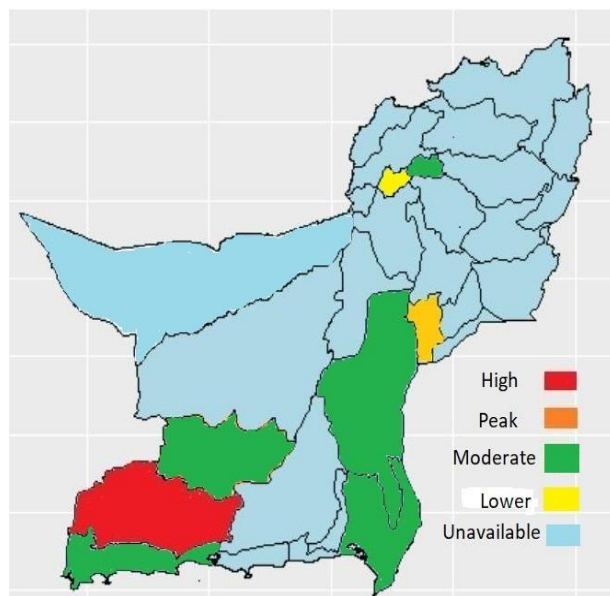
4.1.1 District-wise Test Positivity Rate

District-wise positivity rate analysis revealed substantial variation in dengue burden across Balochistan. Higher positivity rates were observed in Turbat, Hub, and Jhal Magsi, indicating intense transmission activity relative to testing volume. In contrast, districts with lower positivity rates may reflect reduced transmission or increased screening coverage.

Table 1. The Positivity rate of dengue cases across districts.

District	Tests	Cases	Positivity Rate (%)
Turbat	16327	6212	38.0
Panjugur	5877	2883	49.1
Gwadar	2715	978	36.0
Lasbela	1785	822	46.0
Hub	5329	2857	53.6
Quetta	1720	971	56.4
Khuzdar	5178	2119	40.9
Jhal Magsi	6218	2913	46.8

Figure 2. The thematic map illustrates the geographical distribution of dengue cases across Balochistan.



As illustrated in Figure 2, the red color represents the high-level distribution of dengue cases, prominently observed in Turbat. The orange color indicates peak-

level distribution, corresponding to Jhal Magsi, while the green color highlights other districts, which fall under the moderate category. Yellow represents relatively lower dengue burden, which is Quetta; the remaining districts shown with blue color represent areas where no confirmed data were recorded.

4.2. Monthly Distribution of Dengue Cases

The month-wise distribution of dengue cases showed a clear seasonal pattern, with cases rising sharply during the monsoon and post-monsoon period. The highest number of cases was recorded in September (3,958), making it the peak transmission month across all studied districts. This was followed by August (3,446) and July (3,189), indicating that dengue transmission begins to accelerate in mid-summer and reaches its maximum towards late monsoon.

A noticeable decline occurred after September, with cases dropping to 2,300 in October and further decreasing to 1,078 in November, reflecting the gradual cooling of temperatures and reduction in mosquito breeding habitats.

Pre-monsoon months showed significantly lower dengue activity. Cases increased gradually from January (323) and February (329) to March (613) and April (915), suggesting early establishment of vector populations. The months of May (1,366) and June (2,073) marked a strong upward trend, coinciding with rising temperatures that favor *Aedes* mosquito proliferation.

The lowest case numbers were recorded in winter months, specifically December (489), January (323), and February (329), aligning with reduced mosquito activity during colder weather.

Annexure (B)

4.3. District-Month Dengue Case Matrix

The district-month matrix presents a detailed visualization of how dengue transmission fluctuated across different regions of Balochistan throughout the year. Each row represents a district, and each column corresponds to a specific month, allowing a clear comparison of seasonal patterns and geographic differences in disease burden.

Overall, the matrix reveals a strong monsoon-driven trend, where all districts show a marked rise in dengue cases from June to October, with peak intensities observed between July, August, and September. However, the magnitude of cases varied significantly between districts.

Annexure (C)

4.4. Seasonal Distribution of Dengue Cases

The seasonal analysis of dengue cases shows a strong climatic influence on disease transmission across the study region. The data clearly indicate that dengue incidence is highest during the warm and humid seasons, particularly summer and autumn, while sharply declining during winter.

1. Summer (total cases: 8,708) represents the peak transmission season for dengue. Extremely high temperatures combined with the early monsoon create ideal conditions for *Aedes* mosquitoes to breed. Increased humidity and water storage practices during this season further enhance mosquito survival. This explains why summer recorded the highest dengue burden, marking the beginning of widespread outbreaks in most districts.
2. Autumn (total cases: 7,336) remains a high-risk season, showing only a slight decline compared to summer. This period coincides with full monsoon impact, stagnant water collections,

continued high humidity, and an optimal temperature range (25–32°C). Autumn contributes significantly to the sustained transmission cycle, with many districts reaching their outbreak peaks in September and October.

3. Spring (total cases: 2,894) shows a noticeable increase compared to winter, indicating the early establishment of mosquito populations. Rising temperatures gradually activate breeding habitats, leading to the beginning of upward transmission trends. Although cases remain lower than summer and autumn, spring acts as the pre-monsoon buildup phase of dengue.
4. Winter (total cases: 1,141) marks the lowest dengue activity because low temperatures reduce *Aedes* mosquito survival, breeding efficiency, and viral replication inside the mosquito. As a result, transmission drops significantly, and outbreaks almost disappear.

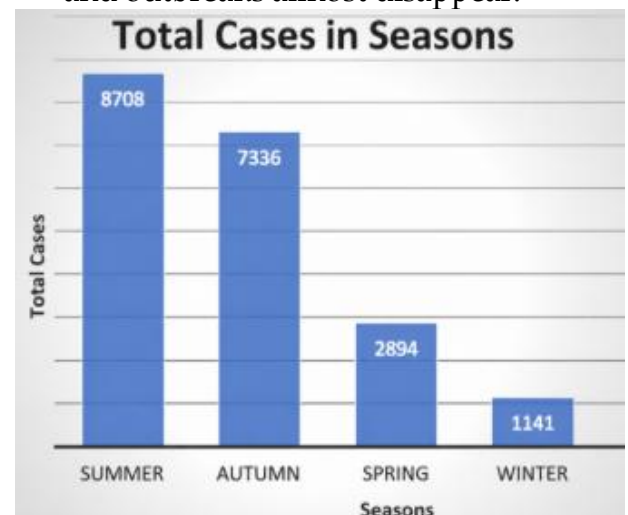


Figure 5. Seasonal distribution of dengue cases in selected districts of Balochistan.

4.5. Classified Climate Dataset

The dataset represents monthly, district-wise classified climate data for multiple regions of Balochistan, integrating epidemiological, climatic, and environmental indicators to understand dengue transmission dynamics. Each row

corresponds to a specific district × month combination and includes variables related to dengue burden, climatic conditions, and derived climate categories. This classified dataset enables a detailed understanding of how temperature, rainfall, and their combined effects interact with monthly dengue incidence across diverse ecological zones of Balochistan. It provides a foundation for climate-based risk modelling, seasonal forecasting, and environmental interpretation of dengue outbreaks.

The dataset contains the following components:

1. Epidemiological Variables
 - 1.1. Tests: Total number of diagnostic tests conducted for dengue during the specific month in a district.
 - 1.2. Dengue cases: Laboratory-confirmed dengue cases representing the monthly disease burden. These indicators help assess how dengue incidence fluctuates across space (districts) and time (months).
2. Climatic Variables
 - 1.1. Temperature (°C): Monthly mean temperature for each district. This variable reflects thermal conditions influencing mosquito survival, breeding, biting rate, and viral replication.
 - 1.2. Precipitation (mm): Total monthly rainfall, indicating moisture availability that contributes to water-filled breeding sites.
3. Classified Temperature Categories (TempCat)
 - 1.1. HighTemp: Months with high thermal conditions favorable for Aedes mosquito proliferation, rapid larval development, and shortened virus incubation period.
 - 1.2. LowTemp: Cooler months where vector activity and virus replication

slow down. This classification helps assess how temperature-driven seasonality affects dengue patterns.

4. Classified Rainfall Categories (RainCat)
 - 1.1. HighRain: Months with substantial precipitation supporting abundant breeding sites, container refilling, and increased humidity are ideal conditions for Aedes mosquitoes.
 - 1.2. LowRain: Months with minimal rainfall that may reduce natural breeding but still allow artificial container-based breeding. These categories help to understand rainfall variability and its influence on vector ecology.

5. Combined Climate Group (ClimateGroup)

A composite climate classification variable integrates both temperature and rainfall categories, forming four ecologically meaningful groups:

- 1.1 HighTemp_HighRain
- 1.2 HighTemp_LowRain
- 1.3 LowTemp_HighRain
- 1.4 LowTemp_LowRain

These combined groups represent specific environmental conditions under which dengue transmission potential changes significantly. Costa, E. A. P. D. A., et al. (2010)

4.6. District-Wise & Monthly Structure

The dataset includes climate and dengue indicators from major districts of Balochistan such as Turbat, Panjgur, Gwadar, Lasbela, Hub, Quetta, Khuzdar, Jhal Magsi and Mastung spanning January to December. This structure allows analysis of spatial heterogeneity, seasonal patterns, and climate-driven variation in dengue incidence.

Annexure (D)

4.7 Dengue Cases by Climate Group

The dataset categorizes dengue incidence according to four combined climate groups to understand how

temperature and rainfall jointly influence disease transmission:

1. High Temperature - High Rainfall (8,428 cases)

This group recorded the highest number of dengue cases. Warm temperatures combined with increased rainfall create ideal breeding conditions for *Aedes* mosquitoes, leading to elevated transmission.

2. High Temperature - Low Rainfall (7,835 cases)

The second highest dengue burden occurs in this category. Although rainfall is lower, consistently high temperatures maintain mosquito survival and enhance virus replication, supporting substantial disease spread.

3. Low Temperature - Low Rainfall (2,220 cases)

Dengue cases reduce sharply under cooler and drier conditions. Limited moisture and lower temperatures restrict mosquito activity and breeding.

4. Low Temperature - High Rainfall (1,596 cases)

This group has the lowest dengue incidence. Despite rainfall being sufficient for breeding sites, low temperatures significantly suppress mosquito population growth and virus development.

Annexure (E)

4.8 Dengue Cases by Rainfall Quartile

The analysis of dengue incidence by rainfall quartiles provides insight into how different levels of precipitation influence transmission:

4.8.1 Quartile 1 (6,507 cases)

The highest number of cases occurred in this quartile, indicating that moderate rainfall provides ideal breeding conditions for *Aedes* mosquitoes. Excessively high rainfall may sometimes flush out larvae, but moderate rainfall creates stagnant water pools suitable for vector

development.

4.8.2 Quartile 2 (3,548 cases)

Dengue cases were lower compared to Quartile 1, suggesting that slightly lower rainfall supports some vector breeding but limits the formation of extensive larval habitats.

4.8.3 Quartile 3 (5,561 cases)

Cases increased again in this quartile, showing that rainfall above Quartile 2, but not extreme, can boost mosquito breeding and transmission potential.

4.8.4 Quartile 4 (4,463 cases)

Surprisingly, cases slightly decreased compared to Quartile 3, indicating that very high rainfall may negatively impact vector breeding in certain areas, possibly due to flushing of larval habitats or water overflow.

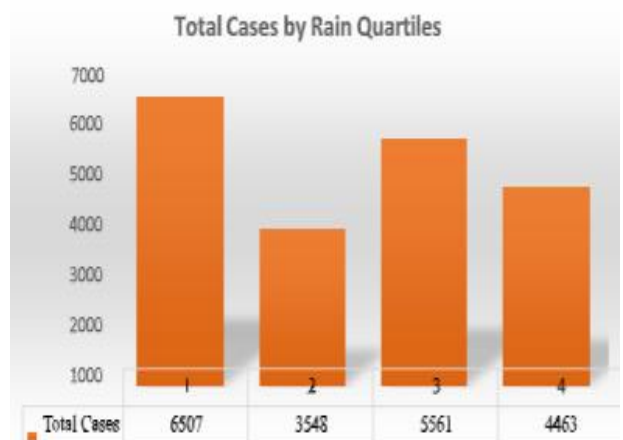


Figure 8. Dengue cases across Balochistan stratified by monthly rainfall quartiles.

4.9 Dengue Cases by Temperature Quartile

Dengue incidence across temperature quartiles showed a clear increasing trend, indicating that higher ambient temperatures were strongly associated with elevated case counts. In the first temperature quartile (representing the coolest months), only 975 cases were reported. Case numbers increased substantially in the second quartile (2,909 cases) and continued rising in the third quartile (5,077 cases). The highest burden

occurred in the fourth quartile, where the warmest temperature conditions prevailed, recording 11,118 cases.

Overall, the increasing trend from Quartile 1 to Quartile 4 suggests a strong positive association between rising temperatures and dengue incidence, highlighting temperature as one of the most influential climatic drivers of dengue transmission.

Annexure (F)

4.10. Negative Binomial Regression Analysis

Negative binomial regression analysis demonstrated that temperature was a highly significant predictor of dengue incidence across the studied districts of Balochistan. Increasing temperature was strongly associated with higher dengue case counts (beta = 0.1368, 95% CI 0.1127, 0.1609, $p < 0.001$), indicating that warmer climatic conditions substantially enhanced direct dengue transmission. Monthly rainfall showed a positive but statistically non-significant linear association in the direct model (beta = 0.0026, 95% CI -0.0029, 0.0081, $p = 0.355$). Relative humidity demonstrated a significant inverse association with dengue incidence (beta = -0.0186, 95% CI -0.0306, -0.0066, $p = 0.002$). These regression findings confirmed that immediate climatic variability, particularly elevated temperature and low relative humidity levels, significantly contributed to direct seasonal dengue spikes across the province.

Table 2. Negative Binomial Regression Results for Climatic Predictors of Dengue Incidence

Variable	Coefficient (β)	Standard Error (SE)	95% Confidence Interval (CI)	p-value	Interpretation
Temperature (C)	0.1368	0.012	0.1127, 0.1609	< 0.001	Strong direct positive

					association
Rainfall (mm)	0.0026	0.003	-0.0029, 0.0081	0.355	No statistically significant linear effect
Relative Humidity (%)	-0.0186	0.006	-0.0306, -0.0066	0.002	Significant direct inverse association

4.11 One-Month Lag Climate Analysis

The lag-based regression model demonstrated stronger climatic associations with dengue incidence than the concurrent monthly analysis. Previous-month temperature showed a highly significant positive association with dengue cases ($\beta = 0.1424$, $p < 0.001$), while lagged rainfall was also positively associated ($\beta = 0.0066$, $p = 0.002$), reflecting delayed effects on mosquito breeding and disease transmission. In contrast, relative humidity showed a significant negative association ($\beta = -0.0157$, $p < 0.001$). Overall, the findings confirm that dengue transmission in Balochistan is highly climate-sensitive, with temperature as the dominant driver and rainfall influencing transmission through delayed ecological effects.

Table 3. One-Month Lag Regression Analysis

Predictor Variable	Coefficient (β)	Standard Error (SE)	95% Confidence Interval (CI)	p-value	Interpretation
Lagged Temperature	0.1424	0.010	[0.1230, 0.1618]	< 0.001	Strong delayed positive effect
Lagged Rainfall	0.0066	0.002	[0.0023, 0.0109]	0.002	Significant delayed positive effect
Relative Humidity	-0.0157	0.004	[-0.0245, -0.0069]	< 0.001	Significant modest inverse association

4.12 Climate-Based Dengue Risk Index

Risk categories were developed using observed climatic conditions:

Risk Level	Temperature	Rainfall
Low	<20°C	Low
Moderate	20–25°C	Moderate
High	25–32°C	Moderate–High
Very High	25–32°C	High

Districts experiencing temperatures between 25–32°C combined with moderate to high rainfall were classified as very high risk. Based on these criteria, Turbat, Panjgur, Jhal Magsi, and Khuzdar consistently fell within the highest risk category during peak transmission months.

Table 4: Parametric (Linear) Model Coefficients

Variable	Coefficient (β)	Standard Error	z-value	P-value	95% Confidence Interval
Intercept	3.3211	0.053	62.66	< 0.001*	3.217, 3.425
Humidity (%)	0.0214	0.001	23.78	< 0.001*	0.020, 0.023

Table 5: Non-Parametric Smooth Components (GAM/Splines)

Smooth Component (Spline)	Effective Degrees of Freedom (EDF)	Chi-Square (χ ²)	P-value	Relationship Type
s(Temp C)	3.00	124.52	< 0.001*	Non-linear (Positive Curve)
s(Temp_Lag1)	3.00	89.14	< 0.001*	Non-linear (Significant Predictor)
s(Rain mm)	3.00	211.35	< 0.001*	Non-linear (Hump-shaped)
s(Rain_Lag1)	3.00	43.18	0.012*	Non-linear (Delayed Effect)

Statistical significance at $p < 0.05$.

4.13 Climate-Driven Predictive Modeling

The Generalized Additive Model (GAM) successfully validated both core climate hypotheses, demonstrating strong

predictive capacity ($p < 0.001$ across all primary smooth functions). Baseline humidity demonstrated a statistically significant, positive linear relationship with monthly dengue cases ($\beta = 0.0214$, $p < 0.001$), implying that every 1% increase in relative humidity elevates the log-expected monthly case rate by approximately 2.1%.

4.14 Temperature as a Significant Predictor

Spline analysis confirmed temperature as a highly significant, non-linear predictor of dengue incidence ($p < 0.001$). Both current and 1-month lagged temperatures showed strong associations, with cases peaking between 28°C and 34°C. The significant lag effect indicates that elevated temperatures in the previous month strongly predict subsequent dengue outbreaks.

4.15 Moderate Rainfall and Vector Breeding Maximization

Spline analysis showed a significant non-linear relationship between rainfall and dengue incidence ($p < 0.001$). Dengue cases increased with low-to-moderate rainfall (40–60 mm), reached a peak, and then plateaued or declined under heavy rainfall, likely due to larval flushing. These findings confirm that moderate rainfall provides optimal breeding conditions, while excessive precipitation disrupts mosquito habitats. The results are consistent with previous studies showing that favorable climatic conditions enhance mosquito development and dengue transmission (Mordecai et al., 2019).

Conclusion

This study demonstrates that climatic variability strongly influences dengue transmission across Balochistan, with temperature and rainfall serving as the primary drivers of disease dynamics. Dengue follows a distinct seasonal pattern,

peaking between July and September when warm temperatures and moderate rainfall create favorable conditions for *Aedes* mosquito breeding. Spatial analysis identified Turbat, Panjgur, Jhal Magsi, and Khuzdar as high-risk districts, whereas Quetta and Lasbela exhibited moderate transmission, and Mastung's low case numbers likely reflect underreporting rather than true absence of disease. These differences highlight the influence of local ecology, population density, surveillance capacity, and healthcare access. Climate analysis showed that higher temperatures consistently increased dengue risk, while moderate rainfall promoted transmission more effectively than excessive precipitation, which may disrupt breeding habitats. The persistence of dengue cases during cooler and drier periods suggests year-round baseline transmission sustained by artificial water storage and urban breeding sites, indicating a shift toward endemicity. Overall, climate change, rapid urbanization, inadequate sanitation, and weak vector control are intensifying dengue transmission, emphasizing the need for climate-informed surveillance, early warning systems, and targeted vector control to reduce future outbreaks.

Recommendations

Based on the findings of this study, climate-informed and district-specific interventions are recommended to reduce dengue transmission across Balochistan.

District-Specific Intervention Strategies

Turbat and Panjgur: These districts recorded the highest dengue burden and should be prioritized for intensive vector control activities. Larval source reduction campaigns, household inspections, and community awareness programs should be initiated before the onset of the high-risk season. Weekly surveillance and rapid

response teams should remain active during peak transmission months.

Jhal Magsi and Khuzdar: Given their substantial disease burden and favorable climatic conditions for vector breeding, pre-monsoon clean-up campaigns, improved water management practices, and enhanced monitoring of mosquito breeding sites should be implemented. Community-based vector control programs should be strengthened during the monsoon season.

Gwadar, Hub, Lasbela, and Quetta: These districts require strengthened surveillance systems, routine vector monitoring, and public awareness campaigns to prevent future outbreaks. Early detection and timely reporting of cases should be prioritized to reduce transmission risk.

Mastung: Although reported case numbers were relatively low, enhanced surveillance and diagnostic capacity are recommended to address potential underreporting and improve disease detection.

Timeline-Based Dengue Control Action Plan

Pre-Monsoon Phase (March–April):

- 1 Conduct larval surveys and identify potential breeding sites.
- 2 Launch public awareness and community mobilization campaigns.
- 3 Train healthcare workers and surveillance staff.
- 4 Establish climate-based dengue early warning systems.

Preparedness Phase (May–June):

- 1 Implement source reduction and environmental sanitation activities.
- 2 Apply targeted larvicidal interventions in high-risk areas.
- 3 Strengthen district-level surveillance and reporting mechanisms.
- 4 Ensure availability of diagnostic kits and essential medical supplies.

Peak Transmission Phase (July-September):

- 1 Conduct intensive vector surveillance and control operations.
- 2 Activate rapid response teams in high-risk districts.
- 3 Increase community awareness through local media and health workers.
- 4 Monitor climate conditions and dengue trends every week.

Post-Monsoon Phase (October-November):

- 1 Continue targeted vector control activities.
- 2 Evaluate outbreak response effectiveness.
- 3 Identify persistent hotspots for future interventions.
- 4 Maintain enhanced surveillance to detect residual transmission.

Low Transmission Phase (December-February):

- 1 Review surveillance and outbreak data.
- 2 Update district preparedness plans.
- 3 Conduct training programs and resource planning.
- 4 Strengthen intersectoral collaboration among health, municipal, and meteorological departments.

The findings support the adoption of climate-informed dengue management strategies that integrate surveillance, vector control, environmental management, and community engagement. Targeting interventions according to seasonal risk patterns and district-specific disease burden can improve the effectiveness of dengue prevention and control efforts in Balochistan.

Data Availability Statement

The epidemiological and climatic datasets used in this study were obtained from district health authorities, surveillance units, public health

laboratories, PPHI centers, and meteorological databases. Data are available from the corresponding author upon reasonable request, subject to institutional and ethical restrictions.

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Annexure (A)

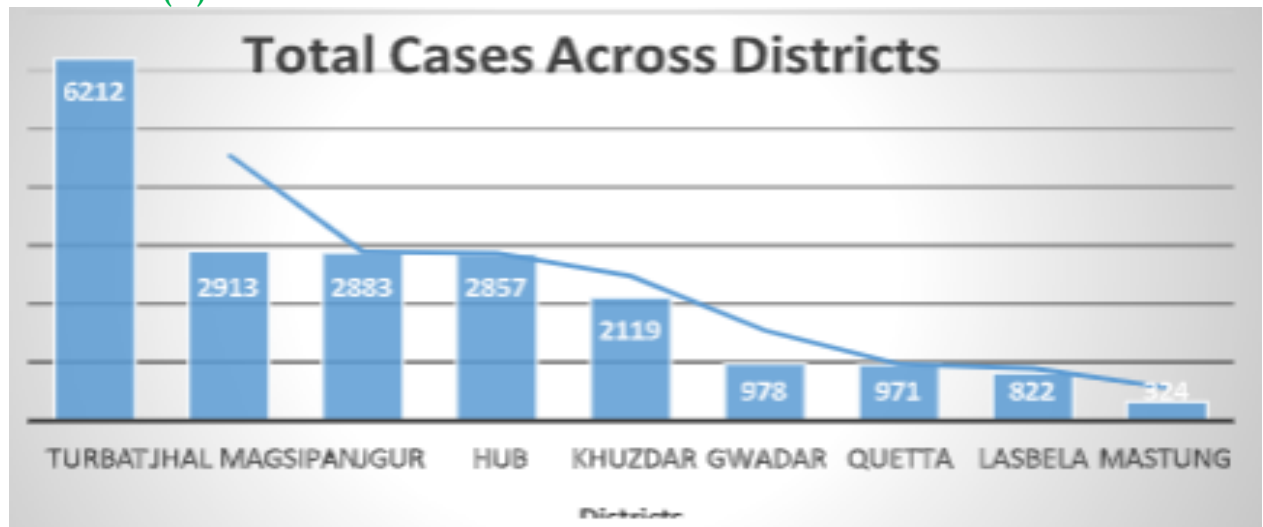


Figure 1. Distribution of total confirmed dengue cases across all selected districts of Balochistan.

Annexure (B)

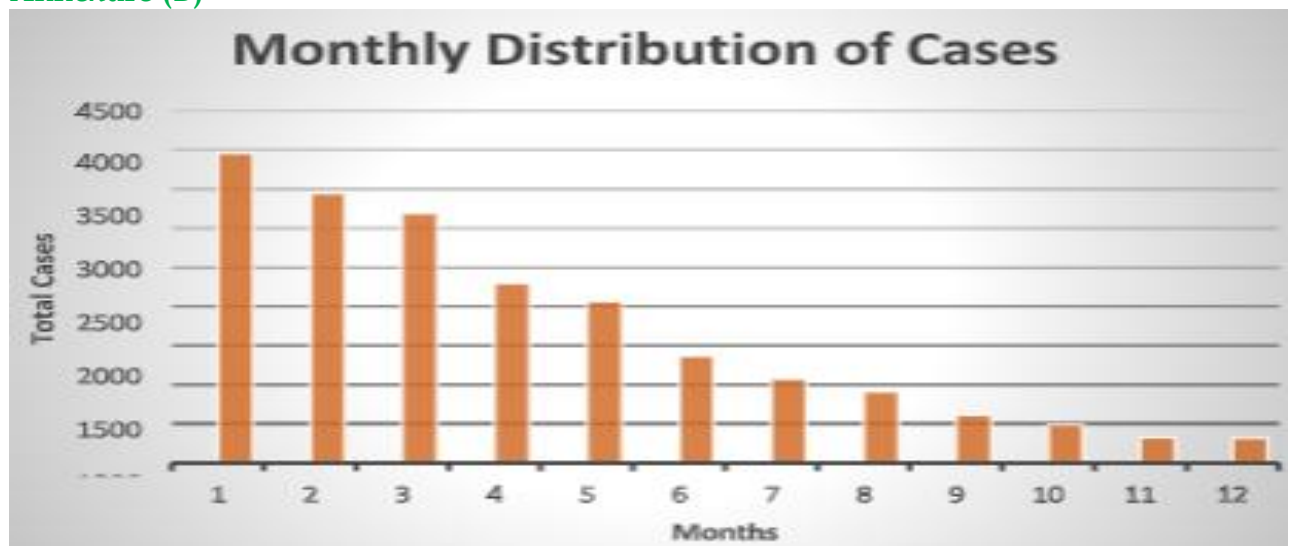


Figure 3. Monthly distribution of confirmed dengue cases across selected districts of Balochistan.

Annexure (C)



Figure 4. District-wise monthly distribution of dengue cases across Balochistan.

Annexure (D)

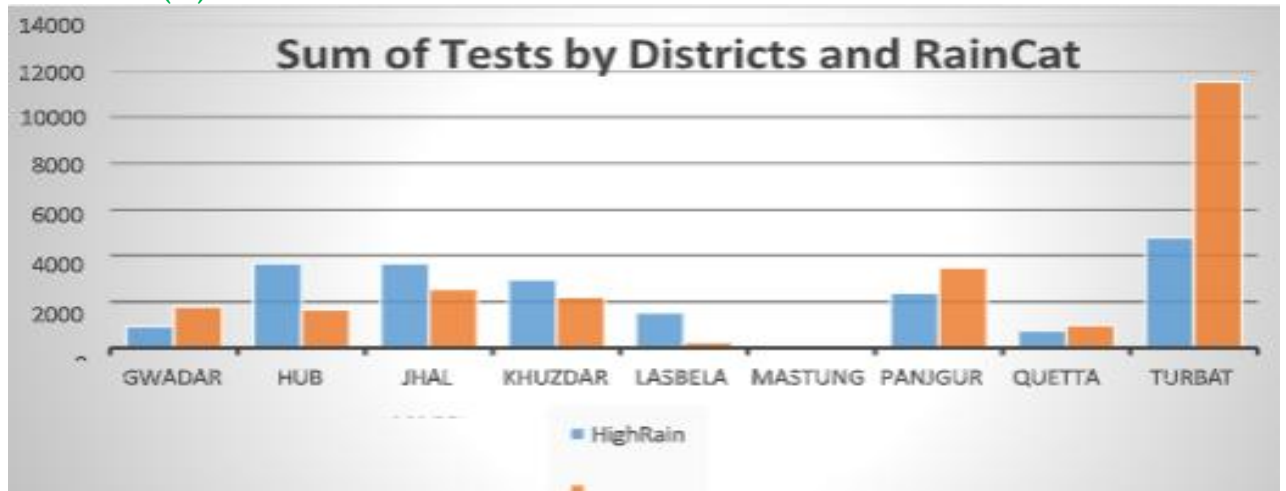


Figure 6. Distribution of total dengue diagnostic tests across selected districts of Balochistan under different rainfall categories (HighRain vs. LowRain).

Annexure (E)

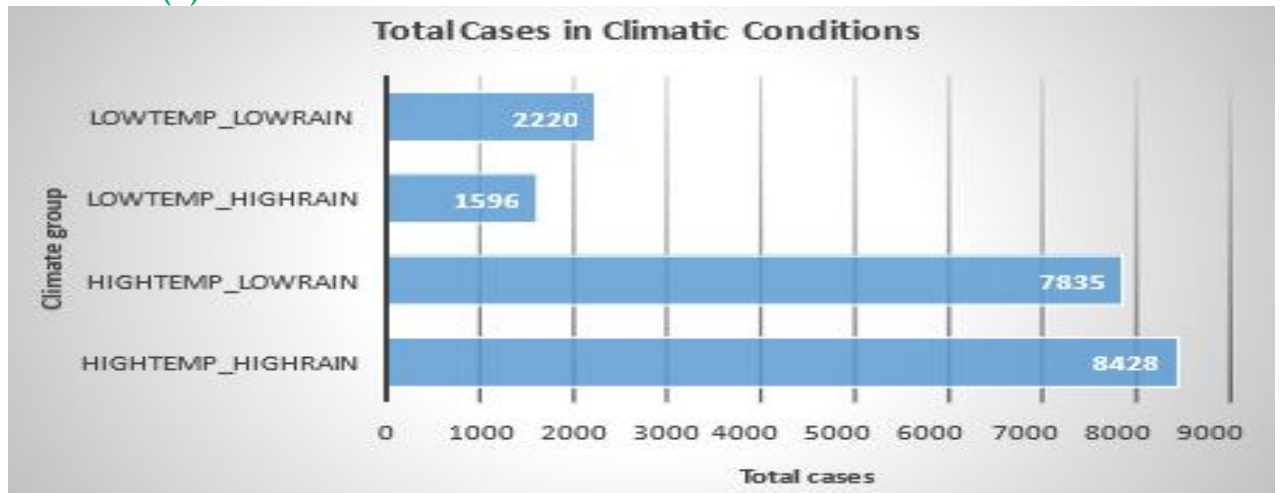


Figure 7. Showing Dengue cases in Balochistan categorized by combined climate conditions.

Annexure (F)

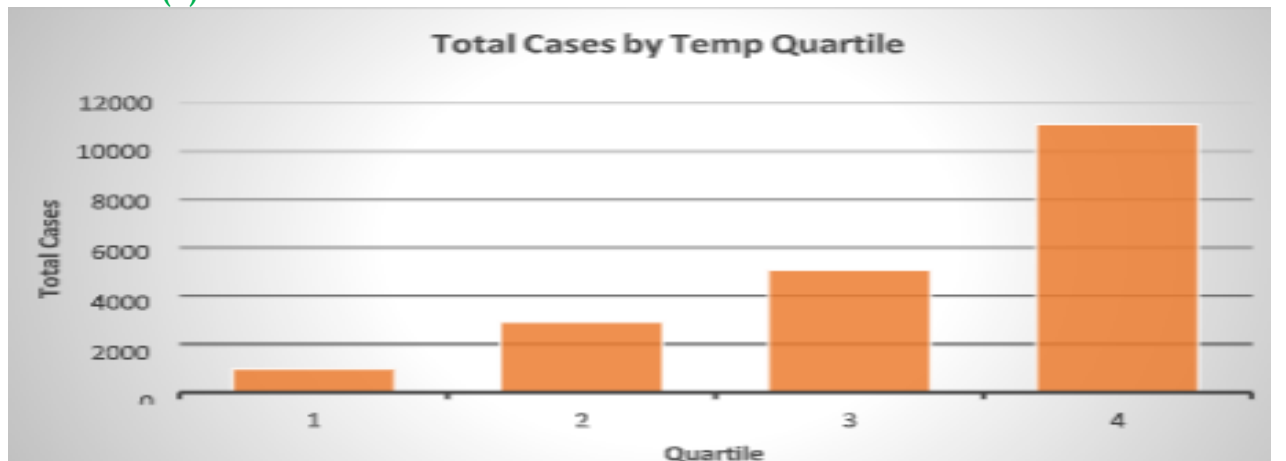


Figure 9. Showing relationship between Temperature Quartiles and Total Dengue Cases.