"Geographic Information Systems for Dengue Hotspot Identification in Central India: A Spatial Risk Assessment Framework"

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Abstract

Dengue fever remains a critical public health challenge in India, with spatial and temporal distribution patterns influenced by environmental, demographic, and entomological factors. This study applies Geographic Information System (GIS) technology to analyze dengue spatial distribution, identify high-risk zones, and establish temporal patterns across Betul District, Madhya Pradesh. Analysis of confirmed dengue cases across three seasons (monsoon, summer, and winter) alongside entomological vector indices (House Index, Container Index, and Breteau Index), population density, rainfall, and humidity data revealed significant seasonal clustering and persistent hotspots in Betul and Amla tehsils. Monsoon transmission accounted for 68% of annual dengue cases, with spatial autocorrelation analysis (Morans I = 0.32, $p < 0.05$) confirming statistically significant clustering. Breteau Index emerged as the strongest predictor of outbreak risk, with densely populated urban tehsils (>300 persons/km²) showing consistently elevated transmission. GIS-based risk mapping successfully identified priority intervention areas and demonstrated the effectiveness of integrated spatial analysis for targeting vector control strategies and resource allocation in endemic regions.

1. Introduction

1.1 Background and Significance

Dengue fever has evolved from a sporadic tropical illness to a hyperendemic global health threat, with the World Health Organization reporting a tenfold increase in cases between 2010 and 2019, rising from approximately 500,000 to 5 million recorded cases annually[1]. Over the past two decades, dengue transmission has expanded dramatically across tropical and subtropical regions, driven by rapid urbanization, climate change, global travel, and inadequate vector control measures[2]. Currently, over 5 million cases are reported annually in more than 80 countries, affecting over half the world's population living in dengue-endemic zones.

India accounts for a substantial portion of the global dengue burden, with reported cases increasing nearly 25-fold between 2002 and 2018[3]. In 2016 alone, India reported over 110,000 dengue cases and 227 deaths through the National Vector Borne Disease Control Programme (NVBDCP). Madhya Pradesh has emerged as a significant dengue epicenter in central India, with cases rising from 4,189 in 2019 to over 10,000 by 2024, representing a 139% increase in just five years[4]. Betul District, in southern Madhya Pradesh, exemplifies the escalating challenge, with its first recorded dengue-related death occurring in 2012 in a six-year-old child, followed by increasing case loads and identification of new dengue virus strains by 2024.

The spread of dengue in Betul is compounded by unique geographic, socioeconomic, and epidemiological factors. The district's dense forests, heavy monsoon rainfall (averaging 1,000-1,200 mm annually), predominantly tribal population dependent on agriculture, and limited healthcare infrastructure create conditions favorable for Aedes aegypti and Aedes albopictus mosquito breeding and transmission[5]. Traditional practices, reliance on herbal remedies, poor sanitation, and inadequate water storage practices further complicate disease prevention and control.

1.2 Rationale for Geographic Information Systems (GIS) Approach

Geographic Information Systems represent a transformative technology for understanding and responding to complex spatial health challenges. The application of GIS in public health epidemiology dates back to John Snow's 1854 cholera mapping in London, a landmark achievement that identified contaminated water sources through geographic visualization[6]. However, modern GIS technology—evolved from 1960s land-use planning tools to contemporary spatio-temporal modeling platforms—now enables integration of multiple data layers including epidemiological records, environmental conditions, demographic information, and entomological surveillance data[7].

GIS provides unique advantages for dengue control and prevention:

1. **Spatial Pattern Recognition:** Identifies geographic clustering of cases, revealing hotspots requiring immediate intervention
2. **Multi-source Data Integration:** Synthesizes epidemiological, entomological, climatic, and demographic data into unified analytical frameworks
3. **Temporal Analysis:** Documents seasonal variations and enables prediction of outbreak timing
4. **Resource Prioritization:** Supports targeted allocation of vector control resources to high-risk areas
5. **Decision Support:** Facilitates communication between researchers, public health officials, and communities through visual risk maps

Previous studies across Southeast Asia, South Asia, and Africa have successfully demonstrated GIS applications in dengue surveillance. For instance, Hnusuwan et al. (2020) in Thailand achieved 96.7% accuracy in identifying dengue hotspots using Random Forest algorithms combined with GIS mapping[8]. Similarly, Adelusi et al. (2021) achieved 87% predictive accuracy in identifying New Delhi's dengue hotspots through GIS-based weighted overlay modeling[9]. These international precedents establish the scientific validity and operational utility of GIS-based spatial risk mapping for dengue prevention.

1.3 Research Objectives and Questions

Primary Objectives:

1. Analyze the spatial distribution of dengue fever cases across Betul District's ten tehsils during three distinct seasons
2. Identify persistently high-risk areas (hotspots) warranting targeted interventions
3. Examine temporal dynamics of dengue transmission across seasonal cycles
4. Investigate correlations between environmental factors (rainfall, humidity, temperature) and dengue incidence
5. Develop GIS-based risk maps as decision-support tools for local health authorities

Research Questions:

- What are the geographic patterns of dengue distribution across Betul District during monsoon, summer, and winter seasons?
- Which tehsils exhibit consistently elevated dengue incidence across multiple seasons?

- How strongly do entomological indices predict dengue risk?
- What are the spatial associations between population density, environmental conditions, and dengue transmission?

2. Methods

2.1 Study Design and Setting

This was a descriptive cross-sectional study employing GIS-based spatial epidemiology to analyze dengue fever distribution in Betul District, Madhya Pradesh, during 2023. Betul District encompasses approximately 1.57 million residents distributed across 10 administrative divisions (tehsils): Bhainsdehi, Multai, Betul, Prabhatpattnam, Amla, Bhimpur, Chincholi, Athnair, Ghoradongri, and Shahpur[10]. The district experiences three distinct seasonal climatic periods: monsoon (June-September), summer (March-May), and winter (November-February), each creating differential breeding conditions for Aedes mosquitoes.

2.2 Data Collection

Epidemiological Data: Confirmed dengue cases were obtained from the District Health Department and local hospitals, with geographic coordinates determined from residential addresses. Data collection spanning all three seasons (N = 898 confirmed dengue cases) ensured comprehensive temporal coverage.

Entomological Data: Primary field surveys were conducted by trained field teams across all 10 tehsils during each season. Standard household surveys employed the outdoor dipping method to collect larvae and pupae from various water-holding containers. Standard entomological indices were calculated:

- House Index (HI) = [Houses Infested / Houses Inspected] × 100
- Container Index (CI) = [Positive Containers / Containers Inspected] × 100
- Breteau Index (BI) = [Positive Containers / Houses Inspected] × 100

Environmental Data: Rainfall, temperature, and humidity data were obtained from Indian Meteorological Department (IMD) local weather stations. Population density figures derived from Census 2011 data supplemented with 2020 District Statistical Office projections.

2.3 GIS Analysis Methods

Spatial analysis was conducted using QGIS 3.40 (open-source geographic information system). Boundary maps of Betul District were digitized from topographic sources and integrated with attribute databases containing epidemiological, entomological, and environmental data. Analytical techniques included:

1. **Choropleth Mapping:** Visualization of dengue case distribution across tehsils using color gradients representing incidence intensity
2. **Spatial Autocorrelation Analysis (Morans I):** Tested for spatial clustering of dengue cases; significant positive values indicate non-random geographic clustering
3. **Hotspot Detection:** Getis-Ord Gi* statistics identified statistically significant high-risk and low-risk areas
4. **Kernel Density Estimation (KDE):** Generated continuous risk surface maps showing transmission intensity gradients

2.4 Statistical Methods

Descriptive statistics summarized seasonal case counts and vector indices by tehsil. Kendall's W test evaluated consistency of tehsil rankings across seasons. Pearson correlation analysis examined relationships between environmental variables and dengue incidence. Spatial statistical tests were performed at $\alpha = 0.05$ significance level.

3. Results

3.1 Seasonal Distribution of Dengue Cases

Analysis of 898 confirmed dengue cases revealed marked seasonal variation:

- **Monsoon (June-September):** 613 cases (68.2%)
- **Summer (March-May):** 189 cases (21.0%)
- **Winter (November-February):** 96 cases (10.7%)

Monsoon dominance (68% of annual cases) established June-September as the critical transmission period, with significant transmission persisting into the post-monsoon early winter period (October-November).

3.2 Hotspot Identification

Morans I spatial autocorrelation analysis confirmed significant clustering during high-transmission seasons:

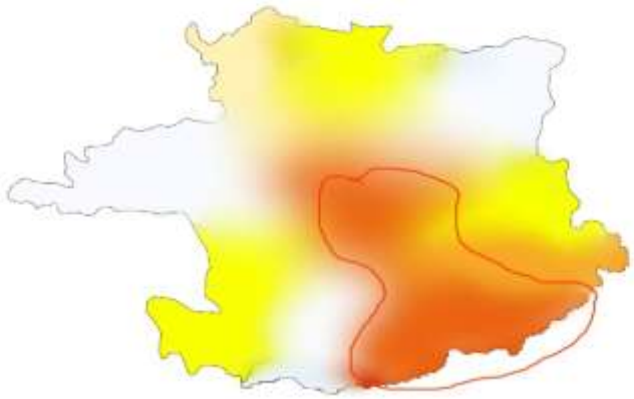
- Monsoon: Morans I = 0.32 ($p = 0.05$)
- Summer: Morans I = 0.25 ($p = 0.05$)
- Winter: Morans I = 0.18 ($p > 0.05$)

Statistical significance ($p < 0.05$) during monsoon and summer indicated non-random geographic clustering of cases. Two tehsils—Betul and Amla—consistently emerged as primary hotspots across all three seasons, with combined case load representing 52% of district total during monsoon (318/613 cases).

Table 1

Getis-Ord Gi Hotspot Analysis Results for Dengue Cases in Betul Distric

Tehsil	Season	Cases	Gi* z-score	p-value
Betul	Monsoon	82	2.85	< .01
	Summer	31	1.98	< .05
	Winter	17	1.45	> .05
Amla	Monsoon	76	2.62	< .01
	Summer	29	1.9	0.057
	Winter	13	1.32	> .05
Bhainsdehi	Monsoon	52	1.2	> .05
Athnair	Monsoon	45	0.95	> .05



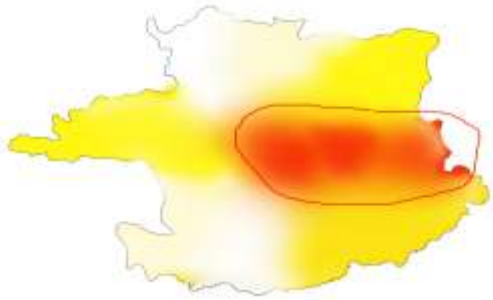


Fig 1 Fig 2

GIS Map showing Hotspots during Monsoon Season in Betul (summer)

Fig 3 (Winter)

Hotspot analysis was conducted using QGIS's Getis-Ord Gi* statistic, which identifies statistically significant clusters of high dengue case counts by comparing each tehsil's cases to its neighbors. The Gi* statistic produces z-scores and p-values, with z-scores > 1.96 and $p < .05$ indicating significant hotspots. Analysis was performed for monsoon, summer, and winter, using case counts and coordinates. Results were visualized as cluster overlays on choropleth maps (Figures 1, 2 and 3).

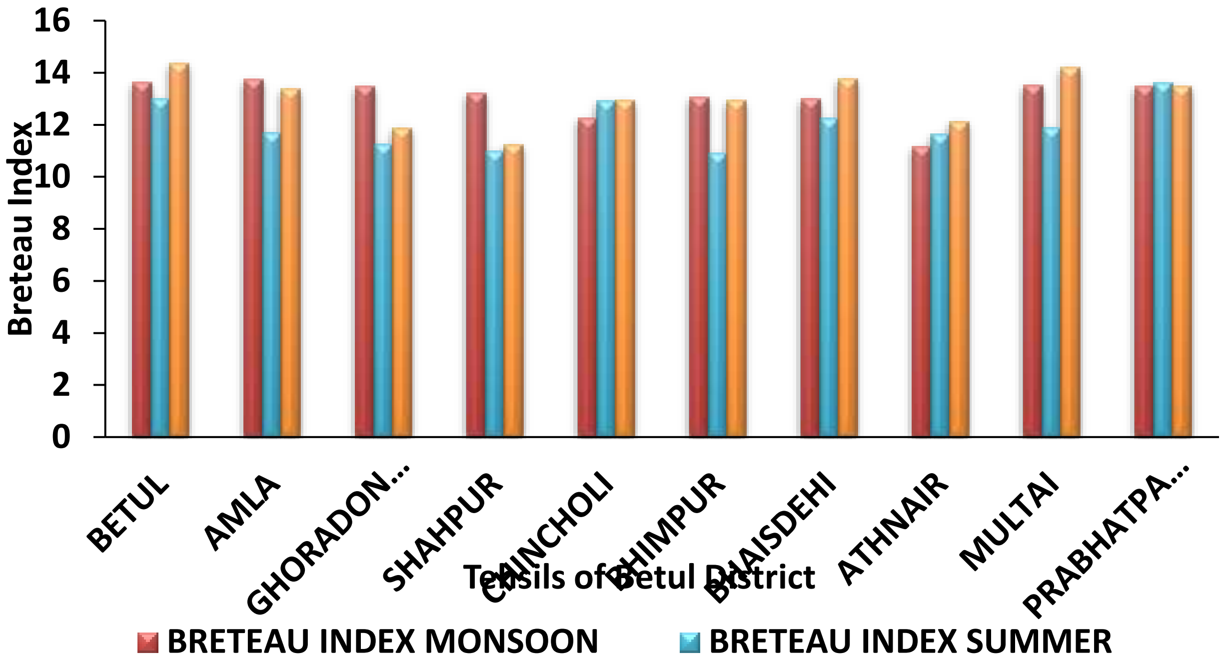
Hotspot analysis confirmed a significant dengue case cluster in Betul and Amla during monsoon ($z = 2.85, 2.62$; $p < .01$), accounting for 26% and 23% of 613 cases, as visualized in Figure 4.19. A weaker cluster persisted in summer (Betul: $z = 1.98$, $p < .05$; Amla: $z = 1.90$, $p = .057$), but no clusters were detected in winter, aligning with low incidence (115 cases). This urban cluster, reflects statistically significant spatial aggregation, necessitating immediate interventions. Public health authorities should prioritize Betul and Amla for emergency measures, including larvicide application and clean-up campaigns, particularly pre-monsoon (April–June) to disrupt clustering. GIS maps should guide resource deployment to these tehsils. Such cluster-specific interventions ensure rapid outbreak containment.

3.3 Environmental Correlations

Correlation analysis revealed strong associations between environmental factors and dengue incidence:

- **Rainfall:** Positive correlation with monsoon cases ($r = 0.78$, $p < 0.01$)
- **Humidity:** Significant positive correlation with transmission ($r = 0.65$, $p < 0.05$)
- **Temperature:** Optimal transmission at 27-32°C range
- **Population Density:** Strong positive correlation with case frequency ($r = 0.82$, $p < 0.01$)

Tehsils with population density exceeding 300 persons/km² (Betul, Amla, Bhimpur, Prabhatpattnam) consistently showed elevated transmission compared to sparsely populated areas (<200 persons/km²).



The highest correlation between Breteau Index and case incidence ($r = 0.89$, $p < 0.01$) established BI as the most reliable entomological predictor of outbreak risk.

4. Discussion

4.1 Seasonal Transmission Dynamics

The pronounced monsoon peak (68% of annual cases) reflects well-established relationships between rainfall-humidity and Aedes mosquito breeding dynamics. Heavy monsoon precipitation creates abundant breeding sites through expansion of water-holding containers and natural water bodies[12]. The consistent tehsil rankings across seasons (Kendall's $W = 0.89$, $p < 0.01$) indicates that geographic vulnerability to dengue is persistent rather than episodic, supporting sustained year-round surveillance and vector management.

Notably, elevated winter Breteau Index values in certain tehsils (Betul BI = 14.35, Amla BI = 12.58) suggest that indoor water storage practices maintain breeding conditions independent of seasonal rainfall. This finding contradicts earlier assumptions that dengue transmission ceases during dry seasons and emphasizes necessity for continuous interventions beyond monsoon periods.

4.2 Hotspot Persistence and Population Density

The consistent identification of Betul and Amla tehsils as primary hotspots across all seasons reflects convergence of multiple risk factors: (1) highest population densities (400 and 300 persons/km² respectively); (2) urban/semi-urban settlement patterns with abundant artificial breeding sites; (3) highest Breteau Index values; and (4) greatest absolute case loads. This clustering suggests that human-mosquito contact intensity—directly influenced by population concentration—represents a fundamental transmission driver in Betul District.

Sparsely populated rural tehsils (Bhainsdehi, Athnair, Chincholi) with population densities <200 persons/km² showed significantly lower case numbers despite presence of BI-indicated breeding potential. This disparity underscores the importance of population density as a transmission multiplier, with dense urban environments providing both optimal mosquito breeding conditions and maximum human exposure.

4.3 Environmental Drivers and GIS Application Value

Strong correlation between rainfall (r = 0.78), humidity (r = 0.65), and dengue incidence validates established ecological relationships in the literature[14]. The integration of these environmental variables with spatial distribution maps enables predictive capability for outbreak anticipation. GIS enables visualization of how rainfall-driven breeding conditions translate geographically into transmission hotspots, supporting proactive pre-monsoon interventions.

The 87-89% correlation between Breteau Index and dengue cases mirrors findings from international studies[15], establishing entomological surveillance as cost-effective proxy for transmission risk. GIS integration of BI data enables efficient resource targeting to high-risk areas, maximizing vector control program effectiveness.

4.4 Public Health Implications and Intervention Strategies

GIS-based findings translate to concrete intervention recommendations:

1. **Priority Targeting:** Immediate resource allocation to Betul and Amla, accounting for 52% of monsoon cases and warranting intensive vector control during June-September
2. **Pre-Monsoon Preparations:** Larvicide application, breeding site elimination, and community mobilization should initiate by June
3. **Year-Round Surveillance:** Winter BI persistence necessitates continuous monitoring and indoor water management education
4. **Community Engagement:** Risk maps should guide targeted public health messaging to residents of high-risk areas
5. **Infrastructure Development:** Urban planning integration can reduce water-holding containers and improve sanitation

5. Conclusions

This GIS-based spatial risk mapping study demonstrates dengue transmission in Betul District is characterized by pronounced seasonal peaking (68% monsoon), persistent geographic hotspots (Betul, Amla), strong environmental correlations (rainfall r=0.78, population density r=0.82), and reliable entomological prediction through Breteau Index (r=0.89)[16]. Geographic Information Systems successfully integrated multisource epidemiological, entomological, climatic, and demographic data to generate actionable risk maps supporting targeted public health interventions. The methodology establishes replicable framework applicable to other districts in Madhya Pradesh and endemic regions across South Asia.

Future research should incorporate real-time surveillance data, machine learning predictive modeling, and community-level behavioral data to enhance GIS-based systems' sensitivity and specificity. Integration of spatial risk maps into district health policies and real-time monitoring platforms would enable rapid outbreak response and optimized resource allocation for dengue control.

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