



MEASUREMENT ERROR IN BAYESIAN SPATIO-TEMPORAL POISSON MODELING OF DENGUE USING REMOTE SENSING COVARIATES

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SUMMARY

SUKARNA. Measurement Error in Bayesian Spatio-Temporal Poisson Modeling of Dengue Using Remote Sensing Covariates. Supervised by HARI WIJAYANTO, ANANG KURNIA, and YENNI ANGRAINI.

Statistical modeling has evolved from the classical Linear Model (LM) to more flexible frameworks, including the Generalized Linear Model (GLM), Linear Mixed Model (LMM), and Generalized Linear Mixed Model (GLMM), enabling the analysis of non-Gaussian, hierarchical, and spatio-temporal data. These methodological advances have become increasingly important in epidemiology, where infectious diseases such as dengue exhibit substantial spatial and temporal heterogeneity. Recent developments in remote sensing provide continuous environmental information for disease surveillance; however, satellite-derived environmental indices are indirect measurements affected by sensor limitations, atmospheric disturbances, cloud contamination, and image-processing procedures. Ignoring this uncertainty may bias parameter estimation and reduce predictive performance. Although measurement-error methods have been extensively investigated in classical statistical models, their integration into Bayesian spatio-temporal disease-mapping remains relatively limited. Therefore, this dissertation develops a unified Bayesian spatio-temporal Poisson framework that explicitly accounts for measurement error in remote-sensing covariates for dengue modeling.

The proposed framework extends the Bayesian hierarchical GLMM by jointly modeling fixed effects, localized spatial dependence, temporal dependence, spatio-temporal interaction, and covariate measurement error within a single coherent inferential framework. Spatial autocorrelation is represented by Localized Conditional Autoregressive (LCAR) priors, while temporal dependence and spatio-temporal interactions are incorporated through hierarchical random effects. This hierarchical Bayesian formulation enables simultaneous estimation of all model components while propagating uncertainty across multiple levels of the model, providing a flexible and statistically rigorous approach for analyzing complex spatio-temporal epidemiological data.

The first study demonstrated that Sentinel-2-derived environmental indices provide reliable environmental proxies for explaining dengue incidence. The study compared four statistical models, including conventional Poisson regression, clustered Poisson regression, localized spatial Poisson regression, and Hierarchical Bayesian Spatio-Temporal Localized Conditional Autoregressive (HBSTLCAR) model. The results showed that explicitly accounting for spatial dependence substantially improved predictive performance and more effectively captured spatial heterogeneity than conventional regression models.

The second study incorporated measurement-error correction into a clustered Poisson regression model and demonstrated that explicitly accounting for uncertainty in remotely sensed environmental covariates improved both parameter estimation and predictive accuracy. These findings indicate that satellite-derived



environmental variables should not be regarded as error-free measurements when used in epidemiological modeling.

The third study developed the proposed HBSTLCAR Model with Measurement Error (HBSTLCAR-ME) and evaluated its performance through both simulation and empirical studies. The simulation considered nine scenarios generated from combinations of three levels of spatial dependence (none, moderate, and high) with three levels of temporal dependence (none, moderate, and high). Across nearly all scenarios, HBSTLCAR-ME consistently outperformed the corresponding model without measurement error correction, yielding lower prediction errors and improved Bayesian model-fit criteria. The simulation further demonstrated that the effectiveness of measurement-error correction depended on the underlying spatio-temporal structure, with greatest improvements observed under moderate temporal dependence. Under strong spatial dependence, the performance gap between the two models become smaller because localized spatial random effects explained much of the residual variation. In the empirical application, the proposed HBSTLCAR-ME model achieved the best overall predictive performance while preserving localized spatial and temporal risk structures. Measurement-error correction primarily improved estimation of environmental covariate effects without materially altering the underlying spatial dependence, indicating that localized spatial heterogeneity remained the primary source of variation, whereas measurement error constituted an important secondary source of uncertainty.

The principal contribution of this dissertation is the development and comprehensive validation of a unified Bayesian spatio-temporal Poisson framework that integrates localized spatial dependence, temporal correlation, spatio-temporal interaction, and measurement error in remotely sensed environmental covariates. Validation through both simulation studies and empirical epidemiological applications demonstrates that explicitly accounting for measurement uncertainty consistently improves predictive performance, enhances parameter estimation, and strengthens Bayesian inference while preserving the underlying spatio-temporal dependence structure. Furthermore, the proposed framework establishes that remotely sensed environmental indices can serve as reliable proxy variables for dengue surveillance, provided that their inherent measurement uncertainty is explicitly accommodated within a Bayesian spatio-temporal modeling framework.

Keywords: Bayesian spatio-temporal modeling; dengue; Hamiltonian Monte Carlo; measurement error; Poisson regression; remote sensing.

RINGKASAN

SUKARNA. Kesalahan Pengukuran pada Pemodelan Poisson Bayesian Spasio-Temporal Dengue Menggunakan Kovariat Penginderaan Jauh. Dibimbing oleh HARI WIJAYANTO, ANANG KURNIA, dan YENNI ANGRAINI.

Pemodelan statistik telah berkembang dari Linear Model (LM) klasik menuju kerangka pemodelan yang lebih fleksibel, yaitu Generalized Linear Model (GLM), Linear Mixed Model (LMM), dan Generalized Linear Mixed Model (GLMM), sehingga memungkinkan analisis data non-Gaussian, hierarkis, serta spasial-temporal. Perkembangan metodologi ini menjadi semakin penting dalam bidang epidemiologi karena penyakit menular, seperti demam berdarah dengue (DBD), memiliki heterogenitas spasial dan temporal yang tinggi. Di sisi lain, perkembangan teknologi penginderaan jauh telah menyediakan informasi lingkungan yang bersifat kontinu secara spasial untuk mendukung kegiatan surveilans penyakit. Namun demikian, indeks lingkungan yang diturunkan dari citra satelit merupakan hasil pengukuran tidak langsung yang dipengaruhi oleh keterbatasan sensor, gangguan atmosfer, kontaminasi awan, serta proses pengolahan citra. Pengabaian terhadap ketidakpastian tersebut dapat menyebabkan bias dalam pendugaan parameter dan menurunkan kemampuan prediksi model. Meskipun metode penanganan kesalahan pengukuran (*measurement error*) telah banyak dikembangkan pada model statistik klasik, penerapannya pada pemodelan penyakit spasial-temporal berbasis Bayesian masih relatif terbatas. Oleh karena itu, disertasi ini mengembangkan suatu kerangka pemodelan Poisson spasial-temporal Bayesian yang terpadu dengan mengakomodasi kesalahan pengukuran secara eksplisit pada peubah kovariat yang diperoleh dari penginderaan jauh untuk pemodelan DBD.

Kerangka pemodelan yang diusulkan merupakan pengembangan dari GLMM hierarkis Bayesian dengan memodelkan secara simultan efek tetap, ketergantungan spasial terlokalisasi, ketergantungan temporal, interaksi spasial-temporal, serta kesalahan pengukuran pada peubah kovariat dalam satu kerangka inferensi yang terpadu. Autokorelasi spasial direpresentasikan menggunakan prior *Localized Conditional Autoregressive* (LCAR), sedangkan ketergantungan temporal dan interaksi spasial-temporal dimodelkan melalui efek acak hierarkis. Formulasi Bayesian hierarkis ini memungkinkan seluruh komponen model diestimasi secara bersamaan sekaligus mempropagasikan ketidakpastian pada setiap tingkat hierarki model, sehingga menghasilkan pendekatan yang fleksibel dan memiliki landasan statistik yang kuat untuk menganalisis data epidemiologi spasial-temporal yang kompleks.

Penelitian pertama menunjukkan bahwa indeks lingkungan yang diturunkan dari citra Sentinel-2 dapat digunakan sebagai peubah proksi lingkungan yang andal untuk menjelaskan kejadian DBD. Penelitian ini membandingkan empat model statistik, yaitu regresi Poisson konvensional, regresi Poisson dengan efek kluster, regresi Poisson spasial terlokalisasi, serta model Hierarchical Bayesian Spatio-Temporal Localized Conditional Autoregressive (HBSTLCAR). Hasil penelitian menunjukkan bahwa pemodelan yang secara eksplisit memperhitungkan ketergantungan spasial mampu meningkatkan kinerja prediksi secara signifikan



serta menggambarkan heterogenitas spasial dengan lebih baik dibandingkan model regresi konvensional.

Penelitian kedua mengintegrasikan koreksi kesalahan pengukuran ke dalam model regresi Poisson berkluster dan menunjukkan bahwa pengakomodasian ketidakpastian pada peubah kovariat lingkungan hasil penginderaan jauh mampu meningkatkan kualitas pendugaan parameter sekaligus akurasi prediksi. Temuan ini menunjukkan bahwa peubah lingkungan yang diperoleh dari citra satelit tidak seharusnya diperlakukan sebagai hasil pengukuran yang bebas dari kesalahan dalam pemodelan epidemiologi.

Penelitian ketiga mengembangkan model Hierarchical Bayesian Spatio-Temporal Localized Conditional Autoregressive dengan Measurement Error (HBSTLCAR-ME) dan mengevaluasi kinerjanya melalui studi simulasi serta aplikasi pada data empiris. Studi simulasi dilakukan menggunakan sembilan skenario yang dibentuk dari kombinasi tiga tingkat ketergantungan spasial (tidak ada, sedang, dan tinggi) dengan tiga tingkat ketergantungan temporal (tidak ada, sedang, dan tinggi). Pada hampir seluruh skenario, model HBSTLCAR-ME secara konsisten menunjukkan kinerja yang lebih baik dibandingkan model yang tidak mengakomodasi kesalahan pengukuran, yang ditunjukkan oleh kesalahan prediksi yang lebih rendah serta nilai kriteria kecocokan model Bayesian yang lebih baik. Hasil simulasi juga menunjukkan bahwa efektivitas koreksi kesalahan pengukuran bergantung pada struktur spasial-temporal yang mendasarinya. Peningkatan kinerja terbesar diperoleh pada kondisi ketergantungan temporal sedang, sedangkan pada kondisi ketergantungan spasial yang tinggi, perbedaan kinerja kedua model menjadi lebih kecil karena efek acak spasial terlokalisasi telah mampu menjelaskan sebagian besar variasi residual. Pada aplikasi empiris, model HBSTLCAR-ME memberikan kinerja prediksi terbaik secara keseluruhan dengan tetap mempertahankan struktur risiko spasial dan temporal yang terlokalisasi. Koreksi kesalahan pengukuran terutama meningkatkan ketepatan pendugaan pengaruh peubah kovariat lingkungan tanpa mengubah secara berarti struktur ketergantungan spasial yang mendasarinya. Hasil tersebut menunjukkan bahwa heterogenitas spasial terlokalisasi tetap merupakan sumber utama variasi, sedangkan kesalahan pengukuran menjadi sumber ketidakpastian tambahan yang penting untuk dipertimbangkan.

Kontribusi utama disertasi ini adalah pengembangan dan validasi secara komprehensif terhadap suatu kerangka pemodelan Poisson spasial-temporal Bayesian yang terpadu, yang mengintegrasikan ketergantungan spasial terlokalisasi, korelasi temporal, interaksi spasial-temporal, serta kesalahan pengukuran pada peubah kovariat hasil penginderaan jauh. Validasi melalui studi simulasi dan aplikasi epidemiologi empiris menunjukkan bahwa pengakomodasian ketidakpastian pengukuran secara eksplisit mampu meningkatkan kinerja prediksi, memperbaiki pendugaan parameter, serta memperkuat inferensi Bayesian tanpa menghilangkan struktur ketergantungan spasial-temporal yang mendasarinya. Selain itu, kerangka pemodelan yang diusulkan membuktikan bahwa indeks lingkungan hasil penginderaan jauh dapat dimanfaatkan sebagai peubah proksi yang andal untuk mendukung surveilans DBD, sepanjang ketidakpastian pengukuran yang melekat pada data tersebut diakomodasi secara eksplisit dalam kerangka pemodelan Bayesian spasial-temporal.

Kata kunci: Bayesian spasio-temporal, demam berdarah dengue, Hamiltonian Monte Carlo, kesalahan pengukuran, penginderaan jauh, regresi Poisson.



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MEASUREMENT ERROR IN BAYESIAN SPATIO-TEMPORAL POISSON MODELING OF DENGUE USING REMOTE SENSING COVARIATES

SUKARNA

Dissertation
as one of the requirements for obtaining a degree
Doctorate
in Study Program on Statistics and Data Science

**STUDY PROGRAM ON STATISTICS AND DATA SCIENCE
SCHOOL OF DATA SCIENCE, MATHEMATICS, AND INFORMATICS
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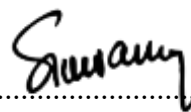


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APPROVAL SHEET

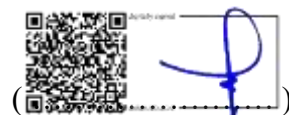
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Finally, it is my sincere hope that this dissertation will contribute to the advancement of scientific knowledge, methodology, and technology, and provide meaningful benefits to the academic community and society at large.

Bogor, August 2026
Sukarna

TABLE OF CONTENTS

SUMMARY	iii
RINGKASAN	v
APPROVAL SHEET	xi
ACKNOWLEDGEMENTS	xii
TABLE OF CONTENTS	xiii
LIST OF TABLES	xv
LIST OF FIGURES	xvi
LIST OF APPENDICES	xvii
LIST OF GLOSSARIUM	xviii
I INTRODUCTION	1
1.1 Research Background	1
1.2 Problems Statement	4
1.3 Research Objectives	5
1.4 Research Contribution	5
1.5 Scope and Limitations of the Study	7
II LITERATURE REVIEW	9
2.1 Generalized Linear Model	9
2.2 Spatial Generalized Linear Mixed Models	11
2.3 Spatio-Temporal Generalized Linear Mixed Models	12
2.4 Disease Mapping Measure	14
2.5 Hierarchical Bayesian Models	15
2.6 Unified Bayesian Models	16
2.7 Measurement Error	17
2.8 Hamiltonian Monte Carlo	19
2.9 Remote Sensing	21
2.10 Environmental Covariates	23
2.11 Dengue Hemorrhagic Fever	24
III HIERARCHICAL BAYESIAN SPATIO-TEMPORAL LOCALIZED CONDITIONAL AUTOREGRESSIVE MODELING USING REMOTE SENSING ENVIRONMENTAL COVARIATES	25
3.1 Introduction	25
3.2 Material and Methods	29
3.3 Evaluation Model	47
3.4 Results and Discussion	49
3.5 Conclusion	58



IV	ENHANCING POISSON REGRESSION FOR DENGUE HAEMORRHAGIC FEVER THROUGH MEASUREMENT ERROR CORRECTION, SPATIAL CLUSTERING, AND REMOTE SENSING– BASED ENVIRONMENTAL PROXIES	60
4.1	Introduction	60
4.2	Method	62
4.3	Results and Discussion	72
4.4	Conclusion	76
V	A BAYESIAN SPATIO-TEMPORAL POISSON MODEL WITH MEASUREMENT ERROR CORRECTION USING HAMILTONIAN MONTE CARLO: A Simulation and Real Data Study	77
5.1	Introduction	77
5.2	Material and Methods	79
5.3	Simulation and Real Data Results	106
5.4	Discussion	117
5.5	Conclusion	119
VI	GENERAL DISCUSSION	121
6.1	General Introduction	121
6.2	General Result	122
6.3	General Discussion	123
6.4	Research Limitations	125
6.5	Future Research Directions	125
VII	GENERAL CONCLUSIONS AND RECOMMENDATIONS	127
7.1	General Conclusions	127
7.2	Recommendations	128
	REFERENCES	129
	APPENDICES	143
	CURRICULUM VITAE	157

LIST OF TABLES

1. Characteristics of Selected Exponential-Family Distributions	10
2. General comparison of major Earth observation satellites	21
3. Number of PKM, sub-district, Area, and Population by District	30
4. Coefficients of each covariate, p-value, AIC, dan RMSE for M1	51
5. Coefficients of each covariate, p-value, AIC, and RMSE for M2	51
6. M2 for each district	52
7. DIC values for each model BSLCAR $G = \{2, 3, 4, 5\}$	53
8. Sub-districts in each Group	53
9. Coefficients of covariate, confidence interval, DIC, and RMSE for M3	54
10. M3 for each group	55
11. Difference between the model's predicted values and the actual values for various mean priors at $G=3$	56
12. The result of HBSTLCAR $G=3$	56
13. Number of PKM, Sub-districts, Area, and Population by District	62
14. Coefficients of each covariate, and p-value	73
15. Number of PKM, Sub-districts, Area, and Population by District	105
16. Factorial Design of simulation study	106
17. Comparison of model performance across the nine simulated	108
18. Comparison of model performance between HBSTLCAR and HBSTLCAR-ME	109
19. Posterior summaries of the HBSTLCAR model	111
20. Posterior summaries of the HBSTLCAR-ME model	114
21. Model Evaluation Results for HBSTLCAR and HBSTLCAR-ME	117
22. Posterior Estimates between HBSTLCAR and HBSTLCAR-ME	118
23. Summary of the Models Developed in This Dissertation	122



LIST OF FIGURES

1. Position of this research, compared to some prior research	7
2. Scope of this research	8
3. Mainland of Makassar City, South Sulawesi, Indonesia, with 14 districts	29
4. Data distributions, histograms, distribution lines, and correlations between variables	49
5. Number of dengue cases across the 14 districts of Makassar, Jan 2022 – Aug 2024	50
6. Descriptive analysis for dengue cases in Makassar, Jan 2022 – Aug 2024	50
7. Classification of Villages by BSLCAR $G=4$	54
8. Flowchart Comparing GLM Poisson Models	71
9. Data distribution between variables	72
10. Roadmap of Simulation Study	90
11. The map of Makassar City with 149 sub-districts	105
12. Roadmap of Simulation Study	107
13. Predictive comparison RMSE	109
14. Predictive comparison absolute bias β_3	110
15. Predictive comparison WAIC	110
16. Trace plots and mixing behavior of posterior chains under the HBSTLCAR model	113
17. Spatial Risk Stratification of Dengue in Makassar Using the HBSTLCAR	113
18. Trace plots and mixing behavior of posterior chains under the HBSTLCAR-ME model	116
19. Spatial Risk of Dengue Incidence Using the HBSTLCAR-ME	116



LIST OF APPENDICES

1. Proof that the Poisson Distribution Belongs to the Exponential Family and Estimation of Its Parameters	144
2. Hamiltonian Monte Carlo (HMC) Process	150

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LIST OF GLOSSARIUM

Abbreviation	Expanding of Abbreviation
AC	Administrative Cluster
AIC	Akaike Information Criterion
BI	Breteau Index
BPJS	Social Security Agency (<i>Badan Penyelenggara Jaminan Sosial</i>)
BSLCAR	Bayesian Spatial Localized Conditional Autoregressive
BYM	Besag–York–Mollié
CI	Confidence Interval
CMP	Conway-Maxwell-Poisson
CSU	Clustered Spatial Unit
DHF	Dengue Hemorrhagic Fever
DHF	Dengue Hemorrhagic Fever
DIC	Deviance Information Criterion
ENSO	El Niño-Southern Oscillation
GLM	Generalized Linear Model
GLMM	Generalized Linear Mixed Model
Green	Green Band (Band-3, B3)
GSMaP	Global Satellite Mapping of Precipitation
HBSLCAR	Hierarchical Bayesian Spatial Localized Conditional Autoregressive
HBSTLCAR	Hierarchical Bayesian Spatial-temporal Localized Conditional Autoregressive
HBSTLCAR-ME	Hierarchical Bayesian Spatio-temporal Localized Conditional Autoregressive model incorporating Measurement Error
HI	House Index
HMC	Hamiltonian Monte Carlo

Abbreviation	Expanding of Abbreviation
ICAR	Intrinsic Gaussian Conditional Autoregressive
IG	Inverse Gamma
IOD	Indian Ocean Dipole
IRS	Indoor Residual Spraying
JOIV	International Journal on Informatics Visualization
LCAR	Localized Conditional Autoregressive
LM	Linear Model
M1	Model-1
M2	Model-2
M3	Model-3
M4	Model-4
MAE	Mean Absolute Error
MC-EM	Monte Carlo Expectation–Maximization
MCMC	Markov Chain Monte Carlo
ME	Measurement Error
MJO	Madden-Julian Oscillation
MLE	Maximum Likelihood Estimation
NDBI	Normalized Difference Built-up Index
NDMI	Normalized Difference Moisture Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NIR	Near-Infra Red band (Band-8, B8)
NIRp	The Narrow NIR Band (Band-8A, B8A)
NUTS	No-U-Turn Sampler
OLS	Ordinary Least Squares
OR	Odd Ratio
PKM	Community health centers (<i>Pusat Kesehatan Masyarakat</i>)



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Abbreviation	Expanding of Abbreviation
Puskesmas	Community health centers (<i>Pusat Kesehatan Masyarakat</i>)
Red	Red Band (Band-4, B4)
RMSLE	Root Mean Squared Logarithmic Error
SIR	Standardized Incidence Ratio
SWIR1	Shortwave Infra-Red Band (Band 11, B11)
TCP	Tweedie Compound Poisson
USGS	United States Geological Survey
WAIC	Widely Applicable Information Criterion
WHO	World Health Organization

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