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ESTIMATION OF THE PERCENTAGE OF CRIME VICTIMS AT THE REGENCY/MUNICIPALITY LEVEL ON PAPUA ISLAND IN 2024 USING HIERARCHICAL BAYES SMALL AREA ESTIMATION

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ABSTRACT

Reliable statistics on crime victims are essential for monitoring public safety and supporting evidence-based policies. In line with Sustainable Development Goal (SDG) 16, which aims to promote peaceful and inclusive societies by reducing all forms of violence, district- and municipality-level estimates of crime victims are particularly important for regional development planning in the Papua region. However, direct survey estimates at this level often suffer from low precision due to limited sample sizes. Therefore, this study aimed to estimate the percentage of crime victims at the district/municipality level in Papua Island in 2024 using the Hierarchical Bayes Small Area Estimation (HB-SAE) approach based on the area-level Fay–Herriot model. The model incorporated three auxiliary variables derived from the 2024 Village Potential Statistics (PODES) published by Statistics Indonesia (BPS): the proportion of villages with base transceiver stations (BTS), the proportion of villages with markets, and the proportion of villages reporting theft incidents. The results showed that the HB-SAE approach produced significantly more precise estimates than direct estimation. The mean Relative Standard Error (RSE) decreased from 47.35% under direct estimation to 37.02% under the HB-SAE approach, representing a 21.82% improvement in estimation precision, and the Page test confirmed that the reduction in RSE was statistically significant (p = 0.01). Furthermore, the HB-SAE approach successfully generated estimates for all districts/municipalities, including four non-sampled areas. These findings indicate that the HB-SAE approach provides reliable small-area estimates to support crime-related policy formulation and regional development planning in Papua Island.

Keywords: *crime victims, SDGs, small area estimation, hierarchical Bayesian.*

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INTRODUCTION

Sustainable development has become an international agenda and a shared aspiration of nations worldwide, as articulated in the Sustainable Development Goals (SDGs) 2015–2030. One of these goals, Goal 16, focuses on peace, justice, and strong institutions (United Nations, 2015). It emphasizes the promotion of peaceful societies, the reduction of violence, the strengthening of legal institutions, and the assurance of equal access to justice for all. Achieving this objective requires reliable and high-integrity institutions capable of effectively reducing crime and crime victimization.

In this context, a crime victim is defined as an individual whose person or property has been harmed by a criminal act or an attempted crime (BPS, 2025). According to the Global Organized Crime Index (GOCI) report, Indonesia recorded an organized crime score of 6,85, ranking second in Asia after Myanmar (Global Initiative Against Transnational Organized Crime, 2021). This figure is concerning and calls for serious governmental attention. Furthermore, in 2024, Statistics Indonesia (Badan Pusat Statistik/BPS), through its publication Welfare Statistics, reported that 0,73 percent of the population experienced crime, reflecting the percentage of crime victims (BPS, 2025). The percentage of crime victims is an important indicator of public safety and socio-economic development. Therefore, continuous monitoring of this indicator is essential for evaluating crime prevention efforts and fostering a greater sense of security within society (United Nations Office on Drugs and Crime, 2019).

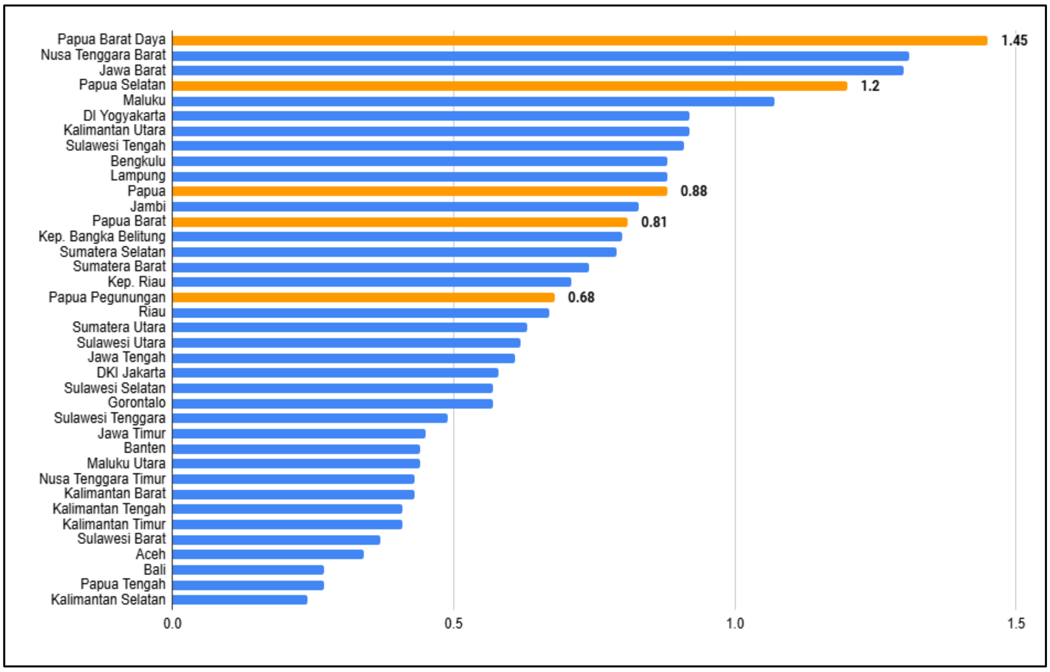

Figure 1. Percentage of Crime Victims by Province in 2024

From the provincial perspective illustrated in Figure 1, four of the six provinces in the Papua region recorded percentages of crime victims above the national average, indicating that the region experiences a relatively high burden of crime victims compared with many other parts of Indonesia. Among these provinces, Southwest Papua recorded the highest percentage of crime victims nationwide, while South Papua ranked fourth. These findings highlight the importance of examining the percentage of crime victims at more detailed administrative levels, such as districts and municipalities, to support more reliable and targeted policy interventions. Previous studies have shown that socio-economic conditions, including deprivation, population mobility, and social heterogeneity, are important determinants of spatial variations in crime. Accordingly, policies aimed at improving socio-economic conditions may contribute to reducing the percentage of crime victims and supporting safer communities (Tarling & Dennis, 2016).

Effective and accurate planning to prevent and address crime requires comprehensive and up-to-date data sources. As the national statistical authority, Statistics Indonesia (BPS) is mandated to support development through the provision of official statistics. However, in practice, the data produced are often limited to the national or provincial level due to the absence of samples or insufficient sample sizes at lower administrative levels, resulting in relatively large Relative Standard Errors (RSEs). Under such conditions, direct estimation of the percentage of crime victims may yield unreliable results and limit the validity of subsequent analyses (Ubaidillah, 2014).

To address parameter estimation at smaller area levels, the Small Area Estimation (SAE) method is employed to produce more precise estimators (Rao & Molina, 2015). In practice, direct estimation at the small-area level is generally unbiased; however, it often results in large variances due to limited sample sizes. To overcome this limitation, variance reduction can be achieved through indirect estimation methods. This approach incorporates auxiliary variables into the estimation of the percentage of crime victims to improve precision. At the area level, the Fay–Herriot model under a Hierarchical Bayesian (HB) framework is considered appropriate for small-area estimation, even in cases where no sample observations are available for certain areas (Rao & Molina, 2015). This is because the HB approach is capable of borrowing strength across areas through its hierarchical structure.

Recent studies have demonstrated the effectiveness of Hierarchical Bayesian (HB) approaches in improving the precision of Small Area Estimation (SAE). Rahmadani and Sumarni (2023) applied SAE to estimate the proportion of theft victims in South Sulawesi. Similarly, Yanuar et al. (2021) applied the HB-SAE method to estimate the proportion of health insurance participants at the subdistrict level and reported higher estimation accuracy than direct estimation. Marcis et al. (2023) further extended the Fay–Herriot model by incorporating a three-level hierarchical structure, resulting in improved estimation accuracy for poverty proportions. In addition, Van den Brakel and Boonstra (2021) employed a Hierarchical Bayesian Fay–Herriot model to estimate discontinuities in the Dutch Crime Victimization Survey, demonstrating that the HB framework can produce reliable estimates for domains with limited sample sizes. More recently, Shiferaw et al. (2024) successfully applied the Hierarchical Bayesian SAE model to estimate health program coverage at small-area levels. These studies demonstrate that Hierarchical Bayesian SAE methods consistently improve estimation precision by borrowing strength from auxiliary information and area-specific random effects.

Despite these advances, the application of the Hierarchical Bayesian Fay–Herriot model to estimate crime victimization at the district/municipality level remains limited, particularly in Indonesia and the Papua region. Existing studies have mainly focused on methodological developments or applications to health and poverty indicators, whereas studies on crime victimization have received relatively little attention. Furthermore, previous studies have rarely integrated estimation results with the classification and thematic mapping of crime victimization to support local policy formulation. Therefore, this study aims to estimate the percentage of crime victims at the district/municipality level in Papua Island in 2024 using the Hierarchical Bayesian Fay–Herriot model, compare its estimation precision with that of direct estimation, and classify districts/municipalities based on the estimated percentages. Scientifically, this study extends the application of the Hierarchical Bayesian SAE approach to crime victimization indicators in small areas using auxiliary variables derived from the 2024 Village Potential Statistics (PODES). Practically, the results provide more reliable local-level statistics to support evidence-based crime prevention policies and regional development planning in Papua Island.

MATERIALS AND METHODS

Crime Victimization

This study employs the Small Area Estimation using a Hierarchical Bayesian approach (SAE-HB). This method accommodates non-normal data distributions and enables parameter estimation by incorporating auxiliary variables. The analysis uses secondary data obtained from Statistics Indonesia (BPS), specifically the percentage of crime victims in 2024 as the response variable. According to BPS, a crime victim is defined as an individual whose person or property was harmed by a criminal act or an attempted crime within the past year (BPS, 2025).

In data collection, BPS operationalizes crime victimization by focusing on individuals who experienced theft, assault, robbery, sexual harassment, and other related offenses during 2024. This simplification is intended to facilitate respondents' understanding, particularly among those unfamiliar with legal terminology used by law enforcement agencies or stipulated in the Indonesian Criminal Code.

The estimation of the percentage of crime victims in the i-th district/municipality can be expressed by the following formula (Perwira et al., 2023):

$$\hat{\theta}_i = \frac{\sum_{j=1}^{n} w_{ij} Y_{ij}}{\sum_{j=1}^{n} w_{ij}} \; ; Y_{ij} = 1 \text{ if the individual is a victim of crime and 0 otherwise} \quad (1)$$

Subsequently, the Mean Square Error (MSE) of the direct estimator is calculated using the following equation.

$$\text{MSE}\ (\hat{\theta}_i) = \frac{\sum_{j=1}^{n} w_{ij}(w_{ij}-1)(Y_{ij}-\hat{\theta}_i)^2}{\left(\sum_{j=1}^{n} w_{ij}\right)^2} \quad \textbf{(2)}$$

where:

$\hat{\theta}_i$ = percentage of the population who are victims of crime in the i-th district/municipality

w_{ij} = sampling weight for the j-th individual in the i-th district/municipality

Y_{ij} = crime victim indicator

Small Area Estimation (SAE)

Small Area Estimation (SAE) applies indirect estimation by incorporating information from other areas through auxiliary variables derived from census or national survey data (Rao & Molina, 2015). This approach improves the quality of estimates, particularly in areas with small sample sizes. This study employs an area-level model because the auxiliary variables used are aggregate data at the district/municipality level. Area-level SAE models within a Bayesian framework are developed under a random effects structure, which includes the Empirical Bayes (EB) and Hierarchical Bayes (HB) approaches (Esteban et al., 2019).

The Hierarchical Bayes (HB) method is a hierarchical model that allows the random effect parameters of a particular area to borrow additional information from other areas with similar characteristics (Noviani, 2016). Within this framework, both the fixed-effect parameters and the variance components are treated as random variables, such that all parameters are specified through a joint prior distribution. This prior distribution is then updated using Bayes' theorem to obtain the joint posterior distribution, which serves as the basis for area-level estimation.

Considering that the percentage of crime victims lies within the range of a proportion, the beta distribution is considered appropriate for modelling this characteristic (Ntzoufras, 2011). Accordingly, the area-level SAE HB Beta model can be expressed as follows (Souza & Moura, 2016):

i. Sampling model

$$\hat{\theta}_i|\theta_i \sim \text{Beta}\ (a_i, b_i), \qquad i = 1, \dots, m \quad \textbf{(3)}$$

In Equation (3), θ_i represents the parameter of interest, taking values between 0 and 1, while $\hat{\theta}_i$ denotes the estimator for the i-th small area. The parameters of the beta distribution are specified as $a_i = \theta_i k$ and $b_i = (1-\theta_i)k$, Where k is a constant assumed to follow a gamma distribution $k \sim \text{Gamma}(g_1, g_2)$.

ii. Linking model

$$\text{logit}(\theta_i)|\beta, \sigma_v^2 \overset{\text{iid}}{\sim} N(x_i^T\beta, \sigma_v^2), \qquad i = 1, \dots, m \quad \textbf{(4)}$$

Where $v_i \sim N(0, \sigma_v^2)$ and $\sigma_v^2 \sim IG(c_1, c_2)$, with IG denoting the Inverse Gamma distribution.

iii. The parameters β and σ_v^2 are assumed to have flat priors and to be mutually independent, with $\beta \sim N(\mu_\beta, \sigma_\beta^2)$.

Under the Hierarchical Bayesian framework, the likelihood specified by the sampling model and the prior distributions defined in the linking model are combined to obtain the joint posterior distribution of the model parameters, including $\theta_i, \beta,$ and σ_v^2. Since this posterior distribution has no closed-form analytical solution, parameter estimation is performed using Markov Chain Monte Carlo (MCMC) methods, specifically the Gibbs sampling algorithm. The algorithm iteratively samples from the full conditional posterior distributions of each parameter until convergence is achieved, and the resulting posterior samples are then used to estimate the small area parameters (Souza & Moura, 2016).

To assess the improvement in precision of the HB Beta estimator compared to the direct estimator, the Relative Standard Error (RSE) is employed. The RSE of the HB estimator is calculated as the square root of the posterior variance divided by the HB estimate, which is obtained from the posterior mean. Mathematically, it can be expressed as follows (Rao & Molina, 2015):

$$\text{RSE}\ \left(\hat{\theta}_i^{\text{HB}}\right) = \frac{\sqrt{V[h(\boldsymbol{\theta})|\mathbf{y}]}}{E[h(\boldsymbol{\theta})|\mathbf{y}]} = \frac{\sqrt{\text{Variance posterior}}}{\text{Mean posterior}} \times 100 \quad \textbf{(5)}$$

RESULTS AND DISCUSSION

A summary of the direct estimation results for the percentage of crime victims across all districts/municipalities in Papua Island is presented in Table 1. Overall, the average percentage of crime victims among the 42 districts/municipalities is 0,80 percent, with inter-regional variation reflected by a variance of 0,47 percent. Dogiyai Regency in Central Papua recorded the lowest percentage of crime victims at 0,03 percent. In contrast, Mamberamo Tengah Regency in Highland Papua exhibited the highest percentage at 2,58 percent. These direct estimates serve as a benchmark for comparison with the Hierarchical Bayes Small Area Estimation (HB-SAE) results presented later in this section.

In addition, four regencies reported no observed cases of crime victimization and are therefore statistically classified as non-sampled areas. These include Pegunungan Arfak Regency in West Papua, Mamberamo Raya Regency in Papua, Puncak Regency in Central Papua, and Lanny Jaya Regency in Highland Papua.

Table 1. Summary of the Percentage of Crime Victims at the District/Municipality Level in Papua Island, 2024

	Minimum	**Median**	**Mean**	**Maximum**	**Variance**
Percentage of Population Experiencing Crime	0,03	0,60	0,80	2,58	0,47

To compare the performance of direct and indirect estimation methods, an indicator capable of evaluating estimation quality is required, one of which is the Relative Standard Error (RSE). This measure is used to assess the precision of estimates obtained through sampling techniques.

Based on Figure 2, the average RSE for the direct estimation of the percentage of crime victims in Papua Island is 47,35 percent, with values ranging from 20,61 percent to 100,24 percent. The boxplot distribution appears right skewed, indicating that the RSE values for most districts/municipalities are relatively high. In addition, four regencies do not have RSE values because no sampled individuals were identified as experiencing crime victimization in those areas.

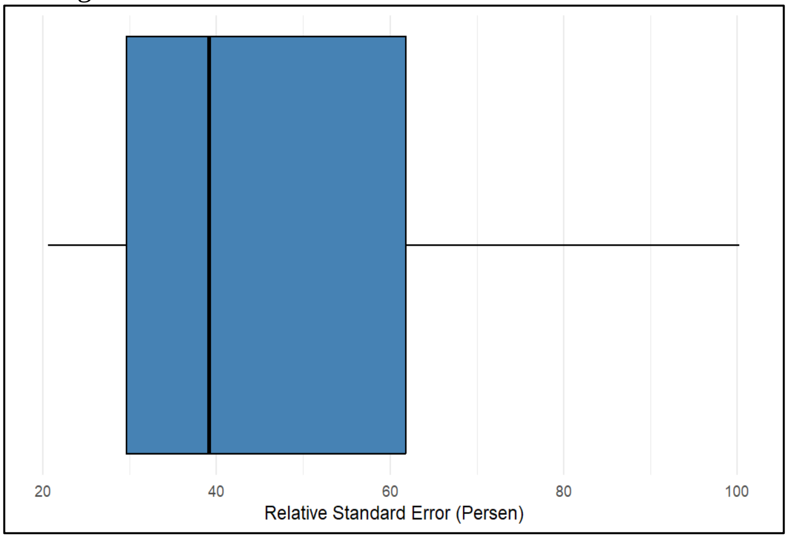

Figure 2. Boxplot of the RSE for the Percentage of Crime Victims at the District/Municipality Level in Papua Island, 2024

The exploratory data analysis indicates that several districts/municipalities exhibit inadequate quality in direct estimation, thereby necessitating the application of an indirect estimation approach through the Small Area Estimation (SAE) method to improve precision. Prior to model implementation, a normality test was conducted to assess the distributional pattern of the percentage of crime victims in Papua Island.

Subsequently, the results of the Shapiro–Wilk normality test with a p-value $< 0,05$ indicate that the data are not normally distributed at the 5 percent significance level. This finding is consistent with the pattern observed in the boxplot in Figure 2, which suggests a non-symmetric distribution.

The distribution of the percentage of crime victims in Papua Island does not follow a normal distribution. Under this condition, the modelling process was conducted using a Hierarchical Bayes (HB) approach with a Beta distribution, as this method does not require normality in direct estimates and is appropriate for data bounded between 0 and 1 with asymmetric distributional patterns

(Hajarisman, 2012). Moreover, the HB Beta method offers the advantage of borrowing strength, enabling estimation in non-sampled areas by utilizing information from sampled areas (Rao & Molina, 2015).

Candidate auxiliary variables were derived from the 2024 Village Potential Statistics (PODES) conducted by Statistics Indonesia (BPS). PODES was selected because it is a complete enumeration of all villages in Indonesia, meaning that the auxiliary variables are free from sampling error, which is an important requirement in area-level Small Area Estimation (Rao & Molina, 2015).

To identify the most appropriate auxiliary variables, a variable selection procedure was performed using stepwise regression. The candidate auxiliary variables were regressed on the logit-transformed direct estimates because the HB Beta model employs a logistic link function. Based on the selection results, three auxiliary variables were found to have a statistically significant relationship with the logit-transformed percentage of crime victims and were therefore retained in the final model. The selected auxiliary variables are presented in Table 3.

Table 3. Auxiliary Variable

Variable	**Notes**	**Definition**
X_1	Proportion of Villages with BTS	$\frac{\text{Number of villages with BTS in the i−th district/municipality}}{\text{Total number of villages in the i−th district/municipality}}$
X_2	Proportion of Villages with Markets	$\frac{\text{Number of villages with markets in the i−th district/municipality}}{\text{Total number of villages in the i−th district/municipality}}$
X_3	Proportion of Villages with Reported Theft Incidents	$\frac{\text{Number of villages with reported theft cases in the i−th district/municipality}}{\text{Total number of villages in the i−th district/municipality}}$

Parameter estimation in the HB Beta model was obtained using the Markov Chain Monte Carlo (MCMC) algorithm after convergence had been achieved. The MCMC procedure was implemented in RStudio using the Beta function from the *saeHB* package (Perwira et al., 2023), which is commonly applied in small area estimation analysis. A total of 100.000 iterations were performed, with a burn-in period of 25.000 iterations and a thinning interval of 25 resulting in 3.000 retained posterior samples for further analysis.

MCMC convergence was assessed using trace plots, density plots, and autocorrelation plots (Ayuningtyas, 2017). As shown in Figure 3, the diagnostic results indicate that the trace plots exhibit no systematic patterns, the density plots are smooth and approximately bell-shaped, and the autocorrelation plots show a cut-off at the first lag. These results suggest that the MCMC algorithm has successfully reached convergence, and the resulting posterior samples are appropriate for further analysis. Accordingly, the coefficient estimates in the SAE model based on the Hierarchical Bayes approach were obtained satisfactorily.

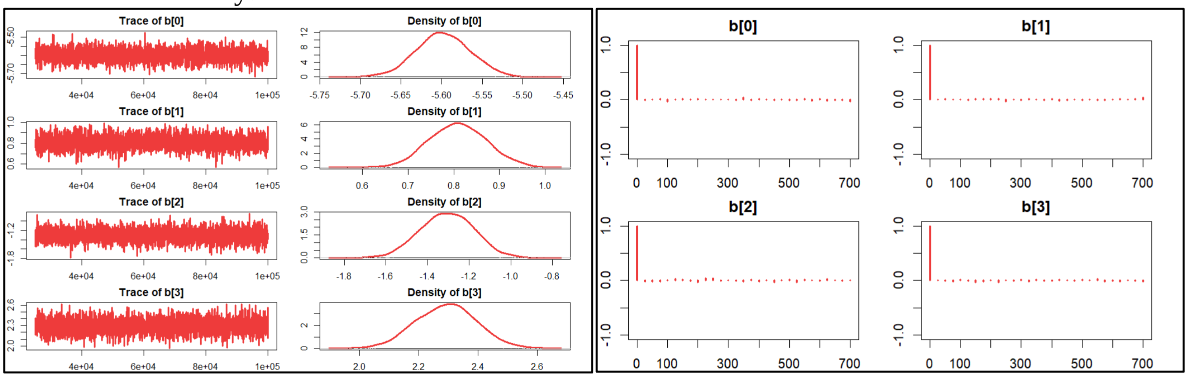

Figure 3. Trace Plot, Density Plot, and Autocorrelation Plot

The parameter estimates of the SAE HB Beta model, along with their corresponding credible intervals, are presented in Table 4. The results indicate that all auxiliary variables included in the model are statistically significant at the 5 percent level, as the 2,5% to 97,5% percent credible intervals for each parameter do not contain zero (Hakim & Ubaidillah, 2026). Therefore, the three auxiliary variables provide relevant and meaningful contributions to the estimation of the percentage of the population experiencing crime at the district/municipality level in Papua Island in 2024.

Table 4. Parameter Coefficient Estimates with 95 Percent Credible Intervals

Coefficient	Mean	Standard Deviation	2,5%	97,5%
b_0	-5,60	0,03	-5,66	-5,53
b_1	0,81	0,06	0,69	0,93
b_2	-1,31	0,13	-1,56	-1,06
b_3	2,29	0,10	2,10	2,49

Based on the modeling results, a comparison was conducted between the direct estimates and the indirect estimates obtained using the SAE HB Beta method. The pattern shown in Figure 4 indicates that the SAE HB Beta estimates follow the general trend of the direct estimates of the percentage of crime victims across districts/municipalities, as expected under a model-based approach. However, the SAE HB Beta curve appears smoother and more stable, suggesting that this method effectively reduces the extreme fluctuations observed in the direct estimates.

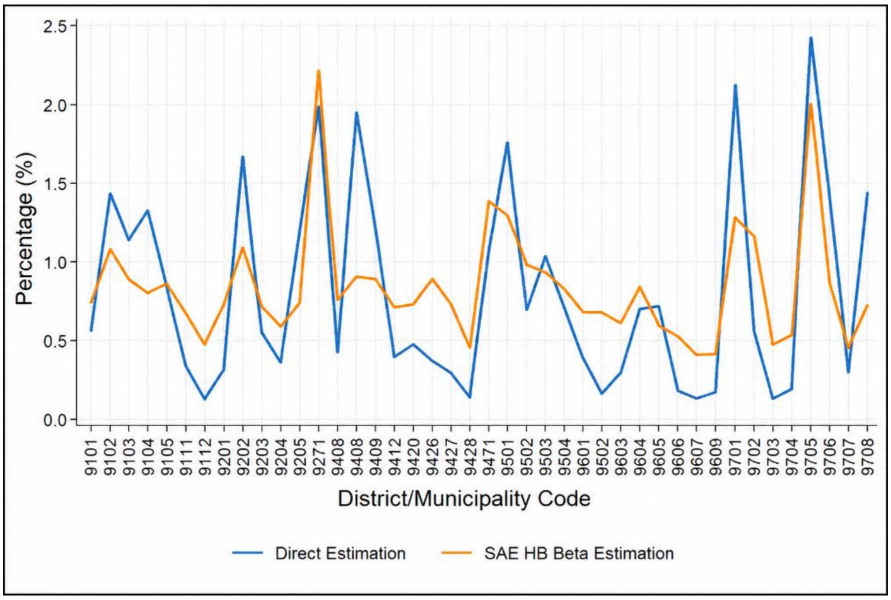

Figure 4. Results of Direct Estimation and SAE HB Beta Estimation

Furthermore, the summary statistics presented in Table 5 support these findings. The maximum relative standard error (RSE) under direct estimation exceeds 100 percent, whereas under the SAE HB Beta method it is approximately 40 percent. This substantial difference indicates a significant improvement in precision when applying the HB Beta approach.

In addition, the SAE HB Beta method generates estimates for the four non-sampled districts/municipalities, which cannot be obtained through direct estimation. This capability arises because the HB Beta approach integrates information across areas through a borrowing strength mechanism and incorporates area-specific random effects generated during the iterative process (Rao & Molina, 2015). Consequently, the SAE HB Beta method not only produces more stable estimates but also consistently improves the precision of the estimated percentage of crime victims across all areas.

Table 5. Summary of Direct and SAE HB Beta Estimation Results with RSE

	Estimation		RSE	
	Direct	HB Beta	Direct	HB Beta
Minimum	0,03	0,29	20,61	30,97
Q1	0,24	0,52	29,62	35,91
Median	0,60	0,65	39,11	36,81
Mean	0,80	0,76	47,35	37,02
Q3	1,26	0,83	61,79	38,29
Maximum	2,58	2,20	100,24	40,89
NA	4	0	4	0

To statistically verify whether there is a significant difference between the RSE values of the direct estimates and those of the HB Beta estimates, a Page test was conducted. The Page test is used to assess ordered differences among related samples (Perwira et al., 2023). Based on the results presented in Table 3.6, the difference is statistically significant, indicating that the RSE values produced by the HB method tend to be lower than those from direct estimation for the same ordering of districts/municipalities, although this pattern does not necessarily apply to every area.

Thus, the HB Beta estimation can be considered to provide better precision compared to direct estimation. Consequently, the estimated percentage of crime victims at the district/municipality level in Papua Island derived from the HB Beta model was selected for use in the subsequent classification and mapping stage.

Table 6. Page Test Results

Test Statistics (L)	p-value	Coclusion
182	0,01	RSE HB Beta < RSE direct

Subsequently, the distribution of the estimated percentage of crime victims at the district/municipality level in Papua Island is presented geographically through a thematic map, as shown in Figure 5. The percentage values are classified into five categories using the natural breaks method. The selection of the natural breaks method is based on its ability to minimize within-class variance while maximizing between-class differences according to the inherent distribution pattern of the data (Gibbons & Chakraborti, 2003).

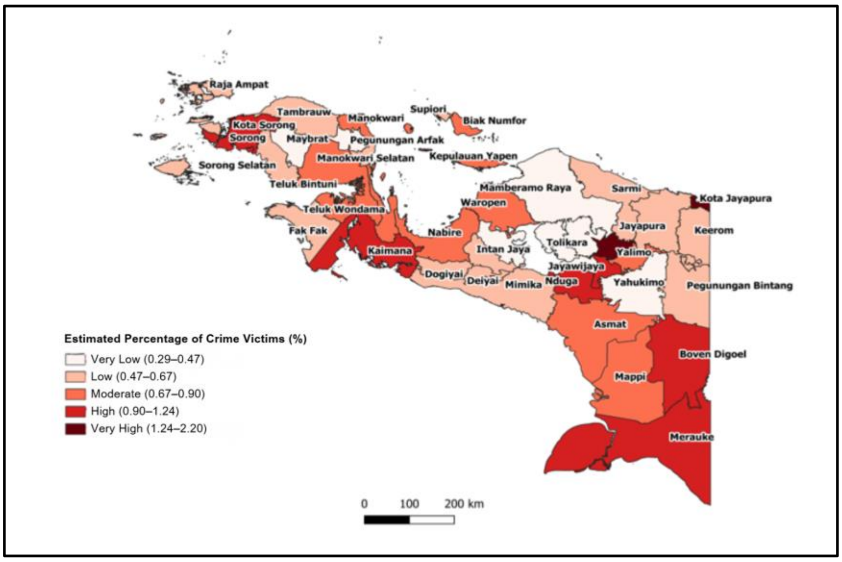

Figure 5. Thematic Map of SAE HB Beta Estimation Results

Geographically, a clustering pattern of crime levels across districts/municipalities in Papua Island can be observed. Areas classified in the very high category tend to be located in several coastal zones and regional activity centers, whereas the very low category is relatively evenly distributed across the central and northern parts of Papua. This pattern suggests that spatial variation in the estimated percentage of crime victims forms concentrations in specific areas, while other regions exhibit comparatively lower levels.

Districts/municipalities categorized as very high in terms of the estimated percentage of crime victims from 1,24 to 2,20 percent include Sorong City, Jayapura City, and Mamberamo Tengah Regency. These findings indicate that the two major cities in Papua Island fall within the group of areas with the highest crime levels. Meanwhile, areas classified as very low, with percentages between 0,29 and 0,47 percent, include Puncak Regency, Puncak Jaya Regency, Yahukimo Regency, Mamberamo Raya Regency, Pegunungan Arfak Regency, Lanny Jaya Regency, Intan Jaya Regency, Tolikara Regency, and Maybrat Regency.

Among the districts classified as having very low estimated percentages of crime victims, four districts Puncak Regency, Mamberamo Raya Regency, Pegunungan Arfak Regency, and Lanny Jaya Regency reported no observed crime victims in the direct survey estimates. Nevertheless, the HB-SAE model estimated their percentages at 0.29%, 0.34%, 0.35%, and 0.36%, respectively. These non-zero estimates demonstrate the ability of the HB-SAE approach to borrow strength from auxiliary variables and information from other districts/municipalities with similar characteristics, thereby overcoming the instability of direct estimates caused by zero observations or limited sample sizes.

CONCLUSION

The application of the SAE HB Beta method to estimate the percentage of crime victims at the district/municipality level in Papua Island in 2024 has been shown to improve the precision of the estimates compared to direct estimation. This improvement is reflected in the absence of districts/municipalities with RSE values exceeding 50 percent. Moreover, the HB approach enables estimation in non-sampled areas through the generation of area-specific random effects.

The mapping results reveal a tendency toward spatial clustering in the estimated percentage of crime victims across regions. Districts/municipalities classified in the very high category appear to be concentrated in several coastal areas and regions functioning as activity centers. Therefore, comprehensive and context-specific policy formulation is required, particularly for areas with relatively high crime levels in Papua Island.

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