Spatial Inequalities in Educational Infrastructure: Bayesian Hierarchical Modelling of School Availability Across North Borneo

Alvin Bong

Abstract

Understanding the spatial distribution of educational infrastructure is essential for ensuring equitable access to schooling. This study examines regional disparities in school availability across Brunei and the neighboring Malaysian states of Sarawak and Sabah, with a focus on identifying potential underserved areas. First, exploratory data analysis (EDA) was conducted to compare school counts and student-teacher ratios at the district level across the three regions. The core analysis employs Standardized Incidence Ratio (SIR) and Bayesian spatial Poisson model using Integrated Nested Laplace Approximation (INLA) to estimate the relative abundance of schools across Brunei's districts, adjusting for expected counts based on population, region size and socioeconomic indicator (house price + partially simulated). Spatially structured and unstructured random effects were incorporated to account for latent spatial processes. Posterior estimates identified districts with significantly lower school availability than the national baseline, supporting future policy planning and school placement.

Introduction

Education is a foundational pillar of national development and its people, influencing social well-being, economic growth, and long-term sustainability. The global significance of education is recognized in Sustainable Development Goal 4, which promotes inclusive and equitable quality education for all [1]. Nationally, Brunei Darussalam's national vision, Wawasan Brunei 2035, positions education as a cornerstone of the country's long-term development goals. Ensuring equitable access to education through sufficient infrastructure, fair resource distribution, and balanced student–teacher ratios is critical to delivering quality learning experiences.

While several studies have examined general aspects of education in Brunei, there have been limited studies based on quantitative spatial methods, with only one examining the spatial distribution and hotspots of schools. This project aims to addresses that gap by first conducting a comparative analysis of school availability and student–teacher ratios across Brunei's districts, with additional context from neighboring Malaysian states, Sarawak and Sabah.

Next, Standardized Incidence Ratios (SIR) and Bayesian hierarchical models are used to identify adminstrative regions in Brunei where school availability falls significantly below the national baseline, supporting future policy planning and school placements.

Data

This study focuses exclusively on government primary and secondary schools, as these institutions serve as the main access points to education for most youth. The school dataset from 2018 was used as it is the most recent year for which disaggregated school-level data is available in Brunei. Although more recent statistics exist, they are published only in summary form.

Population data is drawn from the 2021 national census, the most recent census available in Brunei, despite the mismatch in years with the school dataset. Brunei conducts its national census every ten years, making the 2021 data the best option for population estimates.

The following key data variables were used: school counts, administrative boundary data, population, student–teacher ratios, and house prices. These datasets were cleaned, wrangled, and merged primarily using left_join() and rbind(), with further details provided below.

Brunei

Data on school locations, student–teacher ratios, administrative boundaries, and population were sourced from the `bruneimap` R package. The school dataset `sch_sf` includes georeferenced point data for each institution. For our areal analysis, schools were aggregated by district and mukim (finer administrative level). Despite composing of only four districts, district-level aggregation was used for broader comparisons (student–teacher ratios and school counts) to match the size of available administrative resolution in Malaysian data. Mukims ($N = 39$), which provide finer geographic resolution, were instead used for the Bayesian spatial analysis of school availability in Brunei.

To incorporate a socioeconomic indicator, we used median house prices derived from approximately 30,000 property listings spanning 1993–2025. These were calculated at the mukim level and included as a covariate in the Bayesian model. In cases where house price data were missing, values were imputed using predictions from an INLA-based Gaussian model. Manual imputations based on local knowledge were initially tested, but the INLA-predicted values were ultimately adopted, as both methods produced similar model outcomes. Given the nature of the data, house prices were treated as partially simulated estimates and may not fully reflect actual market values.

Malaysia

Malaysian data variables were sourced from the national open data portal [data.gov.my], and include district-level school counts and population estimates for the states of Sarawak and Sabah. Administrative boundary (districts) were obtained via the `geomdata` R package, as OpenStreetMap (`osmdata`) does not provide required administrative divisions level.

Some inconsistencies were found between school data and adminstrative boundaries, particularly in areas where older districts had been subdivided into newer ones. In these cases, school counts were available only for the original (larger) districts. To ensure consistency, we excluded the newer subdivisions and manually reassigned schools in the affected areas to the nearest valid district.

Method

Exploratory data anlysis using Clorepath maps for schools count, by area (usingst_area) studnet teacher ratio

Spatial regression model

Let Y_i and E_i denote the observed and expected counts of schools, respectively, in mukim $i \in \{1, \ldots, n\}$. Let θ_i represent the *relative abundance* of schools in mukim i, analogous to a relative risk in disease mapping. The model is specified as follow:

$$Y_i \mid \theta_i \sim \text{Poisson}(E_i \cdot \theta_i), \quad i = 1, \ldots, n$$

$$\log(\theta_i) = \beta_0 + \beta_1 \cdot \text{pop}_i + \beta_2 \cdot \text{area}_i + \beta_3 \cdot \text{hp}_i + u_i + v_i$$

Where:

- β_0 is the intercept,
- β_1, β_2, and β_3 are regression coefficients for the standardized covariates:
  - pop_i: population (in units of 10,000),
  - area_i: mukim size (in units of 10 km²),
  - hp_i: median house price (in BND \$1,000,000),
- u_i is a structured spatial effect, modelled using an intrinsic conditional autoregressive (CAR) prior $u_i \mid u_{-i} \sim \mathcal{N}(\bar{u}_{\delta_i}, \frac{1}{\tau_u n_{\delta_i}})$
- v_i is an unstructured random effect, $v_i \sim \text{Normal}(0, \frac{1}{\tau_v})$

The spatial random effect u_i requires a neighborhood (adjacency) matrix. Here, We define two mukims as neighbors if they share at least one boundary point (Queen contiguity). The neighborhood graph is constructed using the `poly2nb()` function from the `spdep` package. Model fitting was performed in a Bayesian framework using the Integrated Nested Laplace Approximation (INLA).

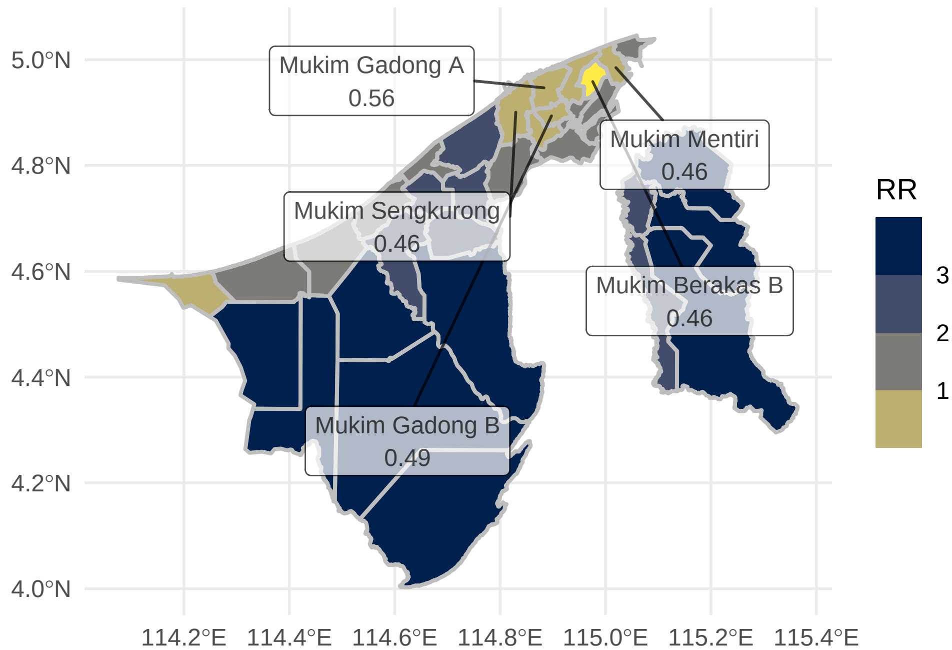
Results

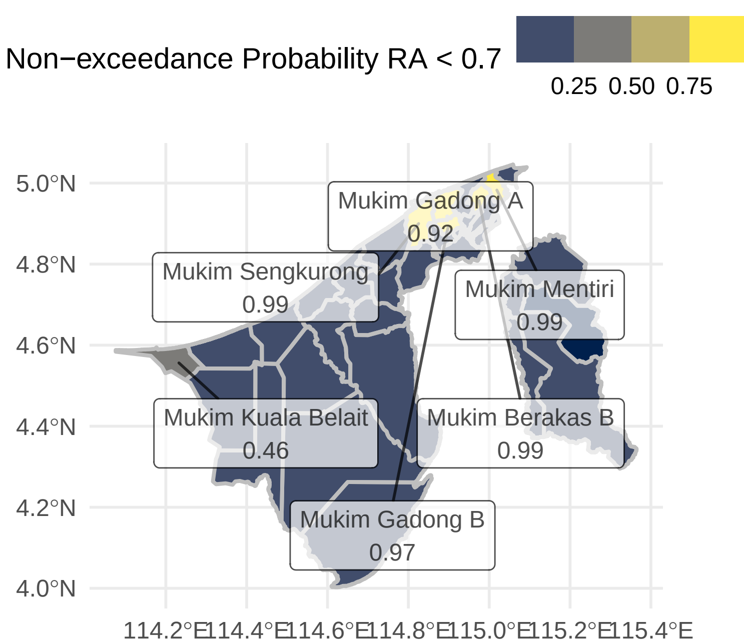
Model

The model results show that the intercept is estimated at $\hat{\beta}_0 = 1.077$, with a 95% credible interval of $(0.239, 1.894)$. The coefficient for population, $\beta_1 = -0.436$, with a 95% credible interval of $(-0.579, -0.295)$, indicates a statistically significant negative relationship between population size and relative school abundance. Specifically, for every 10,000 increase in population, the relative abundance of schools decreases by approximately 35%, since $\exp(-0.436) \approx 0.647$. In contrast, the covariates: mukim size and house price are not statistically significant. The coefficient for mukim size is $\hat{\beta}_2 = 0.015$ (95% CI: -0.002, 0.032), and for house price is $\hat{\beta}_3 = -0.759$ (95% CI: -3.174, 1.704).

The estimated relative abundance (RA) of schools across mukims indicates lower values in the northern coastal mukims, particularly in northern Brunei-Muara District, along the South China Sea. Conversely, higher RA values appear inland, especially in less densely populated regions.

To identify mukims with potentially inadequate school provision, non-exceedence probabilities were computed for a threshold of $RA < 0.7$. The analysis indicates that it is highly likely that several mukims fall below this threshold, including Mukim Sengkurong, Mukim Gadong A, Mukim Gadong B, Mukim Berakas B, and Mukim Mentiri.





Discussion & Limitation

The negative relationship between population and school counts, as well as higher RA values in inland (rural) mukims than coastal ares with larger population suggests that school availability in rural mukims seem to be adequate, potentially due to legacy planning policies or intentional efforts to ensure equitable access in remote areas.

In contrast, urban and peri-urban mukims in the Brunei-Muara District, the country's most densely populated and economically active region, show signs of disparities in school access. Notably, the high non-exceedance probability of $RA < 0.7$ in **Mukim Sengkurong, Gadong A & B, Berakas B, and Mentiri** indicates that they have fewer schools than expected relative to their population sizes. These disparities highlight areas that may be underinvested in educational infrastructure, warranting closer policy attention.

Importantly, these mukims are also encompass several new government housing developments, such as Perpindahan Lugu and Perpindahan Tanah Jambu. This suggests a potential planning gap, where population is increasing due to housing developments, but educational infrastructure has not yet caught up.

However, inspection of the Choropleth map of school counts per mukim reveals that these areas have a similar number of schools compared to their neighboring mukims. This suggests that while the absolute number of schools may not be unusually low, the rapid increase in population within these new housing areas may have outpaced school capacity, leading to a situation where demand exceeds supply within these specific zones.

Nevertheless, this situation represents a strategic opportunity. Prioritizing school construction in these fast-growing neighborhoods could significantly improve access to education, reduce commute times, lower transportation costs, and enhance the overall quality of life for residents. Locating schools closer to homes supports national goals related to sustainable urban development, walkability, and equity in public services.

Limitations

This study is limited to public schools, excluding private and international institutions that may affect school availability in some areas. The data is from 2018, potentially missing recent changes, especially in fast-growing neighborhoods. It also does not account for school types (e.g., primary vs. secondary) or age-specific population data, which are important for demand estimation. Housing price was used as a proxy for socioeconomic status, but data relies on listing prices, which may not reflect actual market values due to negotiation factors. In some areas, price data was also simulated, introducing further uncertainty.

Conclusions

In summary, the analysis reveals a negative relationship between population size and relative school abundance, suggesting urban areas have fewer schools per capita than rural ones. Several mukims in the Brunei-Muara District, including Sengkurong, Gadong A & B, Berakas B, and Mentiri, appear to have fewer schools than expected, despite ongoing population growth driven by new housing developments. While total school counts may seem adequate, local demand in these areas may exceed capacity. Addressing this gap offers a strategic opportunity to improve access, reduce travel time, and support equitable urban planning.

References