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[Chich-Ping Hu](#)*

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Article

Assessment from Multilevel Mixed-Effects Structural Equation Modelling into Urban Resilience

Chich-Ping Hu *

Department of Urban Planning and Disaster Management, Ming Chuan University; chphu@mail.mcu.edu.tw

* Correspondence: chphu@mail.mcu.edu.tw; Tel.: (+886-2-033057001)

Abstract: The resilience of towns and cities refers to their ability to adapt and recover when confronted with pressures or challenges. This study employs ten variables as indicators to assess the resilience of urban areas by analyzing official data and constructing a multilevel mixed-effects structural equation model. The empirical findings demonstrate that enhancing resilience significantly influences urban service functions, such as strengthening healthcare systems, stabilizing the real estate market, and addressing socio-economic challenges. Specifically, factors such as healthcare resources, housing demand, population structure, and social security exhibit varying levels of resilience, which profoundly impact the spatial distribution of these factors and socio-economic development. Disparities in healthcare resource allocation, demographic aging trends, and shifts in the housing market closely correlate with resilience levels in different regions. Additionally, the study emphasizes that improving resilience not only boosts the reliability and security of urban services but also ensures that communities receive necessary support and protection during times of adversity. Consequently, policymakers should recognize the pivotal role of urban resilience in resource allocation and social equity, devising corresponding strategies to enhance the resilience of these areas.

Keywords: multilevel mixed-effects structural equation modelling; urban resilience; urban service functions; real estate market; social equity

1. Introduction

Taiwan, situated in a seismically active zone, grapples with around 239 earthquakes of magnitude 5 or higher annually, alongside 3 to 4 significant typhoons. Flooding threats are exacerbated by rapid urbanization, environmental degradation, and looming climate change. Recent studies suggest climate change could heighten flood risks, particularly in the island's northern and southern regions, and central and southern coastal areas. Taiwan's response has been anchored in resilience, acknowledging disasters as inherent and emphasizing preparation and adaptation. This resilience is fortified by stringent building codes, early warning systems, and community engagement. Integrating indigenous knowledge into disaster management further strengthens Taiwan's approach, serving as a model for sustainable development.

The 7.4 magnitude earthquake off Hualien's coast on April 3, 2024, underscores Taiwan's perpetual vulnerability to natural disasters. However, commendable community resilience has been evident in the swift emergency response and recovery efforts. Harnessing indigenous knowledge and local experience bolsters disaster management effectiveness. These measures, coupled with international cooperation, highlight the importance of multifaceted resilience strategies.

2. Materials and Methods

Taiwan must now assess its towns and cities' resilience comprehensively to confront future challenges effectively. Urban resilience, critical for sustainable development, requires equitable access to resources, resilient infrastructure, and inclusive growth. Collaborative efforts among governments, communities, and international organizations are imperative to foster resilience.

As the global population increasingly urbanizes, urban resilience becomes paramount, especially given cities' economic significance. Sustainable Development Goals emphasize urban resilience's foundational role, yet comprehensive initiatives remain scarce. The COVID-19 pandemic accentuates cities' vulnerability, emphasizing the need for long-term resilience planning. Assessing resilience through tools like the Towns and Cities Resilience Index can guide improvement efforts.

In Taiwan, the Multilevel Mixed-Effects Equation Model assesses resilience levels in towns and cities, identifying areas for enhancement and informing policy decisions. For instance, analyzing disease resistance during the COVID-19 pandemic highlights fluctuations in resilience levels over time. Such assessments are crucial for guiding sustainable development goals amidst dynamic risks and uncertainties.

The United Nations introduced the "2030 Sustainable Development Goals" (SDGs) in 2015, which consist of 17 primary goals encompassing 169 sub-goals and 230 indicators, directing global efforts towards sustainability. Among these goals, SDG 9 aims to "build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation," while SDG 11 aims to "make cities and human settlements inclusive, safe, resilient, and sustainable," with resilience as a central objective. The concept of resilience, initially proposed by [1], originates from physics as "the ability of a system to absorb disturbances and still retain its basic structure and function." Since then, resilience has found wide application in various research fields such as ecology, engineering, and disaster risk management.

Urban studies began incorporating resilience thinking relatively late, with more literature emerging around the turn of the century [2,3]. The concept of resilience in urban systems encompasses characteristics such as robustness, stability, flexibility, agility, coordination, redundancy, diversity, foresight, independence, connectivity, collaboration, adaptability, self-organization, creativity, innovation, efficiency, and equity [4, p. 14]. These characteristics interact and require balanced consideration, such as the trade-off between increasing in redundancy and loss in system efficiency. Sharifi [5] proposed a resilience assessment system for cities based on five dimensions: environmental resources, social welfare, economy, built environment and infrastructure, and governance and organization. Further integration was done by [3] to construct a comprehensive urban resilience assessment system consisting of five criteria and 122 indicators.

In light of the COVID-19 pandemic, urban resilience has become even more critical. Cities worldwide have faced challenges in responding to the pandemic and enhancing public health and disaster resilience. Resilient cities have shown better abilities to address pandemic-related challenges [6]. Factors such as housing, sanitation facilities, ventilation, and lighting directly affect the spread of COVID-19 [7], while stability and diversity increase economic resilience [8]. Engaging in community adaptation and disaster reduction plans strengthens social resilience [9–11].

The COVID-19 crisis has provided an opportunity for urban decision-makers to learn valuable lessons and build long-term resilience against natural or man-made disruptions. As one of the most destructive events to date, COVID-19 has highlighted the importance of resilient cities, with over 95% of cases occurring in urban areas [12].

Similarly, urban vitality is crucial for urban development. It is driven by urbanization, urban contraction, urban reconstruction, and revitalization, leading to urban regeneration. Urban vitality and urban resilience coexist within urban systems, each with its own set of indicators, some of which overlap [13]. The relationship between indicators and their measurements helps clarify the urban development system. Structural equation modeling and path analysis are common methods used in the literature to explain and predict variable.

2.1. Model for Framing Resilience

This article utilizes a multilevel mixed-effects structural equation model to establish a resilience measurement system for towns and cities areas using data obtained from official websites (Figure 1). Figure 1 illustrates that this model includes a lower-level latent variable "resilience" to represent the lower-level resilience, indicating varying levels of resilience at the towns and cities level. A higher-level latent variable "resilience" is used to represent the resilience level at the county level. This model

displays that $x_1, x_2, \dots, x_n$ are measurement indicators of resilience. This can be expressed as follows (1):

$$\begin{aligned} z_1 &= \alpha_1 + \beta_1 Y + \gamma_1 M_{1,c} + \varepsilon_1 \\ z_2 &= \alpha_2 + \beta_2 Y + \gamma_2 M_{1,c} + \varepsilon_1 \\ &\vdots \\ z_p &= \alpha_p + \beta_p Y + \gamma_p M_{1,c} + \varepsilon_p \end{aligned} \quad (1)$$

where z_p represents the p -th resilience measurement variable in town and city area, Y denotes the resilience indicator, which is a latent variable. $M_{1,c}$ stands for the resilience indicator at the upper county level, and the resilience indicators for different towns and cities areas within the same county are identical. $\alpha_p, \beta_p, \gamma_p$ are parameters, and ε_p represents the error term.

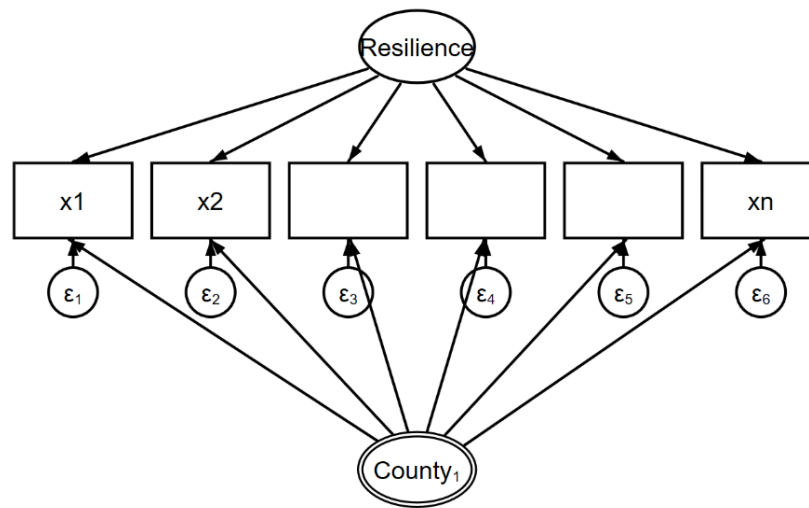


Figure 1. Multilevel mixed-effects structural equation model of town and city areas.

2.2. Prediction of Resilience for Local Districts

The aggregated value of towns and cities resilience indicators can be estimated using the equation: $z = \beta Y + \gamma M + \varepsilon$, assuming $z \sim N(\beta Y + \gamma M, \Psi)$. The logarithmic likelihood function is as follows (2):

$$\begin{aligned} \log L &= -\frac{p}{2} \log(2\pi) \\ &\quad - \frac{1}{2} \log(\Psi) \\ &\quad - \frac{1}{2} (z - \beta Y - \gamma M)^T \Psi^{-1} (z - \beta Y - \gamma M) \end{aligned} \quad (2)$$

where Ψ is covariance. The factor scores obtained after first-order condition derivation are as follows (3):

$$\hat{Y} = (\beta^T \Psi^{-1} \beta)^{-1} \beta^T \Psi^{-1} z \quad (3)$$

where $\hat{Y}$ is town and city area resilience that represents resilience index.

3. Results

The resistance to disease, which serves as an indicator of resilience, is employed to depict the capacity of towns and cities areas to withstand and endure health risks compared to other districts (Figure 2). Figure 2 illustrates that from September 22, 2022, to October 29, 2022, the number of confirmed COVID-19 cases in six direct-controlled municipalities, Hsinchu City, and Keelung City gradually increased in Taiwan. Conversely, during the same period, the number of confirmed COVID-19 cases in the United States steadily decreased, in contrast to the trend observed in Taiwan. Initially, cities and towns in Taiwan exhibited a higher level of resistance to the pandemic compared to the USA. However, this resistance gradually declined and fell below that of the USA between September 22, 2022, and October 29, 2022¹.

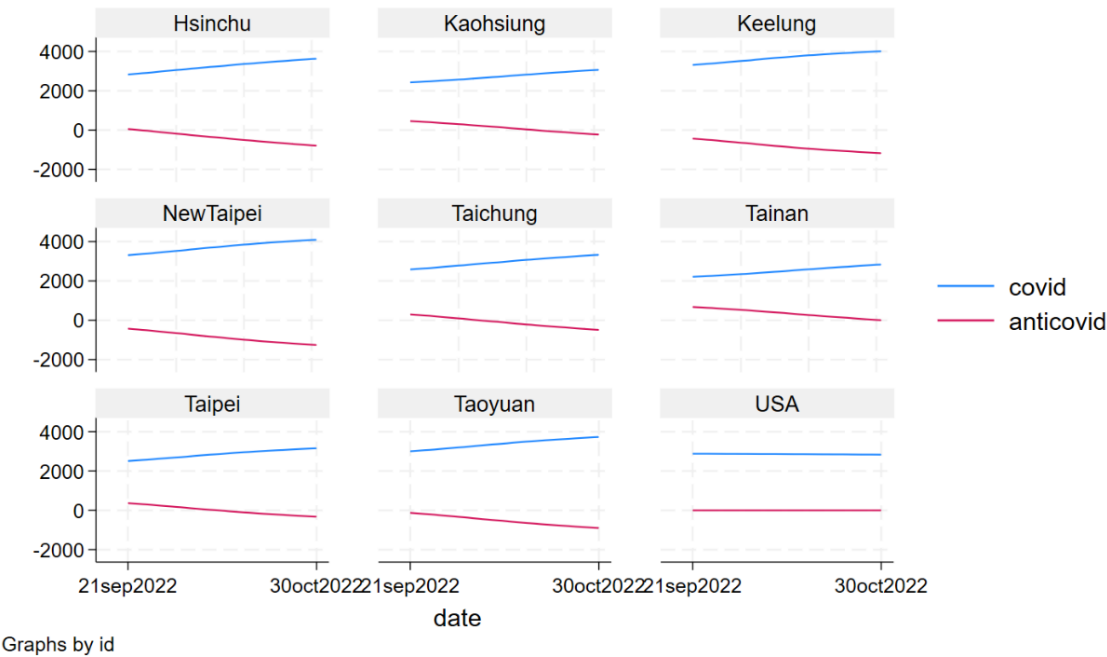


Figure 2. The time series of COVID-19 cases and disease resistance in Taiwan relative to the USA from September 22 to October 29, 2022.

3.1. Data and Variables

Town and city resilience pertains to the capacity of these locales to adapt and rebound when confronted with stress or challenges. This resilience can reshape the service functionalities of these regions. In urban settings, resilience can significantly influence the city's service functions, rendering them more adaptable and resilient. In rural areas, resilience can aid rural communities in more effectively tackling challenges in agriculture, the environment, and the economy (Table 1). Table 1 provides an explanation of the relevant variables, their definitions, and the implications of the data content.

1. Healthcare: Strengthening urban resilience can enhance the healthcare system by expanding the number of hospitals and beds, improving the capacity to address public health emergencies, and ensuring timely access to medical services during crises for residents.
2. Real Estate Market Stability: The improvement of town and city resilience may reinforce local economic and social stability, consequently positively impacting the real estate market. Stable economic and social conditions typically bolster confidence in the real estate sector, stimulating activities among homebuyers and investors and sustaining property prices.

¹ This article defines resistance to disease on COVID-19 as $RD_{it} = C_{At} - C_{it}$, where RD_{it} is level of resistance to disease on COVID-19 of city i of Taiwan on date t , C_{At} is the COVID-19 confirmed cases in the United States on date t and C_{it} is the COVID-19 confirmed cases in city i of Taiwan on date t .

Variable	Specification	Unit	Type	Data Source
low power	Number of residential households with average electricity consumption equal to or less than 60 kilowatt-hours per month in November and December each year	Dwelling Unit	Discrete	Ministry of Interior Real Estate Information Platform (https://pip.moi.gov.tw)

hospital	Number of hospital beds in medical institutions	Hospital Beds	Discrete	Social Economic Geography Information System (https://segis.moi.gov.tw)
	Average number of patients served per medical institution	Person	Continuous	Social Economic Geography Information System (https://segis.moi.gov.tw)
hospital beds	hospital beds per thousand people	Hospital Beds/1000 persons	Continuous	Social Economic Geography Information System (https://segis.moi.gov.tw)
dependency	The ratio of the population aged 0-14 to the population aged 15-64, multiplied by 100	-	Continuous	Social Economic Geography Information System (https://segis.moi.gov.tw)
	The ratio of the population aged 65 and above to the population aged 0-14,	-	Continuous	Social Economic Geography Information System (https://segis.moi.gov.tw)
ageing				

	multiplied by				
	100				
	Average price	Ten		Ministry of Interior Real	
housing price	of residential	Thousand	Continuous	Estate Information Platform	
	property	Dollars		(https://pip.moi.gov.tw)	
	Average area of	Square		Ministry of Interior Real	
building	residential	Meters	Continuous	Estate Information Platform	
	property			(https://pip.moi.gov.tw)	
	Total			Social Economic Geography	
disabilities	population with	Person	Discrete	Information System	
	disabled			(https://segis.moi.gov.tw)	
	Total number of			Social Economic Geography	
low income	low-income	Household	Discrete	Information System	
	households			(https://segis.moi.gov.tw)	

3.2. Discussion and Implications

This study utilizes data released by official agencies to select 10 variables as indicators of town and city resilience, constructing a multilevel mixed-effects structural equation model (Table 2). Table 2 indicates that variables such as "hospital," "hospital beds," "low power," "low income," and "disabilities" exhibit significant spatial distribution variations, suggesting significant disparities and uneven distribution of vacant resources, medical resources, and vulnerable groups across different districts. This unequal distribution primarily stems from differences in town and city resilience. Other variables such as "patients served," "aging," "housing price," "dependency," and "building" demonstrate lower spatial distribution variations, indicating a more even spatial distribution of medical service density, aging population, family burden, and housing services attributed to the resilience where they are. The selection of these variables is based on their appearance in the literature and availability in databases.

The town and city resilience in this study refers to the resistance and adaptation capabilities of communities or districts to various challenges and pressures. The established multilevel mixed-effects structural equation model in this study (Figure 3) illustrates the close correlation between different levels of town and city resilience and the unequal distribution of various resources. Figure 3 indicates the crucial role of town and city resilience in ensuring community development and equity. Moreover, town and city resilience also exhibits spatial distribution differences. Disparities in resource distribution may have profound implications for the socioeconomic development of regions. For instance, differences in the number of hospital beds and beds per thousand people may lead to certain areas facing shortages of medical resources, while unequal spatial distribution of low-income households and persons with disabilities may exacerbate social inequality.

Based on these explanations, policies addressing resource allocation issues can be formulated to improve or enhance town and city resilience. Utilizing maximum likelihood estimation, the estimation results of the model are obtained (Table 3 and Figure 4). Table 3 and Figure 4 present the estimation results of the multilevel mixed-effects structural equation model for the resilience of towns and cities in Taiwan, including coefficients of latent variables, variances, variances of errors, and logarithmic likelihood values. From the results, it can be observed that variables such as the number of low power consumption households, number of hospital beds, average number of persons served per medical institution, average number of beds per thousand people in medical institutions, dependency ratio, aging index, housing prices, average building area, total number of persons with disabilities, and low income households are significantly correlated with district resilience. The coefficients of resilience reach significant levels in each model ($p < 0.01$), indicating the significant influence of town and city resilience on these factors. Additionally, M1[countycode] representing the resilience of the county or city to which the town or city area belongs also significantly impacts these factors. However, except for housing prices and average building area, the impact of town and city resilience on factors is greater than that of county or city resilience. The variance of M1[countycode] is higher than that of town and city resilience, indicating significant differences in resilience between different counties or cities, and the spillover effect of resilience remains more pronounced within small area ranges. This may be related to the level of economic development and allocation of social service resources in each area.

Table 2. Descriptive statistics of variables.

Variable	Observation	Mean	Standard Deviation	Minimum	Maximum	Coefficient of Variation
low power	358	2400.204	2741.791	46	20232	1.142
hospital	358	650.900	1138.048	0	6365	1.748
patients served	358	2012.778	1248.217	281.16	9920	0.620
hospital beds	358	6.861	10.654	0	83.6	1.553
dependency	358	15.315	4.164	6.44	32.29	0.272
ageing	358	196.515	102.696	37.21	722.22	0.523
housing price	160	1028.074	456.170	323	3276	0.444
building	307	168.062	24.478	105	269	0.146
disabilities	358	3328.427	3500.517	122	23389	1.052
low income	358	404.5894	489.6498	20	3906	1.210

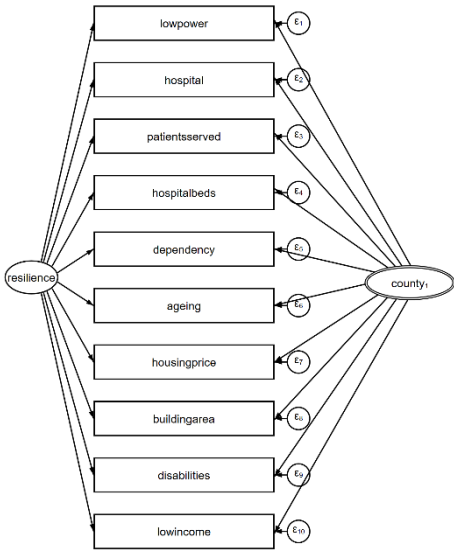


Figure 3. Multilevel mixed-effects structural equation model for resilience of town and city in Taiwan.

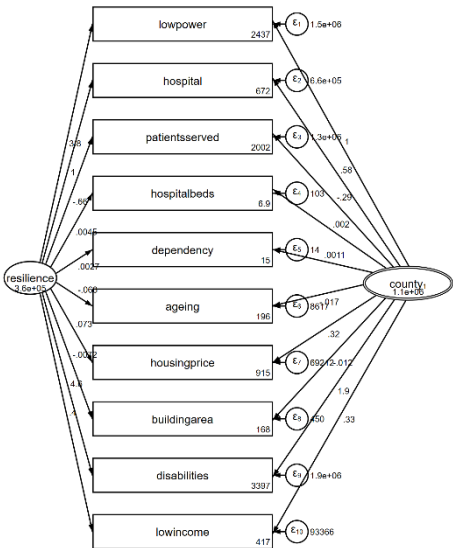


Figure 4. Empirical results of research on multilevel mixed-effects structural equation model of resilience of town and city in Taiwan.

Table 3. Estimation of multilevel mixed effects structural equation model on town and city resilience in Taiwan.

Variable	Coefficient	Standard Deviation
low power		
M1[countycode]	1	
resilience	3.783***	0.327
constant	2437.141***	278.345
hospital		
M1[countycode]	0.581***	0.083
resilience	1	
constant	672.363***	150.580
patients served		
M1[countycode]	-0.287***	0.077
resilience	-0.662***	0.118
constant	2002.172***	94.871
hospital beds		
M1[countycode]	0.002***	0.001
resilience	0.004***	0.001
constant	6.935***	0.738
dependency		
M1[countycode]	0.001***	0.000
resilience	0.003***	0.000
constant	15.357***	0.348
ageing		
M1[countycode]	-0.017***	0.006
resilience	-0.068***	0.010
constant	195.887***	6.768
housing price		
M1[countycode]	0.325***	0.055
resilience	0.073**	0.034
constant	914.897***	82.871
building		
M1[countycode]	-0.012***	0.002
resilience	-0.007***	0.002
constant	168.319***	3.194
disabilities		
M1[countycode]	1.859***	0.197
resilience	4.563***	0.393
constant	3397.088***	478.776
low income		
M1[countycode]	0.331***	0.047
resilience	0.402***	0.041
constant	416.805***	82.707
Var(M1[countycode])	1136491	
Var(resilience)	360776.9	
Var (e. low power)	1532138	
Var (e. hospital)	660546.4	
Var (e. patients served)	1329641	
Var (e. hospital beds)	102.792	
Var (e. dependency)	13.581	
Var (e. ageing)	8617.395	
Var (e. housing price)	69221.59	
Var (e. building)	450.301	
Var (e. disabilities)	1942738	

Var (e. low income)	93365.51
Log likelihood	-22032.252

***: p<0.01, **: p<0.05, *: p<0.1.

4. Discussion

Based on the substituted values of town and city variables into Equation (4), resilience indices are computed, and then presented using ArcGIS maps (Figures 5–8). These figures from 5 to 8 depict different regions (such as townships, districts, and counties) along with their corresponding resilience index values. These values are used to classify regions into categories such as high resilience areas, low resilience areas, hotspots, and cold spots. The analysis reveals that high resilience areas are mainly concentrated in the plains of the northern, central, and southern regions, while low resilience areas are distributed in the central mountain range and eastern regions.

Furthermore, specific areas such as Taipei City, New Taipei City, Chiayi City, and Taichung City are described in terms of their resilience status, along with some hotspots, cold spots, and areas potentially affected by overflow effects. Finally, the study also describes the distribution of overall county-level resilience hotspots.

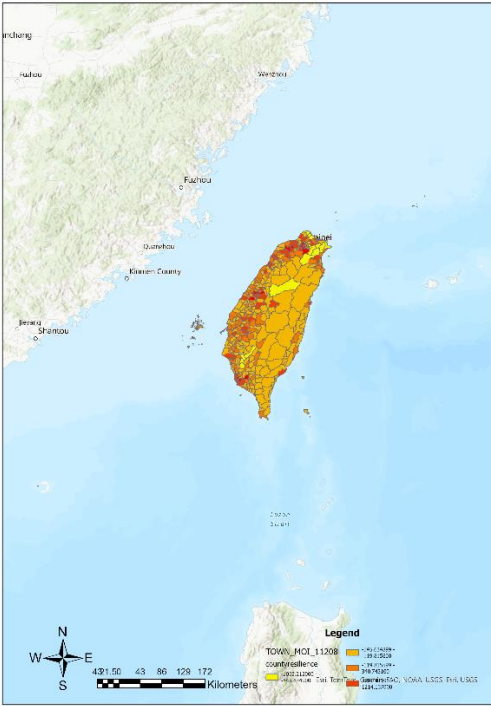


Figure 5. Resilience index distribution of urban and town areas in Taiwan.

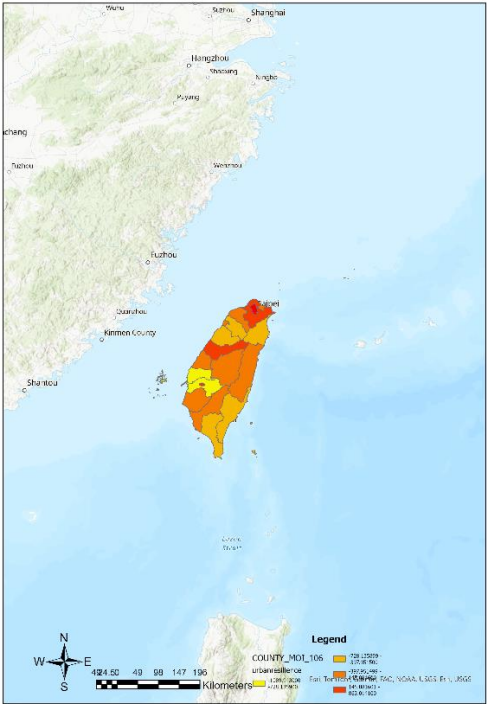


Figure 6. Resilience index distribution of city areas in Taiwan.

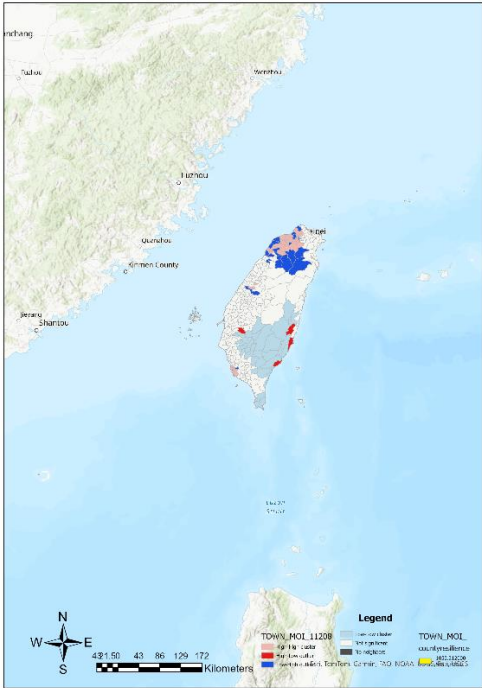


Figure 7. Local indicators of spatial association distribution of resilience indices of urban and town areas in Taiwan.

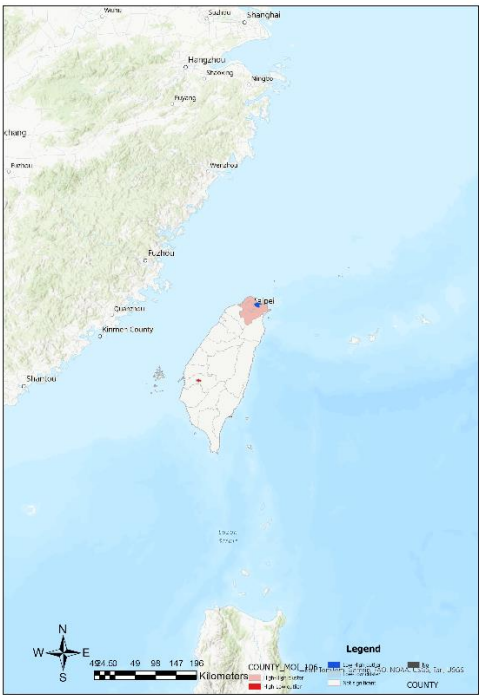


Figure 8. Local indicators of spatial association distribution of resilience indices of city areas in Taiwan.

5. Conclusions

This study utilizes data released by official agencies to filter out ten indicators of town and city resilience and establishes a multilevel mixed-effects structural equation model. The results of the model show that town and city resilience is closely related to the unequal distribution of various resources, including vacant houses, medical resources, and vulnerable populations. Town and city resilience plays a crucial role in community development and equity, exhibiting spatial variations. The model estimation results obtained through maximum likelihood estimation indicate significant correlations between multiple factors and regional resilience, with town and city resilience having a greater impact on factors than county-level resilience. Improvement in town and city resilience may lead to an increase in the number of vacant houses and hospital beds but is negatively correlated with the average number of individuals served per medical institution. Differences in town and city resilience are closely related to changes in the dependency ratio, aging index, residential prices, average building area, total number of disabled individuals, and number of low-income households. These results highlight the importance of town and city resilience for socio-economic development and equity and propose policy recommendations to enhance town and city resilience for promoting sustainable development and social equity across regions.

Below are some recommendations based on the analysis of town and city resilience:

1. Policy for Equal Resource Allocation: Given the disparities in town and city resilience and unequal resource distribution revealed by the analysis, the government can formulate corresponding policies to ensure equitable distribution of resources between town and city areas, especially in healthcare, education, and infrastructure development.
2. Strengthening Healthcare Services in Rural Areas: Considering the relatively lower service population of medical institutions in rural areas, the government can enhance investment in healthcare resources in rural areas to improve the accessibility and quality of healthcare services, thus reducing the urban-rural healthcare gap.
3. Promoting Balanced Urbanization and Rural Development: As urbanization progresses leading to population decline and increased vacant houses in rural areas, the government can promote balanced urbanization and rural development through policy implementation to enhance employment opportunities and living conditions in rural areas, thereby reducing population outflow.

4. **Diversification of Economic Development:** Uneven economic development is one of the significant factors contributing to differences in town and city resilience. The government can promote diversification of economic development to enhance the economic vitality of rural areas, reduce poverty, and improve overall societal resilience.
5. **Enhancing Social Security and Welfare Policies:** Given the income and social welfare disparities between town and city areas, the government can strengthen social security and welfare policies to improve the living standards of low-income households and vulnerable groups, thus reducing social inequality.
6. **Assessment and Monitoring of Regional Resilience:** The government can establish an assessment and monitoring system for town and city resilience to periodically assess and monitor the resilience levels of various regions, promptly identify issues, and formulate corresponding response measures.

In summary, the government can formulate policies and measures tailored to the characteristics and needs of different regions to promote the enhancement of town and city resilience, thereby achieving comprehensive, coordinated, and sustainable development.

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