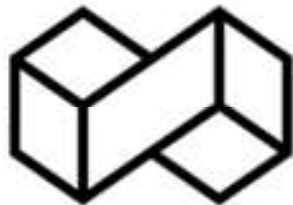


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# **Interdisciplinary Research Review**

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# Interdisciplinary Research Review

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3. To stimulate and support education at the university level

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# Editorial Note

The Interdisciplinary Research Review (IRR) was established with academic cooperation by The Royal Society of Thailand Committee of Interdisciplinary Research and Development, Rajabhat University (Western Group), and Rajamangala University of Technology Rattanakosin. This Issue, Volume 21, No. 4, July – August 2026. This issue contains of five interesting articles in multidisciplinary fields: (1) Development of groundwater management system in Thorthongdaeng Irrigation Project of Thailand,(2) Green Office Method to Low Carbon Office: A Pathway for Thailand's Sustainable Future ,(3)Urban Expansion and Provincial Economic Convergence in Thailand: A Satellite-Based Rank-Size and System GMM Analysis, (4) Analysis of Inflectional Morpheme Use in the Written Compositions of Pre-Service Teachers ,(5) AI-Supported Learning, AI Dependency, and Academic Stress as Predictors of Student Burnout,(6) Praying the Psalms of Anger: A Theological and Exegetical Study of Psalm 137.

The Editorial Board of the IRR encourages anyone to submit articles for evaluation and review. The processes of submission, review and publication of articles are described on the journal's website, <https://www.tci-thaijo.org/index.php/jtir>. The Editorial Board and Committees of the IRR sincerely thank all peer reviewers who have sacrificed their time to help us produce a better journal, and also wish to thank all teachers, researchers and other academicians for submitting their valuable research to this journal. Finally, we thank readers of our journal who help to spread the knowledge and benefits gained to others. With your feedback and suggestions, we will strive to improve the quality and relevance of the IRR.

Yongyudh Vajaradul  
Editor  
Interdisciplinary Research Review



# Development of groundwater management system in Thorthongdaeng Irrigation Project of Thailand

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## Abstract

Thorthongdaeng irrigation project is water storage pond type, located in the upper central region of Thailand. It was found that there was groundwater pumping during the period that the surface water resource is insufficient in the dry seasons. However, the development of groundwater management system for estimating groundwater quantities in various scenarios does not exist for the irrigation project. This study was done to develop the groundwater management system containing the groundwater modeling and monitoring. The groundwater pumping test data was analyzed to determine the hydraulic conductivity, transmissivity and storativity. The groundwater model was calibrated, verified and applied to estimate the annual groundwater use, potential and recharge in the dry, normal and wet years, within the 3 aquifer layers and the 3 irrigation zones. The average annual potential groundwater of 171 million cu.m. was nearly 3 times more than the average annual groundwater uses of 66.5 million cu.m. The average annual groundwater recharge of 64 million cu.m. was almost equal to the annual groundwater uses of 65 million cu.m. However, there should be caution in using and monitoring groundwater in the irrigation zone 1 and zone 2 due to the groundwater use exceeding the groundwater recharge. The groundwater levels in Khampaengphet province had the trend to be rather constant while the groundwater levels in Sukhothai province and Phitsanulok province had the trend to decrease. The groundwater management criteria and the measures to manage the groundwater appropriately and sustainably were set up and presented.

**Keywords:** Groundwater management, Groundwater modeling, Groundwater monitoring, Thorthongdaeng irrigation project

**Article history:** Received 30 June 2026, Revised 10 July 2026, Accepted 25 July 2026

## 1. Introduction

Thorthongdaeng irrigation project is water storage pond type, receiving water from Ping river to the agricultural areas in the provinces of Khampaengphet, Sukhothai and Phitsanulok. It was found that in this region there was groundwater pumping to be water reserve to every water use sector such as comsumptive use, industrial use and agricultural use particularly during the period that the surface water resource from the irrigation water or storage pond was insufficient in the dry seasons. However, there is no development of groundwater management system for estimating groundwater quantities in various scenarios in this irrigation project. This situation causes unable to estimate the

groundwater quantity with reliability and manage the groundwater according to the water years [1-2]. The groundwater management system will be an important tool to estimate and manage the groundwater to be conjunctive use with the surface water appropriately [3-5].

Chulalongkorn University [3] studied the development of groundwater management system to improve conjunctive use water management system in the upper central region of Thailand covering 6 provinces. The groundwater model was developed using MODFLOW simulating 2 aquifer layers and applied to determine the groundwater use, potential and recharge. It was found that the groundwater use was less than the potential groundwater but exceeded the groundwater recharge from the rain and river within the

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study area, however receiving from the net boundary inflow from the surrounding region to avoid the water shortage. For the proportion of conjunctive use of annual surface water and groundwater uses, the total annual volume for all 6 provinces equals to 16,816 million cu.m., dividing into the surface water uses at 95.49% and the groundwater at 4.51%. Nevertheless, the groundwater plays a crucial role where the surface water is inadequate to meet the demand and help to reduce damage to crop production due to the water shortage.

Chulalongkorn University [4] studied the development of groundwater management system for planning improvement to improve conjunctive use water management system in the north of lower central region of Thailand covering 7 provinces. The groundwater model was developed using MODFLOW simulating 4 aquifer layers. The groundwater model was calibrated, verified and applied to determine the groundwater use, potential and recharge in the water years classified to be dry, normal and wet years. From the study results, the average annual groundwater use, potential and recharge were 440, 804 and 544 million cu.m. respectively, indicating the sufficiency of groundwater. In supplying water to the 7 provinces, the annual water supplies from surface water and groundwater amount to 7,344 and 470 million cu.m. respectively, totaling 7,814 million cu.m. On the proportion of the average annual water use type in the 7 provinces, the water uses mainly are the surface water at 94.37%, much more than the groundwater at 5.63%.

This study had the objectives to develop a groundwater management system containing groundwater modeling and monitoring in the Thorthongdaeng irrigation project, mainly receiving and using the surface water but also using the groundwater when the surface water was insufficient [5]. The groundwater model was developed and applied to estimate the groundwater use, potential and recharge to investigate the sufficiency of groundwater in the irrigation areas. The trends of the groundwater levels in the 3 provinces were investigated. In addition, the objectives include the groundwater management criteria and the recommended measures to manage the groundwater appropriately and sustainably.

## 2. Materials and Methods

### 2.1 Study Area

Thorthongdaeng irrigation project is located mainly in Khampaengphet province in the upper central region of Thailand. The irrigation project is the water storage pond type, receiving water from Ping river to the agricultural areas in the provinces of Khampaengphet, Sukhothai and Phitsanulok through the flow system of natural channels having water control structures along the channels. The project receives water through the water control gates at the entrance of Thorthongdaeng channel, supplying water to the irrigation areas of 883.85 sq.km. as shown in Figure 1. The irrigation project area is divided into 3 irrigation zones, zone 1 in the north (green), zone 2 in the east (yellow) and zone 3 in the south (red).

### 2.2 Groundwater Wells

The number of groundwater wells in the study area was referred from the data base collected by the Department of groundwater resources in the year 2019. The number of pumping groundwater wells amounted to 1,679 wells divided into 646 public wells and 1,033 private wells. The number of observation groundwater wells amounted to 18 wells divided into 9 recorder wells and 9 non recorder wells.

### 2.3 Methodology

The methodology contains the following steps.

- 1) Collect data such as meteorology, hydrology, geology, hydrogeology, groundwater level and use data.
- 2) Survey and install automatic groundwater monitoring and recording system.
- 3) Develop groundwater model using MODFLOW.
- 4) Apply the groundwater model to estimate the annual groundwater use, potential and recharge.
- 5) Set up the groundwater management criteria and the measures to manage the groundwater.

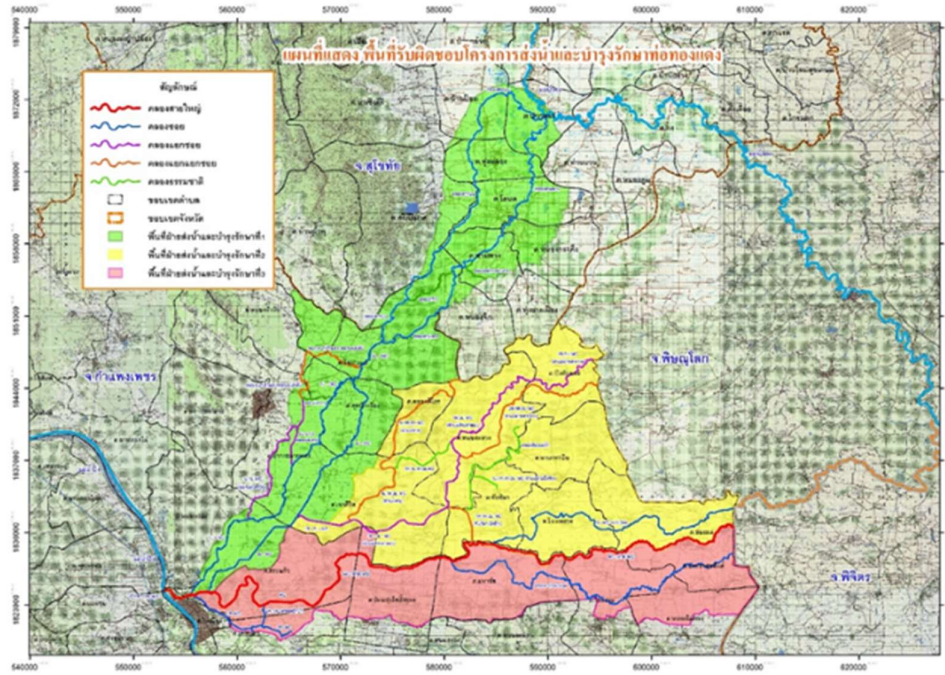


**Figure 1.** Thorthongdaeng Irrigation Project of Thailand.

## 2.4 Groundwater Flow Theory

The Darcy equation explains the groundwater flowing through the porous media as shown in Eq. (1).

$$V = -K \frac{\Delta h}{\Delta l} \quad (1)$$

Where  $V$  = flow velocity ( $LT^{-1}$ )

$K$  = hydraulic conductivity ( $LT^{-1}$ )

$\Delta h$  = difference in hydraulic head (L)

$\Delta l$  = distance along flow direction (L)

The general groundwater flow equation, derived from the conservation of mass (continuity equation) and Darcy equation, describes how water moves through porous media. The governing equation for transient (time-dependent) 3D flow in a heterogeneous, anisotropic medium is explained in the partial differential equation for the case of 3D flow as shown in Eq. (2). The numerical method by implicit finite difference is applied to solve the

groundwater flow equation in the form of system equation.

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \quad (2)$$

Where  $h$  = hydraulic head or groundwater level (L).

$K_{xx}$ ,  $K_{yy}$  and  $K_{zz}$  = hydraulic conductivity in  $x$ ,  $y$  and  $z$  directions ( $LT^{-1}$ ).

$S_s$  = specific storage ( $L^{-1}$ ), representing water released per unit change in head

$W$  = volumetric flux per unit volume as sources or sinks of water (recharge or pumping) ( $T^{-1}$ )

$t$  = time (T)

## 2.5 Groundwater Monitoring

The automatic groundwater monitoring and recording systems were installed at 9 locations at the existing groundwater observation wells as shown in Figures 2 and 3. The groundwater level measuring system through wireless system contains

- 1) sensor is located at the bottom or the specific depth within the well, measuring the groundwater level and sending the water level signal to the controller unit.

2) controller unit receives data from the sensor, processes and presents the result,

sends the data through the wireless network to the cloud system for data storage.

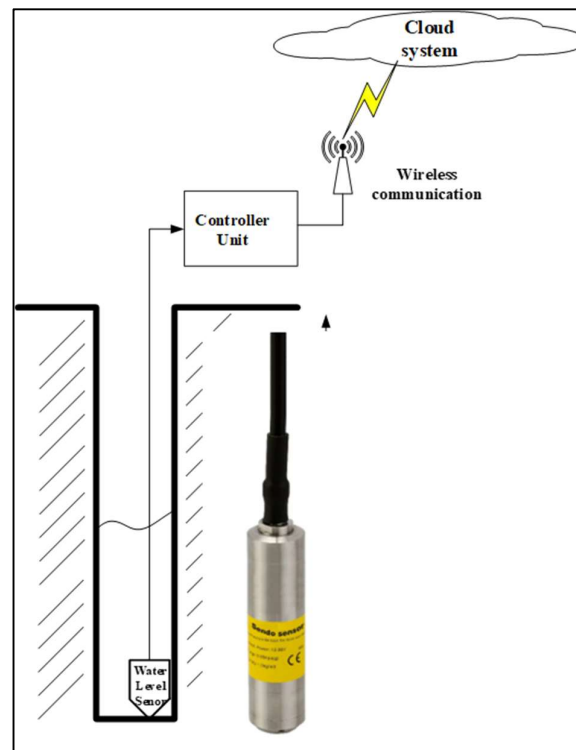


**Figure 2.** Function of automatic groundwater monitoring and recording system.



**Figure 3.** Installation of an automatic groundwater monitoring and recording system.

The principle of water level measurement of the groundwater level sensor is shown in Eq. (3).

$$P = P_0 + \rho gh \quad (3)$$

Where  $P$  = pressure on the sensor

$P_0$  = atmospheric pressure

$\rho$  = density of liquid

$h$  = depth of sensor related to water level

## 2.6 Groundwater Modeling

The groundwater model was developed containing 3 aquifer layers. The first, second

and third aquifer layers are in the depths below the ground surface of 10-40 m, 40-100 m and more than 100 m, respectively. Each aquifer layer was divided into a large number of grids or units of calculation area covering the study area. Each unit was rectangular shape with the small size of 0.5 km \* 0.5 km. as shown in Figure 4.

The boundary conditions of the groundwater model was set up based on the hydrogeological data on the cross sections. The model was calibrated in the steady state flow in the dry season in the year 2010 to calibrate the hydraulic conductivity (K). The model was calibrated in the transient state flow during the years 2011 -2016 to calibrate the transmissivity (T) and storativity (S). The model was verified by comparing the computed groundwater levels in the transient state flow to the observed data during the years 2017 -2020.

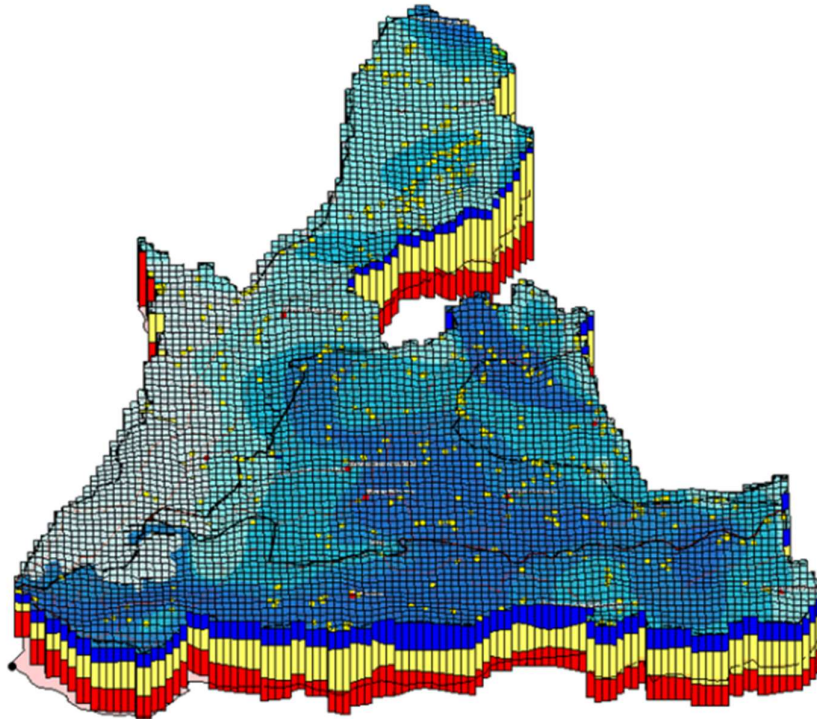
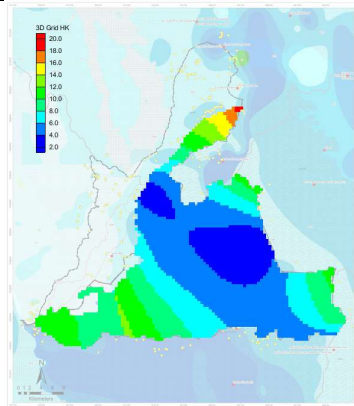


**Figure 4.** View 3D groundwater modeling of 3 aquifer layers with grid cells.

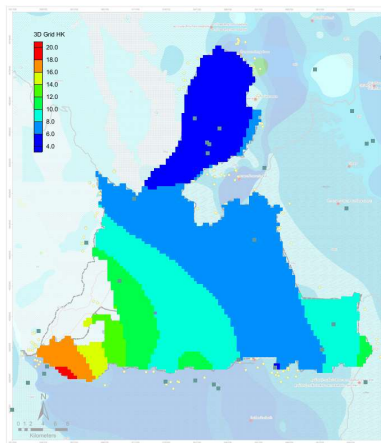
The data of groundwater pumping tests of 147 wells was used to determine the hydraulic conductivity distribution [5]. Table 1 shows the hydraulic conductivity (K), the transmissivity (T) and storativity (S) from the model calibration. Figure 5 shows the hydraulic conductivity distribution in each aquifer layer using Kriging interpolation. In the groundwater modeling using MODFLOW, HK stands for horizontal hydraulic conductivity. Figure 6 shows the comparison between the observed and simulated groundwater levels from the groundwater model verification.

**Table 1.** Hydraulic parameters of groundwater model.

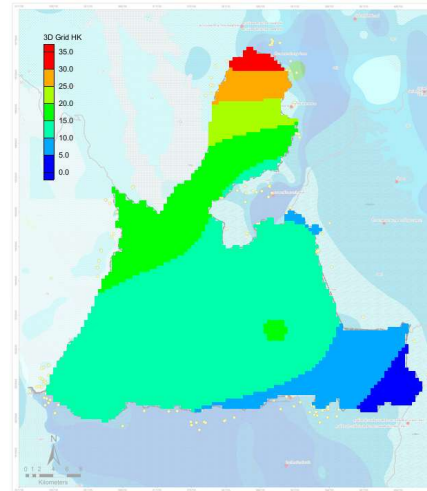
| Parameter                           | Min                   | Max   |
|-------------------------------------|-----------------------|-------|
| hydraulic conductivity (K) m/d      | 0.0216                | 704   |
| transmissivity(T) m <sup>2</sup> /d | 0.173                 | 2,820 |
| storativity (S)                     | $2.93 \times 10^{-6}$ | 0.584 |



aquifer layer 1



aquifer layer 2



aquifer layer 3

**Figure 5.** Hydraulic conductivity distribution.

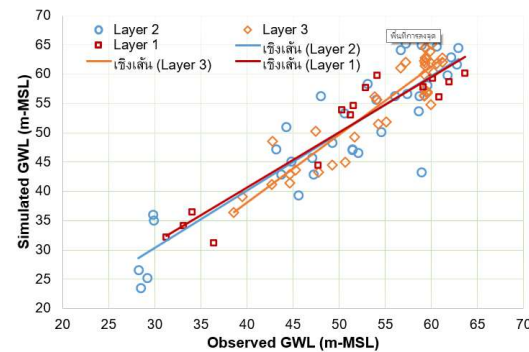


**Figure 6.** Comparison between observed and simulated groundwater levels during years 2017-2020.

## 2.7 Water Year Classification

The water years were classified to be the dry, normal and wet years according to the analysis of annual rainfall depth (P) data for 30 years. The dry year had  $P < 1,000$  mm/year, the normal year had  $P = 1,000$ -1,400 mm/year and the wet year had  $P > 1,400$  mm/year.

## 3. Result and Discussion

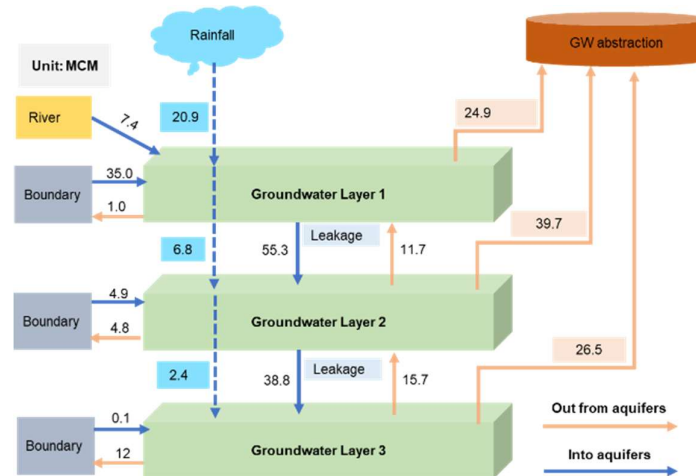
### 3.1 Groundwater Simulation Results

The groundwater model was applied to simulate the groundwater conditions in Thorthongdaeng irrigation project during the years 2010 – 2020.

Figure 7 presents the groundwater balance in the year 2020. Each aquifer layer gained inflow from the rainfall and river recharge and lost as outflow from the groundwater abstraction. The boundary flows were both inflow and outflow in each aquifer. The leakage flows between each pair of the two aquifer layers had the flow direction both downward and upward. The flows had the flow direction from the higher piezometric head to the lower piezometric head.

Figure 8 presents the annual groundwater abstraction or uses in the 3 irrigation zones during the years 2010-2020, varying widely in the range of 30-90 MCM.

Table 2 and Figure 9 present the average annual groundwater abstraction in the 3 irrigation zones and 3 water years. It is seen that every zone had almost equal groundwater abstraction volume in each of the water years. The groundwater use in the dry years was more than the groundwater uses in the normal and wet years. Classified according to the aquifer layers, the average annual groundwater uses were 17, 29 and 19 million cu.m. in the first, second and third aquifer layers respectively. The groundwater use from the second aquifer layer was more than the groundwater uses from the first and third aquifer layers.



(unit : MCM)

**Figure 7.** Groundwater balance in 3 aquifer layers in year 2020.

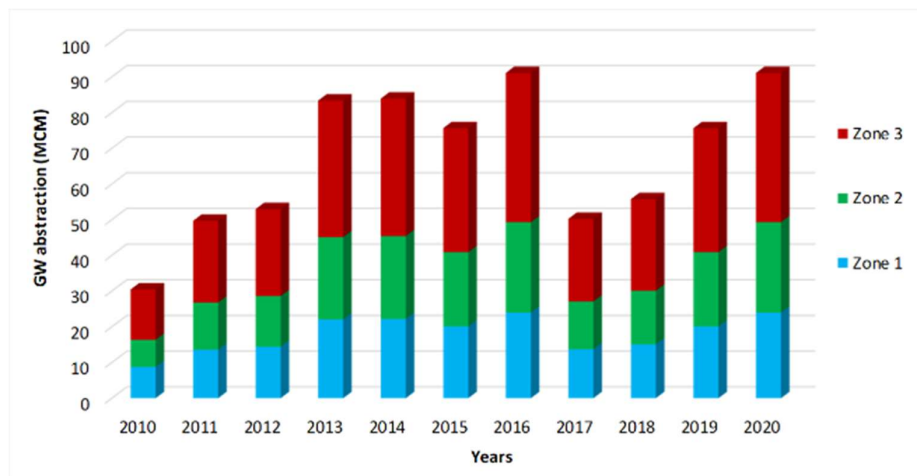


**Figure 8.** Annual groundwater abstraction during years 2010-2020.

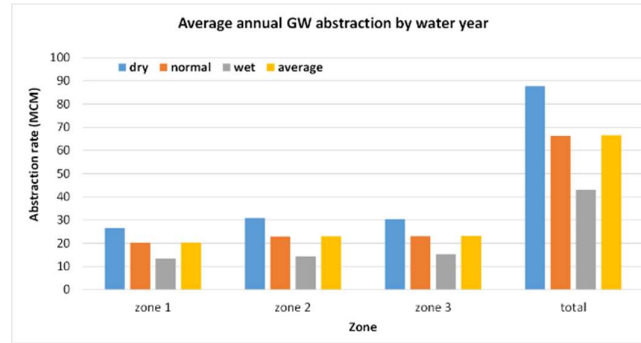


**Figure 9.** Average annual groundwater abstraction in irrigation zones and water years.

Figure 10 presents the relationship between the seasonal groundwater abstraction and the groundwater level at the seasonal end in the 3 irrigation zones. This relationship is useful

to estimate the seasonal groundwater abstraction to be used in the groundwater management.

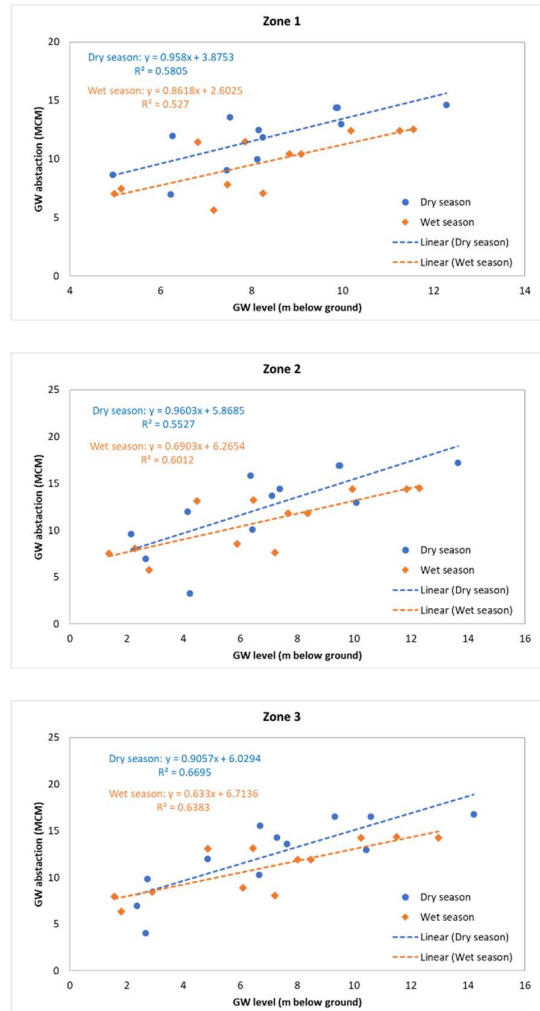


**Figure 10.** Seasonal groundwater abstraction and groundwater level at seasonal end.

Table 3 and Figure 11 present the average annual potential groundwater in the 3 irrigation zones and 3 water years. The zone 2 and zone 3 have almost equal potential groundwater and more than the zone 1 in each of the water years. Table 4 presents the average

annual potential groundwater in the 3 aquifer layers and 3 water years. The aquifer layer 2 has the most potential groundwater while the aquifer layer 1 and layer 3 have almost equal potential groundwater.

**Table 3.** Average annual potential groundwater in irrigation zones and water years.

| water year | potential groundwater<br>(million cu.m./year) |        |        |       |
|------------|-----------------------------------------------|--------|--------|-------|
|            | zone 1                                        | zone 2 | zone 3 | Total |
| dry        | 34                                            | 51     | 49     | 134   |
| normal     | 43                                            | 64     | 66     | 173   |
| wet        | 49                                            | 77     | 80     | 206   |
| average    | 42                                            | 64     | 65     | 171   |

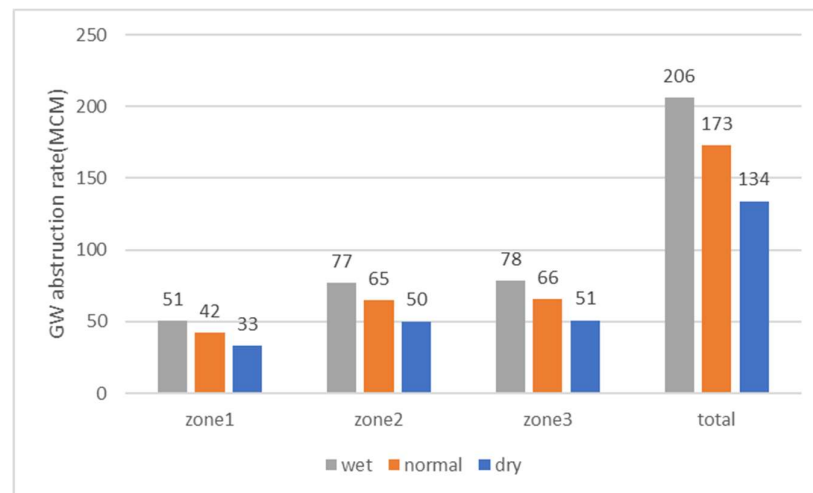


**Figure 11.** Average annual potential groundwater in irrigation zones and water years.

**Table 4.** Average annual potential groundwater in aquifer layers and water years.

| water year | potential groundwater<br>(million cu.m./year) |         |         |
|------------|-----------------------------------------------|---------|---------|
|            | layer 1                                       | layer 2 | layer 3 |
| dry        | 35                                            | 59      | 39      |
| normal     | 46                                            | 76      | 51      |
| wet        | 54                                            | 90      | 60      |
| average    | 45                                            | 75      | 50      |

Table 5 presents the average annual groundwater recharge in the 3 irrigation zones and 3 water years. The groundwater recharge depended on the rainfall amount and the soil moisture content in the study area and years. The groundwater recharge was highest in the wet year, followed by the dry year and the normal year, respectively. The groundwater recharge was very high in the zone 3 but very

low in the zone 1 and zone 2. Therefore, there should be caution in using and monitoring groundwater in the irrigation zone 1 and zone 2 due to the groundwater use exceeding the groundwater recharge. Classified according to the aquifer layers, the average annual groundwater recharge volumes were 44, 15 and 5 million cu.m. in the first, second and third aquifer layers respectively. The groundwater

recharge in the first aquifer layer, close to the ground surface receiving directly rain recharge, **Table 5.** Average annual groundwater recharge in irrigation zones and water years.

was much more than the groundwater recharge in the second and third aquifer layers.

| water year | groundwater recharge<br>(million cu.m./year) |        |        |       |
|------------|----------------------------------------------|--------|--------|-------|
|            | zone 1                                       | zone 2 | zone 3 | Total |
| dry        | 5.9                                          | 18.2   | 45.2   | 69.3  |
| normal     | 3.8                                          | 4.4    | 49.1   | 57.3  |
| wet        | 4.1                                          | 0.6    | 68.3   | 73.0  |
| average    | 4.6                                          | 7.2    | 52.7   | 64.5  |

Table 6 presents the comparison between average annual groundwater use, potential and recharge covering the 3 irrigation

zones in 3 water years and average of all water years 2010-2020.

**Table 6.** Average annual groundwater use, potential and recharge in water years.

| water year | annual groundwater<br>(million cu.m./year) |           |          |
|------------|--------------------------------------------|-----------|----------|
|            | ground water use                           | potential | recharge |
| dry        | 87.7                                       | 134       | 69.3     |
| normal     | 66.2                                       | 173       | 57.3     |
| wet        | 43.0                                       | 206       | 73.0     |
| average    | 66.5                                       | 171       | 64.5     |

Figure 12 presents the observed and simulated groundwater levels at Khampaengphet province during the years 2008-2020 [5]. In each year, the groundwater levels varied significantly in the range of 45-54

m due to groundwater pumping in dry season and recharge from rain in wet season. The trend of the groundwater levels, on the average during the study years, was rather constant, not changing.

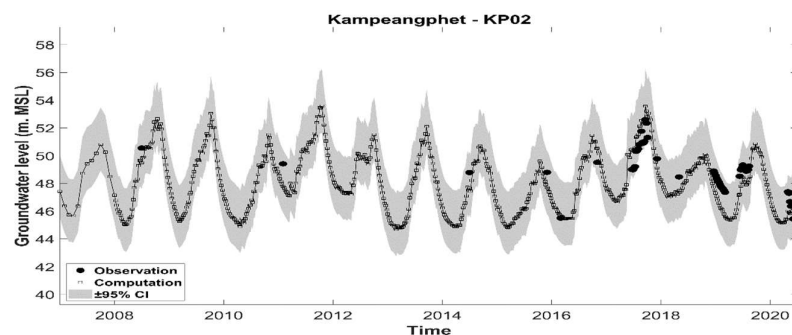


**Figure 12.** Observed and simulated groundwater levels at Kampeangphet province during years 2008-2020.

Figure 13 presents the observed and simulated groundwater levels at Sukhothai province during the years 2008-2020 [5]. In each year, the groundwater levels varied significantly in the range of 32-45 in the year 2008 and changing to the range of 25-36 m in

the year 2020. The groundwater levels had the trend of decreasing evidently with respect to time during the study years. This result indicated that the groundwater use exceeded the groundwater recharge significantly, thus

requiring to reduce the groundwater use to recover the groundwater level.

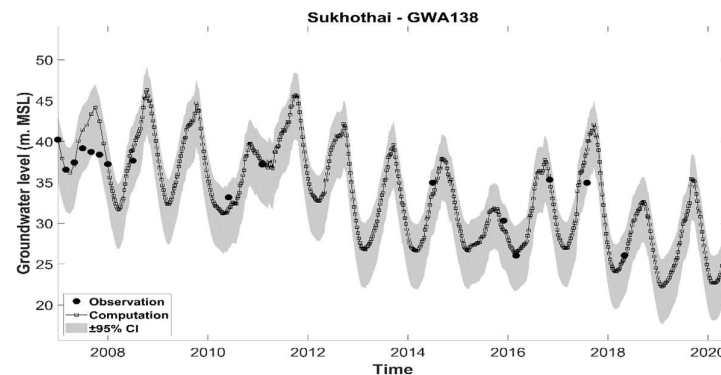


**Figure 13.** Observed and simulated groundwater levels at Sukhothai province during years 2008-2020.

Figure 14 presents the observed and simulated groundwater levels at Phitsanulok province during the years 2008-2020 [5]. In each year, the groundwater levels varied significantly in the range of 27-38 in the year 2008 and changing to the range of 18-33 m in the year 2020. The groundwater levels had the

trend of decreasing evidently with respect to time during the study years. This result indicated that the groundwater use exceeded the groundwater recharge significantly, thus requiring to reduce the groundwater use to recover the groundwater level.

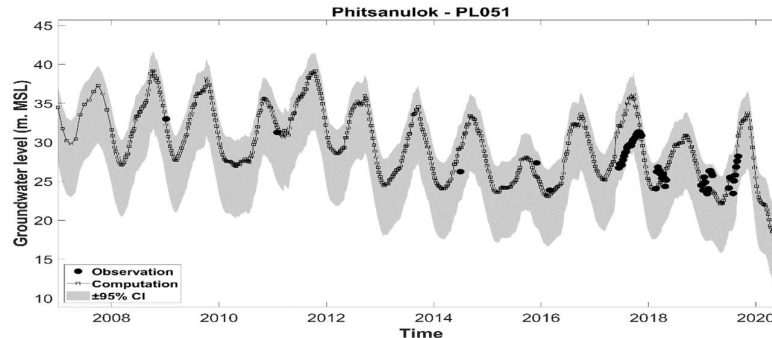


**Figure 14.** Observed and simulated groundwater levels at Phitsanulok province during years 2008-2020.

### 3.2 Groundwater Management Criteria

The groundwater management criteria to manage the groundwater appropriately and sustainably is set up as follows [3-5]

- 1) Specify groundwater to be water resource reserve to be used during the period that the surface water is insufficient to meet the water demand in order to reduce the damages to the crop production and other water use activities from water shortage.
- 2) Specify the available or potential groundwater based on the criteria that the groundwater depth does not exceed 20 m from the ground surface. This groundwater use limitation helps to prevent the loss of groundwater balance and recover the groundwater back to the normal level.
- 3) Use groundwater not exceeding the potential groundwater. Estimate the seasonal groundwater abstraction from the

graphs of relationship between seasonal groundwater abstraction and groundwater level developed for each province. Compare the groundwater abstraction to the potential groundwater in order to determine the sufficiency of groundwater.

- 4) Use groundwater not exceeding the groundwater recharge from rainfall, rivers and nearby aquifers in order to maintain the groundwater balance between the groundwater use and groundwater recharge, leading to sustainable groundwater use.

### 3.3 Recommended Measures

To achieve more efficient groundwater management, the following measures are recommended to be done [6].

- 1) Utilize the study results to be the database including the developed groundwater modeling and monitoring system at full capacity.
- 2) Install automatic groundwater measuring instruments covering the target region.
- 3) Install real time rainfall and river water level measuring instruments covering the target region.
- 4) Improve the model to simulate the interaction between groundwater and surface water.
- 5) Study research on groundwater recharge methods.
- 6) Develop and apply artificial groundwater storage such as groundwater bank.
- 7) Publish information and public warning in advance about groundwater crisis.

## 4. Conclusion

This study was done to develop groundwater management system for Thorthongdaeng irrigation project. The study results presented the groundwater management containing the groundwater well data, groundwater modeling and monitoring. The groundwater model was applied to estimate the groundwater use, potential and recharge according to each type of the 3 water years, the

3 aquifer layers and the 3 irrigation zones. For the whole irrigation zones, the average annual potential groundwater was nearly 3 times more than the average annual groundwater uses while the average annual groundwater recharge was almost equal to the annual groundwater uses, indicating the equilibrium or sustainable groundwater use condition. However, there should be caution in using and monitoring groundwater in the irrigation zone 1 and zone 2 due to very low groundwater recharge such that it is less than the groundwater use. The groundwater levels in Khampaengphet province had the trend to be rather constant while the groundwater levels in Sukhothai province and Phitsanulok province had the trend to decrease, requiring to reduce the groundwater use to recover the groundwater levels. The groundwater management criteria and the measures to manage groundwater appropriately and sustainably were set up and presented.

Considering the sufficiency of groundwater from this study and the previous studies [3-5], it was concluded that the groundwater use in the Thorthongdaeng irrigation project was sufficient in the zone 3 but had the risk of groundwater use exceeding the groundwater recharge in the irrigation zones 1 and 2. This study result indicates that the groundwater distribution in both groundwater use and recharge was different among the local scale areas as the irrigation zones 1 and 2 were vulnerable while the overall project-scale groundwater potential seemed adequate. Thus, the groundwater management should be considered in both the overall project-scale and the individual zone scale in order to prevent the excessive groundwater use and drawdown. The mitigation to solve the excessive groundwater drawdown is to reduce the groundwater use and increase the groundwater recharge to recover the groundwater level.

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# Green Office Method to Low Carbon Office: A Pathway for Thailand's Sustainable Future

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## Abstract

The Green Office Thailand has become an important mechanism for promoting environmentally responsible practices within organizations, such as reducing resource consumption and generating waste. However, in the context of global climate change and increasing pressure to reduce greenhouse gas emissions, organizations are expected to move beyond general environmental management toward more measurable and data-driven carbon reduction strategies. This study examines the role of the Green Office method as a pathway toward the development of Low-Carbon Offices in Thailand. The paper describes the principles of the Thailand Green Office standard, analyzes the concept of Low Carbon Office (LCO) buildings, and explores practical approaches for transitioning from conventional Green Office practices to carbon-oriented office management. Key strategies include carbon footprint assessment, the adoption of energy-efficient building systems, integration of renewable energy technologies such as rooftop solar photovoltaic systems, and the use of smart building technologies for energy monitoring and optimization. In addition, organizational factors such as leadership commitment, employee engagement, sustainable procurement, and behavioral change are identified as essential components in achieving long-term sustainability. The study also highlights future operational strategies, including digital building management, carbon credit mechanisms, circular economy practices, and nature-based solutions. The findings suggest that the transformation from Green Office to LCO represents a significant step toward strengthening organizational sustainability and supporting Thailand's national climate goals. By integrating technological innovation with sustainable organizational culture, offices in Thailand can significantly reduce environmental impacts while improving operational efficiency and contributing to the country's transition toward a low-carbon economy.

**Keywords:** Green Office, Low Carbon Office, Carbon footprint, Thailand, Building energy efficiency, Sustainability

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## 1. Introduction to the Green Office Standard of Thailand

The concept of a Green Office in Thailand has been promoted primarily by the Department

of Environmental Quality Promotion (DEQP), operating under the Ministry of Natural Resources and Environment. The initiative aims to encourage both public and private organizations to operate in a more

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environmentally responsible manner by reducing resource consumption, minimizing waste, and improving environmental management practices within office environments [1].

The Thailand Green Office Standard, commonly known as G-Green or G-Office certification, provides a structured framework for evaluating and improving environmental performance in offices [2]. The certification system categorizes organizations into three levels: G-Gold (Excellent), G-Silver (Very Good), and G-Bronze (Good). These levels serve as benchmarks that motivate organizations to progressively enhance their environmental practices and performance [3].

The Green Office framework evaluates offices across several key categories. These include organizational management, which emphasizes the establishment of clear environmental policies and leadership commitment from executive levels, and internal auditing, which involves regular monitoring and self-assessment of resource consumption and environmental performance [4]. Another important component is resource and energy management, focusing on improving efficiency in electricity, water, and paper usage to reduce operational environmental impacts [5].

In addition, the standard emphasizes waste management, particularly through the implementation of the 3Rs principle: Reduce, Reuse, and Recycle to minimize waste sent to landfills and ensure proper segregation, including the safe handling of hazardous waste [6]. Offices are also encouraged to adopt green procurement practices, prioritizing the purchase of environmentally friendly products and services, such as those carrying eco-labels [7, 8].

Furthermore, the framework includes indoor environmental quality, which addresses factors such as air quality, lighting, and noise levels to ensure a healthy and safe workplace environment [9, 10].

Another critical element of the standard is continuous improvement, which involves environmental awareness training for employees, regular performance monitoring, and ongoing reporting of environmental outcomes [11]. Through these mechanisms, organizations are encouraged to develop a culture of environmental responsibility among staff and management.

In the broader national context, the Green Office initiative aligns with Thailand's strategic environmental and energy policies, including the *Thailand Integrated Energy Blueprint* (TIEB). Rather than focusing solely on resource conservation, the initiative reflects a shift toward a more holistic sustainability model that integrates environmental protection, social responsibility, and economic efficiency [12]. . As global attention increasingly focuses on climate change mitigation, the Green Office standard is also evolving. While the existing framework emphasizes environmental management processes and resource efficiency, there is a growing expectation for offices to transform into low-carbon organizations, placing greater emphasis on measurable greenhouse gas reduction and carbon-equivalent metrics [13].

## **2. Principle of Low-Carbon Office Building**

A Low Carbon Office (LCO) building refers to an office building designed and operated to minimize greenhouse gas (GHG) emissions throughout its entire lifecycle from construction and operation to maintenance and eventual decommissioning [14]. Unlike a conventional green office that mainly emphasizes environmental management practices, a LCO focuses on quantifiable carbon reduction and the concept of carbon balance, where organizations measure and manage their emissions using data-driven approaches [15, 16].

One of the most important principles of a low-carbon office building is energy efficiency, which forms the first pillar of carbon reduction. In tropical climates such as Thailand, energy consumption in office buildings is dominated by cooling demand. Air-conditioning systems typically account for approximately 60–70% of total energy consumption. Therefore, optimizing the building envelope, including insulation, shading devices, and high-performance glazing, helps reduce heat gain and lower the cooling load [17,18]. Additionally, high-efficiency HVAC systems, such as Variable Refrigerant Flow (VRF) air-conditioning, together with LED lighting and smart controls such as motion sensors, significantly improve overall energy performance [19].

Another key principle is passive building design, which aims to reduce energy demand by

utilizing natural environmental conditions. Strategies such as natural ventilation, daylighting, building orientation, shading devices (e.g., overhangs and louvers), and insulated glass help reduce reliance on mechanical cooling and artificial lighting [20]. These passive strategies are particularly important in tropical regions where solar heat gain is a major contributor to building energy consumption.

In addition to improving efficiency, LCO buildings integrate renewable energy systems to reduce dependence on grid electricity. A common solution is the installation of rooftop Solar Photovoltaic (Solar PV) systems, which generate clean electricity directly from sunlight [21]. The integration of renewable energy transforms buildings from purely energy-consuming structures into partially energy-generating systems, thereby lowering operational carbon emissions [22]. A fundamental component of the LCO concept is the carbon accounting framework, where organizations calculate their greenhouse gas emissions based on energy consumption and emission factors. This carbon equation allows organizations to quantify emissions from electricity use, fuel consumption, and other operational activities, enabling them to track progress toward carbon reduction targets [23].

Furthermore, LCO buildings also consider the distinction between operational carbon and embodied carbon. Operational carbon refers to emissions produced during building use, such as electricity consumption for lighting, cooling, and equipment. In contrast, embodied carbon represents the emissions associated with the production, transportation, and construction of building materials. Consequently, material selection plays a significant role in reducing lifecycle emissions. Examples include the use of low-carbon materials, recycled steel, and locally sourced natural materials such as bamboo or clay, which generally require less energy to produce and transport [24]. Finally, water conservation strategies also contribute to sustainable office design. The installation of low-flow plumbing fixtures and rainwater harvesting systems for landscape irrigation helps reduce water consumption and the energy associated with water supply and treatment.

Overall, the transition from a Green Office to a LCO represents a shift from qualitative environmental management toward

quantitative carbon reduction strategies [14]. By integrating passive design, energy-efficient systems, renewable energy technologies, low-carbon materials, and resource conservation measures, low-carbon office buildings can significantly reduce greenhouse gas emissions and support broader climate mitigation goals [15].

### **3. Implementation of Green Office in Thailand toward a Low-Carbon Office**

The transition from a Green Office to a LCO in Thailand requires the following steps:

#### **1. Reducing the quantity of GHG emissions**

Organizations should practice beyond general environmental management toward quantifiable greenhouse gas (GHG) reduction strategies [25]. While the Green Office framework focuses on improving operational practices and resource efficiency, the LCO approach emphasizes data-driven management, carbon accounting, and measurable emission reductions across organizational activities [15].

#### **2. Carbon footprint assessment**

A critical step in this transition is the assessment of organizational carbon footprints. Many Thai organizations apply the Carbon Footprint for Organization (CFO) methodology developed by the Thailand Greenhouse Gas Management Organization (TGO). This framework enables offices to calculate and verify their annual greenhouse gas emissions from activities such as electricity consumption, fuel use, waste management, and transportation [23]. By quantifying emissions, organizations can identify major emission sources and establish effective reduction strategies [15].

#### **3. Digitalization of building management systems**

Another important element is the digitalization of building management systems. Modern offices increasingly integrate smart building technologies, including Internet of Things (IoT) devices, smart meters, and Building Management Systems (BMS), to monitor and control energy consumption in real time. These technologies allow lighting, air-conditioning, and other building systems to adjust automatically according to occupancy patterns. Real-time monitoring also helps identify abnormal energy consumption or “energy

leaks,” enabling immediate corrective action and improving overall energy efficiency [26].

#### 4. Retrofitting and upgrading building systems to improve environmental performance

In Thailand, many office buildings are existing structures (brownfield buildings) rather than newly constructed facilities. Brownfields are the result of changes in the functional use of the area and represent a huge environmental problem and a barrier to the spatial development of municipalities. Therefore, implementation strategies often focus on retrofitting and upgrading building systems to improve environmental performance. Examples include replacing outdated refrigerants such as R-22 with alternatives that have a lower Global Warming Potential (GWP), upgrading conventional air-conditioning systems to more energy-efficient technologies such as Variable Refrigerant Flow (VRF), and installing advanced energy monitoring equipment [19].

#### 5. Green Procurement

Another essential aspect of implementation is the integration of green procurement practices. Organizations are encouraged to select products and services with low environmental impacts throughout their lifecycle. This includes choosing energy-efficient office equipment, environmentally friendly cleaning chemicals, and eco-labeled products. Such procurement policies help reduce indirect emissions associated with supply chains [7,8].

#### 6. Behavioral Change

In addition to technological and managerial improvements, behavioral change among employees plays a significant role in achieving low-carbon objectives. Many organizations apply behavioral science approaches, such as “nudge” strategies, to encourage environmentally responsible habits [27]. These initiatives may include promoting the use of

stairs instead of elevators, setting air-conditioning temperatures at 25–26 °C, encouraging digital workflows to reduce paper consumption, and providing environmental awareness training programs for staff [28].

#### 7. Innovative Waste Management

Furthermore, some organizations in Thailand have implemented innovative waste management initiatives to support carbon reduction. Programs based on the concept of “Zero Waste to Landfill” aim to eliminate waste-related emissions through recycling, composting, and material recovery systems [6]. For instance, projects developed by organizations such as Kasikornbank demonstrate how office complexes can utilize food waste shredders to produce fertilizer and establish plastic upcycling platforms to reduce landfill waste [6].

Overall, the implementation of LCO practices in Thailand represents a transition from simple resource conservation to *integrated carbon management*. Integrated Carbon Management (ICM) is a holistic framework that integrates carbon accounting, operational efficiency, and emissions reduction technology. Organizations need to establish clear boundaries, identify all their emission sources, collect reliable data, and utilize verified emission factors to calculate their carbon footprint accurately. Greenly and similar platforms increasingly automate these processes, reducing complexity while improving accuracy. By combining carbon footprint assessment, smart building technologies, retrofitting strategies, sustainable procurement, waste reduction initiatives, and behavioral change programs, organizations can significantly reduce greenhouse gas emissions while improving operational efficiency and supporting national climate mitigation goals [25]. Figure 1 shows the steps of carbon footprint measurement and calculation.



**Figure 1.** Carbon footprint measurement and calculation.

#### 4. Sustainable Organization toward Green Office

A sustainable organization refers to an organization that integrates environmental responsibility into its core values, management systems, and daily operations. In the context of a Green Office, sustainability is not merely a technical or engineering challenge; rather, it is largely a cultural and organizational transformation. Successful implementation requires that environmental principles become embedded within the organization's corporate system ensuring that sustainability practices are continuously maintained rather than treated as temporary projects [3].

One of the most critical factors in building a sustainable organization is leadership commitment and governance. Strong support from top management provides the strategic direction, policy framework, and financial resources necessary to implement environmental initiatives. In many organizations, particularly small and medium-sized enterprises (SMEs) in Thailand, top-down leadership commitment has been identified as one of the most significant predictors of success in Green Office programs [29]. When senior management actively supports environmental policies and allocates budgets for sustainability initiatives, employees are more likely to participate and align their work practices with organizational sustainability goals.

At the same time, sustainability also requires active employee participation. Many organizations establish internal "Green Teams" or designate "Green Champions" within different departments to promote environmental awareness and encourage sustainable practices across the workplace. These teams help foster a bottom-up culture of sustainability, where employees feel a sense of ownership and responsibility for environmental initiatives [30].

Achieving a sustainable, climate-resilient organization requires systemic shifts across several core areas, such as accelerating clean energy and boosting climate resilience [31]. Another important aspect is the integration of sustainability into Environmental, Social, and Governance (ESG) frameworks. Increasingly, organizations align their Green Office practices with international sustainability reporting standards such as the Global Reporting Initiative (GRI). In Thailand, ESG reporting has

also become increasingly relevant for companies listed on the Stock Exchange of Thailand (SET), encouraging organizations to incorporate environmental management into their broader corporate governance and transparency practices [32].

In addition to structural and governance measures, behavioral strategies play a key role in promoting sustainable workplace practices. Many organizations apply principles from behavioral economics, particularly "nudge" strategies, to encourage environmentally responsible behaviors without imposing strict regulations [27]. Examples include setting default printer settings to double-sided printing, implementing thermostat controls that maintain air-conditioning temperatures at approximately 25°C, and designing office layouts that encourage the use of stairs instead of elevators (Rattanawit, 2019). These subtle interventions help reduce energy and resource consumption while maintaining employee comfort and productivity.

Furthermore, sustainable organizations often extend environmental responsibility beyond internal operations by promoting stakeholder engagement. This includes encouraging suppliers and business partners to adopt environmentally friendly practices and comply with green procurement standards. Such collaboration can create a broader "green network" effect, where sustainability principles are integrated throughout the entire value chain [7,8].

Finally, many organizations align their sustainability strategies with global frameworks such as the United Nations Sustainable Development Goals (SDGs) [32] (Chansomsak & Seggerman, 2022). By linking Green Office initiatives to these international sustainability objectives, organizations can strengthen their corporate reputation, enhance social responsibility, and attract environmentally conscious employees and stakeholders.

Overall, developing a sustainable organization toward a Green Office requires a comprehensive approach that integrates leadership commitment, employee engagement, ESG reporting, behavioral strategies, and stakeholder collaboration. Through these mechanisms, sustainability becomes an integral part of organizational culture and long-term operational strategy.

## 5. Recommendation for Future Operation

In the current complex global economy, sustainability has become a critical necessity that can be promoted with a shift towards renewable energy sources, the promotion of circular economies, and the pursuit of equitable and inclusive growth [33]. To support the long-term transition toward Low-Carbon Offices and a broader low-carbon economy in Thailand, organizations and policymakers must adopt more advanced strategies that integrate technology, policy support, and sustainable operational practices [14]. Future operations should move beyond basic resource efficiency toward innovative, data-driven, and systemic solutions that reduce greenhouse gas emissions while enhancing organizational resilience and environmental performance [25].

One important strategy is the adoption of advanced digital technologies in building management. Emerging concepts such as digital twins, virtual replicas of physical buildings, allow organizations to simulate energy consumption patterns and evaluate potential efficiency improvements before implementing them in real-world environments. Combined with Property Technology (PropTech) solutions, artificial intelligence (AI), and Internet of Things (IoT) sensors, building systems can automatically optimize lighting, air-conditioning, and other energy loads based on real-time occupancy data and weather conditions [26]. These technologies significantly improve operational efficiency and reduce unnecessary energy consumption.

Since retrofitting legacy infrastructure involves high capital expenditure, it presents a severe financial problem for SMEs in Thailand, so there should be an expansion of policy to address it, such as:

*Green financing instruments*, which are specialized financial tools used to channel capital toward environmentally sustainable projects, such as renewable energy, clean transport, and climate adaptation. These instruments help align financial assistance with low-carbon projects, fostering environmental benefits and sustainability goals [34]. Common instruments include:

*Green Bonds*: Debt securities issued by governments, banks, or corporations where the proceeds are strictly earmarked for environmental projects.

*Green Loans*: Lending facilities provided by financial institutions directly to borrowers to develop or overhaul business processes so they yield positive environmental benefits

*Sustainability-Linked Loans & Bonds*: Instruments where the terms (like interest rates) are tied to the borrower's achievement of predetermined sustainability performance targets or key performance indicators (KPIs) [35].

Another key recommendation is the expansion of carbon offsetting and carbon credit mechanisms. Organizations can participate in national carbon reduction programs such as the Thailand Voluntary Emission Reduction Program (T-VER), developed by the Thailand Greenhouse Gas Management Organization (TGO) (Thailand Greenhouse Gas Management Organization, 2024). Through this program, organizations can compensate for unavoidable emissions by supporting verified carbon reduction projects, thereby contributing to national climate mitigation goals [23].

In addition, offices should move toward decentralized and renewable energy systems. The development of micro-grids, where clusters of buildings share locally generated renewable energy, can reduce dependence on centralized electricity grids and improve energy security [21]. Integrating rooftop solar systems and shared energy storage solutions enables office districts to operate more efficiently and sustainably [22].

Operational strategies should also include flexible workplace models. The adoption of hybrid work arrangements, including remote or flexible working schedules, can reduce the overall demand for office space, commuting-related emissions, and energy consumption within buildings. This approach reflects the growing recognition that organizational carbon reduction can also be achieved through changes in work patterns and operational structures [28, 36]. Furthermore, organizations should adopt circular economy principles to reduce resource consumption and waste generation. Initiatives such as “Zero Waste to Landfill” aim to eliminate waste disposal through recycling, reuse, and material recovery systems. By

redesigning procurement practices and waste management processes, offices can significantly reduce emissions associated with waste treatment and landfill disposal [6].

Government policy also plays a critical role in accelerating this transition. Financial incentives, such as tax reductions, subsidies, or low-interest loans, can encourage building owners to retrofit aging buildings with energy-efficient technologies and renewable energy systems[28]. In addition, policymakers should work toward standard harmonization, aligning Thailand's Green Office and sustainability frameworks with international building standards such as LEED and TREES [32]. Such alignment would enhance international credibility and facilitate global collaboration in sustainable development [32].

Finally, future operations should also incorporate nature-based solutions (NbS) to address urban environmental challenges. Strategies such as rooftop gardens, green walls, and urban vegetation help reduce the urban heat island effect, improve air quality, and contribute to carbon sequestration within urban environments. These approaches complement technological solutions by integrating ecological processes into urban infrastructure.

Overall, achieving a low-carbon future for office operations in Thailand requires a comprehensive approach that combines technological innovation, policy support, organizational transformation, and environmental stewardship[14]. By adopting digital technologies, carbon markets, decentralized energy systems, circular economy practices, and nature-based solutions, Thai organizations can significantly accelerate their progress toward sustainable and climate-resilient office environments [25].

## 6. Conclusion

Thailand is currently at a critical turning point in its pursuit of sustainable development. The implementation of the Green Office standard has played an important role in raising environmental awareness and promoting resource conservation within organizations across the country. Through initiatives such as the G-Green certification, thousands of organizations have begun adopting environmentally responsible practices, helping to create a foundation for sustainable workplace

management. However, in the context of global climate change and increasing carbon constraints, these efforts must evolve beyond basic environmental compliance. The transition from Green Offices to LCOs represents the next phase of Thailand's sustainability journey. While the existing framework has successfully encouraged behavioral change and improved operational efficiency in many organizations, achieving deeper climate goals requires a shift toward quantitative carbon management and measurable emission reductions. This includes the adoption of carbon accounting systems, energy-efficient building technologies, renewable energy integration, and data-driven monitoring systems that enable organizations to track and reduce their greenhouse gas emissions more effectively. This transformation is closely aligned with Thailand's national development strategy, particularly the BCG Economy Model, which integrates Bio Economy, Circular Economy, and Green Economy principles to support sustainable economic growth. The transition to LCOs also contributes directly to Thailand's commitment to achieving carbon neutrality by 2050, requiring organizations to move from qualitative environmental management toward structured carbon reduction strategies. To reach these ambitious goals, a combination of structural, technological, and cultural changes is necessary. Offices must integrate passive architectural design strategies, energy-efficient building systems, and renewable energy technologies with advanced digital monitoring tools such as smart energy management systems. At the same time, fostering a strong organizational culture of sustainability remains essential to ensure long-term behavioral change among employees and stakeholders. Furthermore, collaboration between the public and private sectors will play a crucial role in accelerating this transition. Government policies, financial incentives, and regulatory frameworks should support innovation and encourage organizations to adopt low-carbon technologies and practices. At the same time, businesses must demonstrate agility and leadership by integrating sustainability into their core strategies and operations.

By combining innovative technologies, sustainable design principles, and a strong culture of environmental responsibility, Thailand has the potential to significantly

reduce the environmental impact of its office sector. Such efforts will not only lower operational costs and improve energy efficiency but also position Thailand as a regional leader in sustainable urban development and climate resilience within the ASEAN region. Ultimately, moving from compliance-driven Green Offices toward innovation-driven LCOs will be a key factor in achieving Thailand's long-term sustainability and net-zero ambitions.

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# Urban Expansion and Provincial Economic Convergence in Thailand: A Satellite-Based Rank-Size and System GMM Analysis

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## Abstract

This study jointly examines Thailand's urban size distribution and provincial economic convergence over 1995–2024, using multi-epoch satellite-derived built-up area for 77 provinces and gross provincial product (GPP) records for 76 provinces. Three empirical strategies correspond to three objectives: rank-size (Zipf's Law) analysis across six epochs, a test of Gibrat's Law of proportionate urban growth, and a dynamic panel System GMM model of GPP convergence. The Zipf exponent rises modestly from 1.158 (1995) to 1.206 (2020), indicating a stable but persistently primate urban hierarchy. Gibrat's Law is rejected ( $\beta = -0.0039$ ,  $p = 0.010$ ): smaller urban areas expanded faster than Bangkok, whose primacy index fell from 0.493 to 0.443. Cross-sectional beta-convergence in GPP is not significant unconditionally ( $p = 0.142$ ), and urban expansion is only marginally associated with GPP growth ( $p = 0.064$ ); however, once structural controls (initial population, agricultural share, distance to Bangkok, education) are added, the coefficient on initial GPP reverses sign and becomes significant ( $\beta = -0.0055$ ,  $p = 0.012$  including Bangkok;  $\beta = -0.0062$ ,  $p = 0.007$  excluding Bangkok,  $R^2 \approx 0.26$ – $0.28$ ), indicating genuine conditional convergence. The System GMM estimate of GPP persistence is near unity ( $\rho = 0.997$ ), implying a convergence speed of just 0.32% per year and a half-life exceeding two centuries. These results indicate that Thailand's urban system is deconcentrating physically, and that provinces are converging conditionally toward different structurally determined steady states even though absolute convergence is absent, with direct implications for secondary-city infrastructure investment and the use of open-access satellite data for subnational economic monitoring.

**Keywords:** Zipf's Law, Gibrat's Law, Urban primacy, Regional convergence, System GMM, Satellite built-up data

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## 1. Introduction

More than half of the world's population now lives in cities, and city-size distributions worldwide follow the rank-size, or Zipf's Law, regularity, whereby a city's rank is approximately proportional to the inverse of its size [1,2]. Because city-size distributions and urban growth are closely tied to how efficiently economic activity is spatially organized, departures from proportionate growth carry direct implications for national development [3]. Southeast Asia illustrates this tension sharply: regional income convergence coexists with persistent clustering of high-income

activity around primary cities [4,5], and cross-country evidence shows no uniform relationship between urban concentration and growth [6], motivating country-specific study. Thailand is a stark case: Bangkok has been the political, financial, and demographic core for over a century. Panel evidence identifies three distinct provincial convergence clubs rather than uniform catch-up [7], with agglomeration around Bangkok found to slow convergence relative to earlier-invested provinces [8]; remotely sensed built-up area has also been shown to track provincial GPP growth closely in

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Thailand [9], validating satellite data as a high-frequency indicator of subnational activity.

This relationship is grounded in established theory. Zipf's Law is the equilibrium outcome of proportionate urban growth [10]; primate-city concentration is systematically related to a country's stage of development [11,12], and New Economic Geography explains such concentration as the result of circular causation between manufacturing location and demand, with falling transport costs eventually favoring dispersal to the periphery [13]. Empirically, provincial GPP series in developing countries are compiled at low frequency and are prone to revision, motivating remotely-sensed proxies such as built-up area or nighttime lights [14,15]; the Global Human Settlement Layer programme now provides harmonized, multi-temporal built-up grids for this purpose [16,17]. On the convergence side, standard fixed-effects panel estimators are biased when the lagged dependent variable is included and the time dimension is short [18], a problem addressed by difference and system GMM estimators [19,20], the latter well suited to persistent, near-unit-root income series. No published study has combined multi-epoch satellite built-up data, joint Zipf-Gibrat rank-size testing, and dynamic panel System GMM convergence estimation for Thailand within a single framework. This combination is not merely a methodological convenience: the three strategies test related but distinct implications of the same underlying spatial growth process, so that agreement or disagreement among them is itself informative. This paper's central empirical contribution is to show that this triangulation matters in practice: an unconditional test finds no evidence of provincial income convergence in Thailand, yet a conditional specification informed by the same rank-size and proportionate-growth framework reveals that provinces do converge once structural characteristics are held constant, a distinction with direct implications for how targeted the country's regional development policy needs to be.

This paper addresses that gap by jointly examining Thailand's urban size distribution and provincial economic convergence between 1995 and 2024, pursuing three objectives: (1) to examine the rank-size (Zipf) distribution of Thailand's urban system across six epochs from 1995 to 2020 and assess its temporal stability; (2) to test Gibrat's Law of proportionate urban growth; and (3) to evaluate provincial economic convergence through cross-sectional beta-convergence and a dynamic panel System GMM model of GPP persistence over 1995–2024, extended with a conditional convergence specification incorporating structural controls. Section

2 describes the data and empirical specifications; Section 3 reports the results; Section 4 discusses the findings and their robustness; and Section 5 concludes with policy implications and limitations.

## 2. Materials and Methods

This section describes the data sources, variable construction, and empirical specifications used to test the three objectives stated above. The analysis proceeds from the physical (built-up area) to the economic (GPP) dimension of Thailand's spatial development, using rank-size analysis, cross-sectional regression, and dynamic panel estimation in turn.

### 2.1 Data sources and variable construction

Built-up surface area for 77 provincial-level administrative units of Thailand is drawn from the Global Human Settlement Layer built-up surface grid (GHS-BUILT-S R2023A), produced by the European Commission's Joint Research Centre from harmonized Sentinel-2 and Landsat composites at 100-metre resolution [21]; methodology and validation are documented in [16] and the earlier GHSL Data Package release [22]. Administrative boundaries follow the geoBoundaries open database. Built-up surface area is extracted for six epochs (1995, 2000, 2005, 2010, 2015, 2020) and aggregated to the provincial level. Provincial gross provincial product (GPP) at constant 2002 prices (chain volume measures) for 76 provinces is obtained from the Office of the National Economic and Social Development Council (NESDC) for 1995–2024. The cross-sectional analyses (Sections 3.1 and 3.5, Tables 1, 6–8) use these 76 provinces with complete 1995–2020 coverage; the dynamic panel System GMM model (Section 3.6, Table 9) additionally includes Bueng Kan, whose GPP series is unbalanced but partially available, for a total panel of 77 provinces. Ten provinces are classified as regional economic hubs (Chiang Mai, Chiang Rai, Khon Kaen, Nakhon Ratchasima, Udon Thani, Surat Thani, Songkhla, Phuket, Chon Buri, and Rayong), with Bangkok treated as a separate observation given its outsized scale.

### 2.2 Rank-size (Zipf's Law) and urban primacy

To examine the shape of the urban size distribution, provinces are ranked by built-up area within each epoch and the standard rank-size regression is estimated separately for each of the six epochs:

$$\ln(\text{Rank}_i) = \alpha - \zeta \cdot \ln(S_i) + \varepsilon_i \quad (1)$$

where  $\text{Rank}_i$  is the descending-order rank of province  $i$  by built-up area,  $S_i$  is built-up surface area, and  $\zeta$  is the Zipf coefficient. A value of  $\zeta = 1$  corresponds to the

pure rank-size rule;  $\zeta > 1$  indicates a system more concentrated at the top of the size distribution than pure Zipf predicts, and  $\zeta < 1$  indicates a more even distribution [10]. Urban primacy is further summarized for each epoch  $t$  using the conventional four-city primacy index,

$$PI_t = \frac{S_{1,t}}{S_{2,t} + S_{3,t} + S_{4,t}} \quad (2)$$

where  $S_1$  denotes the built-up area of the largest urban unit (Bangkok) and  $S_2$  through  $S_4$  denote the second-, third-, and fourth-ranked units, following [11].

### 2.3 Gibrat's Law of proportionate growth

Gibrat's Law of proportionate growth is tested by regressing each province's annualized 1995–2020 built-up growth rate on its initial (1995) built-up area:

$$g_i = \alpha + \beta \cdot \ln(S_{i,1995}) + \varepsilon_i \quad (3)$$

where  $g_i$  is the compound annual growth rate (CAGR) of built-up area between 1995 and 2020. Under strict Gibrat's Law, as originally formulated by [23], growth is independent of initial size and  $\beta = 0$ ; a significant negative  $\beta$  implies that smaller urban areas grow disproportionately faster, consistent with size convergence in the urban system [24]; [25].

### 2.4 Cross-sectional convergence models

Provincial economic convergence is first assessed with two unconditional cross-sectional ordinary least squares (OLS) regressions over 1995–2020, both estimated with heteroscedasticity-robust (HC1) standard errors to accommodate the small-sample, cross-sectional design. The classical beta-convergence specification is

$$CAGR_i = \alpha + \beta \cdot \ln(GPP_{i,1995}) + \varepsilon_i \quad (4)$$

where  $CAGR_i$  is the compound annual growth rate of provincial GPP,  $GPP_{i,1995}$  is initial GPP, and a significant negative  $\beta$  indicates convergence – poorer provinces growing faster than richer ones [26]. To assess whether physical urban expansion is associated with economic growth, a second specification regresses GPP growth on urban built-up expansion directly:

$$GPPCAGR_i = \alpha + \beta \cdot UrbanCAGR_i + \varepsilon_i \quad (5)$$

where  $UrbanCAGR_i$  is the 1995–2020 built-up area growth rate of province  $i$ .

### 2.5 Dynamic panel System GMM model

Because cross-sectional regressions cannot exploit the full time-series information in the 1995–

2024 GPP panel and are silent on year-specific shocks, a dynamic panel model is estimated using the two-step System Generalized Method of Moments (GMM) estimator of [20], implemented via Stata's `xtabond2` following [27]. Ordinary within-group or first-differenced estimators yield severely biased autoregressive coefficients when the lagged dependent variable is included and the time dimension is short [18]; System GMM [20], which augments the first-differenced moment conditions of [19] with levels equations, corrects this bias and suits the near-unit-root persistence found in provincial income series. The estimating equation is

$$\ln(GPP_{i,t}) = \rho \cdot \ln(GPP_{i,t-1}) + \sum_t \gamma_t \cdot D_t + \eta_i + u_{i,t} \quad (6)$$

where  $GPP_{i,t}$  is provincial GPP in year  $t$ ,  $\rho$  is the persistence parameter,  $D_t$  are year dummies (1997–2024, collapsed, GMM-style instruments lagged two to four periods),  $\eta_i$  is a province fixed effect removed by the System GMM transformation, and  $u_{i,t}$  is an idiosyncratic error. Instrument validity is assessed with the Hansen J-test [28], noting the caution of [29] that excessive instruments can render the test uninformative. From  $\rho$ , an implied convergence speed and income half-life are computed as

$$\lambda = -\ln(\rho), \quad t_{1/2} = \frac{\ln(2)}{\lambda} \quad (7)$$

All cross-sectional regressions were estimated in Python (`statsmodels`); the dynamic panel GMM model was estimated in Stata 18 using `xtabond2`.

## 3. Results

This section presents the empirical findings in three parts, moving from the physical size distribution of Thailand's urban system to its economic convergence properties. Descriptive statistics are reported first, followed by the rank-size (Zipf) and proportionate-growth (Gibrat) results, and finally the cross-sectional and dynamic-panel convergence estimates.

### 3.1 Descriptive statistics

Table 1 summarizes the built-up area and GPP variables across the 76 provinces with complete GPP series. Mean built-up area expanded from approximately 51 km<sup>2</sup> in 1995 to 88 km<sup>2</sup> in 2020, with an average annualized growth rate of 2.26%, while mean GPP grew at 2.64% per year over the same period. GPP's standard deviation is an order of magnitude larger than its mean, reflecting the extreme right skew introduced by Bangkok.

**Table 1.** Descriptive statistics of built-up area and gross provincial product (GPP), 76 Thai provinces, 1995 and 2020

| Variable                               | n  | Mean    | SD      | Min   | Max       |
|----------------------------------------|----|---------|---------|-------|-----------|
| Built-up area, 1995 (km <sup>2</sup> ) | 76 | 51.34   | 37.84   | 8.57  | 212.15    |
| Built-up area, 2020 (km <sup>2</sup> ) | 76 | 87.87   | 61.52   | 15.17 | 334.61    |
| Urban built-up CAGR, 1995–2020 (%/yr)  | 76 | 2.26    | 0.98    | 1.06  | 5.25      |
| GPP, 1995 (million baht)               | 76 | 66,841  | 226,178 | 4,547 | 1,963,319 |
| GPP, 2020 (million baht)               | 76 | 135,634 | 434,528 | 7,591 | 3,740,369 |
| GPP CAGR, 1995–2020 (%/yr)             | 76 | 2.64    | 1.24    | 0.03  | 8.90      |

### 3.2 Rank-size (Zipf's Law) distribution

Table 2 reports the estimated Zipf coefficient for each of the six epochs from 1995 to 2020, obtained

by regressing the log rank of each province's built-up area on its log built-up area.

**Table 2.** Estimated Zipf coefficient by epoch, Thai urban built-up areas, 1995–2020

| Epoch | Zipf coefficient ( $\zeta$ ) | SE <sup>a</sup> | R <sup>2</sup> |
|-------|------------------------------|-----------------|----------------|
| 1995  | 1.158                        | 0.0903          | 0.819          |
| 2000  | 1.181                        | 0.0892          | 0.819          |
| 2005  | 1.190                        | 0.0896          | 0.820          |
| 2010  | 1.196                        | 0.0897          | 0.821          |
| 2015  | 1.199                        | 0.0894          | 0.821          |
| 2020  | 1.206                        | 0.0886          | 0.817          |

Note: <sup>a</sup> SE for all six epochs derived from a bootstrap procedure (2,000 resamples per epoch, resampling provinces and re-estimating the rank-size regression), consistent with the paired bootstrap test of the 1995–2020 difference reported in Section 3.2. SEs are stable across epochs (0.089–0.090), and the corresponding 95% confidence intervals overlap substantially across adjacent epochs, reinforcing the conclusion in Section 3.2 that the rise in  $\zeta$  is not statistically significant.

**Table 3.** Five largest Thai provinces by built-up area, 2020

| Rank | Province          | Built-up area, 2020 (km <sup>2</sup> ) |
|------|-------------------|----------------------------------------|
| 1    | Bangkok           | 334.6                                  |
| 2    | Nakhon Ratchasima | 310.0                                  |
| 3    | Chon Buri         | 244.1                                  |
| 4    | Ubon Ratchathani  | 201.3                                  |
| 5    | Chiang Mai        | 175.4                                  |

The Zipf coefficient rises steadily and monotonically from 1.158 in 1995 to 1.206 in 2020, with model fit essentially unchanged ( $R^2 = 0.817$ – $0.821$ ) across all six epochs. Because  $\zeta$  exceeds unity throughout, Thailand's urban hierarchy is more concentrated at the top than a pure rank-size rule predicts, and this concentration intensified marginally over the 25-year window. This 1995–2020 change in  $\zeta$  is small in magnitude and not statistically distinguishable from zero: a paired bootstrap test (2,000 resamples, resampling provinces jointly across the two epochs) yields a mean difference of 0.046 with 95% CI  $[-0.055, 0.154]$ , and a pooled rank-size regression with a year-interaction term gives an equivalent interaction coefficient of  $-0.048$  (robust

SE = 0.154,  $p = 0.753$ ). The appropriate reading is therefore a stable rather than intensifying urban hierarchy across the sample period. Table 3 lists the five largest provinces by built-up area in 2020: Bangkok remains largest by a wide margin, followed by Nakhon Ratchasima, Chon Buri, Ubon Ratchathani, and Chiang Mai. Figure 1(a) shows that while the log-linear rank-size pattern is preserved, the entire distribution shifted outward as built-up area expanded. This stability mirrors the finding of [30] for the United States (1900–1990) and is consistent with the resilience of national Zipf structures to structural change documented by [31] for Germany. The question that follows is whether the underlying growth was

proportionate across the size distribution, as required by Gibrat's Law, or size-dependent. The use of the province, rather than the city proper, as the unit of rank-size analysis follows directly from [2]'s theoretical result that Gibrat's Law holding within any sub-national partition implies Zipf's Law at that same

spatial scale, a prediction confirmed empirically at the regional level for Germany [41] and, using spatial-econometric methods that account for inter-provincial dependence, for prefectural-level regions in China [42].

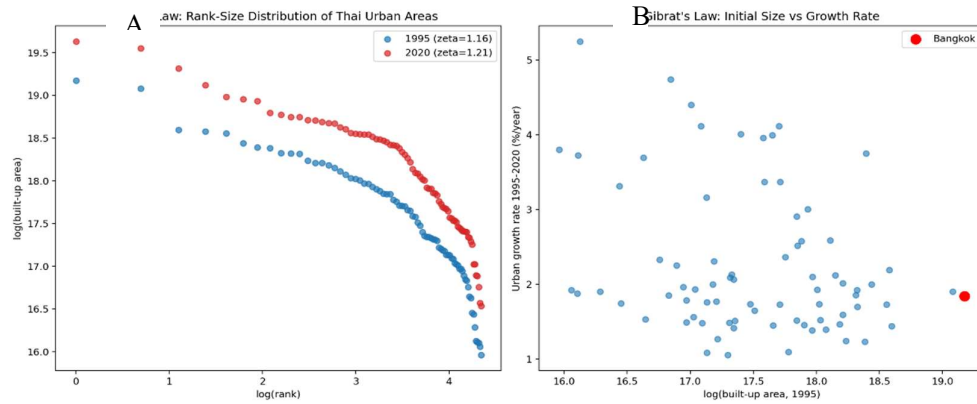


**Figure 1.** (A) Rank-size (Zipf) distribution of Thai urban built-up areas, 1995 and 2020; (B) Gibrat's Law scatter of initial built-up size (1995, log scale) against 1995–2020 urban growth rate, by province. Bangkok is marked separately in panel (B).

### 3.3 Gibrat's Law and proportionate urban growth

Table 4 reports the OLS regression of each province's 1995–2020 built-up growth rate on its

initial (log) built-up area in 1995, the standard test of Gibrat's Law.

**Table 4.** OLS regression of urban built-up growth rate (1995–2020) on initial built-up area, 1995 (test of Gibrat's Law)

| Variable                 | Coefficient | Robust SE (HC1) | z      | p-value |
|--------------------------|-------------|-----------------|--------|---------|
| Constant                 | 0.0906      | 0.027           | 3.362  | 0.001   |
| log(built-up area, 1995) | −0.0039     | 0.002           | −2.572 | 0.010   |

Note:  $n = 77$ ;  $R^2 = 0.082$ ; Dependent variable: built-up area growth rate, 1995–2020.

The coefficient on initial size is negative and statistically significant ( $\beta = -0.0039$ , robust SE = 0.0015,  $z = -2.572$ ,  $p = 0.010$ ), and the model explains 8.2% of cross-sectional variance in growth rates ( $n = 77$ ). Gibrat's Law is therefore rejected: provinces with smaller initial built-up area grew systematically faster than those with larger initial area over 1995–2020. Figure 1(b) plots this relationship, with Bangkok positioned at the lower-right, growing below the sample average. This size-dependent growth pattern is reconciled with the rising Zipf coefficient explicitly in Section 4. Although statistically significant, the model explains only 8.2% of the cross-sectional variance in growth rates, indicating that initial size accounts for a modest share of why some provinces expand faster than

others; the bulk of the variation is attributable to province-specific factors outside the model, such as local infrastructure investment, sectoral composition, and proximity to transport corridors. This limited explanatory power is consistent with comparable Gibrat-law tests in other national contexts [24,25] and cautions against over-interpreting the rejection of Gibrat's Law as a complete account of urban growth dynamics; it should be read as evidence against strict proportionate growth rather than as a fully explanatory growth model.

### 3.4 Urban primacy and deconcentration

Table 5 reports the four-city urban primacy index for each of the six epochs.

**Table 5.** Urban Primacy Index (Bangkok relative to provinces ranked 2–4), 1995–2020

| Epoch | Urban Primacy Index | % change vs. 1995 |
|-------|---------------------|-------------------|
| 1995  | 0.493               | — (base)          |
| 2000  | 0.530               | +7.51%            |
| 2005  | 0.510               | +3.45%            |
| 2010  | 0.487               | –1.22%            |
| 2015  | 0.466               | –5.48%            |
| 2020  | 0.443               | –10.14%           |

The primacy index declines from 0.493 in 1995 to 0.443 in 2020, a fall of roughly ten percent, indicating that Bangkok's built-up area shrank in relative terms compared with the combined area of the second-, third-, and fourth-ranked provinces. This decline is monotonic across every epoch and is directionally consistent with the Gibrat's Law rejection above: smaller and mid-ranked units expanded faster

than the primate city, producing gradual relative, though not absolute, deconcentration.

### 3.5 Provincial economic convergence

Table 6 reports the two cross-sectional convergence regressions for GPP CAGR over 1995–2020.

**Table 6.** Cross-sectional OLS estimates of provincial GPP convergence and the urban expansion–growth relationship, 1995–2020

| Variable            | Model 1: Beta-convergence | Model 2: Urban expansion – growth |
|---------------------|---------------------------|-----------------------------------|
| Constant            | 0.0120 (0.010)            | 0.0177*** (0.004)                 |
| log(GPP, 1995)      | 0.0014 (0.001)            | –                                 |
| Urban built-up CAGR | –                         | 0.3882* (0.210)                   |
| R <sup>2</sup>      | 0.014                     | 0.093                             |
| n                   | 76                        | 76                                |

Note: Robust (HCl) standard errors in parentheses. Dependent variable: GPP CAGR, 1995–2020. \*\*\*  $p < 0.01$ , \*  $p < 0.10$  (Model 1 coefficient of interest not significant,  $p = 0.142$ ; Model 2 coefficient of interest  $p = 0.064$ ).

Because unconditional convergence tests are known to be uninformative when provinces converge to different steady states, Table 7 reports a conditional beta-convergence specification that augments Model 1 with urban built-up CAGR and four structural control variables: log initial population (1995), the agricultural share of GPP (1995), distance to Bangkok, and mean

years of education (2010 census, the only year with complete province coverage in the available data). Investment/GFCF and FDI were confirmed unavailable at the provincial level in Thailand's official statistics and are omitted; this is disclosed as a limitation in Section 4.2.

**Table 7.** Conditional beta-convergence with structural controls, GPP CAGR 1995–2020

| Variable                       | Model 3: Conditional (incl. Bangkok) | Model 4: Conditional (excl. Bangkok) |
|--------------------------------|--------------------------------------|--------------------------------------|
| Constant                       | 0.0317* (0.017)                      | 0.0227 (0.018)                       |
| log(GPP, 1995)                 | –0.0055** (0.002)                    | –0.0062*** (0.002)                   |
| Urban built-up CAGR            | 0.5466** (0.268)                     | 0.5157* (0.285)                      |
| log(Population, 1995)          | 0.0061*** (0.002)                    | 0.0078*** (0.002)                    |
| Agricultural share, 1995       | –0.0329*** (0.012)                   | –0.0275* (0.014)                     |
| Distance to Bangkok (km)       | 0.0000 (0.0000)                      | –0.0000 (0.0000)                     |
| Mean years of education (2010) | 0.0007 (0.001)                       | 0.0016 (0.001)                       |
| R <sup>2</sup>                 | 0.261                                | 0.275                                |
| n                              | 76                                   | 75                                   |

Note: Robust (HCl) standard errors in parentheses. Dependent variable: GPP CAGR, 1995–2020. \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ . Condition number is large ( $\sim 7.1 \times 10^4$ ) in both models, likely reflecting the raw-km scale of distance to Bangkok rather than substantive collinearity; rescaling to 100-km units would improve this diagnostic without altering point estimates or significance.

Once these controls are included, the coefficient on log initial GPP changes sign and becomes statistically significant:  $\beta = -0.0055$  ( $p = 0.012$ ) including Bangkok and  $\beta = -0.0062$  ( $p = 0.007$ ) excluding Bangkok, with  $R^2$  rising to 0.261 and 0.275 respectively. This is the standard signature of conditional, rather than absolute, convergence — provinces converge toward different steady states determined by their structural characteristics, even though no evidence of absolute convergence was found

in Table 6. Initial population and agricultural share are the strongest and most robust controls (both significant at the 1% level in most specifications), while distance to Bangkok and mean education are not statistically significant, possibly reflecting the coarseness of these particular proxies. The urban built-up CAGR coefficient also strengthens under conditioning (0.547 vs. 0.388 unconditional) and regains 5%-level significance including Bangkok, though it weakens to the 10% level once Bangkok is excluded ( $p = 0.070$ ).

**Table 8.** Mean built-up and GPP growth rates by province group, 1995–2020

| Group                  | n  | Urban built-up CAGR (%/yr) | GPP CAGR (%/yr) |
|------------------------|----|----------------------------|-----------------|
| Regional hub provinces | 10 | 2.25                       | 3.10            |
| Other provinces        | 65 | 2.26                       | 2.57            |
| Bangkok                | 1  | 1.84                       | 2.61            |

In the classical beta-convergence specification (Model 1), the coefficient on log initial GPP is positive but not statistically distinguishable from zero ( $\beta = 0.0014$ , robust SE = 0.001,  $z = 1.468$ ,  $p = 0.142$ ;  $R^2 = 0.014$ ,  $n = 76$ ), providing no evidence of unconditional convergence. In Model 2, the coefficient linking urban expansion to GPP growth is positive and marginally significant at 10% ( $\beta = 0.388$ , robust SE = 0.210,  $z = 1.852$ ,  $p = 0.064$ ;  $R^2 = 0.093$ ), indicating that provinces with faster physical expansion tended to also record faster GPP growth, though imprecisely estimated. Table 8 disaggregates growth by province group: the ten regional hubs recorded a mean GPP CAGR of 3.10% against 2.57% for the remaining 65 provinces, while Bangkok grew at only 2.61% despite the lowest built-up growth rate (1.84%) of the three groups. Figure 2 plots both relationships, with hub provinces and Bangkok highlighted. Two robustness

checks were carried out on Model 1 and Model 2. First, excluding Bangkok leaves the beta-convergence coefficient statistically insignificant and of similar magnitude ( $\beta = 0.0019$ , robust SE = 0.001,  $z = 1.580$ ,  $p = 0.114$ ;  $R^2 = 0.018$ ,  $n = 75$ ), confirming that the absence of unconditional convergence is not an artifact of Bangkok's outsized scale. Second, when initial GPP and urban built-up CAGR are entered jointly in a multivariate specification, the coefficient on initial GPP falls essentially to zero in both the full sample ( $\beta = 0.0004$ ,  $p = 0.696$ ,  $n = 76$ ) and the Bangkok-excluded sample ( $\beta = 0.0004$ ,  $p = 0.755$ ,  $n = 75$ ), while the coefficient on urban built-up CAGR remains positive but loses its 10%-level significance once Bangkok is excluded ( $\beta = 0.375$ ,  $p = 0.103$ ,  $n = 75$ , versus  $\beta = 0.377$ ,  $p = 0.091$ ,  $n = 76$  including Bangkok); the urban expansion-growth relationship in Model 2 should therefore be read as suggestive rather than robust.

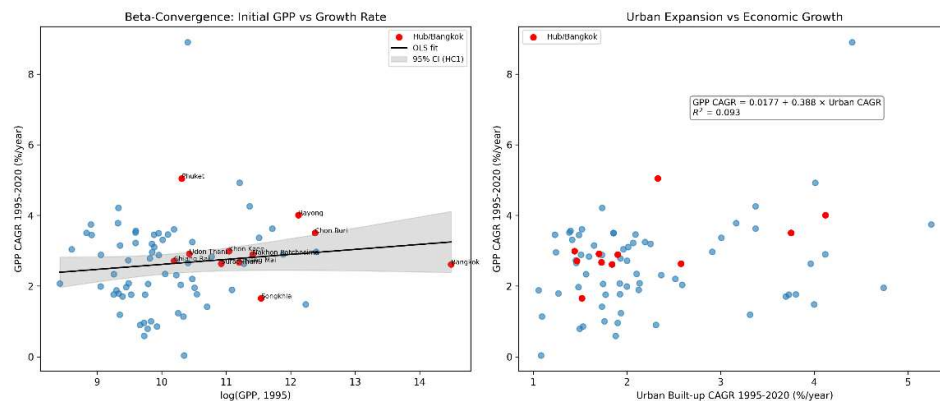


**Figure 2.** (A) Beta-convergence: initial (1995, log) GPP against GPP CAGR, 1995–2020, with OLS fit and 95% confidence interval (HC1); (B) urban built-up expansion against GPP growth, 1995–2020, with fitted regression equation and  $R^2$  annotated. Red markers denote Bangkok and the ten regional hub provinces.

### 3.6 Dynamic panel System GMM convergence estimates

Table 9 reports the key parameters of the dynamic panel System GMM model of log GPP over the full 1995–2024 panel.

**Table 9.** Two-step System GMM estimates of dynamic panel log(GPP) persistence, 77 provinces, 1995–2024 (selected coefficients)

| Variable    | Coefficient | SE       | z      | p-value |
|-------------|-------------|----------|--------|---------|
| L1.log(GPP) | 0.996767    | 0.025201 | 39.553 | <0.001  |
| Constant    | 0.103792    | 0.254858 | 0.407  | 0.684   |

*Note:* Two-step System GMM (Blundell–Bond); GMM-style instruments lagged 2–4 periods, collapsed; year dummies 1997–2024 included (see Appendix Table A1). Dependent variable: log(GPP), 1995–2024, 77 provinces (unbalanced panel; Bueng Kan contributes 14 of 30 years), 2,140 province-year observations, 33 instruments. Specification diagnostics: Arellano-Bond AR(1)  $z = -5.415$ ,  $p < 0.001$  (expected by construction); AR(2)  $z = -0.166$ ,  $p = 0.868$  (fails to reject, supporting instrument validity); Hansen J-test of overidentifying restrictions  $\chi^2(3) = 8.586$ ,  $p = 0.035$ .

The coefficient on lagged log GPP is 0.9968 (SE = 0.0252,  $z = 39.55$ ,  $p < 0.001$ ), indicating extremely high persistence in provincial GPP. The implied annual convergence speed is  $\lambda = -\ln(0.9968) \approx 0.0032$ , or roughly 0.32% per year, corresponding to an income half-life of approximately 214 years – far slower than the canonical 2% annual convergence speed reported for US states and European regions [26]. Year dummies are jointly informative: most are negative and significant relative to the 1995–1996

baseline, with the largest negative deviation in 2020 ( $-0.116$ ,  $p < 0.001$ ), consistent with COVID-19-related GPP contraction, and smaller significant deviations around 2008–2009 and 2011, corresponding to the Global Financial Crisis and the 2011 Thailand floods. Figure 3 maps built-up levels, growth rates, and urban rank across all 77 provinces, corroborating that built-up expansion is fastest around Bangkok and in smaller, lower-rank provinces of the upper North and Northeast, rather than in Bangkok itself.

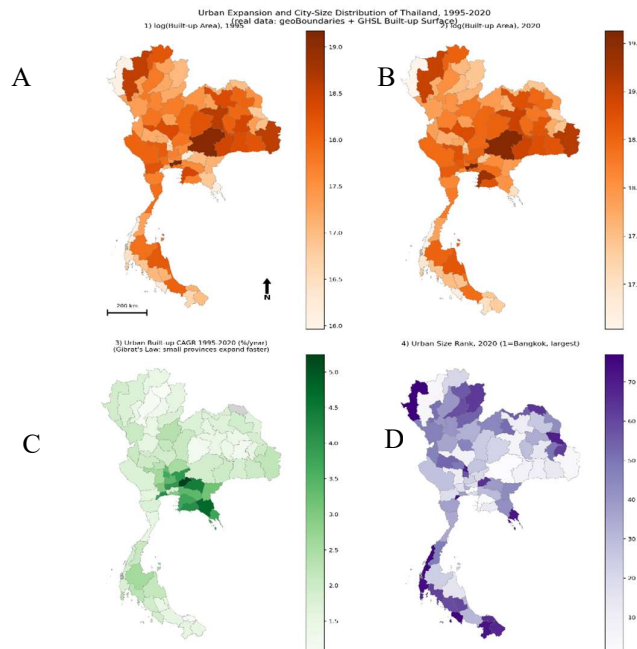


**Figure 3.** Spatial distribution of (A) log built-up area, 1995; (B) log built-up area, 2020; (C) built-up area CAGR, 1995–2020; and (D) urban size rank, 2020 (1 = Bangkok, largest), across 77 Thai provincial-level administrative units. Data: geoBoundaries and GHSL built-up surface.

## 4. Discussion

### 4.1 Urban hierarchy and proportionate growth

The Zipf coefficient of 1.16–1.21 places Thailand's urban hierarchy within the range documented across developing countries generally, where average estimates exceed unity [32,33]; this reflects the historical concentration of administrative, financial, and manufacturing functions in Bangkok, consistent with the primate-city dynamic [11] and circular-causation logic [13] of self-reinforcing agglomeration -- though, as noted in Section 3.2, the modest increase in  $\zeta$  over 1995-2020 is not itself statistically significant, so the hierarchy is best characterized as stable rather than actively intensifying over this period. The rejection of Gibrat's Law ( $\beta = -0.0039$ ,  $p = 0.010$ ) shows that smaller urban areas expanded systematically faster than Bangkok, plausibly reflecting diminishing returns to further agglomeration at the core as congestion and land costs rise, pushing new development toward lower-cost peripheral locations [34]. This departure from strict proportionate growth is consistent with evidence from untruncated city-size samples elsewhere [24,25] and with a comparable developing-country departure documented for Brazil [35]. The apparent tension between a mildly rising Zipf coefficient and a falling primacy index is reconcilable: the Zipf exponent summarizes the full rank-size distribution, including the lower tail of small provinces, whereas the primacy index isolates Bangkok's position relative to its closest rivals only [10,37]. A further caveat applies throughout this section: built-up surface area is a physical footprint measure, not a direct measure of urbanization or economic agglomeration. An increase in built-up area may reflect low-density suburban or peri-urban sprawl rather than the denser, more productive land use typically associated with agglomeration economies, and the elasticity linking built-up or night-light intensity to true economic output has been shown to be unstable across regions even in data-rich settings [45], with proxy performance degrading further in lower-density, more rural contexts [46]. The built-up-based findings in this section should therefore be read as evidence about the physical footprint of Thailand's urban system specifically, which need not move in lockstep with economic concentration; this is one reason the built-up-based results are triangulated against the independent GPP-based convergence evidence in Section 4.2 rather than treated as interchangeable.

### 4.2 Provincial economic convergence

Provincial economic convergence, by contrast, remains extremely slow. Unconditional beta-convergence is not statistically significant ( $p = 0.142$ ), a result that should not be over-interpreted given known limitations of cross-sectional convergence tests [36], while urban expansion is only marginally associated with GPP growth ( $p = 0.064$ ), echoing the built-up–GPP relationship previously documented for Thai provinces [9]; both results are robust to excluding Bangkok, and the urban-expansion coefficient loses even its marginal significance once initial GPP and urban expansion are modeled jointly and Bangkok is dropped (Section 3.5), indicating that this weaker part of the headline finding is not driven by the capital's outsized weight in the sample. However, the absence of unconditional convergence should not be read as an absence of convergence altogether. Because convergence and divergence regimes among sub-national units can shift once conditioned on structural characteristics [40], Table 7 augments the beta-convergence specification with province-level controls shown to matter for Thai provincial convergence [43] and for dynamic-panel convergence across ASEAN more broadly [44]: log initial population, agricultural share of GPP, distance to Bangkok, and mean education. Conditioning on these controls reverses the sign of the coefficient on initial GPP and renders it statistically significant ( $\beta = -0.0055$ ,  $p = 0.012$  including Bangkok;  $\beta = -0.0062$ ,  $p = 0.007$  excluding Bangkok) — the standard signature of conditional convergence: provinces do not converge to a common income level, but do converge toward different steady states once their structural characteristics are held constant. This is a materially stronger and more standard growth-economics finding than the unconditional result alone would suggest, and we regard it as a core contribution of the revised analysis. The System GMM estimate of near-unit-root persistence ( $\rho = 0.997$ ) is consistent with the club-convergence pattern found for Thailand [7] and with evidence that Bangkok-centred agglomeration has historically slowed provincial income convergence [8]. That the ten regional hub provinces outgrew both Bangkok and the remaining provinces in GPP terms, despite built-up expansion rates similar to the provincial average, suggests these hubs function as intermediate growth poles rather than sites of purely physical sprawl.

### 4.3 Robustness and methodological considerations

Three caveats bear on these findings. The Hansen J-test ( $p = 0.035$ ) signals some caution

regarding GMM instrument validity, though the lag-2-to-4 specification follows recommended practice and near-unit-root persistence is itself a challenging setting for any GMM estimator [20,29]; the remaining specification diagnostics are more reassuring, with the Arellano-Bond test correctly rejecting the null of no first-order serial correlation in first differences ( $z = -5.415$ ,  $p < 0.001$ ) while failing to reject the null of no second-order serial correlation ( $z = -0.166$ ,  $p = 0.868$ ), the pattern required for the moment conditions underlying System GMM to be valid. Unlike the cross-sectional regressions, the System GMM model absorbs province fixed effects rather than a small set of observable controls, so its very high estimated persistence should still be weighted heavily when drawing conclusions about long-run convergence, even though Table 7 now provides conditional cross-sectional evidence of convergence. As a further robustness check, urban built-up area was incorporated directly into the System GMM specification (interpolated to annual frequency between the six built-up epochs and necessarily truncating the panel to 1995-2020, since built-up area cannot be observed or extrapolated beyond the most recent epoch). The persistence parameter is essentially unchanged ( $\rho = 0.993$  vs.  $0.997$  in the baseline), built-up area itself is not a significant predictor of GPP once dynamic persistence is controlled for (coefficient =  $-0.025$ ,  $p = 0.618$ ), and AR(2) continues to pass cleanly ( $z = 1.01$ ,  $p = 0.313$ ); the Hansen test also rejects at 5% in this augmented specification ( $\chi^2(5) = 13.335$ ,  $p = 0.020$ ), confirming that the borderline Hansen result is a pre-existing feature of the GMM specification rather than one introduced by adding built-up area. Even so, the Zipf, Gibrat, and System GMM results triangulate through three independent channels on a consistent picture: gradual physical deconcentration alongside very slow unconditional (though not conditional) income convergence.

## 5. Conclusions

This study examined the joint evolution of Thailand's urban size distribution and provincial economic convergence between 1995 and 2024 using multi-epoch satellite built-up data, rank-size analysis, and dynamic panel GMM estimation. Three findings correspond to the study's three objectives. First, Thailand's urban hierarchy is stable but mildly intensifying, with the Zipf coefficient rising from 1.158 (1995) to 1.206 (2020) while model fit remains essentially unchanged ( $R^2 \approx 0.82$ ). Second, Gibrat's Law is rejected: smaller urban areas grew significantly faster than larger ones ( $\beta = -0.0039$ ,  $p = 0.010$ ), and Bangkok's primacy index fell from 0.493 to 0.443. Third, provincial income convergence is absent

unconditionally but present conditionally: unconditional beta-convergence is insignificant and the System GMM model implies an income half-life exceeding two centuries ( $\rho = 0.997$ ), yet once initial population, agricultural share, distance to Bangkok, and education are held constant, the coefficient on initial GPP reverses sign and becomes significant ( $\beta = -0.0055$  to  $-0.0062$ ,  $p < 0.05$ ), indicating genuine conditional convergence toward structurally-determined steady states, even as regional hub provinces outgrew both Bangkok and the remaining provinces.

These results carry three policy implications. First, because physical expansion has not yet translated into commensurate unconditional income convergence in 2014 though the conditional convergence evidence in Table 7 shows that provinces with more favorable initial population, industrial structure, and urban expansion do converge toward higher steady states in 2014 regional development policy should prioritize complementary investments in human capital, secondary-city industrial capacity, and logistics connectivity, so that urban growth in smaller provinces yields durable income gains rather than built-up area alone [38], noting that mean education was not itself a significant control in Table 7, so this recommendation rests on the general growth literature rather than on direct evidence from this specification. Second, the ten regional hub provinces, which recorded the fastest GPP growth despite average built-up expansion, warrant continued policy attention as intermediate growth poles that can absorb activity that would otherwise concentrate further in Bangkok, consistent with the New Economic Geography prediction that falling transport costs favor gradual dispersal from a dominant core [13,39]. Third, given that provincial GPP statistics are compiled at low frequency and are subject to revision, national planning agencies should consider open-access satellite-derived built-up and nighttime-light indicators as a complementary, higher-frequency monitoring tool, particularly where administrative data capacity is limited [15,16].

Two limitations qualify these conclusions: the conditional convergence model in Table 7 should still be read as descriptive rather than strictly causal, since the control variables are not plausibly exogenous and the education control is limited to a single 2010 cross-section rather than a true 1995 initial condition; investment and FDI, two theoretically important controls, could not be included because they are not published at the provincial level in Thailand's official statistics; and the System GMM model's very high estimated persistence leaves limited scope to distinguish genuine slow convergence from a unit-root

process, a concern only partly mitigated by confirming that adding built-up area to the dynamic panel leaves this persistence estimate essentially unchanged ( $\alpha = 0.993$ ). Future research should extend the conditional convergence framework with instrumented or panel-based controls, update the satellite panel beyond 2020 as new GHSL epochs become available, and apply spatial econometric methods to model inter-provincial spillovers [7]. Overall, four independent empirical strategies converge on a nuanced narrative: Thailand's urban system is deconcentrating gradually in physical terms, absolute provincial income convergence is absent, yet conditional convergence toward structurally-determined steady states is present and statistically robust, underscoring the continued relevance of Bangkok-centred agglomeration to the country's regional economic geography.

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## Analysis of Inflectional Morpheme Use in the Written Compositions of Pre-Service Teachers

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### Abstract

This study examined the use of English inflectional morphemes in the short-written compositions of 26 first-year Bachelor of Technology and Livelihood Education (BTLED) from a university in Caraga during the academic year 2025-2026. Specifically, it analyzed the types and frequencies of inflectional morpheme errors involving plural (-s/-es), past tense (-ed), progressive (-ing), and possessive (-'s), and classified them based on the Surface Strategy Taxonomy of Dulay, Burt, and Krashen (1982). The study employed a descriptive quantitative error analysis design supported by qualitative interpretations. The unit of analysis consisted of 26 reflective written compositions produced during an extemporaneous speech activity. Errors were identified and classified using the Surface Strategy Taxonomy, while frequency counts and percentage distributions were used to analyze the data. The most frequent errors involved past tense inflectional morphemes, followed by plural, progressive, and possessive. The most dominant type of error was misformation, indicating that learners found it challenging to select and apply correct grammatical forms, and further suggesting that L1 transfer, overgeneralization of grammatical rules, and limited morphological awareness may have contributed to such difficulties. The study recommends strengthening explicit morphological instruction and focused writing activities.

**Keywords:** Inflectional morphemes, Error analysis, ESL learners, English morphology, Surface Strategy Taxonomy

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### 1. Introduction

Language learning involves not only vocabulary acquisition but also mastery of grammatical systems that enable learners to participate in clear and meaningful communication. One such system is Morphology, which governs how words change form to express grammatical relations such as tense, number, aspect, and possession. Inflectional morphemes such as plural markers

(-s/-es), past tense regular inflections (-d/-ed), progressive aspect marker (-ing), and possessive enclitics (-'s) play a very important role in ensuring grammatical accuracy and effective communication in English. The appropriate use of inflectional morphemes helps promote communicative precision, language proficiency, and grammatical accuracy, whereas misuse may impair comprehension, reduce fluency and obscure the intended meaning [1].

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Studies in relation to inflectional morphology have revealed substantial variation in learner production and differences in morphological processing. Almakrob [2] pointed out that the performance of second language learners varied across verb types and task conditions and suggested that factors such as first language background and task variation may influence the use of English past tense morphology. This emphasizes the context-dependent nature of inflectional morpheme use. Similarly, Dogar et al. [3], through corpus-based analysis of the ICNALE dataset, observed discrepancies in ESL learners' use of inflectional morphemes, particularly in possessive forms, plural nouns, subject-verb agreement, and tense-related forms. The study also identified challenges in the usage of comparative and superlative structures and noted variations in patterns according to linguistic background, stage of acquisition, and instructional exposure. Jacobson and Yu[4] also reported in their study that inflectional and derivational morphemes are processed differently in the mental lexicon, with morphological structure influencing word recognition and language comprehension tasks. Collectively, these studies indicate variability in both production and processing of morphology among second language learners.

In the Philippine context, Resueno and De Leon [5], examined the morphosyntactic performance of senior high school learners in translation tasks, reported frequent errors in verb tense, subject-verb agreement and pluralization, attributing them to both interlingual transfer from the first language and intralingual developmental processes. In a related study involving university students, Rabadi [6] found a significant positive relationship between morphological awareness and vocabulary knowledge, indicating that learners with stronger awareness of word formation processes tend to demonstrate higher vocabulary knowledge. These findings highlight the role of morphological knowledge in second language learning and provide

evidence that learners' morphosyntactic performance and lexical development may be shaped by linguistic transfer and developmental processes. Studies on ESL and EFL learners' writing have consistently reported difficulties in the use of English inflectional morphemes such as plural -s/-es, past tense -ed and subject-verb agreement markers [7, 8, 9]. These studies typically employ descriptive error analysis frameworks such as Error analysis [10] and Surface Strategy Taxonomy [11], to classify errors in written output. In the Philippine context, existing research has also identified recurring grammatical and morphological errors [9], indicating that such difficulties persist among Filipino ESL learners.

However, despite these findings, few studies have specifically examined the use of inflectional morphemes among Filipino pre-service teachers enrolled in teacher education programs. Existing studies have largely focused on general ESL or EFL learners or on broad categories of grammatical errors which provide limited evidence on the specific morphological difficulties encountered by beginning pre-service teachers. This represents an important gap because first-year Bachelor of Technology and Livelihood Education (BTLED) students are future educators whose proficiency in English grammar and writing is essential for effective classroom communication and professional practice. Examining their inflectional morpheme use can provide valuable insights into their early morphosyntactic development and inform language support initiatives within teacher education programs. Moreover, by focusing on inflectional morphemes in authentic classroom writing, the present study extends existing research by providing localized evidence on error patterns of Filipino pre-service teachers.

To address this gap, the present study examined the use of inflectional morphemes in written compositions of first-year BTLED students. Specifically, it sought to: 1) identify the frequency and distribution of errors in the use of English inflectional morphemes,

particularly plural (-s/-es), past tense (-d/-ed), progressive (-ing), and possessive (-'s); 2) categorize the inflectional morpheme errors based on the Surface Strategy Taxonomy; and 3) distinguish the possible linguistic and developmental factors that influence the occurrence of inflectional morpheme errors among the students. The findings aim to contribute to a deeper understanding of morphological acquisition among Filipino ESL and provide pedagogical insights for enhancing writing instruction in teacher education.

## **2. Methodology**

### **2.1 Research design**

A descriptive quantitative error analysis design was utilized in this study. Although the analysis included descriptive linguistic interpretations of errors, the study remained quantitative with the use of frequency counts and percentage distributions to identify recurring morphological error patterns. Error analysis was suitable as it systematically classified errors and provided insights into learners' interlanguage development and morphological difficulties. Using the Surface Strategy Taxonomy developed by Dulay, Burt, and Krashen [11], errors were categorized into omission, addition, misformation, and misordering. To ensure comparability with prior studies, this study combined quantitative frequency analysis with close interpretive reading of students' written forms and linguistic contexts.

### **2.2 Participants of the study**

The participants consisted of twenty-six (26) first-year Bachelor of Technology and Livelihood Education (BTLED) students from a higher education institution in Caraga during the Academic Year 2025-2026. Purposive sampling was employed to select students who were officially enrolled in the BTLED program, completed the required English reflective writing task during the extemporaneous speech

activity, and voluntarily agreed to participate in the study. These criteria ensured that the participants could provide authentic written compositions relevant to the analysis of English inflectional morpheme use. Informed consent was obtained prior to data collection and anonymity was maintained by assigning identification codes to each participant.

### **2.3 Data collection and analysis**

The primary source of data consisted of students' short-written compositions. The participants were asked to write a reflective composition about their experiences during the extemporaneous speech activity, which consisted of a minimum of one paragraph with approximately 100-150 words. The 26 compositions served as the unit of analysis, from which 50 inflectional morpheme errors were identified and analyzed.

The researchers reviewed all compositions to identify errors involving the English inflectional morphemes for plural (-s/-es), past tense (-ed), progressive (-ing) and possessive (-'s). The errors were classified according to the Surface Strategy Taxonomy[11], which categorizes learner errors into omission, addition, misformation and misordering.

To ensure consistency and prevent overrepresentation of recurring errors, each error was recorded separately when students committed multiple errors within a sentence or different errors across sentences. However, repeated instances of the same error committed by the same students throughout a composition were counted as a single distinct error type. This procedure minimized the overrepresentation of repetitive errors and resulted in a validated dataset of 50 identified errors. Although some identified errors occurred within broader syntactic inaccuracies, only the inflectional morpheme component was analyzed and classified. Errors involving noun pluralization, past tense forms, progressive aspect markers, and possessive markers were included, while errors outside the scope of

English inflectional morphology were excluded. Frequency counts and percentage distributions were used to determine the number and distribution of errors while interpretive analysis was used to explain possible sources of the identified errors.

## 2.5 Reliability and validation

The identification and classification of inflectional morpheme errors were validated by two external language experts with the primary researcher serving as the initial coder. The experts independently reviewed a randomly selected 20% of the coded compositions using an operational guide based on Surface Strategy Taxonomy[11]. Although no formal inter-rater

reliability coefficient was calculated, independent review and consensus strengthened the reliability of the coding process.

## 3. Results and Discussion

### 3.1 Types and frequencies of errors in inflectional morphemes

The analysis of the students' written compositions identified 50 errors in the use of English inflectional morphemes across four categories, as presented in Table 1. Past tense (-ed) errors were the most frequent (58%), followed by plural (-s/-es) errors (24%), progressive (-ing) errors (10%) and possessive (-'s) errors (8%).

**Table 1.** Distribution of Inflectional Morphemes Errors

| Type of Morpheme          | Frequency | Percentage |
|---------------------------|-----------|------------|
| <i>Plural (-s/-es)</i>    | 12        | 24         |
| <i>Past tense (-ed)</i>   | 29        | 58         |
| <i>Progressive (-ing)</i> | 5         | 10         |
| <i>Possessive (-'s)</i>   | 4         | 8          |
| <i>Total</i>              | 50        | 100        |

Past tense (-ed) errors primarily involved the use of base or present tense verb forms instead of the required past tense forms. Examples include "I *feel* nervous," instead of "I *felt* nervous" and "I *will deliver*" instead of "I *delivered*." These errors occurred because the learners described complete past events but failed to apply the appropriate past inflection. These findings indicate that learners experienced greater difficulty applying past tense inflectional markers than other English inflectional morphemes.

Pluralization errors accounted for 24% of the total errors. These included unnecessary plural markers in nouns such as "*weaknesses*" instead of "*weakness*," "*strengths*" instead of "*strength*," and "*students*" instead of "*student*." These examples suggest that learners overgeneralized the plural marker by applying it to nouns that were intended to express singular or general meaning. Progressive and possessive errors occurred less

frequently but still reflected inconsistencies in the use of English inflectional endings.

The predominance of past tense errors is consistent with Wahid et al [12], who reported that verb-related errors were among the most prominent inflectional errors committed by learners. Similarly, Almakrob [2] found that the learners' acquisition of English past tense morphology may be influenced by the type of elicitation task and by learners' first language contributing to variations in the use of English past tense markers across lexical categories. Dogar et al. [3] also noted that learners often experience difficulties with past tense inflection, particularly in the acquisition of irregular verb forms, which may result in the overapplication of regular past tense markers and other non-target-like forms. The authors further suggested that such patterns may be associated with differences in language exposure, instructional experiences and native language influence. Furthermore, Khan [13]

found that learners who received explicit morphological instruction showed significantly greater gains in the acquisition of irregular inflectional morphemes than those who did not. These findings indicate that the mastery of past tense inflectional morphemes remains challenging for most learners and that explicit instruction and consistent practice may help improve grammatical accuracy.

Similarly, the pluralization errors observed in the present study are consistent with Rabadi [6], who reported that learners with limited morphological awareness may struggle to manipulate inflectional suffixes accurately. In addition, Niez et al. [9], noted that ESL learners often struggle to maintain grammatical accuracy in authentic writing tasks, which resulted in recurring errors in pluralization and

tense marking. These findings support the present results, suggesting that students continue to experience challenges in accurately applying English inflectional morphemes in authentic writing tasks, reflecting limitations in their knowledge of English morphology and grammar.

### 3.2 Classification of errors according to Surface Strategy Taxonomy

To examine further the nature of the errors, they were classified according to the Surface Strategy Taxonomy developed by Dulay, Burt, and Krashen as shown in Table 2 [11].

**Table 2.** Classification of errors based on Surface Strategy Taxonomy

| Error Type          | Plural<br>(-s/-es) | Past Tense<br>(-ed) | Progressive<br>(-ing) | Possessive<br>(-'s) | Total<br>Errors | % of Total<br>Errors |
|---------------------|--------------------|---------------------|-----------------------|---------------------|-----------------|----------------------|
| <i>Omission</i>     | 3                  | 7                   | 0                     | 0                   | 10              | 20                   |
| <i>Addition</i>     | 9                  | 4                   | 0                     | 0                   | 13              | 26                   |
| <i>Misformation</i> | 0                  | 18                  | 5                     | 4                   | 27              | 54                   |
| <i>Misordering</i>  | 0                  | 0                   | 0                     | 0                   | 0               | 0                    |
| <i>Total</i>        | 12                 | 29                  | 5                     | 4                   | 50              | 100                  |

Of the 50 identified errors, misformation was the most frequent accounting for 27 occurrences or 54%. These were primarily related to past tense (-ed), progressive (-ing), and possessive (-'s) morphemes, with past forms recording the highest number of instances (18). These errors involved the usage of wrong grammatical forms, such as in the words “*feel*” instead of “*felt*,” “*deliver*” instead of “*delivered*,” and “*stand*” instead of “*stood*.” Rather than omitting the verb, learners supplied an incorrect form, indicating an attempt to apply grammatical rules despite incomplete mastery of English tense inflections.

With 13 or 26% of all errors, addition errors came in second. Most of these errors (9) involved plural (-s/-es) morphemes and consisted of the unnecessary attachment of plural suffixes to words that did not require

them. Examples included “*weaknesses*” instead of “*weakness*” and “*strengths*” instead of “*strength*.” These errors illustrate the unnecessary addition of plural suffixes to abstract nouns used in general sense.

Omission errors accounted for 10 occurrences (20%). Most involved past tense (-ed) forms (7), followed by plural (-s/-es) forms (3). These errors primarily involved the absence of required grammatical markers in sentences referring to completed action, as illustrated by “*conquer*” instead of “*conquered*” and “*observe*” instead of “*observed*.” In these cases, the omission of the past tense markers resulted in verbs that did not agree with the intended time reference of the sentences.

No instances of misordering were identified in the students’ compositions. This suggests that the students generally demonstrated familiarity with basic English

word order. Since the study focused on the use of inflectional morphemes, the findings indicate that students experienced greater difficulty with grammatical marking and word formation than with sentence construction.

The predominance of misformation errors suggests that students experienced challenges in selecting and applying the appropriate grammatical forms rather than simply omitting inflectional markers. This finding is consistent with Hatifi et al. [8], who identified misformation as one of the most common errors among EFL learners. Similarly, Niez et al. [9] reported that ESL students frequently have trouble applying tense and aspect markers correctly in real-world writing activities.

The addition errors further suggest learners' tendency to overgeneralize pluralization rules. This finding aligns with Oz's [14] discussion that morphological awareness involves the recognition and manipulation of inflectional morphemes and that awareness of inflectional morphology contributes to grammar accuracy. Together with omission errors, the prevalence of addition and misformation errors indicates that learners attempted to apply grammatical rules but had not yet fully mastered them.

Overall, the Surface Strategy Taxonomy suggests that the students experienced greater difficulty in applying appropriate inflectional forms than in constructing sentence structure. These findings highlight the need for writing instruction that emphasizes noun inflections, verb tense marking, and the accurate application of English inflectional morphemes.

### 3.3 Possible sources of inflectional morpheme errors

To interpret the observed inflectional morpheme errors, the present study adopted an analytical framework informed by Error Analysis [10], where errors are viewed as systematic indicators of language development,

and Interlanguage Theory [15], which proposes that learners develop an evolving interlanguage system. Guided by these perspectives, the identified error patterns were examined in relation to four possible sources commonly discussed in the second language acquisition literature: (1) L1 transfer, (2) overgeneralization of grammatical rules, (3) developmental factors, and (4) cognitive constraints. Since these factors were not directly investigated in the present study, they are presented as possible explanations rather than confirmed causes.

**L1 Transfer.** Because inflectional marking rarely occurs in many Philippine languages, which rely more on particles and contextual cues rather than on bound inflectional morphemes to signal tense and aspect, the inflectional errors observed in the present study may reflect L1 transfer in English writing. The present study provides evidence consistent with this interpretation, as evidenced by 54% misformation errors, 20% omission errors, and 58% of the total errors involving tense marking. Alsawsh and Shormani [16] reported that first language transfer plays a significant role in L2 acquisition, where learners' first language structures may influence the production of English forms, alongside developmental and intralingual factors. Similarly, Munder [17] observed recurring grammatical errors in Filipino ESL learners' written outputs, particularly in areas involving verb tense, subject-verb agreement and noun-related forms. The study also suggests that such errors may be influenced by first language structures and differences between English and learners' native linguistic systems. This interpretation is further supported by Lin et al. [18], who suggested that grammatical errors in L2 writing reflect the combined influence of L1 transfer and learners' developing interlanguage system.

**Overgeneralization of Grammatical Rules.** Another possible explanation is the overgeneralization of grammatical rules. This was particularly noticeable in addition errors

(26%), where the students added plural markers to singular or non-count nouns needlessly, such as “*weaknesses*” instead of “*weakness*” and “*strengths*” instead of “*strength*.” These errors may indicate attempts to apply familiar grammatical rules beyond appropriate contexts. Rabadi [6] similarly reported that limited morphological awareness may hinder learners’ ability to manipulate English inflectional suffixes accurately.

**Developmental Factors.** The identified errors may also reflect learners’ developmental stage in acquiring English morphology. Consistent with Selinker’s Interlanguage Theory [15], learners gradually construct knowledge of the target language and may apply grammatical rules inconsistently. This interpretation is supported by the predominance of misformation errors, particularly the use of the base forms such as “*feel*” and “*deliver*” instead of “*felt*” and “*delivered*.”

**Cognitive Constraints.** Cognitive demands may influence the written output of the students. Writing is a cognitively demanding activity that requires learners to coordinate multiple processes, including planning, language formulation, monitoring, and revision [19]. Because these processes draw on limited cognitive and attentional resources, increased task demands may result in tradeoffs among different aspects of writing performance [20]. Consistent with the principle of limited attentional capacity, learners may not be able to attend fully to all dimensions of writing simultaneously [20].

Overall, consistent with Corder’s view of errors as indicators of language development and Selinker’s Interlanguage Theory [10, 15], the observed error patterns may be associated with L1 transfer, overgeneralization of grammatical rules, developmental factors, and the cognitive demands of writing. These interpretations are based on the observed error patterns and existing literature and should be regarded as

possible explanations rather than confirmed causes.

The findings indicate that the first-year BTLED students experienced greater difficulty in applying English inflectional morphemes than in constructing sentence structure. Past tense (-ed) errors were the most frequent, while misformation was the predominant error type, suggesting that learners often attempted to apply grammatical rules but selected inappropriate forms.

Taken together, these findings highlight the need for explicit instruction that strengthens learners’ morphological awareness and provides meaningful opportunities to apply English inflectional morphemes accurately in authentic writing tasks.

#### 4. Conclusion

This study examined how first-year BTLED students at a higher education institution in Caraga used English inflectional morphemes in their written works during the 2025-2026 academic year. The findings showed that students still experience difficulties with grammatical inflections involving tense, number, aspect, and possession. A total of fifty (50) inflectional morpheme errors were identified across four main inflectional categories: possessive (-’s), past tense (-ed), progressive (-ing), and plural (-s/-es). The most frequent errors involved past tense (-ed) morphemes, accounting for 58% of all errors. These errors mostly included the use of present tense and base form verbs incorrectly when past tense forms were needed. Pluralization errors ranked second, accounting for 24% of all errors, and were mainly related to the unnecessary insertion of plural markers to nouns. Errors involving progressive (-ing) and possessive forms were less common, at 10% and 8% respectively, but they still reflected the students’ confusion about verb forms and apostrophes. When sorted by error types based on the Surface Strategy Taxonomy, misformation was the most dominant at 54%, followed by addition errors at 26% and

omission errors at 20%. Because the study focused on inflectional morpheme errors rather than word arrangement, no misordering errors were identified. These findings indicate that the learners mainly struggled in selecting and applying English inflectional endings accurately. Several overlapping factors may have led to these errors such as native language interference, over-application of grammatical rules beyond appropriate contexts, limited morphological awareness, and natural stages of second language learning.

The findings highlight the need for explicit morphological instruction in ESL classrooms. Instructional activities should provide focused practice on past tense formation, pluralization, progressive and possessive forms through guided sentence construction, error identification and correction exercises, editing tasks and short paragraph writing with teacher feedback. Such activities may help strengthen learners' morphological awareness and improve learners' accurate use of English inflectional morphemes in written communication.

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# AI-Supported Learning, AI Dependency, and Academic Stress as Predictors of Student Burnout

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## Abstract

Generative artificial intelligence (GenAI) can enhance university learning by providing immediate feedback, clarifying complex concepts, supporting problem-solving, and improving access to personalized academic assistance. However, excessive reliance on AI may weaken independent reasoning, academic self-efficacy, and students' ability to complete tasks without technological support. Previous studies suggest that constructive AI use may function as a learning resource, whereas AI dependency and persistent academic stress may contribute to exhaustion, disengagement, and reduced academic efficacy. Nevertheless, these factors have rarely been examined simultaneously in relation to academic burnout, particularly among Thai university students. This study therefore examined AI-supported learning, AI dependency, and academic stress as predictors of academic burnout among undergraduate students at Ubon Ratchathani University. Data were collected from June 2025 to March 2026 using a quantitative cross-sectional survey. Proportionate stratified sampling across academic fields, supplemented by quota-assisted convenience sampling, yielded 372 students with experience using GenAI for academic purposes. Data were analyzed using descriptive statistics, reliability and validity assessments, Pearson's correlation, and multiple regression analysis. The model explained 46.0% of the variance in academic burnout. Academic stress was the strongest positive predictor, followed by AI dependency, whereas AI-supported learning had a negative but nonsignificant effect. The findings highlight the importance of promoting responsible AI use while reducing academic pressure and preventing excessive AI dependency.

**Keywords:** AI-supported learning, AI dependency, academic stress, academic burnout, university students, generative artificial intelligence

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## 1. Introduction

Generative artificial intelligence (GenAI) has become increasingly integrated into higher education, supporting activities such as concept clarification, idea generation, summarization, feedback, academic writing, and problem-solving [1,2]. Its educational value, however, depends on how students use it. When GenAI is used to support rather than replace students' own thinking, it may improve learning efficiency, self-regulation, creativity, and access to personalized assistance [3,4]. In this study, this constructive use is conceptualized as AI-supported learning,

referring to the purposeful use of AI to enhance understanding, feedback seeking, problem-solving, and self-directed learning while students remain responsible for evaluating AI-generated information [2,4].

AI-supported learning may function as an academic resource by helping students understand difficult tasks, obtain immediate feedback, and manage learning demands more efficiently. Such support may conserve cognitive and emotional resources and potentially reduce academic burnout [1,5]. Nevertheless, the benefits of GenAI may be weakened when students rely on it excessively.

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Overreliance can encourage cognitive outsourcing, uncritical acceptance of AI-generated content, and reduced independent reasoning, critical thinking, and analytical judgment [4,6]. This maladaptive pattern is conceptualized as AI dependency, which refers to cognitive, functional, or emotional reliance on AI and difficulty controlling its use [7]. Unlike frequent but purposeful AI use, AI dependency occurs when students transfer responsibility for academic reasoning or task completion to AI systems. It may weaken academic self-efficacy, autonomous learning, and confidence in completing tasks independently, particularly when AI is unavailable or provides inaccurate responses [7,8]. Repeated dependence may therefore increase students' vulnerability to exhaustion, disengagement, and reduced academic efficacy, which are central dimensions of academic burnout [9]. Academic burnout is a prolonged psychological response to persistent academic demands and is characterized by exhaustion, cynicism toward studying, and reduced academic efficacy [9]. It is associated with poorer psychological well-being, reduced motivation, weaker academic functioning, and disengagement from university study [10,11]. The construct is commonly measured using the Maslach Burnout Inventory–Student Survey. Recent evidence supports the validity and reliability of its three-dimensional structure among Thai undergraduate students, providing an appropriate basis for examining academic burnout in Thailand [12].

Academic burnout develops when persistent academic demands, such as heavy workloads, examinations, overlapping deadlines, and performance expectations, exceed students' available cognitive, emotional, and social resources [11,13,14]. Prolonged exposure to these demands may lead to emotional exhaustion, cynical attitudes toward study, and reduced academic efficacy, particularly among students with limited coping capacity, low self-efficacy, or inadequate social

support [9,15]. Burnout can adversely affect students' motivation, engagement, concentration, academic performance, and psychological well-being, while increasing absenteeism and intentions to withdraw from university [10,11,14,16]. Therefore, understanding the causes of academic burnout is essential for promoting student well-being, academic persistence, and sustainable educational outcomes.

Among the various causes of academic burnout, academic stress represents a central demand that may directly deplete students' cognitive and emotional resources. At the same time, the growing use of generative AI introduces both potential learning resources and emerging risks. Constructive AI-supported learning may help students manage difficult tasks and obtain timely feedback, whereas excessive reliance on AI may weaken autonomous learning, academic self-efficacy, and confidence in completing academic work independently. Examining academic stress together with AI-supported learning and AI dependency may therefore provide a more comprehensive explanation of how conventional academic pressures and emerging technology-related behaviors jointly contribute to student burnout. Academic stress arises when students perceive that workloads, examinations, deadlines, and performance expectations exceed their coping resources [14,17]. Persistent stress depletes cognitive and emotional resources and contributes to exhaustion, detachment, and reduced academic competence [9,11]. Although AI may help students manage some academic demands, it may also create concerns regarding information accuracy, academic integrity, technological competence, and acceptable use [1,18]. Despite growing research on GenAI in higher education, several gaps remain. Previous studies have primarily focused on AI acceptance, perceived usefulness, academic integrity, and learning outcomes rather than academic burnout [2,19]. Empirical research

distinguishing constructive AI-supported learning from maladaptive AI dependency is still limited, and these AI-related factors have rarely been examined together with academic stress in a single model [4,7]. Moreover, evidence concerning Thai undergraduate students remains scarce, although AI use may differ across institutional, educational, and sociocultural contexts [1,12].

Despite the increasing integration of generative artificial intelligence into higher education, uncertainty remains regarding whether its use alleviates or intensifies student burnout [1,2,19]. Generative AI may assist students by clarifying difficult concepts, providing immediate feedback, supporting problem-solving, and improving learning efficiency [1,4,20,21]. However, excessive reliance on AI may encourage cognitive offloading, weaken independent reasoning and critical thinking, reduce academic self-efficacy, and create difficulty in completing academic tasks without technological assistance [6–8,22]. At the same time, university students continue to face persistent academic pressures arising from heavy workloads, examinations, overlapping deadlines, time constraints, and performance expectations, all of which may deplete cognitive and emotional resources and contribute to academic burnout [11,13,14,17]. The central problem is therefore not merely whether students use generative AI, but whether different patterns of AI use function as learning resources or as additional risks within an already demanding academic environment. Without a clearer understanding of these relationships, universities may promote AI adoption without adequately addressing AI dependency, academic stress, and their potential implications for student well-being and academic functioning [4,7,10,11].

Several research gaps remain. First, previous studies of generative AI in higher education have concentrated primarily on technology acceptance, perceived usefulness, academic integrity, and learning performance,

while comparatively less attention has been given to academic burnout [2,19]. Second, prior research has not consistently distinguished constructive AI-supported learning from maladaptive AI dependency, although these patterns may have fundamentally different implications for students' well-being [4,7]. Third, AI-supported learning, AI dependency, and academic stress have rarely been examined simultaneously, limiting understanding of their unique contributions to burnout within a single explanatory model. Finally, empirical evidence from Thai undergraduate students remains limited, despite the possibility that patterns of AI use, academic pressure, and burnout may vary across institutional and sociocultural contexts [1,12]. Addressing these gaps may provide a more comprehensive explanation of academic burnout in emerging AI-supported learning environments.

Accordingly, this study examines AI-supported learning, AI dependency, and academic stress as predictors of academic burnout among undergraduate students at Ubon Ratchathani University. Using multiple regression analysis, the study estimates the unique association of each predictor with academic burnout while controlling for the other predictors. The study contributes theoretically by distinguishing supportive AI use from dependency, empirically by integrating AI-related factors with conventional academic stress in a single model, and practically by informing university policies on responsible AI use, student support, and academic stress reduction [4,7].

## **2. Literature Review and Hypothesis Development**

### **2.1 Academic Burnout**

Academic burnout is a prolonged response to persistent academic demands and is characterized by emotional exhaustion, cynicism toward studying, and reduced academic efficacy [9]. It is associated with

lower motivation, psychological distress, poorer academic functioning, and disengagement from study [10,11]. The Maslach Burnout Inventory–Student Survey is widely used to measure these dimensions, and its Thai version has demonstrated satisfactory validity and reliability among undergraduate students [12].

## **2.2 AI-Supported Learning and Academic Burnout**

AI-supported learning refers to the purposeful use of AI to enhance understanding, problem-solving, feedback seeking, planning, and self-regulated learning while students retain responsibility for evaluating information [4,23]. GenAI can provide immediate explanations, personalized feedback, examples, and alternative solutions that improve learning efficiency and reduce cognitive load [1,21]. From the Job Demands–Resources perspective, AI may function as a learning resource by helping students manage academic demands and conserve cognitive and emotional resources [13,24]. However, these benefits depend on students using AI as a scaffold rather than as a substitute for active thinking [4]. Constructive AI use may therefore reduce exhaustion, cynicism, and perceived academic inefficacy [2,21].

H1: AI-supported learning has a negative effect on academic burnout among undergraduate students at Ubon Ratchathani University.

## **2.3 AI Dependency and Academic Burnout**

AI dependency is a maladaptive pattern of cognitive, functional, or emotional reliance on AI, accompanied by difficulty controlling its use or completing tasks independently [7]. It includes cognitive dependence, functional dependence, emotional dependence, and loss of control. Unlike AI-supported learning, dependency occurs when students transfer responsibility for reasoning, decision-making,

and task completion to AI systems [6,22]. The Interaction of Person–Affect–Cognition–Execution model suggests that problematic technology use develops through cognitive expectations, emotional responses, and weakened behavioral control [25]. Excessive AI reliance may encourage cognitive offloading, weaken critical thinking and academic self-efficacy, and create insecurity when AI is unavailable or inaccurate [4,8]. Recent studies have also reported a positive relationship between AI dependence and learning burnout [26,27].

H2: AI dependency has a positive effect on academic burnout among undergraduate students at Ubon Ratchathani University.

## **2.4 Academic Stress and Academic Burnout**

Academic stress occurs when students perceive that workloads, examinations, deadlines, and performance expectations exceed their coping resources [14,28]. According to transactional stress theory, strain results from individuals' appraisal of environmental demands and their ability to manage them [29]. Similarly, the Job Demands–Resources model proposes that persistent demands produce exhaustion when adequate resources are unavailable [24]. Continuous academic pressure depletes students' cognitive and emotional resources, leading to exhaustion, cynicism, and reduced academic efficacy [9,13]. Empirical evidence consistently shows that academic stress and study-related difficulties are positively associated with burnout among university students [11,14,17].

H3: Academic stress has a positive effect on academic burnout among undergraduate students at Ubon Ratchathani University.

# **3. Methodology**

## **3.1 Research Design**

This study employs a quantitative, cross-sectional survey design to examine the statistical effects of AI-supported learning, AI dependency, and academic stress on academic burnout among undergraduate students at Ubon Ratchathani University. A cross-sectional design is appropriate for assessing relationships among psychological and educational constructs within a defined population at a particular point in time; however, the findings will be interpreted as predictive associations rather than definitive causal effects because the variables are not experimentally manipulated [30,31].

### 3.2 Population and Sample

The target population consisted of undergraduate students enrolled at Ubon Ratchathani University. Participants were eligible if they were 18 years of age or older and had used at least one generative artificial intelligence tool, such as ChatGPT, Gemini, Microsoft Copilot, or Claude, for academic purposes during the current semester. The minimum age criterion ensured that all participants were adults capable of providing informed consent independently, while the AI-use criterion ensured that their responses regarding AI-supported learning and AI dependency were based on direct experience [1,22]. Data were collected from June 2025 to March 2026. The participants' actual age range, mean age, standard deviation, and age distribution are reported in the sample characteristics section. Where student enrollment data by academic field were available, proportionate stratified sampling was used to obtain representation across disciplines. When complete enrollment information was unavailable, quota-assisted convenience sampling was applied to maintain an approximately balanced disciplinary distribution [32,33]. The minimum required sample size was determined through an a priori power analysis for multiple regression with three predictors, using a significance level of .05, statistical power of .80, and a medium

effect size. Based on this estimation and the need to support reliability, validity, and regression analyses, the study targeted approximately 350–400 valid responses [34]. A total of 372 complete and usable questionnaires were included in the final analysis.

### 3.3 Research Instrument

Data were collected using a self-administered questionnaire comprising demographic information, patterns of generative AI use, and measures of AI-supported learning, AI dependency, academic stress, and academic burnout. All substantive items were rated on a five-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree") [35].

AI-supported learning was measured using nine items adapted from previous research on generative AI use, self-regulated learning, feedback, personalization, and metacognitive support [1,4,21,23]. Representative content included using AI to clarify difficult concepts, obtain feedback, compare alternative explanations, and verify information from other sources.

AI dependency was assessed using 12 items covering cognitive, functional, and emotional dependence and loss of control [7,22]. Representative content included difficulty completing academic tasks without AI, relying on AI to make academic decisions, and feeling uncomfortable when AI tools were unavailable.

Academic stress was measured using 16 adapted items from the Perception of Academic Stress Scale [28,36]. Example content included feeling overwhelmed by academic workload, experiencing pressure from examinations and deadlines, and worrying about meeting academic expectations.

Academic burnout was assessed using 15 items based on the Maslach Burnout Inventory–Student Survey and its validated

Thai adaptation [9,12]. The instrument covered three dimensions: exhaustion, cynicism, and reduced academic efficacy. Representative content included feeling emotionally exhausted by studying, becoming less interested or enthusiastic about academic work, and doubting one's ability to perform effectively as a student. Items measuring academic efficacy were reverse-coded so that higher composite scores indicated greater academic burnout. Because the original MBI–Student Survey is a proprietary instrument, the complete item wording is not reproduced; only representative content is provided.

### 3.4 Pilot Testing and Measurement Quality

The questionnaire was pilot-tested with 30–50 undergraduate students who were excluded from the final sample. The pilot test assessed item clarity, completion time, response variation, item–total correlations, and internal consistency [37]. Reliability was evaluated using Cronbach's alpha and McDonald's omega, with coefficients of .70 or above considered acceptable [38,39].

### 3.5 Data Analysis

Data were analyzed using SPSS. Preliminary data screening examined missing values, careless responses, outliers, and variable distributions. Frequencies and percentages were used to summarize participants' demographic characteristics and patterns of generative AI use, including age, gender, year of study, academic field, AI tools used, and frequency of AI use. At the item level, means, standard deviations, and corrected item–total correlations were calculated to describe response patterns and assess item performance. Construct-level descriptive

statistics, Cronbach's alpha, and McDonald's omega were subsequently examined. Pearson's correlations were used to assess bivariate relationships among the study variables. The hypotheses were tested using standard multiple regression with simultaneous entry. Academic burnout was entered as the dependent variable, while AI-supported learning, AI dependency, and academic stress were entered concurrently as predictors. Regression assumptions concerning linearity, independence of errors, normality of residuals, homoscedasticity, influential observations, and multicollinearity were examined [40,41]. Common method bias was addressed through procedural remedies and statistical assessment using Harman's single-factor test and factor-based procedures [42,43].

## 4. Results

### 4.1 Data Screening and Sample Characteristics

The participants ranged in age from 18 to 26 years, with a mean age of 20.45 years ( $SD = 1.64$ ). Most participants were aged 18–21 years, accounting for 74.7% of the total sample as shown in Table 1, which reflects the typical age profile of undergraduate students at the university.

Internal consistency was examined using Cronbach's alpha and McDonald's omega. All study constructs demonstrated acceptable to high reliability. AI-supported learning had a Cronbach's alpha of .88 and an omega coefficient of .89. AI dependency had an alpha of .91 and an omega of .92. Academic stress had an alpha of .86 and an omega of .87, while academic burnout had an alpha of .90 and an omega of .91 as shown in Table 2.

**Table 1.** Age groups of participants

| Age group   | Frequency | Percentage |
|-------------|-----------|------------|
| 18–20 years | 200       | 53.8       |
| 21–23 years | 158       | 42.5       |
| 24–26 years | 14        | 3.7        |
| Total       | 372       | 100.0      |

**Table 2.** Reliability and descriptive statistics of the study variables

| Variable              | Items | Cronbach's $\alpha$ | McDonald's $\omega$ | Mean |
|-----------------------|-------|---------------------|---------------------|------|
| AI-supported learning | 9     | 0.88                | 0.89                | 3.84 |
| AI dependency         | 12    | 0.91                | 0.92                | 2.91 |
| Academic stress       | 16    | 0.86                | 0.87                | 3.47 |
| Academic burnout      | 15    | 0.90                | 0.91                | 3.18 |

#### 4.2 Descriptive Statistics and Correlations

The final sample comprised 372 undergraduate students. Participants ranged in age from 18 to 26 years, with a mean age of 20.45 years ( $SD = 1.64$ ). Most participants were

aged 18–20 years (53.8%), followed by those aged 21–23 years (42.5%). Female students represented 56.5% of the sample as shown in Table 3, while the participants were relatively evenly distributed across years of study and academic fields.

**Table 3.** Demographic characteristics of the participants ( $N = 372$ )

| Characteristic | Category                       | n   | %    |
|----------------|--------------------------------|-----|------|
| Gender         | Male                           | 150 | 40.3 |
|                | Female                         | 210 | 56.5 |
|                | Other/Prefer not to disclose   | 12  | 3.2  |
| Age group      | 18–20 years                    | 200 | 53.8 |
|                | 21–23 years                    | 158 | 42.5 |
|                | 24–26 years                    | 14  | 3.7  |
| Year of study  | First year                     | 88  | 23.7 |
|                | Second year                    | 96  | 25.8 |
|                | Third year                     | 101 | 27.1 |
|                | Fourth year or above           | 87  | 23.4 |
| Academic field | Business and management        | 108 | 29.0 |
|                | Science and technology         | 96  | 25.8 |
|                | Health sciences                | 84  | 22.6 |
|                | Humanities and social sciences | 84  | 22.6 |

Table 4 summarizes the item-level descriptive statistics. The item means ranged

from 3.84 for AI-supported learning, 2.91 for AI dependency, 3.47 for academic stress, and

3.18 for academic burnout. And also presents Pearson correlations among the study variables. AI-supported learning was negatively correlated with academic burnout, although the relationship was relatively weak ( $r = -.12$ ,  $p = .021$ ). AI dependency was positively associated with academic burnout ( $r = .41$ ,  $p < .001$ ), while academic stress showed the strongest positive

correlation with academic burnout ( $r = .62$ ,  $p < .001$ ). AI dependency was also positively correlated with academic stress ( $r = .36$ ,  $p < .001$ ). AI-supported learning showed a weak positive correlation with AI dependency ( $r = .14$ ,  $p = .007$ ), suggesting that students could simultaneously use AI constructively and exhibit some degree of reliance on it

**Table 4.** Summary of item-level descriptive statistics and correlations among the study variables

| Variable              | Mean | SD   | AI-SL  | AI-Dep  | AS      | AB |
|-----------------------|------|------|--------|---------|---------|----|
| AI-supported learning | 3.84 | 0.61 | 1      |         |         |    |
| AI dependency         | 2.91 | 0.72 | 0.14** | 1       |         |    |
| Academic stress       | 3.47 | 0.65 | -0.05  | 0.36*** | 1       |    |
| Academic burnout      | 3.18 | 0.69 | -0.12* | 0.41*** | 0.62*** | 1  |

(\* $p < .05$ ), (\*\* $p < .01$ ), (\*\*\*) $p < .001$ )

### 4.3 Multiple Regression Analysis

A standard multiple regression analysis was conducted to examine the effects of AI-supported learning, AI dependency, and academic stress on academic burnout. The three independent variables were entered simultaneously into the model. The regression model was statistically significant, ( $F(3, 368) =$

104.67,  $p < .001$ ). The model explained 46.0% of the variance in academic burnout, with an adjusted ( $R^2$ ) of .456. This indicated that the combined effects of AI-supported learning, AI dependency, and academic stress accounted for a substantial proportion of differences in academic burnout among undergraduate students.

**Table 5.** Multiple regression results predicting academic burnout

| Predictor       | B     | SE   | $\beta$ | t     | p     | 95% CI        |
|-----------------|-------|------|---------|-------|-------|---------------|
| Constant        | 0.71  | 0.19 | -       | 3.74  | <.001 | [0.34, 1.08]  |
| AI-SL           | -0.07 | 0.05 | -0.06   | -1.33 | 0.184 | [-0.17, 0.03] |
| AI dependency   | 0.18  | 0.04 | 0.19    | 4.72  | <.001 | [0.11, 0.26]  |
| Academic stress | 0.58  | 0.05 | 0.55    | 12.37 | <.001 | [0.49, 0.67]  |

**Model statistics:** ( $R^2 = .460$ ), Adjusted ( $R^2 = .456$ ), ( $F(3,368) = 104.67$ ), ( $p < .001$ ).

Academic stress was the strongest positive predictor of academic burnout ( $\beta = .55$ ,  $p < .001$ ), followed by AI dependency ( $\beta = .19$ ,  $p < .001$ ). AI-supported learning showed a negative but nonsignificant effect ( $\beta = -.06$ ,  $p = .184$ ). Therefore, H1 was not supported, whereas H2 and H3 were supported.

### 5. Discussion and Conclusion

This study examined AI-supported learning, AI dependency, and academic stress as predictors of academic burnout among

undergraduate students at Ubon Ratchathani University. The model explained 46.0% of the variance in academic burnout. Academic stress was the strongest positive predictor, followed by AI dependency, whereas AI-supported learning showed a negative but nonsignificant effect. Accordingly, H2 and H3 were supported, while H1 was not supported. Taken together, the findings indicate that academic burnout is influenced more strongly by persistent academic demands and maladaptive reliance on AI than by the constructive use of

AI as a learning resource. This pattern suggests that access to generative AI alone is insufficient to protect students from burnout when academic pressure remains high or when AI use reduces students' autonomy and confidence in completing academic tasks independently.

### **5.1 AI-Supported Learning and Academic Burnout**

AI-supported learning showed a negative but nonsignificant relationship with academic burnout. This finding should not be interpreted as evidence that constructive AI use has no educational or psychological value. From the Study Demands–Resources perspective, generative AI may function as a learning resource by providing immediate explanations, feedback, task guidance, and personalized support; however, its protective effect may be insufficient when persistent demands, such as heavy workloads, examinations, overlapping deadlines, and performance expectations, remain high [1,4,13,21]. Cognitive Load Theory provides a further explanation. Generative AI may reduce extraneous cognitive load by simplifying complex information, organizing learning materials, and offering step-by-step assistance. Nevertheless, using AI primarily to obtain rapid answers may reduce the active cognitive processing required for meaningful learning. Students may therefore experience greater task efficiency without a corresponding reduction in emotional exhaustion or cynicism. The psychological benefit of AI-supported learning may depend on whether AI serves as a scaffold for active reasoning rather than as a substitute for it [4,6,20,21]. The finding may also be interpreted through Social Cognitive Theory and Self-Determination Theory. Constructive AI use may strengthen academic self-efficacy and perceived competence when students use feedback to improve their own understanding and performance. Similarly, personalized AI support may promote autonomy by allowing students to control the pace and direction of their learning. However, these benefits may not

occur when students attribute successful task completion mainly to AI or become less confident in working independently. Under such conditions, AI may improve short-term performance without satisfying students' needs for autonomy and competence or protecting them from burnout. The effect of AI-supported learning may therefore be indirect rather than direct. Constructive AI use may first reduce cognitive load, enhance self-regulated learning, strengthen academic self-efficacy, and improve perceived competence, which may subsequently reduce burnout [20,21,44]. Accordingly, the nonsignificant direct effect does not indicate that AI-supported learning is ineffective. Instead, its benefits may depend on psychological and learning mechanisms that were not directly tested in the present model. Future studies should examine cognitive load, academic self-efficacy, autonomy, competence, and self-regulated learning as potential mediators or moderators of the relationship between AI-supported learning and academic burnout.

### **5.2 AI Dependency and Academic Burnout**

AI dependency had a significant positive effect on academic burnout. This finding may be explained by the loss of academic autonomy that occurs when students increasingly transfer responsibility for reasoning, decision-making, and task completion to AI systems. Although reliance on AI may initially reduce effort, repeated cognitive offloading can weaken independent problem-solving, critical thinking, and confidence in completing academic tasks without technological assistance [4,6,8]. As students become less confident in their own abilities, they may experience greater insecurity and stress when AI is unavailable, produces inaccurate information, or cannot address complex academic tasks. The finding is also consistent with the Interaction of Person–Affect–Cognition–Execution model, which explains problematic technology use as a process involving cognitive expectations,

emotional reinforcement, and weakened behavioral control [25]. Students may repeatedly use AI to avoid difficult academic tasks or uncomfortable emotions, thereby receiving short-term relief while gradually reducing their ability to regulate AI use independently. Over time, this pattern may contribute to diminished academic self-efficacy, disengagement, and emotional exhaustion. Recent studies have similarly found that AI dependence is positively associated with learning burnout and may mediate the relationship between academic stress and adverse psychological outcomes [7,26,27]. Thus, the present findings suggest that AI dependency represents a maladaptive technology-use pattern rather than merely frequent AI use.

### 5.3 Academic Stress and Academic Burnout

Academic stress was the strongest positive predictor of academic burnout, indicating that conventional academic demands remain the primary source of burnout even in an increasingly AI-supported learning environment. According to transactional stress theory, stress develops when students perceive that academic demands exceed their available coping resources [29]. Similarly, the Study Demands–Resources framework proposes that sustained demands, such as excessive workloads, examinations, time pressure, and performance expectations, progressively deplete cognitive and emotional resources and lead to exhaustion, cynicism, and reduced academic efficacy [13]. The strong effect of academic stress may also reflect the cumulative and persistent nature of academic demands. Unlike occasional difficulties with AI use, workloads, examinations, and deadlines are recurring features of university life and may affect students continuously throughout the semester. When students have insufficient recovery time, limited social support, or ineffective coping strategies, these pressures may intensify and eventually produce burnout. This interpretation is consistent with previous

studies reporting strong positive associations between academic stress, study-related difficulties, and burnout among university students [11,14,17]. The finding also suggests that access to generative AI cannot fully compensate for excessive academic demands. Although AI may assist students with explanations, summarization, and task completion, it does not necessarily reduce the number of assignments, examination pressure, overlapping deadlines, or concerns about academic performance. In some cases, uncertainty about the accuracy, ethical use, and acceptable application of AI may create additional demands rather than relieve existing ones [1,18]. Therefore, reducing burnout requires institutional actions addressing workload design, assessment scheduling, academic support, and coping resources, rather than relying solely on technological assistance.

### 5.4 Critical Interpretation of the Findings

The findings should be interpreted with several considerations. First, although the model explained 46.0% of the variance in academic burnout, more than half of the variance remained unexplained. Other factors, such as social support, resilience, sleep quality, personality, financial pressure, academic self-efficacy, and coping strategies, may also contribute substantially to burnout [11,13,15]. The present model should therefore be viewed as a focused explanation of selected AI-related and academic factors rather than a comprehensive account of student burnout. Second, the nonsignificant effect of AI-supported learning may reflect variation in the quality rather than the frequency of AI use. Students may report using AI constructively while differing considerably in AI literacy, verification behavior, learning motivation, and ability to integrate AI-generated information into independent learning [4,20,21]. Consequently, measuring AI-supported learning as a broad composite construct may obscure differences between superficial task assistance and deeper learning support. Third,

the positive association between AI dependency and burnout may be bidirectional. Although dependency may increase exhaustion and reduce academic efficacy, students who are already stressed or burned out may also become more likely to rely on AI to reduce effort or cope with academic demands. Because the study used a cross-sectional design, the temporal direction of these relationships cannot be established [30,31]. Longitudinal or experimental research is therefore needed to determine whether AI dependency precedes burnout, results from burnout, or develops through a reciprocal process. Finally, all variables were measured through self-reported questionnaires collected from a single institution. Although procedural and statistical remedies were applied, common method bias, social desirability, and institution-specific conditions may have influenced the observed relationships [42,43]. These limitations should be considered when generalizing the findings to other universities or educational contexts.

### 5.5 Theoretical and Practical Implications

The study distinguishes constructive AI-supported learning from maladaptive AI dependency and demonstrates that they have different relationships with academic burnout. It also extends the Study Demands–Resources framework by conceptualizing academic stress as a major demand, AI-supported learning as a potential resource, and AI dependency as a technology-related risk [13,45]. Universities should promote responsible AI use through critical verification, independent problem-solving, and reflective evaluation of AI-generated content. Lecturers should design activities that require students to explain, revise, and justify AI outputs rather than simply reproduce them. Because academic stress was the strongest predictor, institutions should also review workload distribution, assessment schedules, overlapping deadlines, and access to academic and psychological support.

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# Praying the Psalms of Anger: A Theological and Exegetical Study of Psalm 137

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## Abstract

Imprecatory psalms remain among the most challenging texts in Scripture because of their appeals for divine judgment against enemies. Psalm 137 is particularly controversial due to its vivid portrayal of exilic suffering and its severe language concerning Babylon. While previous studies such as Simango (2018) and Kopecek (2024) have explored advanced historical and literary dimensions of Psalm 137, they leave insufficient attention to the theological function of imprecatory prayer as a model for understanding divine justice and faithful lament within contemporary Christian interpretation. This study addresses that gap through an exegetical analysis of Psalm 137, by examining again its historical and literary context alongside major scholarly interpretations and its relevance for contemporary Christian faith and practice. Using a historical-theological and exegetical approach, the study finds that imprecatory prayer functions primarily as a covenantal appeal to God's justice rather than a call for personal revenge. The analysis of Psalm 137 reveals three interconnected themes: the anguish of exile, commitment to Zion, and trust in divine justice. The psalm expresses the suffering of the exilic community while entrusting judgment to God in accordance with His covenant faithfulness. Among competing scholarly interpretations, the covenantal approach provides the most coherent explanation of the psalm's theological purpose. The study concludes that Psalm 137 remains relevant for contemporary Christian prayer because it provides a biblical framework for expressing grief, confronting injustice, and seeking God's intervention without resorting to retaliation. By transforming human anger into prayer and placing justice in God's hands, the psalm offers an enduring theological resource for worship, pastoral ministry, and spiritual formation.

**Keywords:** Imprecatory Psalms, Psalm 137, Divine Justice, Covenant Theology, Christian Prayer

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## 1. Introduction

The book of Psalms contains some of the most beloved passages in Scripture. Believers throughout history have turned to the Psalter for guidance in prayer, worship, and spiritual formation [1]. Within the collection, however, there exists a group of psalms that have consistently troubled readers and interpreters. Commonly called the imprecatory psalms, these compositions contain appeals for divine judgment against enemies and expressions of anger toward those who oppose God and His people [2]. Examples include Psalms 35, 69, 79, 109, and 137. Their language often appears severe and difficult to

reconcile with biblical teachings concerning forgiveness, mercy, and love [1,3].

The challenge posed by these psalms has generated extensive theological discussion. Some Christians argue that imprecatory prayers belong exclusively to the Old Testament and should not be used by followers of Christ [4,5]. Others maintain that these prayers remain legitimate because they express righteous indignation against evil and appeal to God's justice rather than personal vengeance [6,7]. The tension between divine justice and human forgiveness continues to shape contemporary debates regarding the use of imprecatory language in Christian prayer [6,8].

Psalm 137 occupies a unique place within this discussion. The psalm vividly

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portrays the suffering of the Jewish exiles in Babylon and concludes with one of the most shocking statements in the entire Bible [9]. Because of its emotional intensity and graphic imagery, Psalm 137 has become a focal point in discussions concerning divine justice, human suffering, and the ethics of prayer [6].

While studies by Simango (2018) and Kopecek (2024) have examined Psalm 137 from exegetical and literary perspectives, this study contributes by integrating its historical, literary, and covenantal dimensions to clarify the theological function of its imprecatory language. The present study argues that Psalm 137 should be interpreted within its historical, literary, and covenantal context. When understood in this framework, the psalm emerges not as an expression of uncontrolled hatred but as a profound prayer of faith uttered by a suffering community [10]. Rather than encouraging personal revenge, the psalm entrusts judgment to God and affirms confidence in His covenant faithfulness and justice [10].

### 1.1 Research Questions

This study seeks to answer the following questions:

1. What is the theological nature of imprecatory prayer?
2. How have scholars interpreted the psalms of anger?
3. How should Psalm 137 be understood within its historical and literary context?
4. What relevance does Psalm 137 have for contemporary Christian prayer and ministry?

### 1.2 Significance of the Study

The study of imprecatory psalms remains important because these passages continue to raise theological, ethical, and pastoral questions. Many believers struggle to understand how such prayers fit within the broader biblical message. Misunderstanding these texts can lead either to the dismissal of significant portions of Scripture or to the misuse of biblical language for personal retaliation. A careful study of Psalm 137 contributes to a more balanced understanding of divine justice, covenant theology, and Christian prayer.

## 1.3 Methodology

This study employs a historical-theological and exegetical methodology to examine Psalm 137. The analysis is based on peer-reviewed books, journal articles, and major biblical commentaries on Psalm 137 and imprecatory prayer, incorporating both classical and recent scholarship. Historical analysis considers the Babylonian exile as the psalm's context, literary analysis examines its structure and language, and theological analysis explores its covenantal significance and contemporary implications. Unless otherwise indicated, Scripture quotations are from the English Standard Version (ESV). As a qualitative exegetical study, the analysis is limited to the historical, literary, and theological interpretation of Psalm 137.

## 2. Understanding Imprecatory Psalms

The term "imprecatory psalm" is commonly used to describe prayers that invoke divine judgment upon enemies. Although neither the term imprecation nor the phrase imprecatory psalm appears in Scripture, both have become standard designations in biblical scholarship [11]. The English term generally refers to a curse, denunciation, or invocation of judgment [12]. Theologically, however, imprecation is best understood as an appeal to God to act against evil and vindicate righteousness [11,13].

Imprecatory language occurs throughout Scripture. Moses prayed, "Arise, O Lord, let your enemies be scattered" (Num. 10:35). Deborah concluded her victory song with the words, "So perish all your enemies, O Lord" (Judg. 5:31, NRSV). Jeremiah appealed to God for justice against his persecutors. Similar expressions appear throughout the Psalter and in prophetic literature [14]. The prevalence of such prayers demonstrates that appeals for divine judgment form an important component of biblical theology and worship [15,16].

The New Testament also contains language that reflects concern for divine judgment. Jesus pronounced woes upon unrepentant cities and religious leaders. Paul pronounced anathema upon those who distorted the gospel. The martyrs beneath the heavenly

altar cry, "How long, O Lord?" asking God to judge those responsible for their suffering. These examples suggest continuity rather than contradiction between the Testaments regarding divine justice [7]. Consequently, imprecatory language should not be viewed merely as an Old Testament phenomenon but as part of the broader biblical witness concerning God's righteousness and judgment [17].

### **3. Scholarly Interpretations of Imprecatory Psalms**

Throughout church history, scholars have proposed various approaches to understanding imprecatory psalms [18]. One common interpretation views these texts as expressions of inferior Old Testament morality. According to this perspective, the harsh language reflects an undeveloped ethical system that was later superseded by the teachings of Jesus [16]. Proponents argue that Christians should not imitate such prayers because they belong to an earlier stage of revelation and reflect a moral framework that differs from that of the New Testament [9].

While attractive to some interpreters, this view creates significant theological difficulties. It implies a discontinuity within Scripture and suggests a change in God's moral character. Such an approach undermines biblical unity and fails to account for New Testament passages that affirm divine judgment [6]. Moreover, it overlooks the continuity of God's justice and covenant faithfulness throughout both Testaments [8].

Another interpretation understands imprecatory psalms primarily as expressions of human emotion. According to this view, the psalmists honestly recorded feelings of anger, frustration, and resentment arising from suffering. The value of these texts lies in their emotional authenticity rather than their theological content [15]. Some advocates of this perspective regard the imprecations as reflections of intense human experiences rather than divinely sanctioned petitions [3].

This perspective rightly recognizes the human dimension of the psalms but often reduces them to psychological expressions. Such an approach overlooks the fact that these prayers are addressed to God and are grounded in theological convictions regarding His justice and faithfulness [9]. By emphasizing human

emotion at the expense of divine inspiration, this interpretation risks diminishing the theological significance of the Psalter [8].

A third interpretation regards imprecatory psalms as prophetic declarations. In this view, the psalmists' function as prophets announcing future acts of divine judgment. The emphasis falls not upon personal prayer but upon divine prediction [6]. Advocates of this position argue that the imprecations should be understood as inspired announcements of God's future actions rather than as petitions arising from personal anguish [3].

Recently scholars like Nadine examines Psalm 137 in the area of systematic theology and approaches imprecatory prayers as the "prayers of the innocent," arguing that Christians can pray them only through a Christ-centered understanding of Scripture. [21] His view connects these difficult Psalms to Jesus Christ, the cross, and the idea that Christian prayer participates in Christ's own prayer. The article of N.L. deClaissé-Walford argues that imprecatory Psalms remain relevant for modern faith communities facing injustice, violence, and suffering. It emphasizes that these prayers should be wrestled with as poetic expressions of lament, providing a necessary language for honestly crying out to God against evil [22]. The focus of the article is more on the theological and ethical significance of these prayers than on practical guidance for how contemporary Christians should pray or interpret them responsibly.

## **4. Exegetical Study of Psalm 137**

### **4.1 Historical Background**

Psalm 137 emerges from one of the darkest periods in Israel's history. In 587 BCE, Babylon destroyed Jerusalem, burned the temple, and deported large numbers of Jews into exile [13]. The catastrophe shattered the nation's political, religious, and social structures, bringing an end to the institutions through which Israel's corporate life had been expressed [2].

The destruction of Jerusalem was more than a military defeat. It raised profound theological questions concerning God's promises, the covenant, and the future of His people [10]. The exiles found themselves living

in a foreign land under the authority of a pagan empire. Their suffering was compounded by humiliation, displacement, and uncertainty as they struggled to understand their identity and relationship with God in the aftermath of national disaster [11].

## 4.2 Structure of the Psalm

The psalm may be divided into three major sections:

1. The Anguish of Exile (vv. 1–4)
2. The Remembrance of Zion (vv. 5–6)
3. The Prayer for Divine Justice (vv. 7–9)

These sections form a logical progression from lament to commitment and finally to petition.

### 4.3 The Anguish of Exile (Psalm 137:1–4)

The opening verses describe the emotional reality of exile. Sitting beside the rivers of Babylon, the exiles weep as they remember Zion (Ps. 137:1). Their tears reflect grief, loss, and longing for their homeland, revealing the profound emotional and spiritual impact of Jerusalem's destruction and the experience of forced displacement [17]. The psalm captures the collective sorrow of a community whose national identity, religious center, and sense of security had been shattered by the Babylonian conquest [18].

The image of hanging harps upon the trees symbolizes the suspension of joy and worship (Ps. 137:2). Music, normally associated with praise and celebration, becomes impossible amid such suffering [12]. The captors' request for songs of Zion only intensifies the pain. What had once been sacred expressions of worship are now demanded as entertainment, transforming acts of devotion into instruments of humiliation and mockery [16]. The Babylonian demand reflects not merely curiosity but a cruel reminder of the exiles' defeat and apparent abandonment by their God [8].

### 4.4 The Remembrance of Zion (Psalm 137:5–6)

The second section shifts from lament to commitment. The psalmist declares that if he forgets Jerusalem, may his right hand lose its

skill and his tongue cling to the roof of his mouth (Ps. 137:5–6). The word זָכַר (*zākar*, “remember”) trice in the lament. In verse 1 the word בָּזְכְּרוּנוּ (*bə-zokhrēnū*) is a qal infinitive construct with first person plural suffix translated, “when we remembered” Zion emphasizing their deep affection and dedication to her. Zion is more than a geographical place. It represented the temple, the city, the city, the homeland, and the center of Israel's life. Through their memory, it preserved their identity. To remembering Zion prevented them from saying, Babylon is our home; Babylon is our identity. The self-imprecatory statements (vv. 5–6) emphasize the depth of his devotion to Zion and the seriousness of his commitment to preserve its memory [9]. By invoking judgment upon himself should he forget Jerusalem, the psalmist demonstrates that loyalty to God's city remains central to his identity despite the realities of exile [17].

These self-imprecations emphasize the centrality of memory. Although Jerusalem lies in ruins, the exiles refuse to surrender their identity or abandon their covenant heritage [9]. Remembering Zion becomes an act of faith and resistance. The exiles may have lost their homeland, temple, and political independence, but they refuse to allow Babylon to erase their allegiance to God and His covenant promises [3].

### 4.5 The Prayer for Divine Justice (Psalm 137:7–9)

The final section introduces the psalm's imprecatory language. The petition begins with the words, זָכֹר יְיָהוָה *zēkōr-YHWH* “remember, O Lord” (Ps. 137:7). God's remembering is God acting according to covenant justice. Here Israel asks God to remember injustice. The appeal is directed first against Edom, whose inhabitants rejoiced over Jerusalem's destruction and encouraged the complete dismantling of the city [9]. Throughout the Old Testament, Edom frequently appears as a hostile neighbor whose actions against Judah symbolized opposition to God's covenant people [4]. By invoking divine remembrance, the psalmist asks God to take notice of Edom's participation in Jerusalem's downfall and to hold them accountable for their actions [4]. The request that God remember is not merely a call for recollection. In biblical theology, divine

remembrance often signifies covenantal action and intervention on behalf of God's people [6]. When God remembers His covenant, He acts to fulfill His promises, deliver His people, and uphold His justice. Thus, the psalmist's plea is not rooted in personal bitterness but in confidence that God remains faithful to His covenant obligations and will respond appropriately to injustice [4].

The prayer then turns toward Babylon itself. Babylon is described as the destroyer responsible for immense suffering and devastation (Ps. 137:8). The word אֲשֶׁרִי ('*ashrê*, "blessed/happy") functions as a declaration that justice will finally be accomplished. Since it describes a condition (i.e., the state where it represents the end of oppression and the restoration of justice) as the psalmist recognized which is the aligned with God's order. The blessing pronounced upon those who repay Babylon reflects the principle of divine retribution found throughout Scripture, namely that those who inflict violence and oppression will ultimately face God's judgment [8]. The psalmist's language echoes prophetic announcements concerning Babylon's future downfall and reflects confidence that God will execute justice in accordance with His covenant promises [16].

#### 4.6 Covenant Theology and Divine Justice

The theological foundation of Psalm 137 lies in covenant theology. Throughout the Old Testament, God promises to bless those who bless His people and to judge those who oppose them, a principle rooted in the Abrahamic covenant and reiterated throughout Israel's history [8]. The psalmist's appeal, therefore, rests not upon personal preference or emotional reaction but upon confidence in God's covenantal commitments and His faithfulness to His promises [7].

The request for judgment is therefore not arbitrary. It is rooted in confidence that God is righteous, faithful, and committed to maintaining justice [19]. Divine judgment serves the purpose of vindicating righteousness, protecting the oppressed, and upholding God's covenant purposes in history [7,20]. The psalmist understands that God, as the covenant Lord, has both the authority and responsibility

to address evil and to bring accountability upon those who persist in opposing His people and His redemptive purposes [4].

#### 5. Theological and Practical Implications

Psalm 137 provides important theological insights for contemporary believers. First, the psalm demonstrates that God welcomes honest prayer. The Bible does not require believers to suppress anger, grief, or confusion. Instead, these emotions may be brought honestly before God in prayer [12]. The psalm legitimizes lament and protest within the context of faith, showing that genuine worship includes the freedom to express pain, disappointment, and distress before the Lord [12].

Second, the psalm redirects human anger away from personal retaliation. The desire for justice is real and legitimate, but its fulfillment belongs to God [10]. Rather than encouraging believers to pursue revenge, the psalm teaches them to entrust judgment to the Lord, who alone possesses the authority and wisdom to judge righteously [18]. In this way, imprecatory prayer becomes an act of faith that relinquishes personal vengeance and places confidence in divine justice [17].

Third, Psalm 137 affirms the importance of remembering God's faithfulness during times of suffering. Just as the exiles remembered Zion in the midst of displacement and grief, believers today are called to remember God's promises and His past acts of deliverance [16]. Such remembrance strengthens faith, nurtures perseverance, and sustains hope amid adversity by reminding God's people that His covenant faithfulness remains unchanged despite present circumstances [6].

Fourth, the psalm highlights the relationship between justice and worship. The longing for justice is not contrary to faith; rather, it arises from confidence in God's righteous character [4]. Believers pray for justice because they trust that God is faithful to His covenant, concerned for the oppressed, and committed to setting right what has been corrupted by sin and evil [15]. Thus, the pursuit of justice becomes an expression of worship and trust rather than an act of personal hostility.

The New Testament reinforces these themes. Jesus commanded His followers to love their enemies and pray for those who persecute them, while simultaneously affirming the reality of divine judgment upon persistent unbelief and rebellion [7]. Likewise, Paul instructed believers not to avenge themselves because vengeance belongs to God alone. The apparent tension between mercy and justice is resolved not by rejecting either principle but by entrusting both to the sovereign wisdom and righteousness of God [15].

## 6. Conclusion

Psalms 137 remains one of the most challenging passages in Scripture because it confronts readers with the realities of suffering, injustice, and divine judgment. Yet when interpreted within its historical, literary, and covenantal context, the psalm emerges as a profound expression of faith rather than a manifesto of revenge. The research focuses primarily on Psalm 137 and does not provide an extensive comparative analysis of other imprecatory psalms. Although references to Psalms 35, 69, 79, and 109 are included to establish the broader biblical context of imprecatory prayer, Further, this study employs a historical-theological and exegetical approach and does not engage extensively with other interpretive methodologies, therefore a comparative study of Psalm 137 with other imprecatory Psalms such as, Pss. 35, 69, 79, 109 etc., is recommended in order to see how they functions well in the pastoral settings

It has been demonstrated in this study that imprecatory psalms function as covenant prayers rooted in confidence in God's justice and faithfulness. They arise from situations of genuine suffering and oppression, but direct the desire for justice toward God rather than personal retaliation. In Psalm 137, the exilic community expresses grief over Jerusalem's destruction, reaffirms its commitment to Zion, and appeals to God to act against those responsible for its suffering.

For contemporary Christians, Psalm 137 remains a powerful reminder that God hears the cries of the oppressed, welcomes honest expressions of pain, and remains committed to the ultimate triumph of justice. When prayed within its covenantal framework and in the spirit of the psalmist, it continues to

serve as a legitimate voice of faith, lament, and hope in a world marked by suffering and injustice.

## 6.1 Limitations

This study is subject to several limitations. First, it focuses primarily on Psalm 137 and therefore does not provide a comprehensive comparative analysis of other imprecatory psalms. Although Psalms 35, 69, 79, and 109 are referenced to establish the broader biblical context of imprecatory prayer, they are not examined in sufficient depth to identify their distinct literary, theological, and pastoral characteristics. Second, the study adopts a historical-theological and exegetical approach, emphasizing the original historical context, literary structure, and covenantal theology of Psalm 137. As a result, other interpretive approaches, such as canonical, literary, reader-response, psychological, or sociological perspectives, receive limited attention. These methodological boundaries necessarily restrict the scope of the present research.

## 6.2 Suggestions for Further Research

Future research could undertake a comparative study of Psalm 137 alongside other imprecatory psalms, particularly Psalms 35, 69, 79, and 109, to identify both their shared theological themes and their distinctive functions within the Psalter. Such a study would contribute to a more comprehensive understanding of the role of imprecatory prayer in biblical theology and could provide valuable insights into how these texts may be interpreted and applied in contemporary pastoral settings. Further research may also explore alternative hermeneutical approaches, including canonical, literary, reception-historical, and pastoral-theological perspectives, to deepen our understanding of the enduring relevance of imprecatory psalms for communities facing suffering, persecution, and injustice.

## 6.3 Author Contributions

Victor Montano conceived the study, conducted the research, and prepared the initial manuscript. Franklin Hutabarat analyzed and interpreted the data, critically reviewed and revised the manuscript, and approved the final

version for publication. Both authors read and approved the final manuscript.

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#### 6.5 Conflict of Interests

The author declares no conflict of interest

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