Assessments of Spatiotemporal Variations and Driving Factors of Ecological Quality in the Greater Penang Conurbation Based on Remote Sensing Ecological Distance Index

AI-Assisted Tools Usage Statement: During the preparation of this work, ChatGPT (OpenAI) was used only to assist with grammar correction and language refinement. AI-Assisted tools were not involved in any part of the research design, data analysis, scientific interpretation, or content generation. Furthermore, all AI-suggested modifications were thoroughly reviewed, verified, and revised by the authors to ensure accuracy, appropriateness, and academic integrity.

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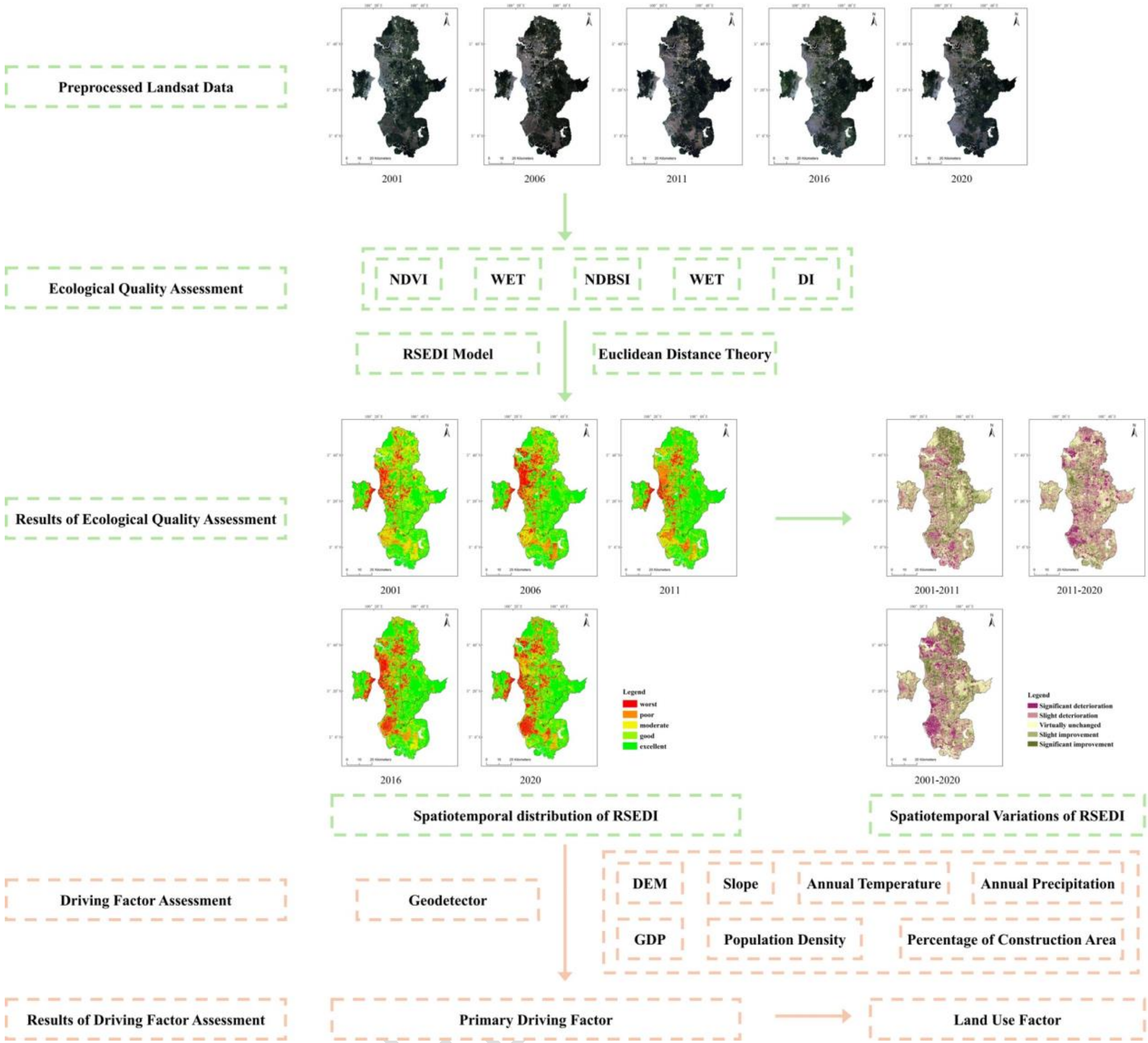
Graphical abstract:



Abstract: The Greater Penang Conurbation, one of the three major conurbations in Malaysia, has experienced rapid urbanization since the beginning of this century, leading to various ecological challenges. The rapid and accurate assessments of ecological quality and its driving factors is crucial for improving ecological quality and achieving sustainable development goals across diverse regions. This study applied the Remote Sensing Ecological Distance Index (RSEDI) model based on Euclidean distance theory and Landsat series images, as the main method and data source respectively, to assess spatiotemporal variations in ecological quality in the Greater Penang Conurbation from 2001 to 2020. Subsequently, the driving factors of ecological quality were assessed through the factor detector and interaction detector components of the Geodetector model. The results showed that: (1) The RSEDI values for the Greater Penang Conurbation in 2001, 2006, 2011, 2016 and 2020 were 0.64, 0.64, 0.67, 0.64 and 0.62, respectively, showing a trend of slightly increasing, then slightly decreasing, and an overall slight decrease. The overall ecological quality was good over the 19-year period but showed a slightly declining trend. (2) Low-ecological-quality areas were mainly in western Penang Island and eastern Kuala Muda, while high-quality areas were concentrated in Kulim, Bandar Baharu, and eastern Penang Island. Ecological quality in South Seberang Perai and eastern Kerian declined significantly after 2011. (3) The Geodetector results indicated that land use was the primary driving factor. Patterns and changes in land use effectively explained the distribution and variations of ecological quality in the Greater Penang Conurbation over the 19-year period. The results can offer scientific guidance for future ecological protection and management of the Greater Penang Conurbation. By early applying the simple and efficient RSEDI model, this study also provides a reference for rapid, accurate ecological quality assessment in tropical coasts, tropical islands, and other tropical regions.

Key words: ecological quality, Remote Sensing Ecological Distance Index, Geodetector, spatiotemporal variations, Greater Penang Conurbation

1. Introduction

Ecological quality is crucial to the quality of living environment and the comfort of urban residents (Li et al., 2022; Rahaman et al., 2022b; Silva et al., 2018). However, rapid urbanization has often resulted in a series of ecological problems, which have, in turn, impacted the sustainable development of urbanization(Seto et al., 2012; Zhang et al., 2018). Ecological quality assessment can obtain regional current status of ecological quality and its change. Exploring the driving factors of the ecological quality can further reveal the mechanism of ecological quality variations (Zhang et al., 2024). Understanding the spatiotemporal trends and driving mechanisms of ecological quality is crucial for effective ecological management and formulating economic, social, governance, and energy-related policies under the current framework of sustainable development goals (Cai et al., 2024a; Cai et al., 2024b; Cai et al., 2025a, b). The introduction of Geographic Information System (GIS) and remote sensing (RS) technology ensures the rapid, simple and accurate assessments of ecological quality.

The Greater Penang Conurbation is one of the three largest metropolitan areas in Malaysia (Abdullah et al., 2009). Since the beginning of this century, the Greater Penang Conurbation has experienced rapid urbanization (Hasan and Nair, 2014; Mahamud et al., 2016; Tan et al., 2009). Specifically, Penang Island experienced rapid urbanization during the first decade of the century, with large areas of land converted to built-up land, while the Penang Mainland and some regions in neighboring districts of Penang State underwent a similar urbanization process during the second decade (Mahamud et al., 2016; Tew et al., 2019). However, due to its high population density and the excessively rapid urbanization process in some regions, pronounced human-land conflicts have emerged (Tew et al., 2019). These conflicts have given rise to a series of ecological problems, including droughts, floods, the urban heat island (UHI) effect, and increased emissions from vehicle exhaust, leading to a decline in living conditions and property losses suffered by residents. (Mudashiru et al., 2022; Rahaman et al., 2022b; Sukor et al., 2021; Tan et al., 2022). The deterioration of ecological quality was gradually accelerating in the Greater Penang Conurbation since this century (Rahaman et al., 2022b; Tan et al., 2022). Therefore, the rapid and accurate assessments of ecological quality and its driving factors in the Greater Penang Conurbation is of great significance for improving ecological quality and achieving the goal of sustainable development.

Recent studies on the ecological quality of the Greater Penang Conurbation mostly focused on the analysis of individual ecological factors and the relationships among different ecological factors (Rahaman et al., 2022b; Tan et al., 2022). However, the ecological quality of the Greater Penang Conurbation was affected by multiple ecological factors simultaneously. Exploring a single factor or the relationship among different ecological factors alone was difficult to fully reflect the status of ecological quality. A comprehensive ecological quality index needs to be established to understand the status of ecological quality. The Remote Sensing Ecological Distance Index (RSEDI), introduced by Zhang (2016), was a model for computing the comprehensive ecological index based on the Euclidean distance theory. Zhang (2016) integrated four components, namely the greenness index, humidity index, salinity index and desertification index by Remote Sensing Ecological Distance Index model based on Euclidean distance theory to assess the ecological quality of the Guazhou-Dunhuang Basin, located in an arid region. Subsequently, considering the significant differences in ecological environmental backgrounds across different regions, Yan et al. (2022) applied four components including greenness index, humidity index, dryness index, and heat index to establish a Remote Sensing Ecological Distance Index suitable for subtropical karst areas, which was then used to assess the ecological quality and spatiotemporal changes in Du'an County. RSEDI can overcome the influence of subjectively determined weights and effectively integrate various indicators. In addition, due to its ease of use, RSEDI also offered the advantages of being simple, rapid, and accurate. Therefore, the Remote Sensing Ecological Distance Index (RSEDI), established by selecting appropriate types and quantities of ecological components, has been successfully applied to the assessments of ecological quality in different types of regions, including Yulin City, Ningxia, Oases of Hexi Corridor, and the Shiyang River Basin (Guo et al., 2021; Shi et al., 2018; Wang et al., 2021;

Yang et al., 2021). However, although the RSEDI model has achieved successful applications within a certain scope, it has rarely been applied to tropical or coastal areas. Therefore, testing the RSEDI model in a wider range of regions is still necessary to further expand its scope of application.

The changes of ecological quality are influenced by multiple factors, such as topography, climate, and human activities, with complex influencing mechanisms (Wang et al., 2024b; Yang et al., 2023). Understanding the driving mechanisms of changes in ecological quality can provide more scientific references for ecological restoration and mitigating ecological degradation. Geodetector, introduced by Wang and Xu, is a new statistical method to reveal the driving factors behind the spatial stratified heterogeneity (Wang and Xu, 2017). In recent years, the Geodetector model has demonstrated good applicability in the assessment of driving forces for rural spatial patterns, urban expansion, population distribution patterns, vegetation coverage, drought, soil fertility in agricultural land, and comprehensive ecological quality (Chen et al., 2022b; Liu et al., 2022; Liu et al., 2020; Lv et al., 2023; Wang et al., 2019; Wang et al., 2024a; Yuan et al., 2019). Appropriate variable selection and reasonable sample size remain critical for the effective use of the Geodetector model (Wang and Xu, 2017).

In summary, taking the Greater Penang Conurbation as the study area, the objectives of this study were: (1) to establish the Remote Sensing Ecological Distance Index (RSEDI) model by integrating multiple ecological index to assess the ecological quality of the Greater Penang Conurbation from 2001 to 2020. (2) to analyze spatiotemporal distribution and variations of the ecological quality of the Greater Penang Conurbation from 2001 to 2020. (3) to apply the factor detector and interaction detector in the Geodetector model to assess the driving factors of ecological quality. The novelty of this study lies in the early application of the RSEDI model, a method based on Euclidean distance theory and easy to implement, for assessing ecological quality in tropical regions. The results of this study provide scientific reference for the future ecological protection and management of the Greater Penang Conurbation, as well as for achieving sustainable development goals. In addition, the methods applied in this study could provide a reference for ecological quality assessments in tropical coastal areas, tropical islands, and other types of tropical regions.

2. Materials and methods

2.1 The study area

The Greater Penang Conurbation, consisting of Penang State and its neighboring districts, is located in the northwestern part of Peninsular Malaysia, between latitude 4°50' N-5°52' N and longitude 100°10'- 100°52' E (Fig. 1(a) and Fig. 1(b)). The total area of the Greater Penang Conurbation is approximately 3938 km^2, of which the total area of the Penang State is 1048 km^2. Penang State consists of Penang Island, Seberang Perai (Penang mainland) and other small islands, and the neighboring districts of Penang State include Kuala Muda, Kulim and Bandar Baharu from Kedah State and Kerian from Perak State. The Greater Penang Conurbation has a tropical rainforest climate with monsoon influence, featuring hot and humid conditions year-round. Penang island contains some mountainous regions which are mainly located in the middle and north part of the island, while mainland part of the Greater Penang Conurbation is low-plain-dominated region. Penang State has a population of 1.774 million and is the highest population density state in Malaysia. (1691/km^2) (Department of Statistics Malaysia 2021). And the total population in the whole Conurbation was around 3 million in 2020 and is expected to reach 3.7 million in 2030 (Samat et al., 2020). The Greater Penang Conurbation has experienced rapid urbanization in the past years, which has also led to some urban and ecological problems (Rahaman et al., 2022b; Stiepani et al., 2021). With almost all land, population and urban areas, Penang Island and the mainland areas of the Greater Penang Conurbation, are chosen as research area and scope (Fig. 1(c)). To ensure research feasibility, the study will exclude other small islands in the Greater Penang Conurbation due to their minimal size and population. From the perspective of administrative divisions, the study area includes 9 districts (Fig. 1 (c)).

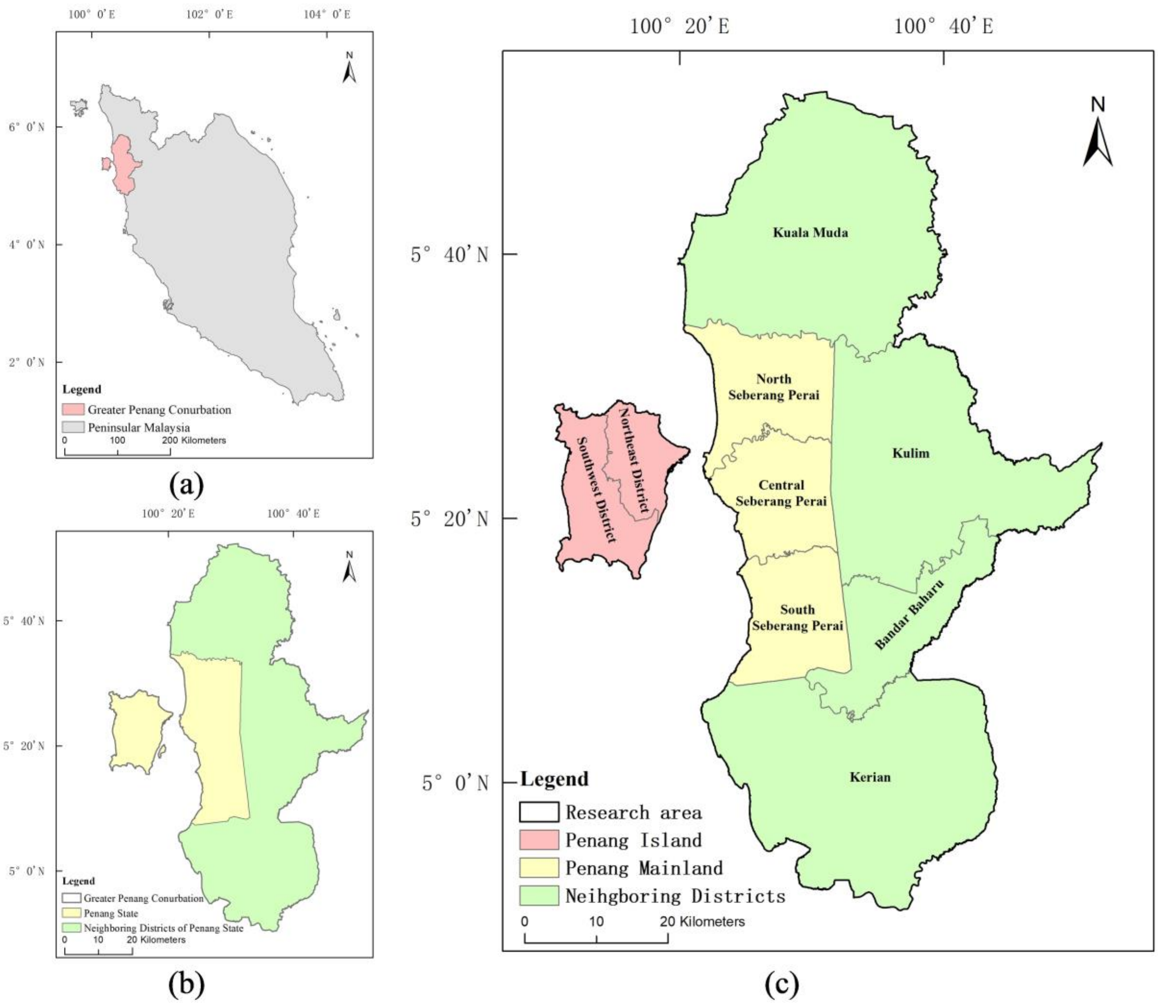


Fig. 1 Geographical location of the research area

2.2 Data Sources and preprocessing

Considering the time span of this study, the Landsat series images were chosen as main data and acquired from the United States Geological Survey (USGS, https://earthexplorer.usgs.gov). This study obtained suitable images from Landsat 5 (TM), Landsat 7 (EMT+) and Landsat 8 (OLI/TIRS) Collection 2 Level 2 datasets. All selected Landsat images have a spatial resolution of 30 meters. As the study area is located in tropical rainforest region where Landsat data quality is greatly affected by cloud cover, the selection of images had to balance several factors by maintaining approximately equal temporal intervals, minimizing interannual temporal span, and ensuring minimal cloud cover. Accordingly, Landsat data in different period, i.e., 2001, 2006, 2011, 2016 and 2020 were selected, which served as appropriate representations in the study period. To ensure data reliability, the temporal span of the selected Landsat images was limited to within three months, with low cloud coverage over the study area. The Landsat images used in this study are shown in Table 1.

Table 1 Landsat images used in this study

Date	Landsat Data	Remark
2001.02.15	LE07_L2SP_128056_20010215_20200917_02_T1	Surface Reflectance/ Surface Temperature
2001.02.15	LE07_L2SP_128057_20010215_20200917_02_T1	Surface Reflectance/ Surface Temperature
2006.02.21	LT05_L2SP_128056_20060221_20200901_02_T1	Surface Reflectance/ Surface Temperature
2006.02.21	LT05_L2SP_128057_20060221_20200901_02_T1	Surface Reflectance/ Surface Temperature
2011.03.07	LT05_L2SP_128056_20110307_20200823_02_T1	Surface Reflectance
2011.03.07	LT05_L2SP_128057_20110307_20200823_02_T1	Surface Reflectance
2011.04.08	LT05_L2SP_128056_20110408_20200823_02_T1	Surface Temperature
2011.04.08	LT05_L2SP_128057_20110408_20200823_02_T1	Surface Temperature
2016.02.01	LC08_L2SP_128056_20160201_20200907_02_T1	Surface Reflectance
2016.02.17	LC08_L2SP_128056_20160217_20200907_02_T1	Surface Temperature
2020.02.28	LC08_L2SP_128056_20200228_20200822_02_T1	Surface Reflectance/ Surface Temperature

To get the optimal image of the study area, Fmask model was applied to detect and mask clouds in the images (Qiu et al., 2019). To minimize errors, cloud-free images of the same season from the same year or the previous year were chosen to replace the clouds. Other preprocessing included subset, mosaic, and water body masking. Further details on the water body masking procedure are provided in Section 2.3.

Auxiliary data used in this study included water body data, terrain data, climate data (precipitation and temperature data), gridded GDP and population data. The auxiliary data are shown in Table 2. The DEM data was applied to calculate slope data. Both DEM and slope data were resampled to 1 km resolution.

Table 2 Auxiliary data used for the study

Data Type	Data Name (Resolution)	Data Source
Water body data	Global Surface Water Dataset (30 m)	Joint Research Centre of the European Commission (https://global-surface-water.appspot.com)
Terrain data	SRTM DEM (30 m)	USGS (https://earthexplorer.usgs.gov)
Precipitation data	Precipitation dataset by Zhao et al. (2023) (1 km)	Science Data Bank (https://doi.org/10.11922/sciencedb.j00001.00384)
Temperature data	Global seamless and high-resolution temperature dataset (GSHTD) by Yao et al. (2023) (1 km)	Yangtze River Delta Science Data Center (https://cjgeodata.cug.edu.cn)
GDP data	Global gridded revised real gross domestic product by Chen et al. (2022a) (1 km)	Figshare (https://doi.org/10.6084/m9.figshare.17004523.v1)
Population data	LandScan Population Data (1 km)	Oak Ridge National Laboratory (https://landscan.ornl.gov)

The flow chart of this study is shown in Fig. 2.

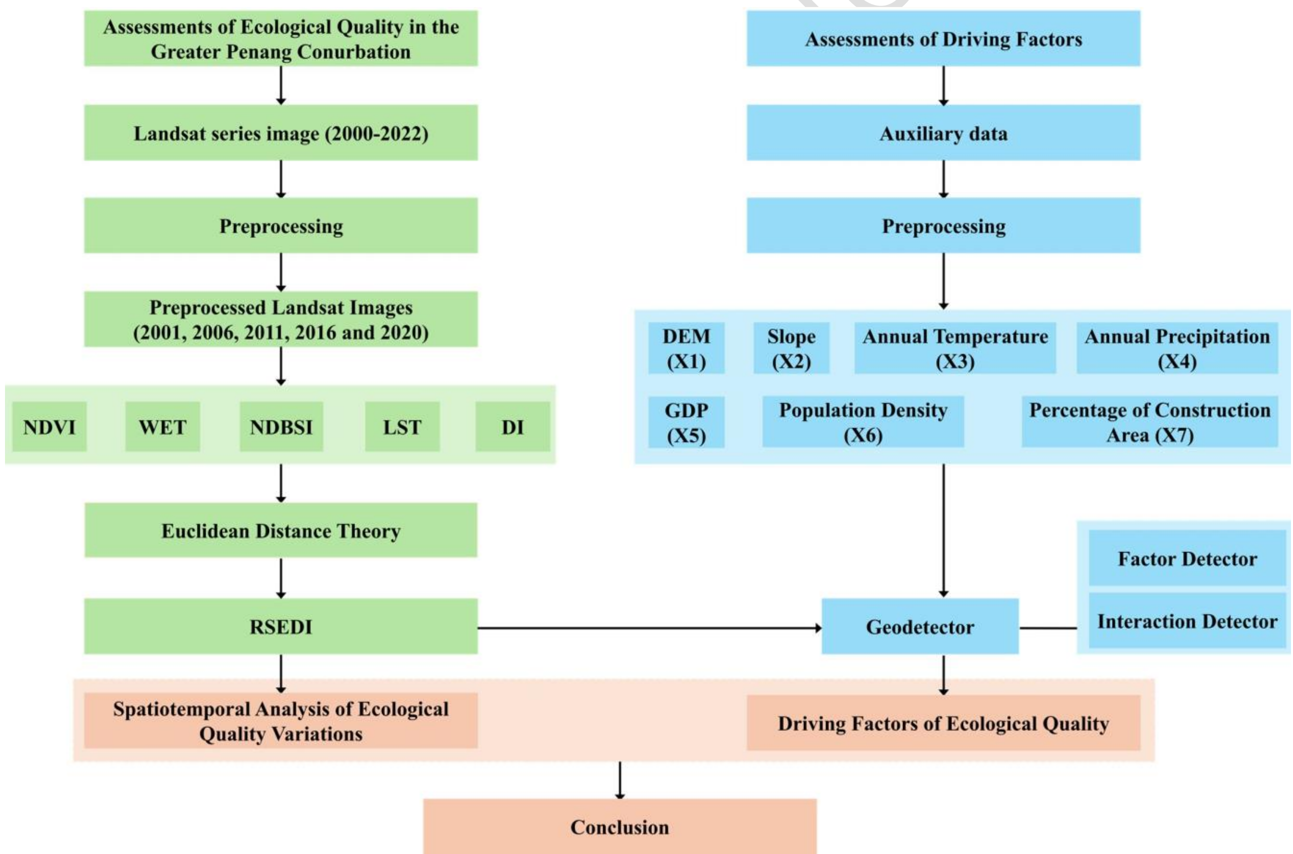


Fig. 2 The flow chart of the study

2.3 Remote Sensing Ecological Distance Index

The Remote Sensing Ecological Distance Index (RSEDI) is a new synthetic index for assessing the comprehensive ecological quality based on the Euclidean distance theory (Zhang, 2016). Constructing the RSEDI requires selecting suitable types and quantities of ecological components. With full consideration of the context of the study area and previous studies, the components involved in the RSEDI of this study were greenness index, humidity index, dryness index, heat index, and air quality index (Helili and Zan, 2023; Liu et al., 2024; Xu, 2013). The 5 components were highly correlated with the ecological status and can be directly perceptible to people (Feng et al., 2018; Xu et al., 2018). The calculation and reasons for the selection of the 5 components are as follows:

(a) Greenness index

The greenness index applied in this study is the Normalized Difference Vegetation Index (NDVI), which can represent the vegetation growth and vegetation coverage status (Goward et al., 2002). The formula for NDVI is as follow:

$$\mathrm{NDVI} = \frac{(\rho_{nir} - \rho_{red})}{(\rho_{nir} + \rho_{red})} \tag{1}$$

where ρ_{nir} and ρ_{red} corresponding to the near-infrared and red bands of TM, ETM+ and OLI images, respectively.

(b) Humidity index

The humidity index utilized in this study is the WET component of a Tasseled Cap Transformation, which reflect soil moisture that signifying the moisture conditions of soil and plants (Baig et al., 2014; Crist, 1985; Huang et al., 2010). The formula for WET is as follow:

$$\mathrm{WET_{TM}} = 0.0315\rho_{blue} + 0.2021\rho_{green} + 0.3102\rho_{red} + 0.1594\rho_{nir} - 0.6806\rho_{swir1} - 0.6109\rho_{swir2} \tag{2}$$

$$\mathrm{WET_{ETM+}} = 0.2626\rho_{blue} + 0.2141\rho_{green} + 0.0926\rho_{red} + 0.0656\rho_{nir} - 0.7629\rho_{swir1} - 0.5388\rho_{swir2} \quad (3)$$

$$\mathrm{WET_{OLI}} = 0.1511\rho_{blue} + 0.1973\rho_{green} + 0.3283\rho_{red} + 0.3407\rho_{nir} - 0.7117\rho_{swir1} - 0.4559\rho_{swir2} \quad (4)$$

where ρ_{blue}, ρ_{green}, ρ_{red}, ρ_{nir}, ρ_{swir1} and ρ_{swir2} corresponding to the blue, green, red, near-infrared, SWIR1 and SWIR2 bands of TM, ETM+ and OLI images, respectively.

(c) Dryness index

The dryness index is denoted with the Normalized Difference Build-up and Soil Index (NDBSI), combining the Index-based Built-up Index (IBI) and Soil Index (SI), which can reflect the surface dryness caused by soil desiccation and impervious surfaces (Rikimaru et al., 2002; Xu, 2008; Xu, 2013). The formula for NDBSI is as follow:

$$\mathrm{SI} = \frac{(\rho_{swir1} + \rho_{red}) - (\rho_{nir} + \rho_{blue})}{(\rho_{swir1} + \rho_{red}) + (\rho_{nir} + \rho_{blue})} \quad (5)$$

$$\mathrm{IBI} = \frac{2\rho_{swir1}/(\rho_{swir1} + \rho_{nir}) - [\rho_{nir}/(\rho_{nir} + \rho_{red}) + \rho_{green}/(\rho_{green} + \rho_{swir1})]}{2\rho_{swir1}/(\rho_{swir1} + \rho_{nir}) + [\rho_{nir}/(\rho_{nir} + \rho_{red}) + \rho_{green}/(\rho_{green} + \rho_{swir1})]} \quad (6)$$

$$\mathrm{NDBSI} = \frac{\mathrm{SI} + \mathrm{IBI}}{2} \quad (7)$$

where ρ_{blue}, ρ_{green}, ρ_{red}, ρ_{nir} and ρ_{swir1} corresponding to the blue, green, red, near-infrared and SWIR1 bands of TM, ETM+ and OLI images, respectively.

(d) Heat index

The heat index is represented by Land Surface Temperature (LST), which is applied to monitor ecological processes, climate change, evapotranspiration, and surface energy balance. The Land Surface Temperature (LST) is directly represented by Landsat surface temperature products.

(e) The air quality index

The air quality index is referred to as Difference Index (DI), which can reflect PM 2.5 condition, the main pollutant of the air pollution, and other particle pollutant (Feng et al., 2018). The air pollution was highly correlated with ecological quality in recent years, especially in urban areas. The formula for DI is as follows:

$$\mathrm{DI} = \rho_{red} - \rho_{nir} \tag{8}$$

where ρ_{nir} and ρ_{red} corresponding to the near-infrared and red bands of TM, ETM+ and OLI images, respectively.

Due to the different dimensions, the five components need to be normalized so that their values are between 0 and 1. To minimize the influence of outliers, this study used a 98% confidence interval. The formula for NI is as follows:

$$\mathrm{NI} = \frac{(I - I_{min})}{(I_{max} - I_{min})} \tag{9}$$

where NI is the normalized index; I is the original index; I_{max} and I_{min} are the maximum and minimum values of the original index I, respectively.

Due to the significant difference between the value of WET component in water bodies and land surfaces, the WET component may fail to accurately reflect land moisture conditions in areas with large water bodies (Wu et al., 2008). The WET component in this study is used to represent land humidity conditions. As large-area water bodies are distributed in some areas in the Greater Penang Conurbation, they were masked and excluded during preprocessing, before the calculation of the index, to eliminate their impact on the accuracy of RSEDI (Xu and Deng, 2022). In this study, the Global Surface Water Dataset (1984-2021) provided by the Joint Research Centre of the European Commission (Pekel et al., 2016) was applied to mask the water area before the calculation of the index.

The normalized index, including greenness index (NDVI), humidity index (WET), dryness index (NDBSI), heat index (LST) and air quality index (DI) were used to construct the Remote Sensing

Ecological Distance Index (RSEDI) in this study. The 5 index were applied to form a five-dimensional space. The minimum value of NDVI and WET and the maximum value of NDBSI, LST and DI were chosen as the worst ecological quality point in the space. The distance from other points in the space to the worst point was applied to represent the RSEDI to assess the ecological quality of the research area. The RSEDI was a positive index, which means that a higher value (distance) represents better ecological quality. The formula for calculating RSEDI is as follows:

$$RSEDI = \sqrt{(NDVI - NDVI_{min})^2 + (WET - WET_{min})^2 + (NDBSI - NDBSI_{max})^2 + (LST - LST_{max})^2 + (DI - DI_{max})^2} \quad (10)$$

where $NDVI_{min}$ and WI_{min} are the minimum values of the NDVI and WET, respectively; $NDBSI_{max}$, LST_{max} and DI_{max} are the maximum values of the NDBSI, LST and DI, respectively.

To ensure the comparability of the results in different years, the calculated RSEDI was normalized to a common scale of 0 to 1 based on annual min and max values by formula (9). This study adopted the ecological quality classification method proposed by Xu (2013), in which the RSEDI values were divided into 5 ecological quality grades by 0.2 interval: worst (0.0-0.2), poor (0.2-0.4), moderate (0.4-0.6), good (0.6-0.8) and excellent (0.8-1.0). This method is widely recognized for its practical effectiveness and has been successfully applied in various regional ecological assessments, providing a clear and interpretable basis for distinguishing ecological quality levels (Chen et al., 2024; Xu et al., 2018; Yang et al., 2021).

2.4 Geodetector

Geodetector is a statistical method applied to spatial variability and reveal the driving factors, which is currently widely used in ecological and environmental studies (Wang and Xu, 2017). The Geodetector includes four types of detectors, namely factor detector, interaction detector, risk zone detector, and ecological detector. In this study, factor detector and interaction detector were selected to analyze the driving mechanisms of RSEDI. The factor detector is the model for exploring the influence of each independent variable (X) on the dependent variable (RSEDI). The degree of the influence is expressed as a q value. The formula for factor detector is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad (12)$$

where h=1, …, L is the stratification of the independent (X) or dependent variable (RSEDI); N_h and N are the number of units in stratum h and the entire area, respectively; σ_h^2 and σ^2 are the variance of dependent variable (RSEDI) in stratum h and the entire area, respectively. The value of q ranges from 0 to 1, where a higher value indicates a stronger the explanation of the independent (X) on dependent variable (RSEDI).

The interaction detector is a tool that applied to detect interactions between the independent variables, assessing the joint effort of different factors enhance or weaken the explanatory power on the dependent variable (RSEDI). The types of the interactions are shown in the table 3.

Table 3. Interaction types

Description	Interaction
$q(X_1 \cap X_2) < \text{Min}[q(X_1), q(X_2)]$	Nonlinear weakening
$\text{Min}[q(X_1), q(X_2)] < q(X_1 \cap X_2) < \text{Max}[q(X_1), q(X_2)]$	Single-factor nonlinear weakening
$q(X_1 \cap X_2) > \text{Max}[q(X_1), q(X_2)]$	Bivariate enhancement
$q(X_1 \cap X_2) = q(X_1) + q(X_2)$	Independent
$q(X_1 \cap X_2) > q(X_1) + q(X_2)$	Nonlinear enhancement

Based on previous studies, the conditions of topography, climate and human activities are seen as the main factors leading to the ecological change (Wang et al., 2024b; Yang et al., 2023). Accordingly, in this study, DEM (X1), slope (X2), annual temperature (X3), annual precipitation (X4), GDP (X5), population density (X6) and percentage of construction area (X7) were chosen as the independent variables for factor and interaction detector. The percentage of construction area, representing land use condition, was calculated by formula (6). In this study, the terrain condition is indicated by DEM and slope, and the climate condition is revealed by temperature and precipitation. GDP, population density and percentage of construction area can represent the extend of the human activities, as well as the scale of the urbanization.

3. Results

3.1 Overall Assessment of the Ecological Quality

As shown in table 4, all correlation coefficients between the RSEDI and individual index exceeded 0.75, with annual averages above 0.8, indicating strong correlations. This demonstrates that the RSEDI has a good comprehensive representativeness and can represent the ecological quality of the Greater Penang Conurbation.

Table 4. Results of correction coefficient between RSEDI and each index

Year	NDVI	WET	NDBSI	LST	DI	Average
2001	0.921	0.754	0.954	0.774	0.782	0.837
2006	0.942	0.871	0.961	0.838	0.855	0.893
2011	0.917	0.822	0.964	0.761	0.842	0.861
2016	0.953	0.906	0.969	0.840	0.865	0.907
2020	0.953	0.915	0.965	0.782	0.878	0.899

The average values of the RSEDI in the Greater Penang Conurbation in 2001, 2006, 2011, 2016 and 2020 were 0.64, 0.64, 0.67, 0.64 and 0.62, respectively. These values show a trend of slightly increasing, then slightly decreasing, and an overall slight decrease. The results indicated that the overall ecological quality of the Greater Penang Conurbation was good but showed a slightly declining trend from 2001 to 2020. Fig. 3 presents the percentage of RSEDI levels across the years. The good and excellent level area accounted for more than 60% of the total area during 2001 to 2020, which also explained the overall ecological quality in the Greater Penang Conurbation was in good condition. The area proportion of worst area and poor area generally increased from 2001 to 2020, from 8.67% to 13.62% and from 10.19% to 12.67%, respectively. Despite slight fluctuations, the proportion of the sum of the worst area and poor area showed a steady increasing trend during the 19 years, rising from 18.80% in 2001 to 26.69% in 2019. The percentage of the moderate area decreased from 17.38% in 2001 to 13.35% in 2006 and fluctuated around 13% after 2006. The proportion of good area continuously declined from 26.34% in 2001 to a low of 19.42% in 2016, fell back slightly to 20.77% in 2020. The proportion of excellent area rose from 37.48% in 2001 to a peak of 46.61% in 2011, followed by a gradual decline to 40% in 2020. The reduction in good and excellent areas, alongside the expansion of poor and worst areas was the reasons for the slight decline in the overall ecological quality of the Greater Penang Conurbation.

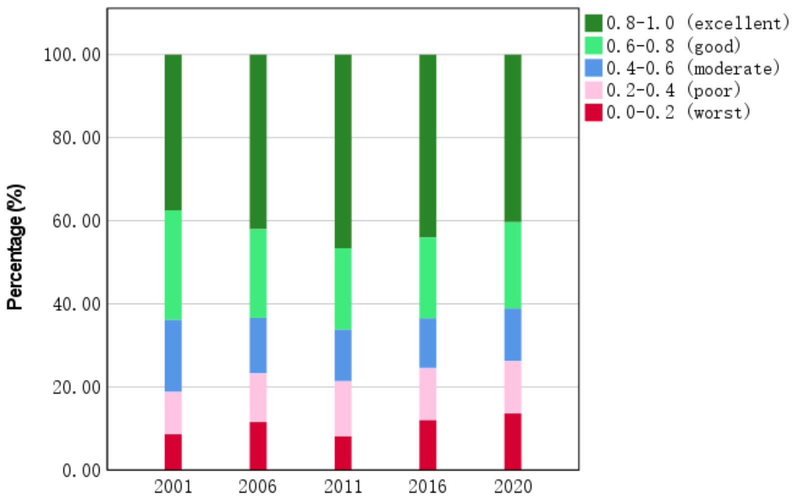


Fig. 3. The percentage of RSEDI levels in the Greater Penang Conurbation from 2001 to 2020

3.2 Spatiotemporal distribution Characteristics of ecological quality

The spatiotemporal distribution of the RSEDI in the Greater Penang Conurbation is shown in Fig. 4. The area with good and excellent ecological quality during the 19 years was mainly distributed in the western part of the Penang Island, Bandar Baharu district and eastern part of Kuala Muda, Kulim and Keran districts. In contrast, the area with relatively bad ecological quality was mainly located in the east part of the Penang Island, North Seberang Perai, Central Seberang Perai and western part of Kuala Muda district. Meanwhile, the area with worst and poor ecological quality has been significantly and continuously expanded in the South Seberang Perai and western part of Kerian district during the 19 years, especially after 2011.

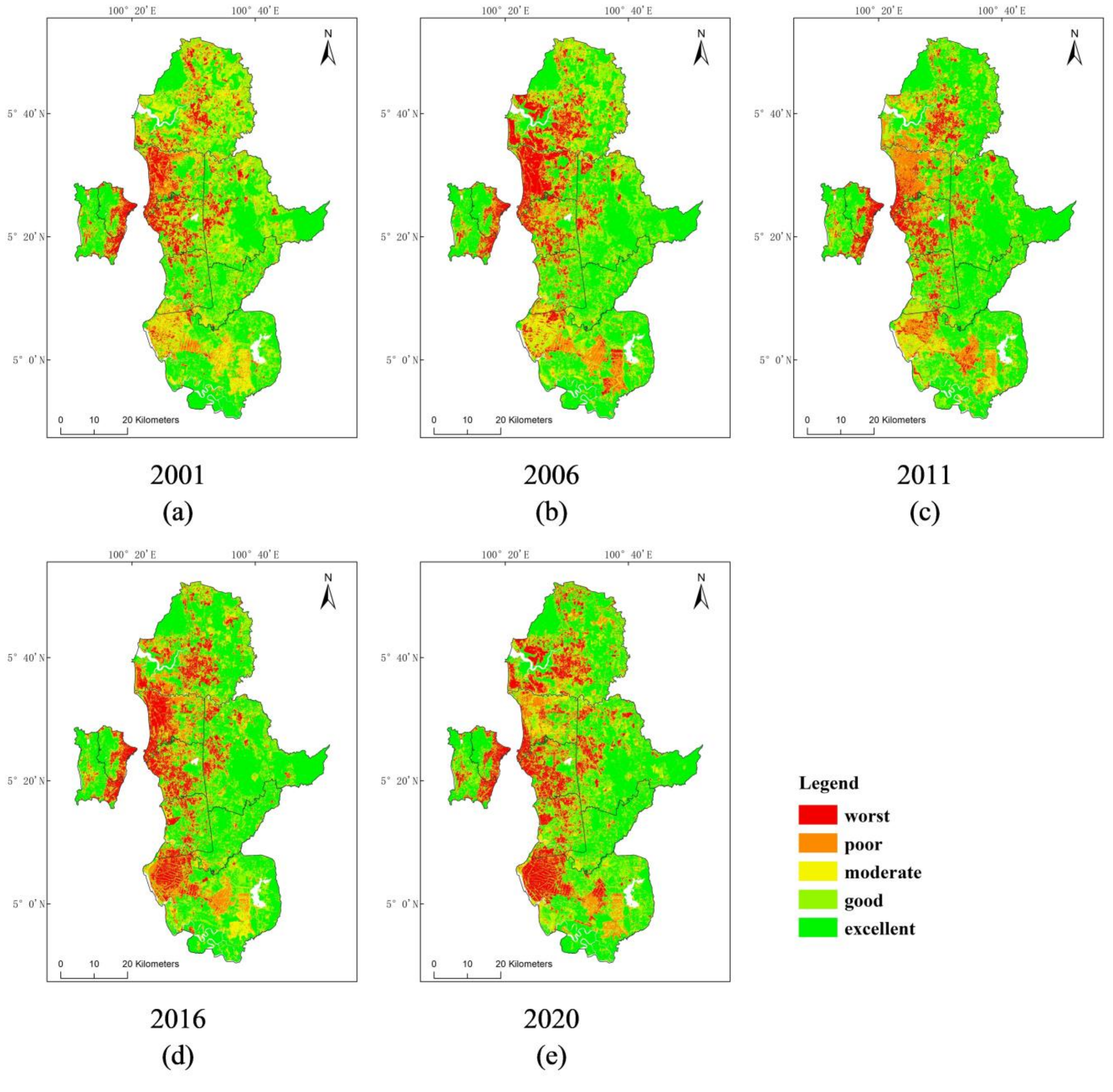


Fig. 4. Spatiotemporal distribution of RSEDI of the Greater Penang Conurbation from 2001 to 2020

To further analyze the spatiotemporal distribution of ecological quality in the study area, the average value of the RSEDI of each district in the Greater Penang Conurbation was calculated, and the results are shown in Table 5 and Fig. 5. The ecological quality of Northeast District, North Seberang Perai and Central Seberang Perai remained at moderate level throughout the 19 years. The average value of the RSEDI of North Seberang Perai and Central Seberang Perai was both below 0.5 during the 19 years, indicating that the ecological quality of these two districts was the lowest. As shown in Fig. 5, the ecological quality of North Seberang Perai experienced slight fluctuations, as evidenced in Fig. 4, which showed significant variations in the distribution of worst, poor and moderate levels area in the east part of Central Seberang Perai across different years. By contrast, the ecological quality of Central Seberang Perai showed limited variation. Similarly, the ecological quality of Northeast District showed minimal variation after 2011, maintaining an RSEDI of 0.55. The mean value of the RSEDI of Kulim and Bandar Baharu remained above 0.7 over the 19 years, and these two districts had the highest ecological quality within the study area. And Fig. 4 can also illustrate that most areas of these two districts were areas with excellent and good level. The average value of the RSEDI of Southwest District and Kuala Muda fluctuated slightly between 0.6 and 0.7 over the 19 years. As shown in Fig. 4, this was attributed to the coexistence of contiguous areas of high and low ecological quality within the two districts, with the area with high ecological quality being more extensive. Both South Seberang Perai and Kerian showed a consistent decline in their RSEDI values over the years from 2001 to 2020, indicating a gradual deterioration in ecological quality. In South Seberang Perai, the RSEDI values continued to decline from 0.66 to 0.51, especially sharply after 2011, with a drop by one ecological quality level. Kerian also showed a continuous decline in RSEDI values, from 0.69 to 0.61. Fig. 4 further supports this trend, showing the continuous and large-scale expansion of poor and worst ecological areas in both districts.

Table 5. Average value of RSEDI in each district and the Greater Penang Conurbation

District	2001	2006	2011	2016	2020
Northeast District	0.54	0.59	0.55	0.55	0.55
Southwest District	0.67	0.70	0.65	0.67	0.64
North Seberang Perai	0.44	0.35	0.43	0.39	0.48
Central Seberang Perai	0.46	0.49	0.48	0.46	0.44
South Seberang Perai	0.66	0.64	0.63	0.58	0.51

Kuala Muda	0.62	0.61	0.69	0.66	0.62
Kulim	0.71	0.75	0.78	0.76	0.71
Bandar Baharu	0.74	0.78	0.81	0.79	0.77
Kerian	0.69	0.66	0.66	0.64	0.61
Greater Penang Conurbation	0.64	0.64	0.67	0.64	0.62

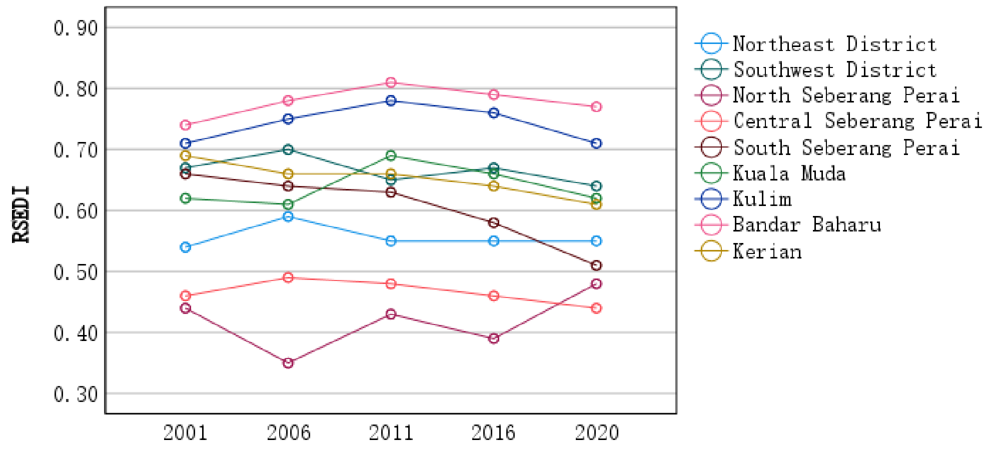


Fig. 5 The variations of the RSEDI in each district from 2001 to 2020

3.3 Spatiotemporal Variations Characteristics of ecological quality

To analyze spatiotemporal variations in ecological quality across the Greater Penang Conurbation, the RSEDI differences were calculated by subtracting earlier-year data from later-year data for three intervals: 2001–2011, 2011–2020, and 2001–2020. The results were classified into five levels, corresponding to five types of variations: significant deterioration [-1, -0.2), slight deterioration [-0.2, -0.05), virtually unchanged [-0.05, 0.05), slight improvement [0.05, 0.2), and significant improvement [0.2, 1]. The results are shown in Table 6 and Fig. 6.

Table 6 Percentage and area of RSEDI variations in the Greater Penang Conurbation during 2001 to 2011, 2011 to 2020 and 2001 to 2020

Variations Level	2001-2011		2011-2020		2001-2020	
	Percentage (%)	Area(km2)	Percentage (%)	Area(km2)	Percentage (%)	Area(km2)
Significant deterioration	11.01%	421.96	15.43%	591.37	18.24%	699.35
Slight deterioration	17.12%	656.18	28.91%	1108.10	19.48%	746.68
Virtually unchanged	27.90%	1069.52	31.54%	1209.13	28.28%	1084.08
Slight improvement	28.91%	1108.23	16.72%	640.86	20.41%	782.26
Significant improvement	15.06%	577.48	7.41%	283.91	13.59%	521.00

From Table 6, it can be observed that the proportion of virtually unchanged area across the three intervals was approximately 30%, indicating a trend of coexistence between ecological degradation and improvement in the Greater Penang Conurbation from 2001 to 2020. During 2001 to 2011, 28.91% of areas showed slight improvement, 15.06% of areas showed significant improvement, while 17.12% and 11.01% of areas showed slight and significant deterioration respectively. The improved areas exceeded deteriorated ones, corresponding to a slight overall improvement during this period. From Fig. 6(a), it can be observed that during this period, areas with improved ecological quality were primarily concentrated in Kulim, Bandar Baharu, and the eastern part of Kuala Muda. The areas with ecological deterioration were mainly continuously distributed in the western part of Kerian and the eastern part of Kuala Muda, while they were more scattered across the entire Seberang Perai and the Southwest District. Additionally, the Northeast District featured a relatively large proportion of areas that remained virtually unchanged. In contrast, during the subsequent period of 2011–2020, the proportion of area with slight deterioration increased to 28.91%, while those with significant deterioration rose to 15.43%. Concurrently, the proportions of areas with slight improvement and significant improvement declined significantly, dropping to 16.72% and 7.41%, respectively. This trend also explained the decline in ecological quality within the study area during the period from 2011 to 2020. Further analysis of Fig. 6(b) shows that during this period, areas with improved ecological quality were mostly isolated, except in the western part of North Seberang Perai. Additionally, the Northeast District continued to have a significant proportion of areas that remained virtually unchanged. In contrast, other areas exhibited large areas of ecological deterioration, either continuously or dispersed. Notably, although Kulim and Bandar Baharu generally maintained good ecological quality during this period, both districts also had certain areas where ecological quality deteriorated. Over the entire period from 2001 to 2020, the proportion of areas with slight improvement and slight deterioration was roughly equal, both around 20%. However, the proportion of areas with significant deterioration, at 18.24%, exceeded that of areas with significant improvement, which accounted for 13.59%. This corresponded to a slight overall decline in ecological quality within the Greater Penang Conurbation over these 19 years. The results from Fig. 6(c) can further analyze the spatiotemporal variations between 2001 and 2020. Areas with ecological improvement were primarily distributed in the western part of North Seberang Perai and the eastern part of Kuala Muda, with a certain amount also found in Kulim and Bandar Baharu. Areas with virtually unchanged ecological quality clustered in in the Northeast District and the southeastern part of Kulim. Ecological deterioration was predominantly concentrated in the western part of Kuala Muda, the eastern part of North Seberang Perai, South Seberang Perai, Kerian, and the northern part of Kulim. Additionally, there were also some deteriorating areas in the Southwest District and Central Seberang Perai, but these were more scattered in distribution. Furthermore, Fig. 4 and Table 5 show that although a significant area within the study area experienced variations in ecological quality over the 19 years, these variations have not influenced the distribution patterns of high-level and low-level ecological quality areas in most parts of the Greater Penang Conurbation, except for South Seberang Perai and Kerian. However, these variations can explain the variations in the overall ecological quality of each district.

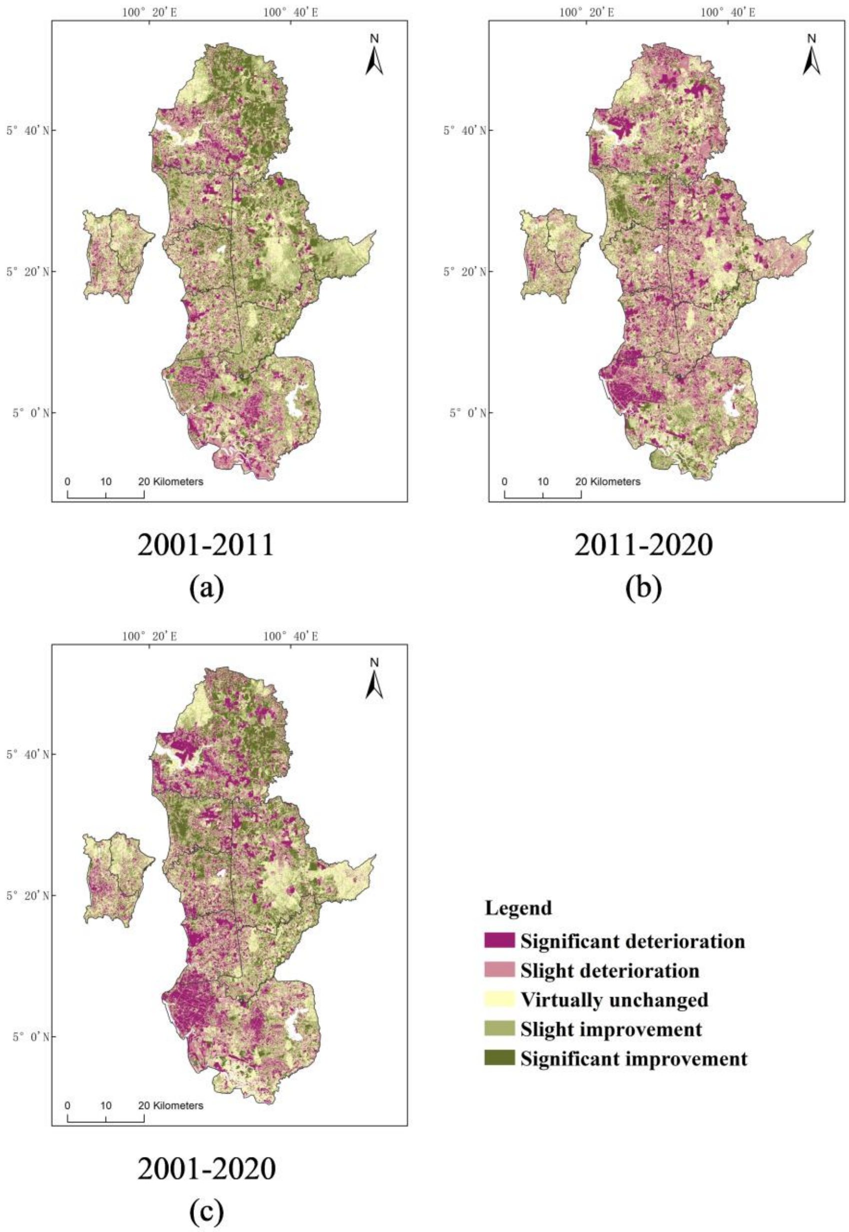


Fig. 6. The variations of RSEDI in the Greater Penang Conurbation during the period of 2001 to 2011, 2011 to 2020 and 2001 to 2020

3.4 Driving factors of ecological quality

3.4.1 Factor detector

After calculation, the q value of factors for each year was shown in Table 7. All influencing factors have p-values equal to 0.000 (less than 0.05), indicating that each factor has a significant impact on the spatial distribution of the ecological quality in the Greater Penang Conurbation. The results showed that the q values of X7 (Percentage of construction area) remained the highest from 2001 to

2020 and were substantially higher than that of other factors, indicating that land use for ecological quality influence was the greatest. X3 (Annual temperature) ranked second throughout the period, and it showed an increase trend in q value from 0.344 in 2001 to 0.462 in 2020, reflecting that it had the second greatest influence on the ecological quality of the study area, with this influence gradually strengthening over time. The q values of X2 (Slope), X5 (GDP), and X6 (Population density) fluctuated between third and fifth ranks over the 19-year period, and the q values of these three factors changed relatively closely over time. This revealed that the impact of these three factors on ecological quality of the Greater Penang Conurbation was relatively close and all had a medium influence. X1 (DEM) and X4 (Annual precipitation) consistently ranked sixth and seventh, respectively, remaining below 0.2 throughout the 19 years, indicating that their influences were weak and very weak, respectively. In conclusion, land use was the primary driving factor for the variations of ecological quality of the Greater Penang Conurbation, while temperature was the secondary driving factor. Slope, GDP, and population density were tertiary driving factors, and the influences of elevation and precipitation were weak and can be considered negligible.

Table 7. The results of single factor detection

Factor	2001	q ranking	2006	q ranking	2011	q ranking	2016	q ranking	2020	q ranking
X1 (DEM)	0.172	6	0.196	6	0.179	6	0.190	6	0.181	6
X2 (Slope)	0.181	4	0.254	3	0.249	5	0.269	4	0.248	4
X3 (Annual temperature)	0.344	2	0.438	2	0.429	2	0.562	2	0.462	2
X4 (Annual precipitation)	0.126	7	0.024	7	0.014	7	0.057	7	0.083	7
X5 (GDP)	0.272	3	0.237	4	0.329	3	0.280	3	0.247	5
X6 (Population density)	0.176	5	0.196	5	0.264	4	0.205	5	0.278	3
X7 (Percentage of construction area)	0.852	1	0.888	1	0.901	1	0.904	1	0.897	1
The p-value of each factor across all years is 0.000.										

3.4.2 Interaction detector

Fig. 7 shows the results of the interaction detection. The interaction results of any two factors were greater than that of a single factor, with exhibiting both bivariate enhancement and nonlinear enhancement. This indicated that the interactions between factors had a greater impact on the RSEDI of the Greater Penang Conurbation than any single factor. As shown in Fig. 7, The strongest explanatory power for the RSEDI in the Greater Penang Conurbation in each year was X3(Annual temperature) ∩ X7 (Percentage of construction area), indicating that the interaction between the two largest influencing factors, temperature and land use, can make the impact on ecological quality the strongest. In addition, the results of nonlinear enhancement all appeared in the interaction between X4 (Annual precipitation) and other influencing factors. The interaction between X4 (Annual precipitation) and other factors can significantly increase the explanatory power. This indicated that while the standalone influence of precipitation on ecological quality in the Greater Penang Conurbation was weak, its interaction with other factors can also have a certain influence. In general, the ecological quality of the Greater Peang Conurbation resulted from the combined influence of topography, climate and human activities.

Fig. 7. Interactive detection matrix

4. Discussion

4.1 Analysis of spatiotemporal distribution of ecological quality

According to the results of this study, in Penang State, except for South Seberang Perai, the ecological quality of other districts remained relatively stable between 2001 and 2020. The areas with low ecological quality were mainly concentrated in the eastern part of Penang Island and the western parts of North Seberang Perai and Central Seberang Perai. Meanwhile, the areas with high ecological quality were mainly concentrated in the western part of Penang Island, as well as the western part of North Seberang Perai and Central Seberang Perai. This pattern resulted from early urbanization in the eastern part of Penang Island and the western parts of North and Central Seberang Perai, which had already developed continuous built-up areas at the beginning of this century (Rahaman et al., 2022b; Tew et al., 2019). Therefore, the ecological quality in these areas was relatively bad. In contrast, the western part of Penang Island was mainly covered by forested land, and the eastern parts of North Seberang Perai and Central Seberang Perai were mainly forested land and agricultural land (Elhadary et al., 2013; Rahaman et al., 2022b). These areas had good vegetation coverage, resulting in relatively high ecological quality. The ecological quality in South Seberang Perai declined rapidly after 2011, with areas with low ecological quality expanding rapidly. This was due to large-scale conversion of agricultural and forested land into residential and industrial uses before and after the opening of the Second Penang Bridge in 2014 (Rahaman et al., 2022a; Tew et al., 2019). The rapid built-up expansion in South Seberang Perai led to a sharp ecological decline. For the neighboring districts, their ecological quality was greatly influenced by the urban expansion of Penang State (Samat et al., 2020). In Kuala Muda, areas with low ecological quality were mainly located in the western part of the district during the 19 years. This was because this area bordered North Seberang Perai, which experienced early urbanization, leading to a higher concentration of built-up areas (Abd

Rahim et al., 2021; Rahaman et al., 2022b). As a result, the western part of Kuala Muda had a relatively stable distribution of areas with poor ecological quality. In contrast, the eastern part of Kuala Muda was less affected by urban expansion, with fewer built-up areas, resulting in better ecological quality. Similarly, Kerian experienced notable ecological decline after 2011, with a significant expansion of low-level ecological quality areas in the western part of Kerian, bordering South Seberang Perai. This was also due to spillover urbanization, which extended quickly southward following the opening of the Second Penang Bridge in 2014 (Rahaman et al., 2022a). For Kulim and Bandar Baharu, the ecological quality was high across most areas during the 19 years, except for a small area in the eastern part of Kulim. This was because the adjacent areas in Penang State had lower urbanization levels (Tew et al., 2019). Apart from the eastern part of Kulim, most areas in these two districts were not significantly influenced by the urban expansion of Penang State and exhibited lower urbanization levels. Therefore, the ecological quality in these two districts was good.

4.2 Analysis of driving factors

Based on the factor detector results, land use was the primary driving factor for the variations of ecological quality in the Greater Penang Conurbation. By reviewing the relevant literature (Rahaman et al., 2022b; Samat et al., 2020; Tew et al., 2019), it was evident that that the Greater Penang Conurbation was still undergoing rapid urbanization, with rapid expansion of built-up areas, which had led to land use becoming the main driving factor for changes in ecological quality. In contrast, other influencing factors such as temperature, slope, GDP, and population density also showed some driving forces in the factor detector results. However, as the driving force of land use was significantly greater than other factors, their impact on ecological quality was comparatively less apparent. In addition, based on Rahaman's research, from 1996 to 2021, variations in built-up areas and forested land in the Greater Penang Conurbation led to an increase in land surface temperature, resulting in an intensified urban heat island (UHI) effect (Rahaman et al., 2022b). Rahaman's study can further confirm the results of interaction detector, showing that the ecological quality of the Greater Penang Conurbation was influenced by the combined effects of multiple factors.

4.3 Performance of RSEDI

As demonstrated in Section 3.1, based on the Euclidean distance theory, the remote sensing ecological distance index (RSEDI) can provide a simple, rapid, and accurate assessment of the ecological quality in the Greater Penang Conurbation. By choosing different assessment index, the Remote Sensing Ecological Distance Index (RSEDI) model has been effectively applied in certain types of regions, including subtropical and temperate regions in inland areas (Guo et al., 2021; Yan et al., 2022; Yang et al., 2021; Zhang, 2016; Zhong et al., 2025). However, its application in tropical or coastal areas has been rare, and this study expanded its applicability.

As a widely used method in recent years, the Remote Sensing based Ecological Index (RSEI) model developed by Xu (2013) has been extensively applied in various types of regions (Chen et al., 2024). The RSEI is a model of assessing the regional ecological quality by applying principal component analysis (PCA) to integrate multiple single ecological indicators into a comprehensive index (Xu, 2013), with selected indicators that are largely similar in RSEDI. The RSEI model has greatly improved the efficiency of ecological quality assessment (Chen et al., 2024). However, there were some problems in the application of the RSEI model, mainly focusing on the principal component analysis (PCA) process. For example, the signs of the loadings of PC1 sometimes need to be further adjusted based on the positivity or negativity of the indicator (Chen et al., 2024; Xu and Deng, 2022). In addition, when the percentage of eigenvalues of PC1 is low, the reliability of the RSEI results is still controversial (Chen et al., 2024; Jia et al., 2021; Xu et al., 2022). By contrast, the RSEDI only requires calculating the distance between other points and the worst point in a multidimensional space based on Euclidean distance theory to obtain the comprehensive index. Direct distance calculation is simpler than principal component analysis (PCA), and it can also avoid problems that may occur after the PCA process. Therefore, RSEDI is simpler in method and more convenient in practice. Nevertheless, RSEI is already a mature method widely applied in various types of regions, while RSEDI is still in the early stages of development with a small application scope.

In summary, in the future, RSEDI will require further optimization of indicator selection and validation in different types of regions to ensure its reliability.

4.4 Limitations and future work

This study established the RSEDI model to assess the ecological quality of the Greater Penang Conurbation and applied the Geodetector model to assess its driving factors. Although the results were generally positive, the study still has certain limitations that could be addressed in future research. First, the Landsat data used in this study have inherent limitations, including spatial resolution, cloud cover, and revisit cycle, which may inevitably affect the reliability of the results of ecological assessments, despite the mitigation measures applied. With continuous advancements in data preprocessing techniques and the increasing availability of higher-resolution data such as Sentinel-2, these improvements are expected to further mitigate such negative impacts in the future. Second, this study selected the commonly used 0.2-interval classification method for RSEDI grading, but its rationality still requires further validation. Future research could use recent data together with field observations to further improve the classification method. Last, the interaction detector of Geodetector can reveal the joint effort of two factors to ecological quality but did not explain the underlying mechanisms of their interaction. In order to support ecological management with stronger scientific evidence, future research should further explore the interaction mechanisms of factors based on results of interaction detector.

In addition to addressing the current limitations, future research may also consider the following aspects. Considering under the rapid urbanization of the research area, future research should further examine the direct and indirect effects of economic, social, governance, and energy-related policies on ecological quality (Jin et al., 2024; Lei and Zhao, 2024a, b; Li and Lei, 2024; Tian et al., 2024). Moreover, although land use was the main driving factor of ecological quality, the impact of temperature factor of climate showed an increasing trend and consistently ranked second. As the study area is located in tropical island and coastal regions, the influence of global climate change on the living environment in these areas is continuing to intensify (Tang, 2019). Therefore, future research should additionally explore the direct and indirect effects of climate factors on ecological quality. Furthermore, apart from examining the interaction mechanisms of multiple driving factors, future research should also focus more on the combined effects of topography, climate and human activities on the spatiotemporal distribution and variations of ecological quality.

5. Conclusion

Using Landsat series images as the data source, this study applied the Greenness Index (NDVI), Humidity Index (WET), Dryness Index (NDBSI), Heat Index (LST), and Air Quality Index (DI) to establish the Remote Sensing Ecological Distance Index (RSEDI) to assess the ecological quality and its spatiotemporal variations of the Greater Penang Conurbation from 2001 to 2020. Subsequently, the factor detector and interaction detector in the Geodetector model were selected to assess the driving factors of ecological quality.

The novelty of this study was reflected in the early application of the Remote Sensing Ecological Distance Index (RSEDI) model, a method based on Euclidean distance theory and simple to implement, for assessing ecological quality in tropical regions.

The conclusions are as follows:

(1) The RSEDI values for the Greater Penang Conurbation in 2001, 2006, 2011, 2016 and 2020 were 0.64, 0.64, 0.67, 0.64 and 0.62, respectively, showing a trend of slightly increasing, then slightly decreasing, and an overall slight decrease. The overall ecological quality of the Greater Penang Conurbation was good over the 19-year period but showed a slightly declining trend.

(2) Over the 19-year period, low-ecological-quality areas were mainly distributed on the western part of Penang Island and the eastern parts of Kuala Muda, North Seberang Perai, and Central Seberang Perai, which were mainly built-up area, while high-ecological-quality areas were concentrated on Kulim, Bandar Baharu and the eastern part of Penang Island, which were mainly forested and agricultural land. Due to the rapid conversion of forested and agricultural land into residential and industrial land during and after the construction of the Second Penang Bridge, the ecological quality in South Seberang Perai and the eastern part of Kerian declined rapidly after 2011.

(3) The results of factor detector indicated that land use was the primary driving factor. The patterns and changes in land use have been able to explain the distribution and variations of ecological quality the Greater Penang Conurbation over the 19-year period. The results of interaction detector showed that the ecological quality was influenced by the combined effects of topography, climate and human activities.

These results can provide scientific reference for the future ecological protection and management of the Greater Penang Conurbation. The study offers a method reference for assessing ecological quality rapidly and accurately in tropical coastal areas, tropical islands, and other types of tropical regions.

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