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Research on Urban Heat Island Effect in Chengdu Based on Landsat Images and Analysis of Influencing Factors

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Abstract:

The urban heat island effect exacerbates energy consumption and destroys ecology. Remote sensing technology has the advantages of a wide monitoring range and fast speed, which can realize the dynamic monitoring and analysis of the urban heat island effect. Therefore, this paper analyzed the heat island effect in Chengdu city from 2014 to 2024 based on Landsat8/9 satellite image data, and at the same time, explored the influencing factors of surface temperature based on Normalized Vegetation Index (NDVI) products, annual average precipitation data, and land use data. The results show that: the average summer temperature and average surface temperature in Chengdu city in the past 10 years generally show an increasing trend, which is consistent with the performance of the inversion results; the distribution range of the urban heat island is expanding, and the area of the heat island grows rapidly by about 40% from 2013-2018, and the growth of the area of the heat island decreases by about 25%, and the heat island area decreases by about 5% again in 2021-2023. area decreases again by about 5%. New heat island centers appear in Longquanyi District and Jintang County urban areas. Meanwhile, Longquan Mountain and other scenic areas can effectively mitigate the heat island effect. Urban development and construction should carry out rational functional area planning, and appropriately increase the area of urban water bodies and vegetation to weaken the intensity of the heat island effect.

Keywords: urban heat island effect; vegetation index; average annual precipitation; land use; influencing factors.

1. Introduction

The urban heat island effect refers to the phenomenon that the temperature in the urban area is higher than that in the suburban area due to the change in the natural state of the subsurface as a result of urban expansion, and the superimposition of anthropogenic heat emissions, local wind field changes and other factors [1]. This effect not only changes the local climate environment of cities, increasing the frequency of hot weather and decreasing the temperature difference between day and night but also has far-reaching impacts on urban ecosystems, residents' health, and energy consumption.

At a time when global urbanization is accelerating, urban areas are expanding and evolving at an unprecedented rate. According to UN-Habitat, by 2024, many large cities and megacities will emerge. The rapid expansion of urban scale has brought about significant changes in land use, with a large number of natural surfaces being covered by artificial building materials such as concrete and asphalt, and the nature of the urban subsurface fundamentally altered. At the same time, intensive human activities in cities continue to release large amounts of heat and greenhouse gases into the atmosphere. Under such a background, the urban heat island effect (UHI) has become more and more prominent as a typical climate phenomenon in the process of urbanization [2]. The UHI affects the health of the residents and the operation of the city, and its spatial and temporal dynamics are significant, which requires real-time monitoring to capture the intensity fluctuations, identify the hotspots, and prejudge the risk trends. Traditional monitoring means have limited coverage and insufficient timeliness, while remote sensing technology has the advantages of large-scale simultaneous observation, high-frequency data acquisition, and multi-spectral information fusion, which can realize the refined dynamic monitoring of the heat island effect and provide key data support for governance. Chen Pinhao et al. studied the land use and heat island effect in Nanjing based on Landsat8 data and found that the heat island south of the Yangtze River is strong and diffuse, and the expansion of impermeable surfaces dominates the heat island, and its interaction has a significant impact [3]. Wei Wei et al. used Landsat images to invert the summer surface temperature of Baotou City from 2013-2023 and found that the heat island range is expanding, new industries and new urban heat island centers are added, and vegetation and water bodies can alleviate the heat island effect, and it is recommended to optimize the planning of the functional area and to increase the green and expand the water [4]. Zhao Xuan et al. used meteorological and remote sensing data to analyze the heat island effect in Beijing from 2010 to 2021, and found that the temperature heat island rises first and then falls, and the suburbs are improving well; the proportion of strong surface heat island is reduced, and the improvement is significant after the implementation of the master plan [5].

Although the urban heat island effect has attracted widespread attention from all walks of life, with the continuous development and change of the city, there are still many issues that need to be studied in depth in terms of its mechanism, spatial and temporal evolution characteristics and coping strategies. Chengdu city, due to its large city scale, basin location, significant heat aggregation and rapid urbanization, becomes the research object of heat island effect in this paper. The purpose of this paper is to analyze the causes and effects of the urban heat island effect and its changing law, which is of great practical significance for the sustainable development of the city, the improvement of the human environment and the response to global climate change [6].

2. Materials and methods

2.1 Source of Materials

Landsat-8 satellite was launched by NASA on February 11, 2013, and the sensors it carries are OLI Land Imager and TIRS Thermal Infrared Sensor. In this paper, Landsat8-9 OLI/TIRS satellite images are used as the remote sensing data source, which is obtained from the USGS website (https://earthexplorer.usgs.gov/). Landsat 9 and Landsat 8 orbits are combined to obtain 8 d resolution. The related information is shown in Table 1. Among them, a small amount of thin clouds existed within the study area of the 2014 image.

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Table 1. Landsat 8-9 image selection in the study area

Imaging time	Bands	Resolution	Clouds
2014-6	Band1, 2, 3, 4, 5, 6, 7, 9 Band8 Band10, 11	30 15 100	16.42
2018-7	Band1, 2, 3, 4, 5, 6, 7, 9 Band8 Band10, 11	30 15 100	2.40
2021-8	Band1, 2, 3, 4, 5, 6, 7, 9 Band8 Band10, 11	30 15 100	3.12
2024-7	Band1, 2, 3, 4, 5, 6, 7, 9 Band8 Band10, 11	30 15 100	0.65

2.2 Data Processing

Firstly, data preprocessing was carried out. In order to eliminate environmental interference and various errors generated during data transmission, obtain accurate visible and near-infrared surface reflectance, and eliminate atmospheric effects in the thermal infrared band, Landsat images were preprocessed by ENVI, including splicing and cropping, radiometric calibration, atmospheric correction, urban land use classification, and calculation of the NDVI. The NDVI is calculated from the reflectance of near-infrared and red light bands, with higher values indicating denser vegetation. It has the roles of monitoring vegetation growth, inverting heat island (high value area to mitigate heat island), assisting land classification, assessing ecological changes, etc. It can be used to analyze the scenarios such as the relationship between vegetation distribution and heat island. Its algorithm formula is.

$$NDVI = \frac{(\rho NIR - \rho RED)}{(\rho NIR + \rho RED)} \quad (1)$$

A large number of scholars have studied the ground temperature inversion algorithms based on Landsat satellite images, and at present, there are mainly single-window algorithms, single-channel algorithms, atmospheric correction methods (Radiative Transfer Equation), and split-window algorithms. The surface heat radiation transport equation (atmospheric correction method)[7] (RTE) is an equation that describes the thermal radiation propagation through the medium when it interacts with the medium (absorption, scattering, emission, etc.) so that the thermal radiation can be transported according to a certain law. The author uses the atmospheric correction method to invert the surface temperature, the principle is to estimate the atmospheric influence on the surface thermal radiation, and then eliminate this part of the atmospheric influence in the total amount of thermal radiation observed by the satellite sensor to get the surface thermal radiation intensity, and then convert the surface thermal radiation intensity to the corresponding surface temperature, the algorithm formula is.

$$L_\lambda = [\varepsilon B(T_s) + (1-\varepsilon) L\downarrow]\tau + L\uparrow \quad (2)$$

$$B(T_s) = [L_\lambda - L\uparrow - \tau(1-\varepsilon) L\downarrow] / \tau \quad (3)$$

$$T_s = K_2 / \ln[K_1 / B(T_s) + 1] \quad (4)$$

In the formula: L_λ is the thermal infrared brightness received by the satellite; L↑ is the atmospheric upward radiant brightness; L↓ is the atmospheric downward radiant brightness; ε is the surface specific emissivity; Ts is the real temperature of the ground surface (K); B(Ts) is the thermal radiant brightness of the blackbody; and τ is the atmospheric transmittance in the thermal infrared band. For the Landsat8 image of TIRSBand10,K1=774.89 W/(m2-μm -sr),K2=1321.08 K. The atmospheric profile parameters τ, L↑ , and L↓ are obtained by entering the imaging time and the central latitude and longitude at NASA's public website (http://atmcorr.gsfc.nasa.gov/).

2.3 Temperature Classification

In order to eliminate the differences between remote sensing images and surface temperatures at different times and seasons, and to increase the comparability of the data, compared with the equally spaced division of n sub-intervals with maximum and minimum values as the endpoints, which is subjective [8], this paper adopts the method of mean-standard deviation equidistant spacing [9,10], which is based on the mean and standard deviation of surface temperatures, and reflects the temperature differences of different regions through the combination of different multiples, thus realizing the analysis and calculation of the spatial and area of heat island distribution. Based on the mean and standard deviation of surface temperature, different multiples of the mean and standard deviation can be combined to reflect the temperature differences in different regions, thus realizing the analysis and calculation of the space and area of heat island distribution. In order to better characterize the range of urban heat island, the low-temperature and sub-low-temperature zones are defined as cold island areas, and the sub-high-temperature and high-temperature zones are defined as heat island areas, and the different temperature ranges and definitions are shown in Table 2.

Table 2. Temperature class classification

Regions	heat island intensity	temperature scale	Criteria for classification
1	Uncooked island	Low temperatures	LST ＜ μ - std
2	Stronger cold island	Low bottom temperature	μ - std ≤ LST ＜ μ - 0.5std
3	Central temperature area	Medium temperature	μ - 0.5std ≤ LST ＜ μ + 0.5std
4	Stronger heat island	High bottom temperature	μ + 0.5std ≤ LST ＜ μ + std
5	Island of intense heat	High temperatures	LST ≥ μ + std

3. Results

3.1 Characteristics of Annual Changes in the Urban Heat Island Effect

The distribution of surface temperature in Chengdu urban area shows differentiation in different seasons. In this paper, the urban area of Chengdu and its surrounding areas are selected as representative areas for analysis. Specifically, in 2018 and 2021, the temperature in the central city is significantly lower than that in the suburban areas, showing the characteristics of "cold island". The main high-temperature areas in Chengdu city appear in the city boundaries, especially in the east and southwest border high-temperature area is more concentrated, the reason is that the above area more concentrated factories, and industrial production raising the surrounding environmental temperature, resulting in high temperature, and the central city within the scope of the majority of residences, shopping malls, schools, and other places, buildings are dense, the artificial heat source is relatively dispersed and low intensity, while the passive ultra-low-energy buildings, centralized heating, Park green space [8] and other factors superimposed on each other, further causing the central city temperature reduction, the phenomenon of lower temperature in the city center.

In recent years, with the planning and establishment of some new districts and core areas in Chengdu, the scale of development has been expanding, and the proportion of population growth in the suburbs has continued to grow, and the intensity of the heat island has gradually declined (the urban heat island in 2021 and 2024 had a significant decline compared with 2018).

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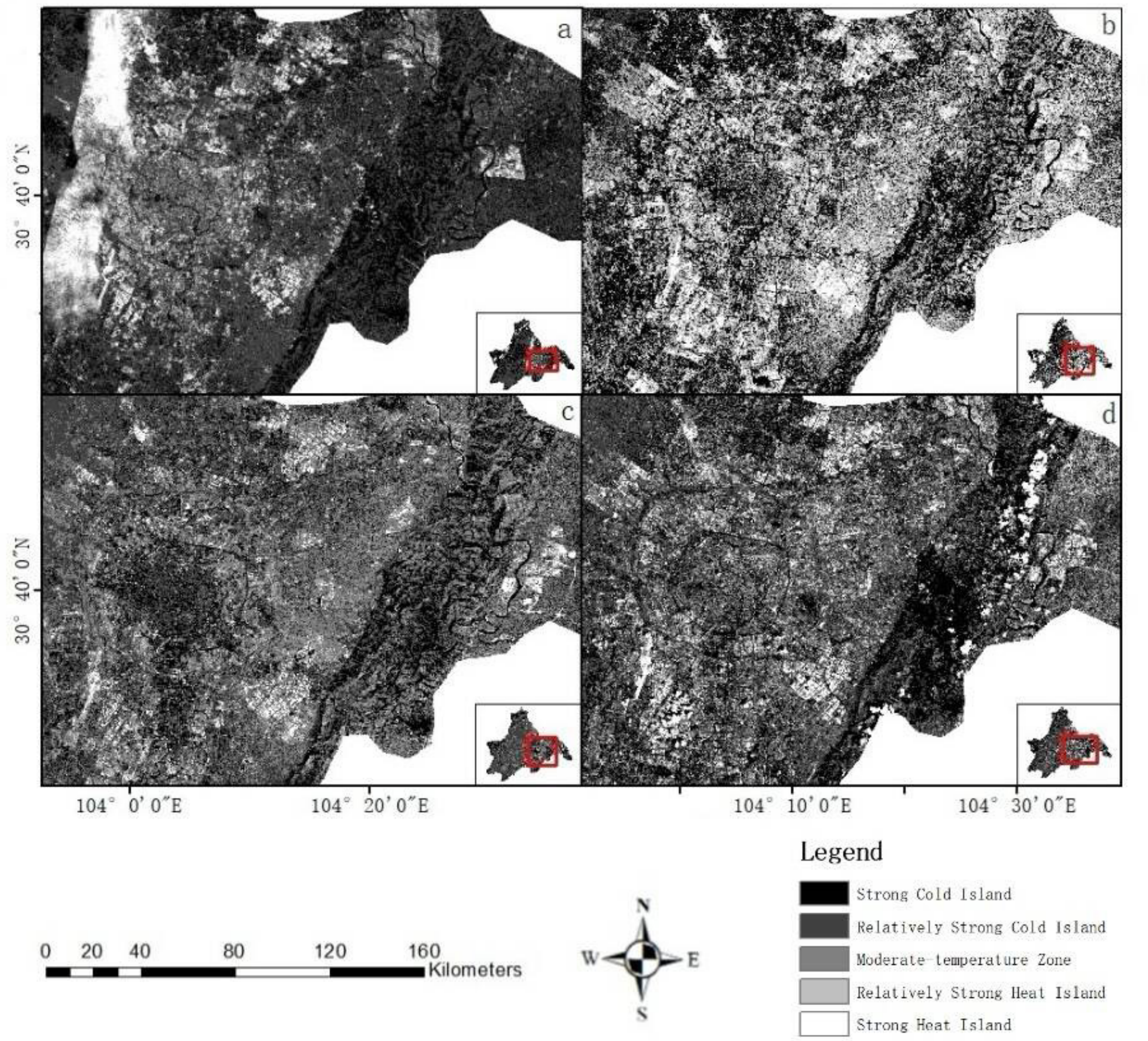

Fig.1 Land surface temperature inversion plot (a: urban land surface temperature in 2014; b: urban land surface temperature in 2018; c: urban land surface temperature in 2021; d: Urban surface temperature in 2024)

Figure 1 shows the spatial and temporal pattern of urban heat islands in Chengdu, from abcd four small figures show that the intensity of urban heat islands in Chengdu in 2014-2024 shows a trend of first increase and then decrease, the urban heat island area from 2014-2018 rapidly increased by about 40%, the heat island area growth in 2018-2020 decreased by about 25%, and the heat island area decreases again by about 5% in 2021-2023. Meanwhile, in terms of spatial distribution, the increase of heat island area in Longquanyi District and Jintang County is more obvious compared with other regions.

3.2 Aspects of the factors affecting the heat island effect

3.2.1 vegetation cover

It was found by combining the NDVI of Chengdu City (Figure 2: a-d correspond to the four vegetation index images from 2014-2024, respectively):

From the perspective of vegetation impact, the spatial distribution map of the vegetation index was obtained by using the inversion of red and near-infrared bands of one Landsat 8 data for each year (see Fig. 2), and the larger value represents the higher vegetation coverage, and the distribution of vegetated and non-vegetated areas can be better distinguished by calculating the NDVI. From the spatial distribution of NDVI in the urban city in the figure, it can be seen that there is a large area of vegetation cover outside the third ring road of the city and in the suburbs. Comparing with the LST inversion results of the current year in the figure, the cultivated land around Longquanshan, wetlands and other vegetation cover are all higher, and the corresponding surface temperatures of the area are also lower, which are mostly in low-temperature and sub-low-temperature zones. Parks with more vegetation cover in the city center, such as People's Park, also show low-temperature zones. Thus, the high vegetation cover has a positive effect on suppressing the heat island effect.

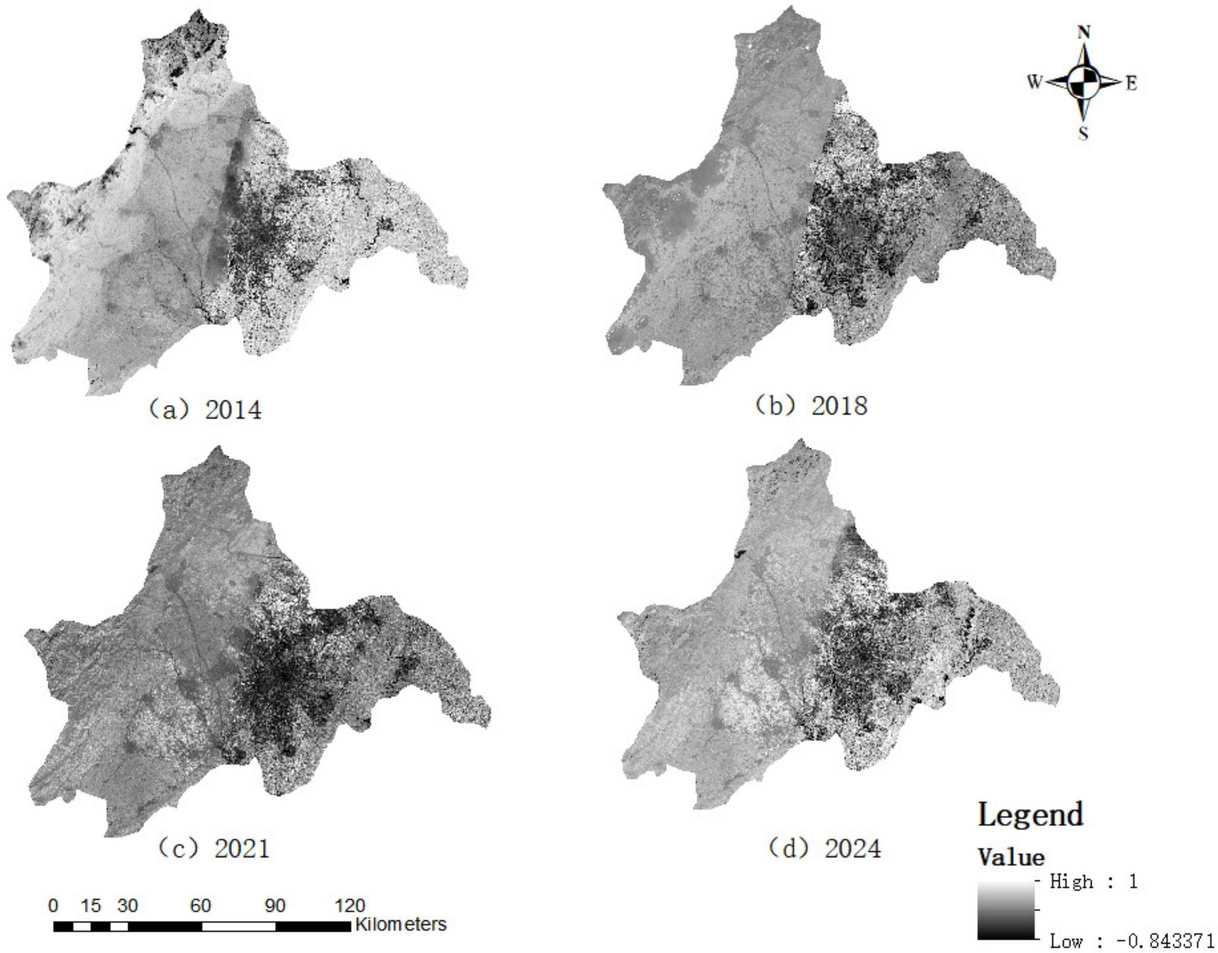

Fig. 2 2014-2024 NDVI images

3.2.2 measured quantity of rain

In this paper, the average annual rainfall of Chengdu City during 2014-2024 was obtained from the National Meteorological Science Data Center (https://data.cma.cn/). Combined with the rainfall, it can be seen that during the decade 2014-2024, the average annual precipitation is maintained between 1265-1434 mm, of which the average annual precipitation in 2014 is the lowest at 1265 mm, and peaks in 2018 (1434 mm) followed by a gradual decline and stabilized at about 1350 mm. And rainfall is positively correlated with the urban heat island effect (Figure 3), analyzing the reasons for this, including the cooling effect of rainfall, the improvement of airflow, and the negative feedback of the heat island effect: first of all, when it rains, the evaporation of rainfall absorbs heat and reduces the temperature of the near-surface air. At the same time, rainwater can wash the urban subsurface, and take away part of the heat, so that the surface temperature of the city decreases, easing the intensity of the heat island effect; secondly, rainfall is often accompanied by airflow, which helps the air exchange between the city and the surrounding areas, promotes the diffusion of hot air, makes it easier for the city heat to be dispersed, and weakens the heat island circulation; lastly, the amount of precipitation is affected by the urban heat island effect at the same time: the urban heat island effect makes the air over the

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city Convection is enhanced by the urban heat island effect, and hot air rises to form clouds easily, increasing the likelihood of urban precipitation and potentially causing changes in precipitation frequency and intensity. Under certain conditions, this can lead to an increase in rainfall in the city and its downwind direction.

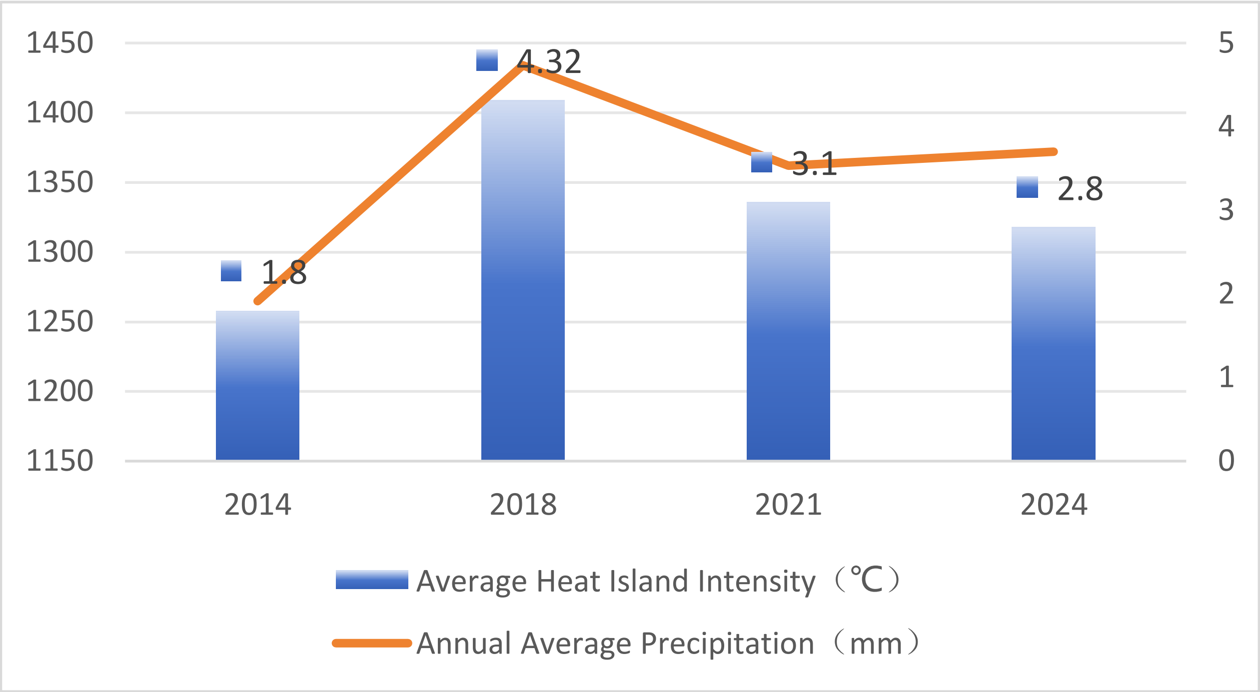

Fig.3 Schematic diagram of heat island intensity change and average rainfall in Chengdu from 2014 to 2024

3.2.3 Land Use

Combined with the land use data (Figure 4), it is found that the urban heat island effect is closely related to urban land use. The newly developed areas (Tianfu New Area) are warming up, while some old cities are cooling down: in new urban cities and new development areas, the surface temperature is warming up significantly due to the hardening of the subsurface and the rise of buildings, which increase the ground heat fusion. In addition, irrational land use planning, such as the layout of industrial zones in the city center, over-concentration of commercial and residential areas, etc., makes it difficult for heat and exhaust to diffuse, further exacerbating the heat island effect. Therefore, in urban planning and land use, it is necessary to pay attention to increasing the area of green space and water bodies, the scientific layout of functional areas, and optimize the distribution of construction land, so as to alleviate the urban heat island effect and improve the livability of the city.

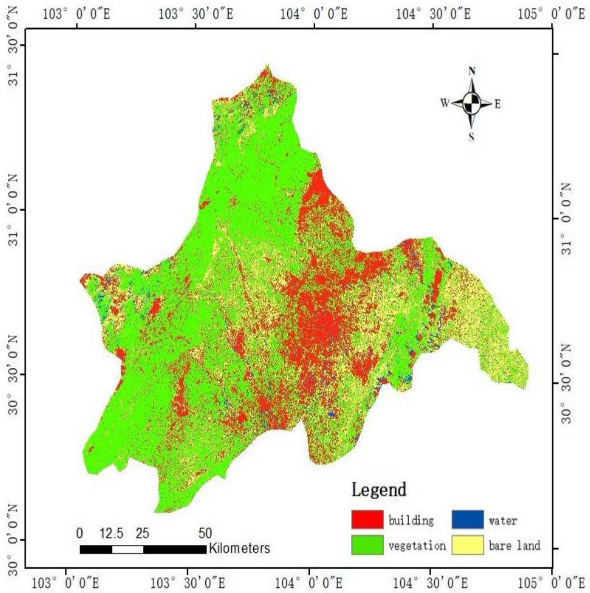

Fig.4 Land use map of Chengdu City

4. Discussion

Combined with the research results, this paper tries to put forward several measures and countermeasures to mitigate the urban heat island effect with regard to the characteristics of the industrial city of Chengdu. Urban expansion and population growth is one of the important factors leading to the aggravation of the heat island effect, in the process of urban construction, reasonable planning should be carried out through reasonable functional zoning of the city. For example, when planning residential areas and ancillary functional areas, the mitigation of the heat island effect should be taken into account. The destruction of natural surfaces by new houses and factories is inevitable, so in urban construction, green belts and water bodies should be added near the destroyed natural surfaces to alleviate the heat island effect. In areas with high population density, parks and green belts are constructed to form artificial forest areas, thus improving the urban heat island effect and lowering the near-surface temperature in nearby areas. In addition, there are many heavy industries and energy-consuming factories in Qingbaijiang and Xindu Districts of Chengdu, most of which operate at full capacity 24 hours a day and consume a lot of heat energy while bringing economic benefits to the city. To address this problem, it is recommended to gradually upgrade production capacity, effectively improve resource utilization, and strictly implement environmental protection measures in the production process to reduce heat emissions.

This paper systematically reveals the spatial and temporal characteristics and influencing factors of the heat island effect in Chengdu City through long time series remote sensing data and multi-factor analysis, with scientific research methods, practical conclusions, and high academic and application value. However, there is still room for improvement in the quantification of anthropogenic heat sources, integration of meteorological factors, and evaluation of policy effects. In the future, we can further introduce machine learning models, high-frequency ground monitoring data, and combine social and economic statistics to construct a more comprehensive model of the heat island effect driving mechanism and strengthen the cost and benefit analysis of countermeasures, so as to provide more accurate scientific support for the sustainable development of the city.

5. Conclusion

This paper analyzes the interannual variation of annual average temperature based on Landsat remote sensing image data, and finds that in 2014-2024, the areas with higher temperatures have been concentrated in the urban area, and the extremely high-temperature area, high-temperature area, and sub-high-temperature area have been gradually expanded and concentrated in the periphery of the urban area from the original city center area. The heat island effect in the main urban area of Chengdu City is generally on the rise, and with the urban construction and time-lapse, new heat island centers are gradually appearing in Longquanyi District, Xinjin City District and Jintang County, and their areas are also expanding. And the vegetation and water bodies have a very strong dilution effect on the heat island effect.

Conclusion and outlook

The study can further shift from “phenomenon description” to “mechanism - prediction - application” analysis of the whole chain, such as constructing a synergistic evolution model of the heat island effect and extreme heat events based on historical meteorological data and climate models (e.g., CMIP6). Identify the sudden change threshold of heat island intensity when a heat wave occurs (e.g., when the temperature is ≥35°C, the increase of heat island intensity is 40%-60% higher than the normal), and predict the risk of exacerbation of the heat island effect under the trend of warming in the future. This will provide a more three-dimensional scientific basis for heat island management in megacities.

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