Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 24 | No. 3 | Article ID D1752 | 2025

Original Research Paper
https://doi.org/10.46488/NEPT.2025.v24i03.D1752
Open Access Journal

Assessing Climate Sensitivity to Urban Land-Use Changes in Iraq

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Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com

Received: 16-12-2024
Revised: 24-01-2025
Accepted: 01-02-2025

Key Words:

Climate response
Land cover/use
Urbanization
Mean surface temperature

Citation for the Paper:

Muter, S.A., Tawfeek, Y.Q., Al-Jiboori, M.H. and Abd Al Rukabie, J.S., 2025. Assessing climate sensitivity to urban land-use changes in Iraq. *Nature Environment and Pollution Technology*, 24(3), D1752. https://doi.org/10.46488/NEPT.2025.v24i03.D1752

Note: Since 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

ABSTRACT

Iraq has been suffering from a continuing rise in surface air temperature, causing a general deterioration in ecosystems. Land-use climate sensitivity focuses on how changes in land cover (e.g., deforestation, urbanization, or agricultural expansion affect local or regional climate conditions, particularly surface temperatures. Using yearly data on built-up areas and air temperature over the period (1971-2022), this sensitivity is assessed based on alterations in built-up areas for three Iraqi cities-Basrah, Baghdad, and Mosul, as well as for the entire country of Iraq. The time series of the areal yearly averages for air temperatures was analyzed. Standardized Euclidean distance and linear regression models were used to assess the effect of built-up changes and temperature trends, respectively. The results revealed that the trend in Iraq has positively increased, with a value of 0.07°C/year. The results also illustrate that alterations in built-up areas have contributed to the increase in yearly temperature in Basrah and Baghdad, but not in Mosul, which seems to be more affected by global warming and land cover changes. Urbanization plays a significant role in shaping the social, economic, and environmental landscapes of Baghdad and Basrah.

INTRODUCTION

Continuous urbanization in the urban environment, including increasing built-up areas and other human activities, has caused a significant modification in substantial surface properties and then altered the urban climate (Mahmood 2014, Mohowes & Al-Jiboori 2023, Pushpalatha et al. 2024). Anthropogenic changes in land cover, such as impervious surfaces of asphalt and other dark materials, have contributed to local or regional warming through changes in the properties of biophysical surfaces, land fragmentation, and biodiversity (Novio et al. 2024). The amount of sunlight absorbed by the Earth is dramatically increased by these surfaces, which is re-radiated longwave radiation heating the atmosphere by its interaction with molecules of greenhouse gases (GHGs) that subsequently re-emit a portion of this heat to the surface, leading to increased average air temperature (Mahmood et al. 2024).

Climate sensitivity (CS) is a quantitative metric of the climate to human action and is defined as the response of the local near-surface temperature (NST) to different physical and human influences (Xian et al. 2020). Accurate estimates of the climate response are needed to assess the impacts of climate change and to inform policy. Generally, several natural factors influence NST at a certain place, like latitude, elevation, distance from water bodies, synoptic pressure systems, and local aspects (Ahrens & Henson 2022). Radiative forcing, which is the difference between incoming and outgoing radiation at the top of the Earth's atmosphere, can be linked to temperature changes by comparing it to a reference level of forcing. Human activities, such as fossil fuel combustion, transportation, land-use changes, and elevated air pollution levels, have altered radiative forcing (Anad et al. 2022).

For instance, increased atmospheric carbon dioxide (CO_2) enhances net radiative forcing by reducing atmospheric transparency to thermal radiation, ultimately contributing to human-induced global warming (Otero 2020). It leads to increasing NSTs and then to changes in climate patterns.

CS cannot be measured directly, but it must be estimated using historical instrumental records, palaeoclimate data, or mathematical models. Over the past years and in the context of ongoing global warming, Iraq has become increasingly concerned about the frequent consequences of rising air temperatures. These include extreme temperatures, heat waves, severe drought, sand and dust storms, rainfall variability, water scarcity and salinity, especially in the central and southern parts of the country (Zahraa et al. 2020). There is an urgent need to explore estimates of CS for future action to avoid exacerbating these threats.

Many studies have described the warming climate over Iraq in terms of temperature trends (Salman et al. 2017, Ibraheem et al. 2023, Al Rukabie et al. 2023) and increased CO_2 over different long periods, but up to our knowledge, there are a few studies carried out on rising temperature caused by land use changes in urban areas. Two studies were performed by Abdaki et al. (2021) and Binder et al. (2022) for predicting long-term climate change in which the future annual mean temperature was projected for four years: 2025, 2050, 2075, and 2100 using coupled model inter-comparison project phases under different scenarios of representative concentration pathways, and they expected that annual mean temperature to increase in the range 1-4°C. Based on historical real data of NST and its connection to surface built-up changes and temperature trends, future studies can provide a crucial localized perspective, bridging the gap between urbanization and Iraq's warming climate. In this paper, the data for urban expansion in three major cities of Iraq: Basrah (in the south), Baghdad (in the middle), and Mosul (in the north) were collected. The main objectives are to 1) examine the local sensitivity to built-up areas under different climate conditions, 2) determine the reliable value of CS resulting from changes in built-up areas, highlighting the need for mitigation and adaptation strategies for future alterations, and 3) compare the sensitivity variables and analyze their correlations.

MATERIALS AND METHODS

Description of the Site and Data Collection

The presented study was carried out in Iraq, located in the Middle East, and a country in southwestern Asia (Fig. 1). The total area is 437072 km^2 and consists of agricultural land (23%), urban and suburban areas (3%), and water bodies (1%), with the remainder being about 73% desert (World Data 2023). The latter percentage reflects the common

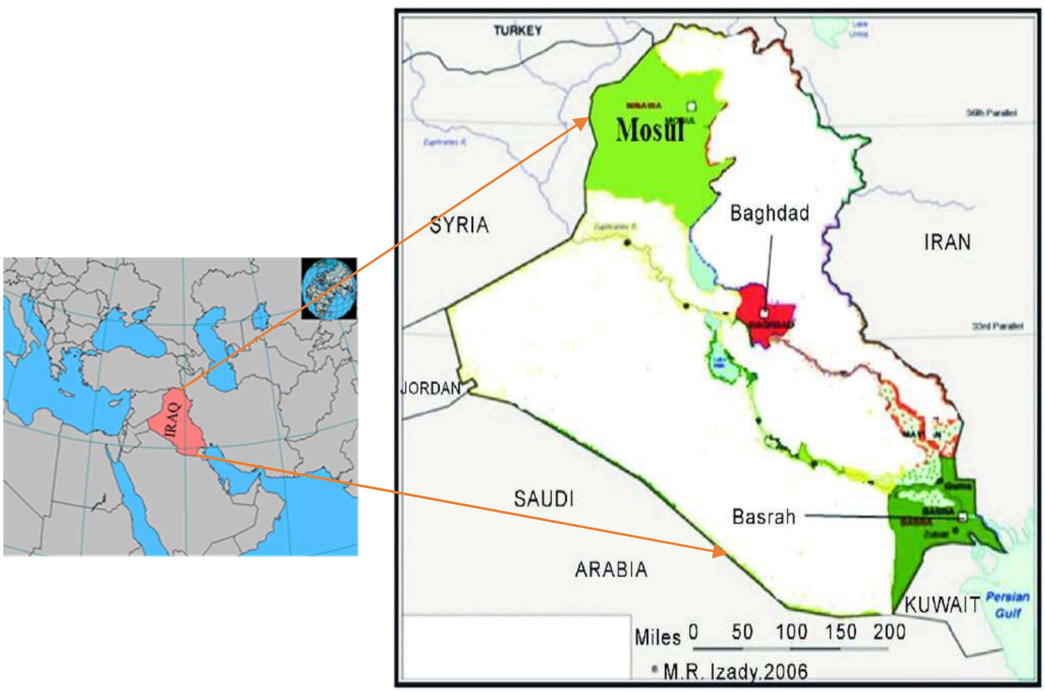

Fig. 1: Iraq's map on which the studied areas are: Basrah, Baghdad and Mosul.

Table 1: Geographic features for the three cities: Basrah, Baghdad, and Mosul.

Province	Latitude [°] E	Longitude [°] N	Elevation [m]	Pop. density [pop.km^{-2}]	Total area [km^2]	% of Iraq
Basrah	30.52	47.82	5	160.6	19070	4.4
Baghdad	33.3	44.43	34	187.9	894.2	0.2
Mosul	36.31	43.15	223	105.2	180	0.04

influence of drought. Iraq's topography is characterized by mostly broad plains, with large desert plateaus dominating the west of the country. To prevent these threats from worsening, there is an urgent need to explore estimates of CS for future policies. The elevation above sea level has a wide variation, from remnants of sea level in the southeast to mountains with heights of 3583 m in the north and northeast along the borders with Iran and Turkey (Al-Ansari 2021). Iraq's terrain comprises four main regions: highlands (north), alluvial plains (middle), deserts (west and southwest), and rolling uplands (northwest) (Khadduri et al. 2003). From the latter region, two rivers (Tigris and Euphrates) flow southeast. They join the Shatt-Al-Arab.

The study area was divided into three parts: south, central, and north, each represented by the major cities of Basrah, Baghdad, and Mosul. These are the most densely populated cities and contribute significantly to the total population (World Population Review 2023). Geographic coordinates such as latitude, longitude, and elevation above mean sea level (msl), areas and their ratios to the total area of Iraq, and the population density in 2022 (in pop.km^{-2}) for the cities above are presented in Table 1. Iraq's climate in general ranges from semi-arid to arid, with dry, hot summers and cooler winters. The average yearly NST ranges from 0°C (winter) to 38°C (summer). Rainfall is a seasonal event that occurs between November and May, with an annual average ranging from 150 mm in the south to 400 mm in the northeast parts (Muter et al. 2024).

Yearly means of NST at the three cities obtained from the Iraq Meteorological Services and Seismology for 52 years running from 1971 to 2022 were analyzed. In addition, the built-up areas for the three Iraqi regions: Basrah, Baghdad, and Mosul, were obtained from the most recent studies conducted for each city, as displayed in Table 2, using Landsat images with 30x30 m resolution and very good accuracy. During the interval 2014-2016, the political situation in Baghdad was unstable due to military operations, so the built-up area in 2015 (437.8 km^2) was less than that in 2008 (621.7 km^2).

Table 2: Built-up areas of the three cities in different years.

Provinces	Year	Build-up area [km^2]	Reference
Basrah	1990 2003	3280 3756.8	Hadeel et al. (2009)
	2000 2015	192.8 437.2	Al-Jiboori et al. (2020)
Baghdad	2008 2013	621.7 706.3	Tawfeek et al. (2020)
	2013 2019	706.3 727.3	Tawfeek et al. (2020)
Mosul	2013 2021	132 115.4	Saleh & Ahemd (2021)

CS Variables

CS to changes in land cover can be viewed as radiative forcing (ΔF) factors for assessing climate change. These factors can directly and indirectly affect the change in mean near-surface temperature (ΔNST) through a simple equilibrium model (Sherwood et al. 2020)

$$\Delta NST_k = -\frac{\Delta F_k}{\phi} \quad ...(1)$$

ϕ represents the climate feedback variable, and k denotes the forcing agent. Radiative forcing encompasses contributions from both anthropogenic and natural factors. The latter generally has a minor effect on the yearly mean temperature trend in most regions (Rälsänen 2021). On the other hand, the former has significant effects as reported in many studies (Egorova et al. 2018, Sherwood et al. 2020). In this study, the changes in the urban areas as a function of the anthropogenic forces are studied. One of the above forcing agents is commonly used to estimate the NST response through modeling simulations, such as general circulation models for the global climate system and regional climate models for specific areas. However, studying each agent in isolation introduces uncertainty into this estimate. For future years, these data can be derived by interpolation using the trend analysis over a given period (Mahmood et al. 2024). In a review paper, Sherwood et al. (2020) show that an estimate of climate sensitivity can be achieved not only by future climate projections, but also by analysing relevant observational data (e.g., Goodwin & Cael 2021). Therefore, the present study tries to determine the urban surface changes that can account for the regional effects in a global climate without relying on climate models. Subsequently, their results are correlated, as historical land cover changes can contribute significant amounts of CO_2 (Mahowald et al. 2017).

Human-induced changes in land cover, such as the expansion of built-up areas, have greater values than changes in NST (Al-Jiboori & Mohowes 2023). To standardize the absolute difference in their values, we subtract the original values from their mean and divide by the standard deviation. This process is necessary to balance the contributions to CS. For easier comparison, we center the variables at their means, ensuring all variables have a mean of zero. Therefore, the Standardized Euclidean Distance (SED) was chosen to measure the rate of change of climate variables in response to built-up areas, A (Ordonez et al. 2014, Xian et al. 2020). To assess the impact of built-up area changes on the regional climate, the difference in built-up area changes over a long-term period was calculated as

$$\Delta A = A_2 - A_1 \quad ...(2)$$

where A_1 and A_2 are built-up areas at the start and ending of the time period in km^2 units. This change is, of course, associated with a change in the annual NST, i.e.

$$\Delta NST = NST_2 - NST_1 \quad ...(3)$$

The subscripts 1 and 2 are the initial and final yearly mean temperatures for the selected period. To quantify the effect of the change in the built-up area on the changing NST over time and space, we use the expression used by Ordonez et al. (2014):

$$SED(\Delta A \text{ or } \Delta NST) = \sqrt{\sum_{i=1}^{n}\left[\frac{(A_{i2} \text{ or } NST_{i2} - A_{i1} \text{ or } NST_{i1})^2}{\sigma^2_{iA \text{ or } iNST}}\right]} \quad ...(4)$$

where i=1, 2,... is the number of regions where the built-up area changes, n is the total number of regions examined, and σ is the standard deviation. The SED is useful for comparing data with different scales but has limitations, like sensitivity to outliers or dependency on variance. The change in response to the forcing of the change in built-up area can directly link the relevant forcing and NST variability without considering other individual factors, as given by Xian et al. (2020).

$$SED(\Delta NST) = \beta \times SED(\Delta A) \quad ...(5)$$

where b is the slope or CS to the change in built-up area forcing, which is a non-dimensional quantity. This equation has the advantage of preventing variables with high variances from dominating the distance calculation.

Data Analysis

Areal yearly averages for the whole of Iraq were calculated by summing the yearly averages for three cities and dividing them by 3. Although these averages may not be sufficient to represent the whole of Iraq, they could provide reasonable results, especially for air temperature, whereas most of the interior of Iraq consists of roughly flat land, with a percentage of 99.8% of the total area. The linear regression model Eq. (6), a fundamental and widely used method of predictive analysis, involves assessing the strength of the relationship between the parameters. This equation also has the advantage of predicting effects and trends (Al-Jiboori et al. 2019).

$$NST = \gamma + \delta \times year \quad ...(6)$$

Where γ and δ are the empirical constants that represent the intercept and the trend, respectively. These constants, derived from the data, are crucial, particularly in climate research, as they help understand historical patterns and predict future events. Fig. 2 displays the flowchart that summarizes the methods mentioned above.

To assess the percentage increase, which is a measure of how much a given value changes build-up area over a period of time, the equation is given

$$\text{Percent of change } (\%) = \left|\frac{A_2 - A_1}{A_1}\right| \times 100 \quad ...(7)$$

In this paper, the absolute value is used to eliminate negative values in certain cases. Lastly, R^2 is employed to assess the goodness of fit between the actual data points, with a value close to 1 indicating a perfect match between the regression predictions and the data.

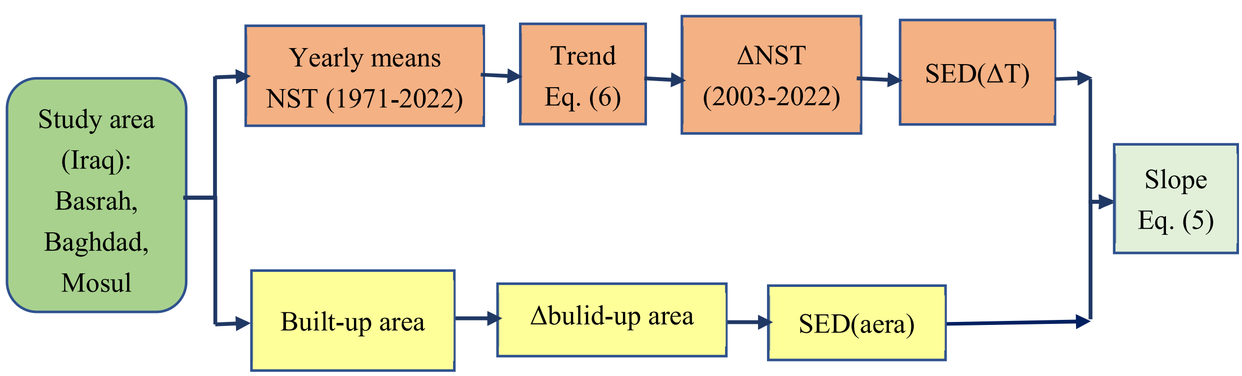

Fig. 2: Flowchart of the methodology used in this paper.

RESULTS AND DISCUSSION

Yearly NST variations

The time series of the historical yearly NST data over three cities, as well as the areal average of temperature in Iraq, were plotted together in Fig. 3 for the period from 1971 to 2022, which depicts the trends in yearly mean surface temperature for Basrah, Baghdad, Mosul, and Iraq as a whole over several decades. The selection of this period is to confirm the increase in NST, which is fair evidence for the local warming effect. Also, to execute the objectives of this research for estimating levels of CS in the future. There is a general increase in NST for all provinces with a tendency from the south to the center and north, although the geographical location and altitude play a role in this distribution. Basrah (red line) shows the steepest upward trend, indicating significant warming over time. Baghdad (blue line) also exhibits an upward trend, though less pronounced than Basrah, Mosul (green line) shows a relatively slower rate of temperature increase compared to the other cities. The overall trend for Iraq represents an average of the three regions and also demonstrates a steady increase in temperature over the years. These regions exhibit increasing temperatures, highlighting the impact of climate change across Iraq.

Equation (6) was used to plot the best fit lines through the yearly NST data with derived empirical constants (i.e, intercept and slope) and R^2, reported in Table 3. The intercepts reflect the initial modeled temperature baseline, influenced by local conditions and trends, and all have negative values. The most negative intercept, as in Basrah, indicates a significantly lower baseline temperature in the model, reflecting a steep upward trend due to rapid warming over time. However, their direct interpretation is less practical, as the focus is often on the trend (slope) and its implications for temperature changes. Basrah province shows the highest positive trend (0.086°C.yr^{-1}), Baghdad is less (0.061°C.yr^{-1}), and Mosul is the lowest (0.048°C.yr^{-1}). The variations in the slopes of the lines indicate regional differences in CS and the influence of local factors such as urbanization, land use, or proximity to water bodies. Basrah is characterized by unique local urban dynamics and geographic features, so several factors combine to drive its highest warming trend, including its southern location near the Arabian Gulf, arid climate, intense urban heat island effect, high humidity, limited vegetation, and frequent heat-trapping dust storms. These factors amplify the warming relative to Baghdad and Mosul. To compare with some previous studies conducted in the same provinces, using the Mann-Kendall test, Al-Timimi and Al-Khudhairy (2018) found the same yearly increasing trends for Baghdad and Mosul, but lower for Basrah (0.07°C.yr^{-1}) over the period (1980-2015). The strongest trend for Basrah is attributed to its low latitude and altitude (see Table 1), as well as its proximity to sea level, where conditions with high levels of water vapor prevail. Mosul exhibited similar mean NST and variation, despite having a different latitude and surface type.

The yearly mean of NST was calculated for the whole of Iraq using the historical records of three areas for the period 1971-2022. Fig. 2 displays the time series of yearly NST and its climate trend. Iraq's mean yearly trend is generally

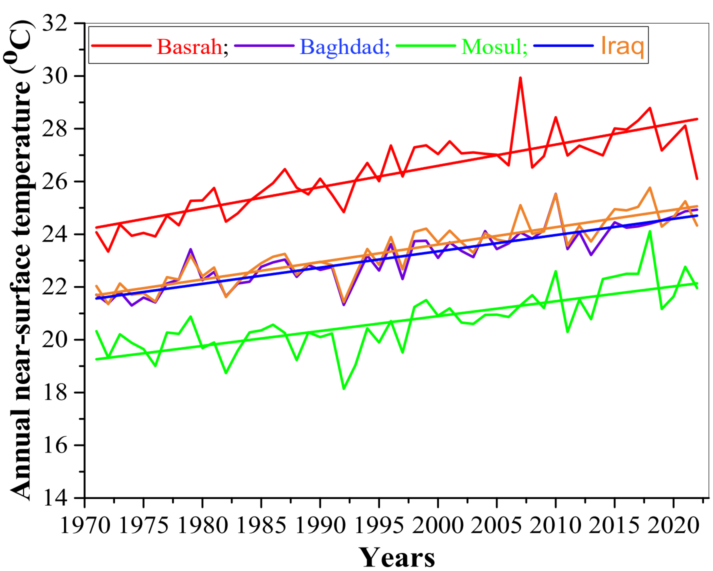

Fig. 3: Yearly variations of NST in Basrah, Baghdad, Mosul, and Iraq over the period (1971-2022).

Table 3: Constant values in Eq. (6) for the annual mean NST of the period (1971-2022) and R^2, and the areal yearly average NST change over the last 20 years.

Province	Intercept	Slope (trend) [°C.year^{-1}]	R^2	ΔNST [°C]
Basrah	-145.3	0.086	0.79	1
Baghdad	-98.8	0.06	0.77	1.4
Mosul	-96.6	0.057	0.55	-0.14
Iraq	-110.5	0.068	0.88	1.6

increasing, with a value of 0.07°C.yr^{-1}, larger than Al-Timimi and Al-Khudhairy's (2018) 0.06°C.yr^{-1}. The largest mean yearly trend found in the present study reflects that Iraq has continued to warm up.

Assessing CS in Iraq

The difference in areal yearly surface temperatures (ΔNST) between the beginning and end of the corresponding 20-year period (2003-2022) was selected for analysis. These differences were calculated separately for each of the studied provinces, as well as for Iraq as a whole, and are shown in Table 4. Notably, positive ΔNST values were observed in Baghdad (1.4°C), Basrah (1°C), and Iraq (0.75°C). Unlike Basrah and Baghdad, Mosul experienced a decrease of a negative value (ΔNST = -0.14°C). Given the strong urban heat island effect in Baghdad, the highest ΔNST in this city is not unexpected (Tawfeek et al. 2020, Wahab et al. 2022). The average temperature increase (ΔNST) across Iraq is 1.47°C, reflecting the cumulative impact of urbanization, land-use changes, and climate change at a national scale.

The persistent changes in built-up areas, as shown in Table 2, can be explained by calculating the differences across all periods, as reported in Table 4. Some notable results include both positive and negative changes in built-up area values. The increasing built-up areas in Basra (+476.7 km²) and Baghdad (+116.7 km²) reflect urbanization growth, while a decrease was observed in Mosul (-16.6 km²) due to the impact of the war during the 2016-2017 period. This is further supported by the study of Jumaah et al. (2021), which assessed the effects of the war on land use in 2003 and 2016. Their findings showed an 18% reduction in agricultural land and a 7% decrease in urban areas, both of which were converted to bare land, accounting for 44% in 2016.

Assuming that changes in built-up areas affect the yearly variation in NST, which is calculated for each city based on the period reported in Table 4, the results of ΔNST are presented in the fifth column of Table 4. The ΔNST values range from 1°C in the lowlands (Basrah) to 1.4°C in the central region (Baghdad) and up to 2°C in the highlands (Mosul). Despite the reduction in built-up areas in Mosul, ΔNST increased to 2°C. This finding aligns with Hebert and Lovejoy (2018), who demonstrated that the highest warming occurred over land in the highlands. From this analysis, we calculate the spatial SED of built-up areas (SED(ΔA)) and the annual NST change SED(ΔT) across Iraq. Subsequently, we determine the CS of these variables by calculating the parameter β (Eq. 5), defined as β = SED(ΔT)/SED(ΔA) = 1.67/2.03 = 0.82. This relatively high value suggests that the transformation of the land cover into impervious surfaces acts as a significant forcing agent for climate and should be considered as a regionally averaged forcing. Our analysis indicates that NST is not only sensitive to built-up areas but also influenced by other factors that we have not accounted for.

When Eq. (7) was applied to find the percentage of change in built-up area, the largest value (27.3%) was found in Baghdad for the period of 20 years (2003-2022), as shown in Table 4. While in Basrah, this change has a small value, with 2.5% and 9% in Mosul. This implies that built-up area has the most effect on the increase in NST and thus on local warming.

CONCLUSIONS

CS to ongoing land use changes remains the key to understanding climate change in a given area. Using built-up areas and regional NST, the yearly variations were analyzed to understand the regional climate response to their influence on NST change. Sensitivity analysis of observed changes in built-up areas as a forcing agent has directly

Table 4: Changes in built-up area and associated NST in three cities: Basrah, Baghdad, and Mosul.

Province	Period	Darea [km^2]	Percent of change [%]	DNST [°C]
Basrah	1990-2003	+476.7	2.5	1
Baghdad	2000-2015	+244.4	27.3	
	2008-2013	+84.6 ⎬ $\bar{A}$=116.7	9.5	1.4
	2013-2-19	+21.1	2.4	
Mosul	2013-2021	-16.6	9.2	2
Iraq				1.47

influenced the regional climate in the three studied cities of Iraq. The ratio of Standardization Euclidean Distance as a function of change of surface temperature to that of change of built-up area is large [i.e., SED(DT)/SED(DA) = 0.82]. This suggests that the transformation of the land cover into impressive surfaces has been implemented as a forcing agent of climate and should be assessed as a regionally averaged forcing for future studies. This change amplifies the effects of rising air temperatures in Iraq, which has several practical implications: exacerbating the urban heat island effect, reducing agricultural productivity, increasing water demand, degrading air quality, and straining energy systems. These findings stress the importance of sustainable urban planning and climate adaptation measures to mitigate temperature increases, especially in rapidly growing cities like Basra and Baghdad. These findings can inform Iraq's urban planning policies and climate adaptation strategies, which include expanding green spaces, improving water management, using green infrastructure, promoting energy-efficient buildings, controlling urban sprawl, improving public transportation, and integrating climate resilience into policies. This study is limited by the available land cover information, highlighting the need for further research to improve our understanding of the impacts of land use change at local to regional scales. It should be improved by including vegetation changes, water bodies, and other forcing factors. For better analysis, we suggest a multifactorial analysis approach, which is suitable for handling complex data sets influenced by multiple variables.

ACKNOWLEDGMENTS

The authors are grateful to Mustansiriyah University and the University of Sumer for accepting this work. The authors also thank the anonymous reviewers for constructive comments to improve the paper.

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