

التوسع الحضري، درجات حرارة سطح الأرض النهارية والليلية، وتعرض السكان لأسطح حارة في جميع أنحاء
العراق، 2000–2020

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Urban expansion, diurnal land-surface temperature, and population exposure to hot surfaces across Iraq, 2000–2020

Urban expansion, diurnal land-surface temperature, and population exposure to hot surfaces across Iraq, 2000–2020

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المخلص

يسعى العراق إلى تحقيق التنمية الحضرية والاقتصادية بينما يواجه حرارة متزايدة، وإجهاداً مائياً، وهشاشة مناخية. ومع ذلك، لا تزال الأدلة الوطنية التي تتبع بشكل مشترك التوسع الحضري،

وديناميكيات درجات حرارة السطح نهاراً وليلاً، وسياق التوطن، وتعرض السكان محدودة. تدمج هذه الدراسة طبقة المستوطنات البشرية العالمية (GHSL) الخاصة بالمناطق المبنية، والسكان، ومجموعات المستوطنات مع بيانات درجات حرارة سطح الأرض (LST) الصادرة عن قمر MODIS Terra للتقييم التغيرات في جميع أنحاء العراق من عام 2000 إلى 2020. زادت الأسطح المبنية بمقدار 495.8 كم²، حيث حدثت أكبر الزيادات المطلقة في أربيل (57.1 كم²)، والسليمانية (52.4 كم²)، وبغداد (47.9 كم²). يقيم الإطار بشكل منفصل درجات حرارة سطح الأرض الصيفية نهاراً وليلاً، ويقارن الظروف الحرارية الحديثة بين فئات المستوطنات، ويحدد السكان في الخلايا المأهولة التي تقع عند أو فوق النسبة المئوية التسعين الوطنية لدرجات حرارة سطح الأرض الحديثة. تشير النتائج إلى اتجاه احترار نهارى وطني ضعيف (+0.35 درجة مئوية لكل عقد؛ $p = 0.401$) واتجاه ليلي أقوى (+0.75 درجة مئوية لكل عقد؛ $p < 0.001$)، إلى جانب تعرض سكاني أكبر بكثير لدرجات الحرارة الليلية المرتفعة مقارنة بدرجات الحرارة النهارية. بشكل عام، توفر الدراسة إطاراً وطنياً شفافاً وقابلاً للتكرار لتحديد المواقع التي يتطابق فيها التنمية الحضرية، والاحترار السطحي اليومي، وتعرض السكان، مما يدعم التكيف المناخي المستهدف مكانياً والتخطيط الحضري المستدام في العراق.

Abstract

Iraq is pursuing urban and economic development while facing intensifying heat, water stress, and climate vulnerability. Yet national evidence that jointly tracks urban expansion, daytime and nighttime surface-temperature dynamics, settlement context, and population exposure remains limited. This study integrates Global Human Settlement Layer built-up, population, and settlement datasets with MODIS Terra land-surface temperature (LST) data to assess changes across Iraq from 2000 to 2020. Built-up surface increased by 495.8 km², with the largest absolute additions occurring in Erbil (57.1 km²), Sulaymaniyah (52.4 km²), and Baghdad (47.9 km²). The framework separately evaluates daytime and nighttime summer LST, compares recent thermal conditions among settlement classes, and identifies residents in populated cells at or above the national 90th percentile of recent LST. The results indicate a weak national daytime warming trend (+0.35 °C decade⁻¹; $p = 0.401$) and a stronger nighttime trend (+0.75 °C decade⁻¹; $p < 0.001$), alongside substantially greater population exposure to high nighttime than daytime temperatures. Overall, the study provides a transparent and reproducible national framework for identifying where urban development, diurnal surface warming, and population exposure coincide, thereby supporting



spatially targeted climate adaptation and sustainable urban planning in Iraq.

1. Introduction

Iraq's development agenda is inseparable from the condition of its cities. Urban areas concentrate population, employment, services, infrastructure and investment, and are central to efforts to diversify an economy that has remained highly dependent on oil revenues. At the same time, the World Bank characterises Iraq's development challenge as a connected climate–development–fragility nexus, shaped by climate hazards, infrastructure constraints, institutional capacity and social inequality (World Bank, 2022). Urban growth can broaden access to jobs and services, but growth that outpaces land-use planning, basic infrastructure and green-space provision can lock in heat exposure, energy demand and uneven environmental risk. A national spatial account of where built-up land has expanded is therefore not merely descriptive: it is essential evidence for directing resilient urban development.

Climate change sharpens this planning problem. Iraq is already exposed to extreme heat, aridity, drought and water scarcity, while the Middle East and North Africa is projected to experience increasingly severe heat extremes under further warming (World Bank, 2022; Zittis et al., 2021). The IPCC identifies heat as a major urban climate risk and emphasises that urban form, land cover and infrastructure can amplify or reduce climate impacts (IPCC, 2022). In Iraq, the thermal burden interacts with declining water availability, reliance on energy-intensive cooling, and unequal access to services. These compound pressures make spatially explicit monitoring particularly important: it can identify not only where urban land is growing, but also whether development is occurring in places where hot-surface conditions and exposed populations are concentrated.

Urban expansion alters the surface energy balance through the replacement and fragmentation of vegetated or moist surfaces by impervious materials, changes in albedo, thermal storage, aerodynamic roughness and anthropogenic heat release. These processes can modify land-surface temperature (LST), although their magnitude and direction depend on background climate, season, vegetation, irrigation, urban morphology and the spatial scale of observation (Oke, 1982; Voogt and Oke, 2003; Weng, 2009). Reviews and multi-city studies consistently show that land-cover conversion and urban form can reshape surface thermal patterns, but they also warn against treating any simple built-up–temperature association as causal proof (Zhao et al., 2014; Li et al., 2024). Iraq-specific work has often focused on individual cities or short

time windows, leaving a gap in comparable governorate-scale evidence across the whole country.

A further weakness in many national heat assessments is the treatment of LST as a single daytime variable. Daytime LST primarily reflects radiative loading and surface energy partitioning; nighttime LST reflects the persistence and release of stored heat and can exhibit different spatial patterns and temporal trends. The distinction matters because diurnal thermal behaviour affects cooling demand, recovery from daytime heat and the location of persistent hot surfaces. Satellite LST remains a surface-climate indicator rather than a substitute for near-surface air temperature, physiological heat stress or health outcomes, but it is uniquely valuable for consistent, spatially complete monitoring where dense in situ networks are unavailable (Voogt and Oke, 2003; Phan et al., 2018). Analysing the two overpasses separately is therefore a scientific necessity, not a cosmetic extension.

This study develops a national, reproducible remote-sensing framework to link settlement expansion, diurnal summer LST and population distribution across Iraq during 2000–2020. The novelty lies in integrating (i) built-up change, (ii) separate daytime and nighttime LST trajectories, (iii) settlement-class contrasts and (iv) a cell-based population-exposure indicator in one common analytical structure. It addresses four questions: (Q1) Where and by how much did built-up land expand? (Q2) How did daytime and nighttime summer LST change spatially and temporally? (Q3) How did recent summer LST differ among settlement classes? and (Q4) Where, and for how many people, were the hottest populated surface conditions concentrated? The analysis is deliberately transparent about the distinction between surface climate and human heat stress, and about the current need to rerun all LST-dependent outputs after correcting the original quality-assurance implementation.

2. Materials and methods

2.1 Study area

The study covered the entire territory of Iraq, located approximately between 29.0° and 37.5° N and 38.7° and 48.7° E in Southwest Asia. Based on the administrative geometry used in this analysis, Iraq covers approximately 436,100 km². The country includes the densely settled Tigris-Euphrates corridor, extensive arid and semi-arid lowlands, sparsely populated desert regions, and more elevated terrain in the north and northeast. These contrasts create pronounced spatial variation in settlement density and summer surface-temperature conditions.

First-level administrative boundaries were obtained from the Food and Agriculture Organization Global Administrative Unit Layers for 2015 (FAO GAUL 2015). Iraq was selected using the ADM0_NAME attribute, resulting in 18 governorate-level units. The complete national terrestrial area was used for the raster analyses, while the governorate boundaries were used to derive subnational summaries. The analysis covered 2000–2020, corresponding to the period with consistent MODIS land-surface temperature observations and the 2000 and 2020 epochs of the Global Human Settlement Layer products.

Urban Expansion, Summer LST, and Heat Exposure in Iraq (2000–2020): Methodology Workflow

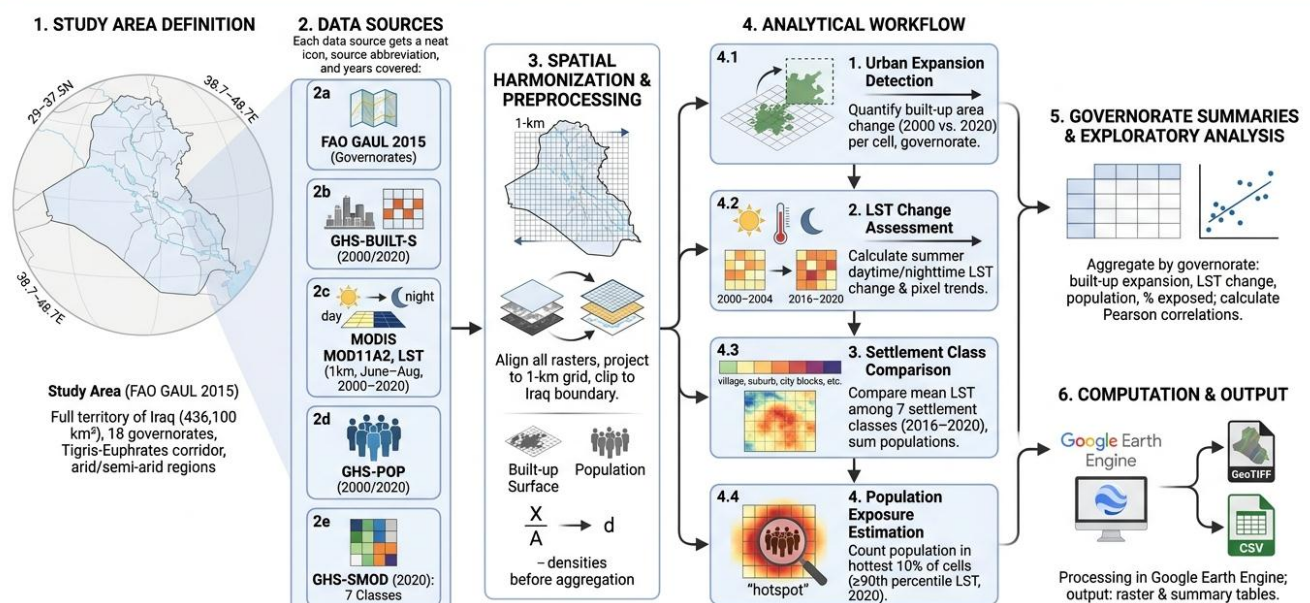


Figure 1. Methodological workflow of the study.

2.2 Data sources

2.2.1 Administrative boundaries

The FAO GAUL 2015 first-level administrative dataset was used to define the national study boundary and the 18 governorates. Administrative geometries were used only for clipping and zonal summaries; they were not rasterised as predictor variables.

2.2.2 Built-up surface

Built-up surface was obtained from the Global Human Settlement Layer Built-Up Surface product, GHS-BUILT-S R2023A (Pesaresi and Politis, 2023). The built_surface band reports the estimated square metres of built-up surface within each approximately 100-m source cell. The 2000 and 2020 epochs were extracted to quantify the location and magnitude of built-up expansion.

2.2.3 Land-surface temperature

Daytime and nighttime land-surface temperature (LST) observations were obtained from the Terra MODIS MOD11A2 Version 6.1 product (Wan et al., 2021). MOD11A2 provides eight-day LST composites at a nominal spatial resolution of 1 km. The LST_Day_1km and LST_Night_1km bands were processed independently. Digital numbers were converted to degrees Celsius as follows:

$$T_c = (DN \times 0.02) - 273.15 \quad (1)$$

where the left-hand term is land-surface temperature in degrees Celsius, DN is the original MODIS pixel value, and 0.02 is the product scale factor.

Quality-control information was obtained from the QC_Day and QC_Night bands. Only observations with mandatory quality bits 0-1 equal to 0 and estimated LST-error bits 6-7 between 0 and 2 were retained. This retained pixels reported as good quality with an estimated error of no more than 3 K. Rejected observations remained masked and were not replaced by unfiltered pixel values.

Meteorological summer was defined as June-August. For each year from 2000 to 2020, all available quality-filtered eight-day composites within this period were averaged separately for daytime and nighttime LST. No temporal interpolation or gap filling was applied.

2.2.4 Population distribution

Population counts were obtained from GHS-POP R2023A (Schiavina et al., 2023a). The dataset reports the estimated number of inhabitants within each approximately 100-m source cell. Population layers for 2000 and 2020 were extracted. The 2020 surface was used to estimate exposure to elevated summer LST, while both epochs were retained for contextual summaries.



2.2.5 Settlement classification

Settlement types were obtained from the GHS Settlement Model, GHS-SMOD R2023A (Schiavina et al., 2023b), which applies the Degree of Urbanisation framework at approximately 1-km resolution. The 2020 classification was used. The analysed terrestrial classes were very low-density rural areas (code 11), low-density rural areas (12), rural clusters (13), suburban or peri-urban areas (21), semi-dense urban clusters (22), dense urban clusters (23), and urban centres (30). Water and no-data cells were excluded.

2.3 Spatial harmonisation and preprocessing

All raster layers were clipped to Iraq and aligned to a common 1-km MODIS sinusoidal grid. A single explicit analysis grid was used so that built-up surface, population, settlement class, and LST referred to spatially corresponding cells. The sinusoidal projection also provided approximately equal-area cells for national and settlement-class averaging.

Built-up surface and population are extensive variables: their source-cell values represent quantities rather than continuous intensities. Directly averaging or summing these values during reprojection would not conserve their totals. Each source value was therefore converted to a density before aggregation:

$$d_i = \frac{X_i}{A_i} \quad (2)$$

where X is the built-up area or population count, A is cell area, d is the corresponding density, and subscript i identifies the source cell.

The source densities were aggregated to the target grid using area-weighted averaging. The resulting density was then multiplied by the area of the target cell:

$$\hat{X}_j = \bar{d}_j A_j \quad (3)$$

where the hatted X is the reconstructed quantity, the barred d is the area-weighted mean density, A is target-cell area, and subscript j identifies the target cell. This procedure conserved built-up area and population totals during aggregation.

Population density was subsequently calculated by dividing the aggregated population count by the target-cell area in square kilometres. The categorical GHS-SMOD layer was aligned using nearest-neighbour assignment to preserve its integer class codes.

2.4 Analytical approaches for the research questions

2.4.1 Research Question 1: Where and how much did built-up land expand between 2000 and 2020?

For each 1-km target cell, the proportion of the cell occupied by built-up surface was calculated for 2000 and 2020:

$$B_{j,y} = \frac{S_{j,y}}{A_j} \times 100 \quad (4)$$

where B denotes percentage built-up cover, S is built-up surface, A is cell area, and subscripts j and y identify the target cell and year, respectively.

Absolute built-up change and percentage-point change were calculated as:

$$\Delta S_j = S_{j,2020} - S_{j,2000} \quad (5)$$

$$\Delta B_j = B_{j,2020} - B_{j,2000} \quad (6)$$

where ΔS and ΔB denote absolute built-up surface change and percentage-point change, respectively, and subscript j identifies the target cell.

The ΔB_j surface was mapped to identify the location and intensity of expansion. Absolute changes were summed nationally and within each governorate and converted from square metres to square kilometres. Governorate-level expansion intensity was calculated as the net increase in built-up area divided by governorate area and multiplied by 100, enabling comparison among administrative units of different sizes.

2.4.2 Research Question 2: How did summer daytime and nighttime LST change between 2000 and 2020?

Two complementary indicators were used. First, the mean LST for an early period (2000-2004) was compared with the mean for a recent period (2016-2020):

$$\Delta T_j = \bar{T}_{j,2016-2020} - \bar{T}_{j,2000-2004} \quad (7)$$

where ΔT is the recent-minus-early LST difference and subscript j identifies the grid cell. Daytime and nighttime differences were calculated separately and expressed in degrees Celsius.

Second, a pixel-level ordinary least-squares trend was estimated from the 21 annual summer means:



$$T_{j,y} = \alpha_j + \beta_j(y - 2000) + \varepsilon_{j,y} \quad (8)$$

where T is summer LST, α is the intercept, β is the annual slope, ε is the residual term, and subscripts j and y identify the grid cell and year, respectively.

$$\beta_{j,decade} = 10\beta_j \quad (9)$$

The mapped trend was reported in degrees Celsius per decade. Trend maps described the magnitude and direction of change and were not masked according to pixel-level statistical significance.

National annual LST values were obtained by averaging all valid cells within Iraq. Because the common sinusoidal grid is approximately equal-area, these means represent area-weighted national conditions. Ordinary least-squares regression was fitted to the national daytime and nighttime annual series for the supporting time-series figures. Governorate-level changes and trends were calculated by averaging valid cells within each administrative unit.

2.4.3 Research Question 3: How did recent summer LST differ among settlement classes?

The 2020 GHS-SMOD classification was overlaid with the 2016-2020 mean summer daytime and nighttime LST surfaces. Mean daytime and nighttime LST was calculated separately for each of the seven terrestrial settlement classes. The comparison was area-based rather than population-weighted: each valid 1-km cell contributed equally to its class mean. The 2020 population within each settlement class was also summed to provide demographic context. This analysis was used to compare recent thermal conditions across the rural-urban settlement gradient.

2.4.4 Research Question 4: How many people were exposed to the highest summer LST conditions in 2020?

Exposure was evaluated by combining 2020 population counts with the 2016-2020 mean summer LST surfaces. Cells containing fewer than one estimated resident or lacking valid LST were excluded from threshold estimation. National 90th-percentile thresholds were calculated independently for daytime and nighttime LST across the remaining populated cells:



$$T_k^{90} = Q_{0.90}(T_{j,k} | P_j \geq 1), k \in \{\text{day, night}\} \quad (10)$$

where T with superscript 90 is the national 90th-percentile threshold, Q is the quantile operator, T is recent mean LST, P is the 2020 population count, j indexes grid cells, and k identifies daytime or nighttime conditions.

A hotspot was defined as a populated cell with LST equal to or greater than the corresponding threshold. Exposed population was calculated as:

$$E_k = \sum_j P_j I(T_{j,k} \geq T_k^{90}) \quad (11)$$

where E is the exposed population, I(·) is an indicator equal to 1 when the hotspot condition is satisfied and 0 otherwise, and k identifies daytime or nighttime conditions.

The exposed share of the population was calculated as:

$$E_{k,\%} = 100 \times \frac{E_k}{\sum_j P_j V_{j,k}} \quad (12)$$

where V equals 1 for a populated cell with valid LST and 0 otherwise. Separate valid-population denominators were therefore used for daytime and nighttime exposure when their data masks differed.

Exposure totals and percentages were calculated nationally and for each governorate using the same national thresholds. The percentile definition identifies residents of the hottest 10% of populated grid cells; it does not identify the hottest 10% of the population because the percentile calculation was not weighted by population count.

2.5 Governorate summaries and exploratory statistical analysis

Governorate-level outputs included built-up surface in 2000 and 2020, absolute and area-standardised built-up expansion, mean daytime and nighttime LST change, mean daytime and nighttime LST trend, population in 2020, and the number and percentage of residents exposed to daytime and nighttime hotspots. Extensive quantities were summed, whereas continuous thermal indicators were averaged over valid cells.



Pearson correlation coefficients were calculated across the 18 governorates to examine the exploratory association between built-up expansion intensity and mean daytime or nighttime LST change. Because these analyses used only 18 spatially aggregated observations and did not control for climate, elevation, vegetation, irrigation, or other confounding factors, the correlations were interpreted descriptively and not as causal effects of urban expansion.

2.6 Implementation and output generation

All geospatial processing was implemented in Google Earth Engine. Raster products were exported as GeoTIFF files on the common 1-km grid, and annual, governorate, and settlement-class summaries were exported as comma-separated value tables. The mapping workflow used the same raster definitions, masks, temporal windows, units, and class labels described above, ensuring consistency between the numerical summaries and the final figures.

3. Results

3.1 Built-up expansion

Built-up surface increased by 495.8 km² between 2000 and 2020. Expansion was distributed across the country but concentrated around existing urban corridors and major centres. Erbil recorded the largest absolute increase (57.1 km²), followed by Sulaymaniyah (52.4 km²), Baghdad (47.9 km²), Ninewa (40.4 km²) and Basrah (37.9 km²). When standardised by governorate area, Baghdad had the highest expansion intensity (0.93%), followed by Babil (0.43%) and Erbil (0.37%). Muthanna recorded the smallest absolute increase (7.1 km²).

Q1. Built-up surface expansion across Iraq, 2000–2020

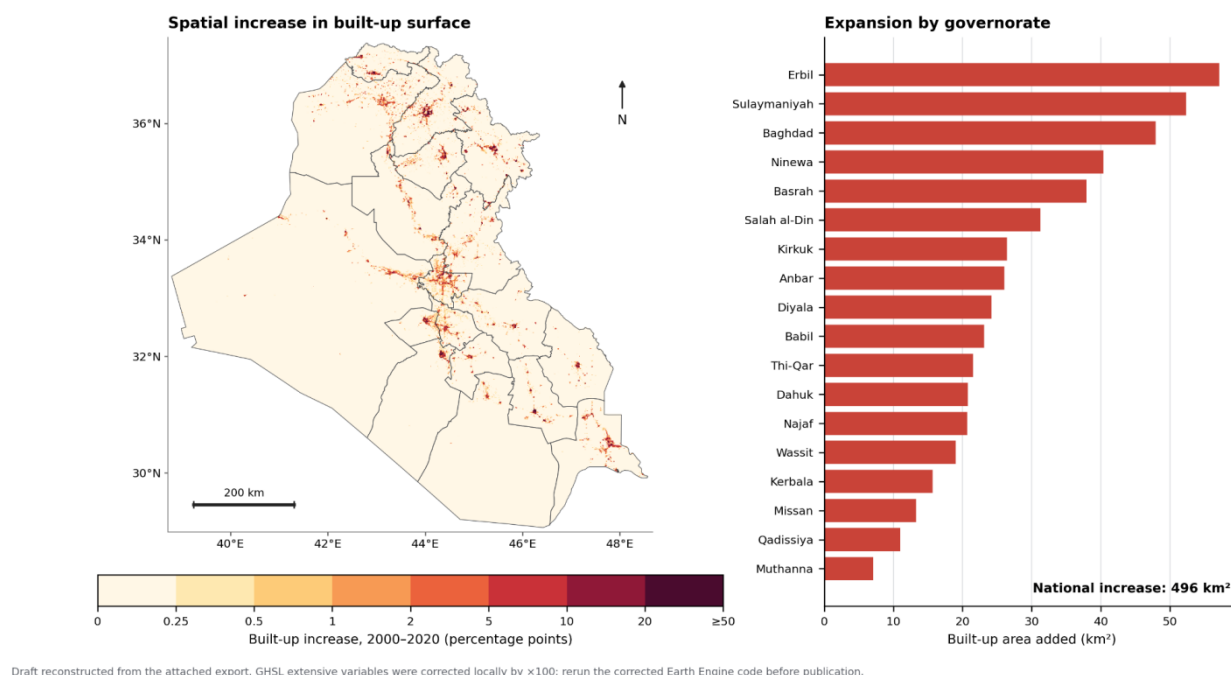
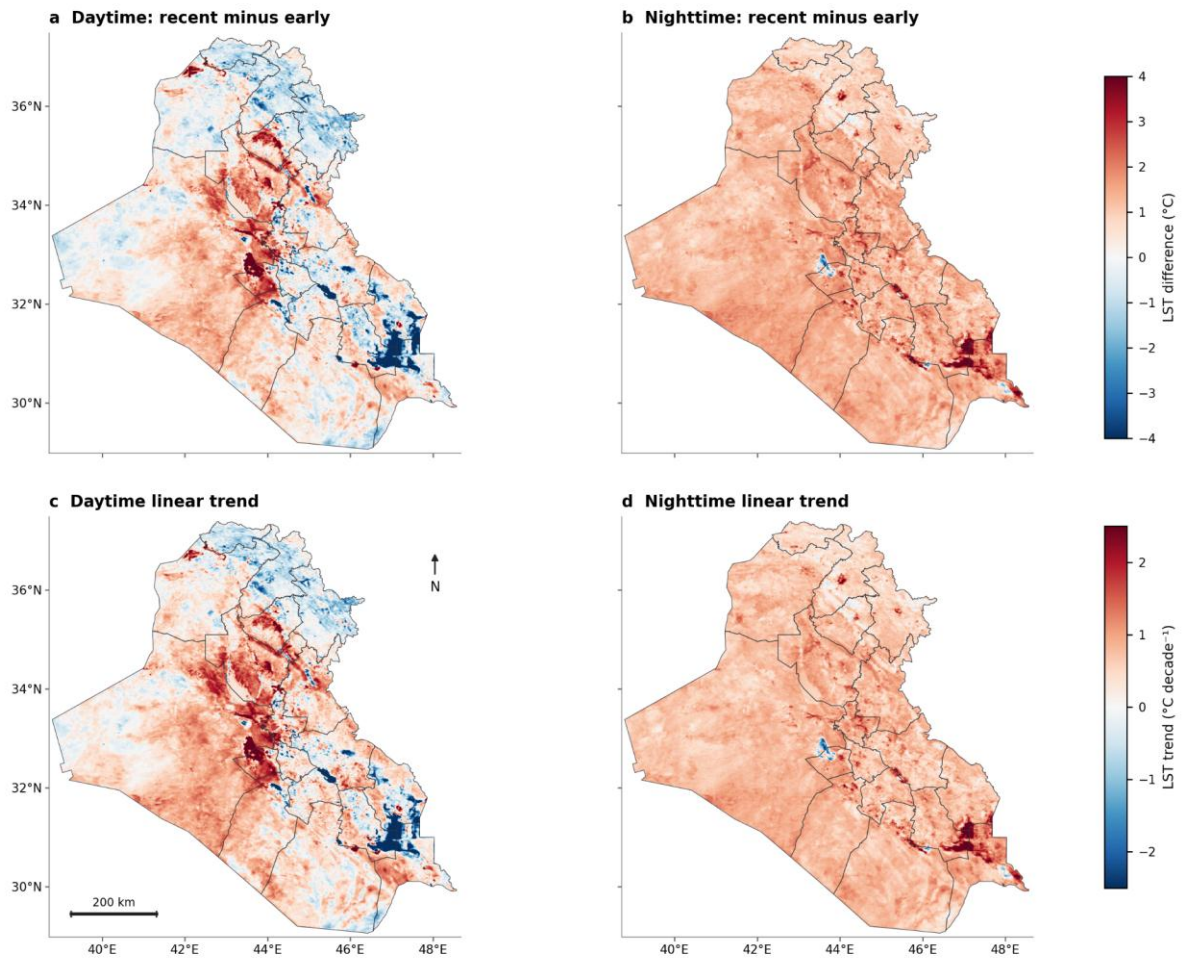


Figure 2. Built-up surface expansion across Iraq, 2000–2020. Map shows the percentage-point increase in built-up surface per 1-km cell; bars show governorate-level built-up area added. The figure incorporates the deterministic correction for extensive-variable aggregation. A final Earth Engine rerun remains required before publication.

3.2 National and spatial LST change

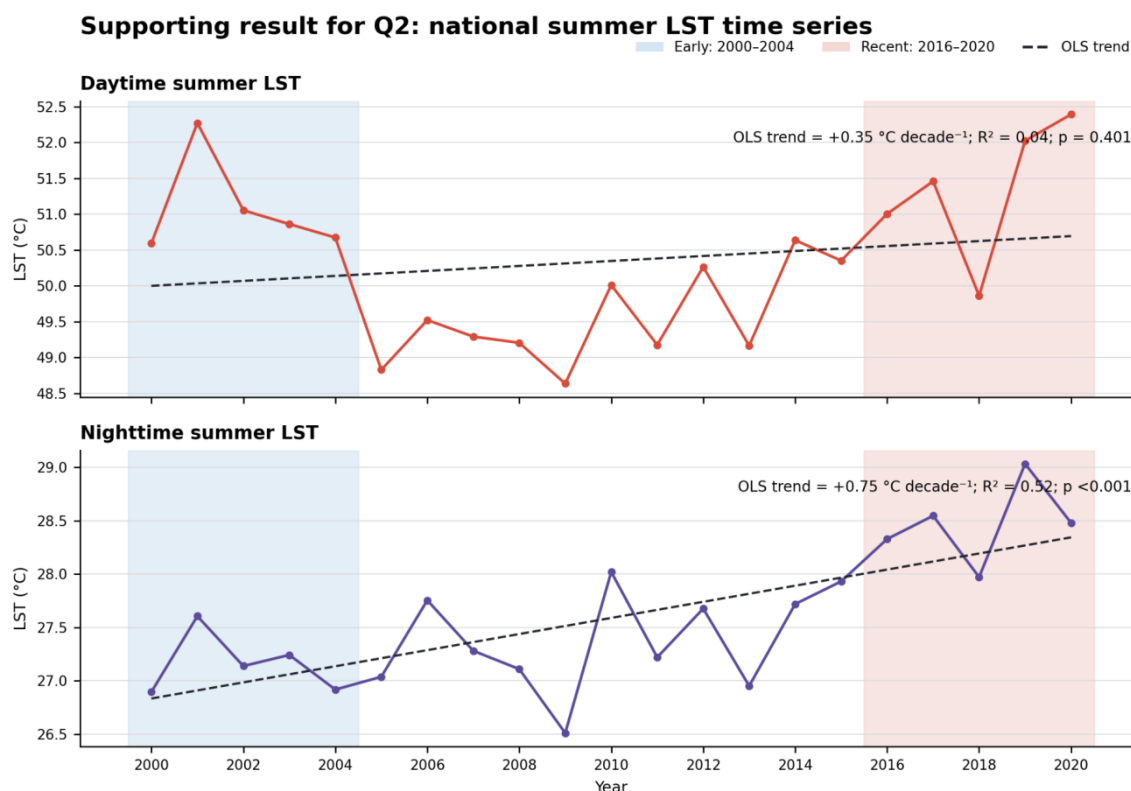
The preliminary national summer LST series showed high interannual variability during the daytime and a more sustained increase during the nighttime. The fitted daytime trend was $+0.35\text{ }^{\circ}\text{C decade}^{-1}$ ($R^2 = 0.04$, $p = 0.401$), whereas the nighttime trend was $+0.75\text{ }^{\circ}\text{C decade}^{-1}$ ($R^2 = 0.52$, $p < 0.001$). Early–recent difference maps showed spatially mixed daytime changes and predominantly positive nighttime changes across much of Iraq. These Q2 estimates are provisional and will be replaced after rerunning the corrected MODIS QA workflow.

Q2. Spatial change in summer land-surface temperature



Early = 2000–2004; recent = 2016–2020. DRAFT: the attached rasters were generated after QA-rejected MODIS observations were restored by unmask(rawBand); rerun is required.

Figure 3. Preliminary spatial change in summer daytime and nighttime LST. Early period: 2000–2004; recent period: 2016–2020. Panels c–d show linear trends for 2000–2020. Do not use for final inference until LST has been re-exported with the corrected QA mask.



Arithmetic national pixel mean for June–August. DRAFT: MODIS QA handling must be corrected and the table re-exported before inferential use.

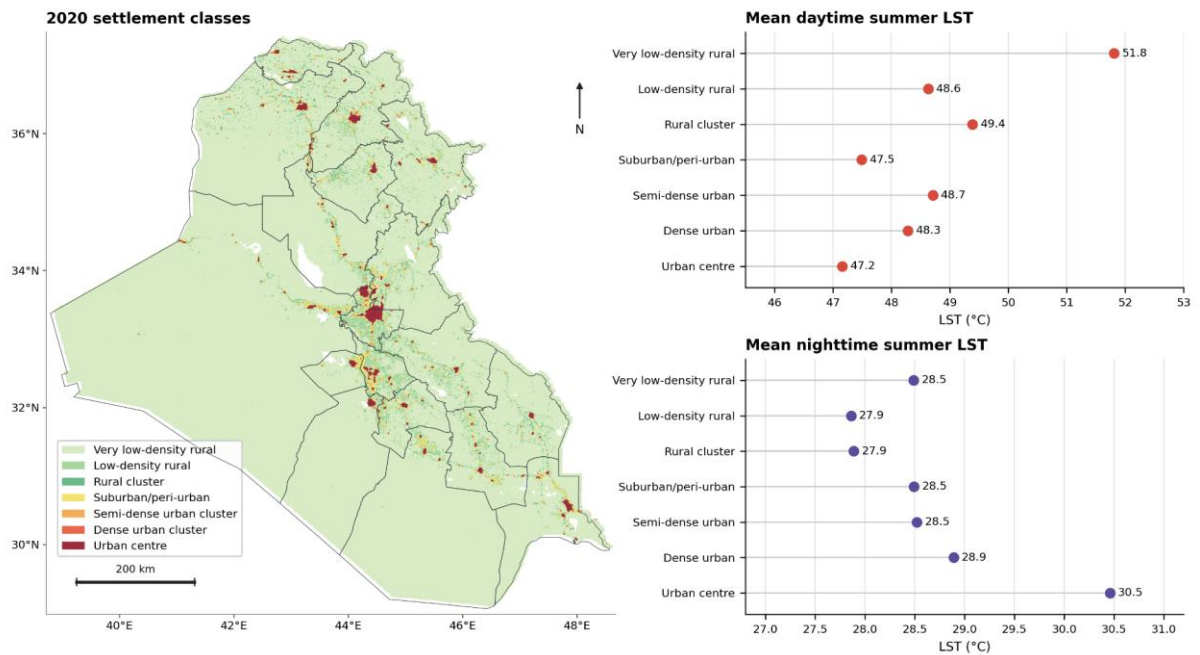
Figure 4. Preliminary national annual summer daytime and nighttime LST, 2000–2020. Trend estimates are based on arithmetic national pixel means and are provisional pending QA-corrected re-export.

3.3 Settlement-class contrasts

Preliminary 2016–2020 class means differed between daytime and nighttime. Daytime LST ranged from $47.2\text{ }^{\circ}\text{C}$ in urban centres to $51.8\text{ }^{\circ}\text{C}$ in very low-density rural areas. Nighttime LST ranged from $27.9\text{ }^{\circ}\text{C}$ in low-density rural areas and rural clusters to $30.5\text{ }^{\circ}\text{C}$ in urban centres. These settlement-class values are provisional because the underlying LST means require QA-corrected re-export.



Q3. Recent summer LST differs among settlement classes



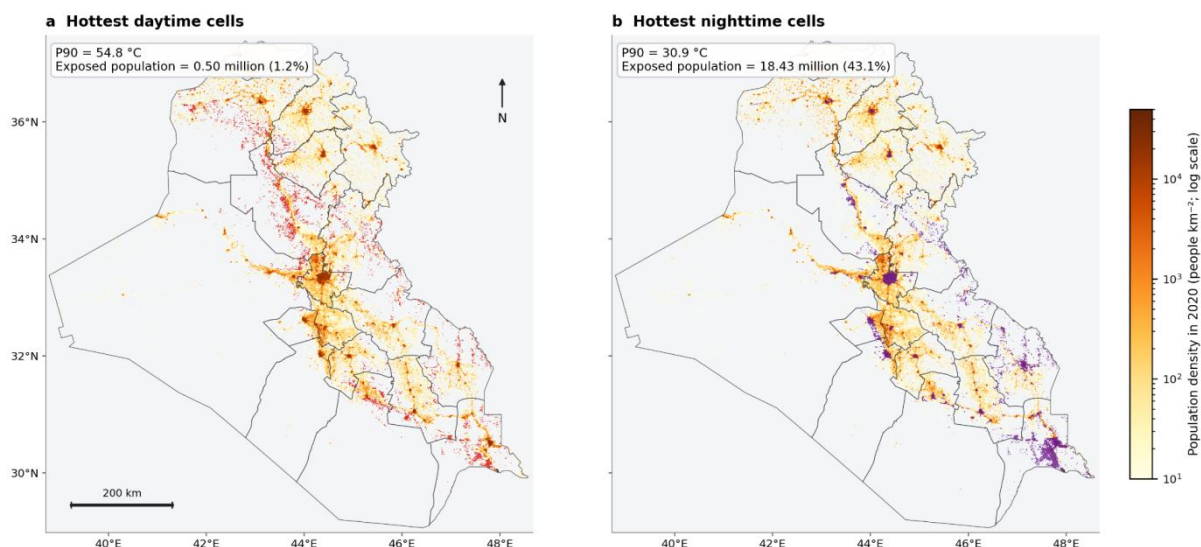
Recent period = 2016–2020. DRAFT: settlement classes are valid, but the LST means must be re-exported after correcting MODIS QA handling.

Figure 5. Preliminary recent summer LST by 2020 settlement class. The left panel maps GHSL settlement classes; right panels show area-based class means for 2016–2020. The settlement classification is final, but LST means must be recalculated after QA correction.

3.4 Population exposure to the hottest populated cells

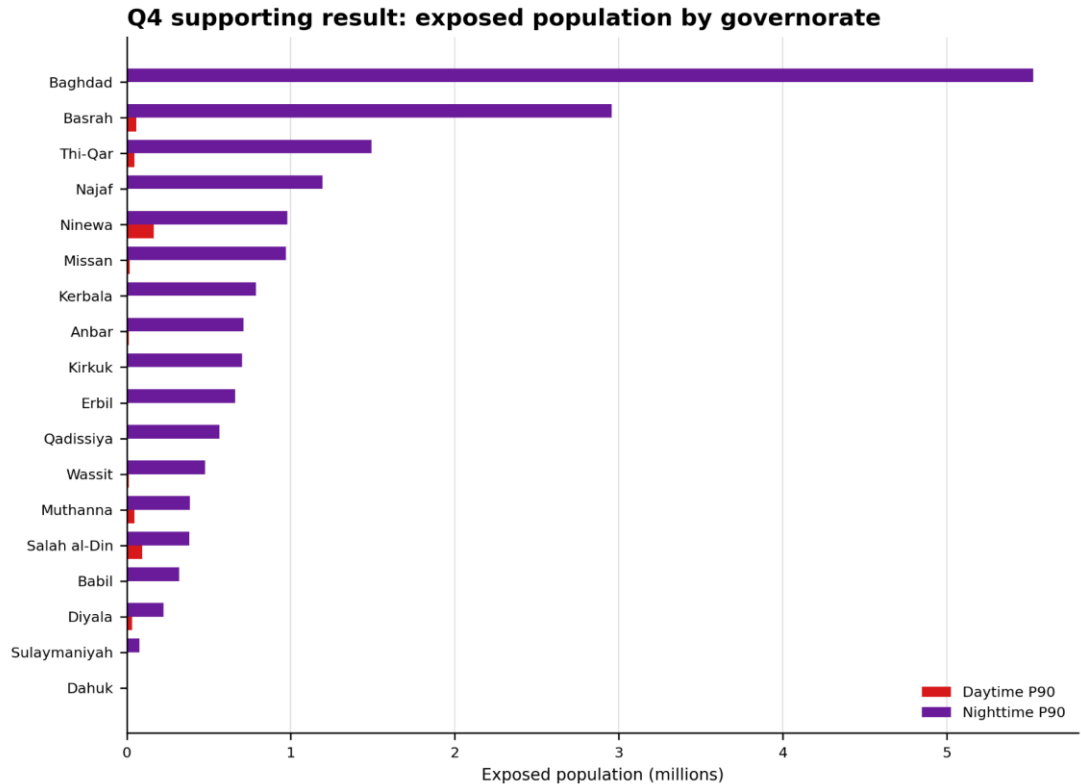
Using locally recomputed thresholds, the preliminary national P90 was 54.8 °C for daytime and 30.9 °C for nighttime LST. An estimated 0.50 million people (1.2% of population with valid LST) lived in daytime P90 cells, compared with 18.43 million (43.1%) in nighttime P90 cells. Baghdad accounted for the largest preliminary nighttime exposed population (5.53 million), followed by Basrah (2.96 million) and Thi-Qar (1.49 million). The preliminary daytime exposure count was concentrated in Ninewa (0.16 million) and Salah al-Din (0.09 million). These values are not final because the percentile masks use LST layers affected by the QA error.

Q4. Population exposure in the hottest 10% of populated cells



Hot cells were recomputed locally using the actual 90th percentile among cells with ≥1 resident. DRAFT: the attached LST rasters still require QA-corrected re-export.

Figure 6. Preliminary population exposure in populated 1-km cells at or above the national P90 of recent summer LST. Daytime and nighttime thresholds were calculated separately. Values remain provisional pending QA-corrected LST re-export.



Top 10% of populated cells defined nationally and separately for daytime and nighttime LST. DRAFT pending MODIS QA-corrected re-export.

Figure 7. Preliminary governorate-level population in daytime and nighttime P90 cells. The classification represents the hottest 10% of populated grid cells by surface temperature, not the hottest 10% of people.

4. Discussion

4.1 Urban expansion creates an adaptation-planning problem, not a thermal verdict

The 495.8-km² increase in built-up surface shows that urban development has left a measurable national spatial footprint during 2000–2020. The absolute concentration of expansion in Erbil, Sulaymaniyah, Baghdad, Ninewa and Basrah points to a geographically uneven development pattern that should be central to infrastructure, transport, housing and green-space planning. Baghdad's leading expansion intensity is particularly relevant because development pressure is concentrated within a relatively small governorate. This is not evidence that urbanisation alone caused the observed thermal patterns. It is evidence that the spatial footprint of development is large enough to demand targeted thermal-risk screening.

The physical rationale is well established: replacing vegetated and moist land with impervious surfaces changes evapotranspiration, albedo, heat storage and roughness, while urban morphology and anthropogenic heat can alter local energy exchange (Oke, 1982; Voogt and Oke, 2003; Weng, 2009). However, the results should not be oversold. Iraq spans arid lowlands, irrigated corridors and mountainous northern regions; topography, bare-soil exposure, irrigation, water availability, aerosols and synoptic weather can all influence LST. The governorate-level association between expansion and LST is therefore descriptive rather than causal. A credible causal claim would require spatially explicit controls, counterfactual design and preferably higher-resolution land-cover and climate covariates.

4.2 The day–night split changes the story

The preliminary contrast between a weak daytime national trend and a stronger nighttime trend is potentially important because it suggests that a single daytime map would miss a key dimension of changing surface thermal conditions. During daytime, LST is strongly influenced by immediate solar heating, surface moisture and the cooling effect of vegetation or irrigation. At night, the persistence of warmth is more closely related to heat storage and release, surface material properties, atmospheric conditions and urban form. The preliminary finding that urban centres had the highest nighttime class mean, while very low-density rural areas had the highest daytime class mean, is consistent with the fact that daytime surface heating in dry, sparsely vegetated landscapes can exceed that in urban cores, whereas built-up areas may remain warmer at night. This difference is precisely why day and night must be assessed independently rather than averaged away.

That interpretation must remain conditional until the QA-corrected rerun is complete. MODIS LST provides a consistent record of surface thermal state, not direct air temperature, indoor temperature, wet-bulb heat stress or individual exposure. The distinction is strongest for daytime LST, which can be decoupled from conditions experienced at pedestrian level. Thus, the present framework should guide screening and prioritisation, while city-level intervention design should combine LST with air temperature, humidity, wind, shade, building characteristics and social vulnerability (Voogt and Oke, 2003; Phan et al., 2018; IPCC, 2022).

4.3 Population exposure reveals why nighttime conditions deserve priority

The preliminary P90 analysis yields a striking difference between daytime and nighttime population exposure: 1.2% versus 43.1% of the population represented by valid LST cells. This does not mean that



nighttime heat is forty times more harmful. It means that the spatial distribution of people overlaps far more extensively with cells exceeding the national nighttime surface-temperature threshold than with cells exceeding the daytime threshold. The difference is scientifically useful because it identifies a potentially large nighttime surface-heat burden that would be invisible in a daytime-only assessment.

Baghdad's large preliminary nighttime count is expected given its population size and warm urban surface conditions, but Basrah and Thi-Qar also emerge as priority areas. These results should be used to target the next stage of analysis: identify the land-cover, housing, energy-access and demographic characteristics of high-exposure cells; test the role of vegetation, water and imperviousness; and evaluate where shade, urban greening, cool materials, electricity reliability and heat-health plans can yield the highest benefit. A national P90 is an intentionally relative indicator. It supports cross-governorate prioritisation but does not replace locally relevant health thresholds or heat-warning criteria.

4.4 Contribution of the framework

The principal contribution is not a claim that every hot pixel is caused by urban growth. It is the creation of a transparent national monitoring chain that makes four linked questions answerable with comparable data: where the built environment is expanding, how surface temperatures evolve by day and night, how conditions differ across the settlement continuum, and where populations overlap with the hottest populated surfaces. This structure is transferable to annual updates and can be strengthened by integrating Landsat-scale thermal detail, meteorological observations, humidity, vegetation, electricity-demand data and social vulnerability indicators. Such an integrated system would be substantially more valuable to Iraqi planning than isolated city case studies or uncontextualised temperature maps.

5. Limitations and required corrections

This manuscript must not be submitted until the corrected Earth Engine workflow is rerun. The original implementation contained three result-changing errors: (1) direct aggregation of GHSL extensive variables produced values approximately 100 times too small; (2) MODIS observations rejected by quality control were restored by unmasking with the raw band; and (3) the Q4 percentile code read the wrong reducer key and silently substituted the mean for P90. Q1 values in this draft were deterministically reconstructed using the mass-conserving correction. Q2–Q4 numerical results, maps and inferential statements remain provisional because they depend on LST layers affected by the QA error.



After rerun, all LST-based tables, figures, the abstract and the results/discussion text must be updated before publication.

Further limitations are intrinsic to the design. MODIS 1-km pixels cannot resolve fine intra-urban heterogeneity. LST is not air temperature or a direct health-exposure measure. The national P90 identifies relative surface-temperature hotspots among populated cells and is not a clinical or regulatory heat threshold. The 2020 settlement classification and population surface do not capture within-period demographic change, and the descriptive governorate analysis does not establish causality. These limitations do not invalidate the framework; they define the boundary of defensible inference.

6. Conclusions

Iraq added an estimated 495.8 km² of built-up surface between 2000 and 2020, with the largest absolute additions in Erbil, Sulaymaniyah and Baghdad. This expansion provides a clear spatial basis for prioritising climate-resilient planning. The national framework integrates urban growth, separate daytime and nighttime LST, settlement context and population exposure, thereby avoiding the common mistake of treating daytime surface temperature as the whole heat story. Preliminary outputs indicate stronger nighttime than daytime surface warming and a broad overlap between population and high nighttime LST, but those LST-based findings require immediate recalculation with the corrected QA workflow. The non-negotiable next step is to rerun the corrected script and replace every provisional Q2–Q4 output. Once validated, the framework can support annual monitoring and the targeting of green infrastructure, cooling strategies, heat-health preparedness and resilient urban development across Iraq.

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