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Thesis title:

**Urban spatial growth and its impact on urban water
management**

Supervisor: Prof. Daniele Ganora

Student: Mohammad Noori

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Dedication

I would like to dedicate this thesis to

my beloved family, especially my wonderful parents, Fereshteh and Abbas.

*Your endless love, patience, and sacrifices have been the greatest source of
strength throughout my journey.*

*Even when distance kept us apart, your support was always with me and
gave me the courage to continue.*

This achievement is not mine alone; it belongs to you as well.

I share this milestone with you with all my love, gratitude, and respect.

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Mohammad Noori

Abstract

Urban growth and population increase are important challenges for large cities, especially where infrastructure systems are already under pressure. Baghdad, the capital of Iraq, represents a relevant case because its urban development is closely connected with increasing demand for water services and wider water-resource constraints. This thesis investigates the relationship between urban spatial growth, population change, and urban water-management pressure in Baghdad.

The study uses spatial and demographic datasets, including GHSL built-up data, GHS-POP, United Nations population data, and WorldPop. An R-based workflow was developed to process raster and tabular datasets, extract built-up area and population indicators, generate maps and figures, and compare changes over time. The main indicators analyzed include built-up area, population growth, population density, built-up area per capita, and differences between population datasets.

The results show that Baghdad's built-up area increased from 179.90 km² in 2015 to 187.18 km² in 2025. During the same period, population increased more strongly in all population datasets. GHS-POP increased from 5.11 million to 6.51 million, United Nations data increased from 6.35 million to 8.14 million, and WorldPop increased from 5.92 million to 7.43 million. Although these datasets produced different absolute values, they all confirmed the same general trend of population growth.

The comparison between built-up expansion and population increase shows that population grew faster than the physical urban footprint. This was reflected in increasing population density and decreasing built-up area per capita. These results suggest that Baghdad is experiencing growing demographic pressure within its urban system. From a water-management perspective, this means that demand may increase not only because of spatial expansion, but also because more people are concentrated within already urbanized areas.

Overall, the thesis highlights the importance of integrating spatial urban-growth analysis with population-based indicators when assessing urban water-management pressure. The findings support the need for coordinated urban planning and water-resource

planning in Baghdad, especially in relation to future population growth, infrastructure capacity, and service coverage.

Keywords: Baghdad; urban expansion; built-up area; population growth; GHS-POP; WorldPop; United Nations population data; urban water management; GIS.

Table of Contents

CHAPTER 1: Introduction	1
1.1 Background and Research Context	2
1.2 Problem Statement	3
1.3 Aim and Objectives of the Study.....	3
1.4 Research Questions	4
1.5 Scope of the Study.....	4
1.6 Thesis Structure	5
CHAPTER 2: Study Area.....	7
CHAPTER 3: Literature Review.....	11
3.1 Urban Spatial Growth and Land-Use Change in Baghdad	12
3.2 Remote Sensing and GIS Applications for Urban and Environmental Monitoring.....	13
3.3 Urban Water Demand and Water Resource Management in Baghdad.....	14
3.4 Water Supply Infrastructure and Distribution Challenges.....	15
3.5 Tigris River Flow, Drought, and Surface Water Availability	16
3.6 Research Gap and Contribution of the Present Study	17
CHAPTER 4: Data and Methodology.....	19
4.1 Administrative Boundary	20
4.2 Available Datasets Considered	21
4.3 Selected Datasets for the Analysis	24
4.3.1 Built-Up Area Dataset: GHS-BUILT-S.....	24
4.3.2 Population Datasets: GHS-POP, UN-Habitat Data, and WorldPop	24
4.4 Data Preprocessing	27
4.5 Built-Up Area Analysis	27
4.6 Population Data Comparison	28
4.7 Linking Urban Growth and Population Change to Water Management	29

4.8 Implementation of the R-Based Processing Workflow	30
4.8.1 Import of Spatial Data and Study Area Preparation	30
4.8.2 Automated Multi-Year Processing of GHSL Built-Up Data.....	31
4.8.3 Processing of Population Datasets	33
4.8.4 Integration of Built-Up and Population Data.....	34
4.8.5 Comparison between Population Sources.....	35
4.8.6 Normalized Growth and Comparative Indicators	36
4.8.7 Generation of Maps and Figures.....	37
4.9 Methodological Limitations.....	38
CHAPTER 5: Results.....	41
5.1 Built-Up Area Expansion in Baghdad	42
5.2 Population Growth Based on GHS-POP	43
5.3 Comparison of Population Estimates from GHS-POP, UN-Habitat Data, and WorldPop	45
5.4 Population Density and Spatial Pressure	47
5.5 Built-Up Area per Capita	48
5.6 Comparison Between Urban Growth and Population Growth	50
5.7 Interpretation of Urban Expansion in Relation to Water-Management Pressure..	51
5.8 Summary of Main Results	54
CHAPTER 6: Discussion	57
6.1 Interpretation of Built-Up Area Expansion in Baghdad	58
6.2 Population Growth and Differences between Population Datasets	58
6.3 Population Density, Built-Up Area per Capita, and Urban Pressure	59
6.4 Relationship between Urban Growth and Urban Water-Management Pressure...	60
6.5 Comparison with Previous Studies on Baghdad.....	60
6.6 Implications for Urban and Water-Resource Planning	61
6.7 Limitations of the Study	62

6.8 Summary of Discussion	62
CHAPTER 7: Conclusions and Recommendations	65
7.1 Conclusions	66
7.2 Recommendations	67
7.3 Future Work.....	68
References.....	69
Appendix.....	72
Appendix A – R Scripts Used for Spatial and Demographic Analysis.....	72
A.1 Initial GHSL Built-Up Raster Test	72
A.2 Multi-Year GHSL Built-Up Area Extraction.....	73
A.3 Built-Up Area Map Generation	76
A.4 United Nations Population Data Processing	79
A.5 WorldPop Population Raster Extraction.....	84
A.6 Comparison between UN and WorldPop Population Data.....	86
A.7 Integration of Built-Up Area and Population Indicators	87
A.8 UN and WorldPop Indicator Plots	89
A.9 Initial GHS-POP Raster Test	91
A.10 Multi-Year GHS-POP Population Extraction.....	92
A.11 Final Comparison Plots and Result Figures	96
Appendix B – Additional Figures, Maps, and Tables.....	120
B.1 – Additional Built-Up Area Maps.....	121
B.2 – Supporting Built-Up Area and Population Figures.....	123
B.3 – Additional Dataset Comparison Figures.....	126
B.4 – Full and Supporting Tables	128
B.5 – Notes on Supplementary Materials.....	129

List of Figures

Figure 1. Tigris River flowing through Baghdad, July 2016. Source: Dominique A. Pineiro / U.S. Department of Defense, public domain.	8
Figure 2. Administrative boundary of Baghdad used as the study area.	21
Figure 3. Built-up area growth in Baghdad based on the GHS-BUILT-S dataset.	43
Figure 4. Population growth in Baghdad based on the GHS-POP dataset.....	44
Figure 5. Population comparison for Baghdad based on GHS-POP, UN data, and WorldPop for 2015–2025.....	46
Figure 6. Population density comparison for Baghdad based on GHS-POP, UN data, and WorldPop for 2015–2025.	48
Figure 7. Built-up area per capita comparison for Baghdad based on GHS-POP, UN data, and WorldPop for 2015–2025.	49
Figure 8. Normalized population growth for Baghdad using 2015 as the reference year.	51
Figure 9. Relationship between built-up area and population in Baghdad for 2015–2025.	53
Figure 10. Spatial distribution of built-up area in Baghdad in 2015 based on GHS-BUILT-S dataset.	53
Figure 11. Spatial distribution of built-up area in Baghdad in 2025 based on GHS-BUILT-S dataset.	54
Figure 12. Spatial distribution of built-up area in Baghdad in 1975, 1980 and 1985 based on the GHS-BUILT-S dataset.	121
Figure 13. Spatial distribution of built-up area in Baghdad in 1990, 1995 and 2000 based on the GHS-BUILT-S dataset.	122
Figure 14. Spatial distribution of built-up area in Baghdad in 2005, 2010 and 2015 based on the GHS-BUILT-S dataset.	122
Figure 15. Spatial distribution of built-up area in Baghdad in 2020 and 2025 based on the GHS-BUILT-S dataset.	123
Figure 16. Absolute population increase in Baghdad based on GHS-POP estimates..	124
Figure 17. Population growth rate in Baghdad based on GHS-POP estimates.....	124

Figure 18. Population density trend in Baghdad based on GHS-POP estimates.....	125
Figure 19. Normalized population growth in Baghdad based on GHS-POP, using 1975 as the reference year.	125
Figure 20. Percentage difference between GHS-POP and the UN and WorldPop population estimates for Baghdad.	126
Figure 21. Population growth-rate comparison for Baghdad based on available GHS-POP, UN data, and WorldPop.....	127
Figure 22. Relationship between built-up area and population in Baghdad based on UN and WorldPop estimates.	127

List of Tables

Table 1. Overview of datasets considered in the study. Source: Author’s elaboration based on Global Human Settlement Layer (GHSL) product documentation, European Commission Joint Research Center.	21
Table 2. Overview Table of GHS-POP Data. Source: Schiavina et al. (2023).....	25
Table 3. Overview Table of UN Demography Data. Source: UN-Habitat (n.d.).	25
Table 4. Overview Table of WorldPop Data. Source: Bondarenko et al. (2025).	25
Table 5. Built-up area and population base data for Baghdad.	43
Table 6. GHS-POP population estimates for Baghdad.....	45
Table 7. Comparison of GHS-POP, UN, and WorldPop population estimates for Baghdad.	47
Table 8. Built-up area and population comparison for Baghdad between 2015 and 2025.	51
Table 9. Full population comparison dataset for Baghdad based on GHS-POP, UN data, and WorldPop.....	128
Table 10. Supporting comparison between WorldPop and UN population estimates for Baghdad.	128

CHAPTER 1:

Introduction

1.1 Background and Research Context

Urban growth is one of the main challenges affecting large cities, particularly in regions where population increase, infrastructure limitations, and environmental stress occur at the same time. As cities expand, the demand for basic urban services also increases. Among these services, water supply and water management are especially important, since they are directly related to public health, urban development, and quality of life (UN-Habitat, n.d.; Zubaidi et al., 2019).

Baghdad, the capital of Iraq, represents an important case for studying the connection between urban expansion and water-management pressure. The city has experienced continuous population growth and spatial development over recent decades, which has increased the pressure on urban infrastructure and created new challenges for planning and service provision. At the same time, Baghdad depends strongly on the Tigris River and on a complex water supply system, making water management a central issue for the city's future development (Asaad & Abed, 2020; Encyclopaedia Britannica, n.d.; Hasan et al., 2020; Kadhim & Abbas, 2021).

Previous studies have shown that Baghdad has been affected by unplanned urban expansion, loss of agricultural and green areas, increasing population demand, and pressure on water supply infrastructure (Al-Mukhtar & Mutar, 2021; Kadhim & Abbas, 2021; Mahal et al., 2022; Waleed & Al-Bakri, 2024; Zubaidi et al., 2019). Other studies have also highlighted the influence of drought conditions, river-flow changes, and broader water-resource constraints on the city (Al-Ali, 2025; Asaad & Abed, 2020; Torabi Haghighi et al., 2023). These issues indicate that urban water management in Baghdad should not be understood only as a technical water-supply problem. It also needs to be examined in relation to urban spatial growth and population pressure.

In this context, spatial data and remote sensing methods provide useful tools for analyzing urban expansion. Datasets such as the Global Human Settlement Layer built-up product can be used to monitor built-up area changes over time (Pesaresi & Politis, 2023), while population datasets such as GHS-POP, UN-Habitat data, and WorldPop (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.) can help evaluate demographic trends. By combining these sources, it becomes possible to understand not

only where the city is expanding, but also how population growth may increase pressure on urban services.

1.2 Problem Statement

The main problem addressed in this thesis is the relationship between urban spatial growth and urban water-management pressure in Baghdad. The city is growing both physically and demographically, but these two processes do not necessarily occur at the same rate. Built-up area expansion reflects the physical development of the city, while population growth represents the increasing number of people requiring access to water and other urban services (Kadhim & Abbas, 2021; Pesaresi & Politis, 2023; Schiavina et al., 2023; Waleed & Al-Bakri, 2024).

If population growth is faster than built-up area expansion, pressure on existing infrastructure may increase even when the urban footprint grows only slowly. This condition can affect water supply systems by increasing demand within already urbanized areas and by requiring service extension toward newly developed zones. Therefore, analyzing built-up area alone is not sufficient. A combined analysis of spatial expansion and population change is needed to better understand urban water-management pressure (Al-Mukhtar & Mutar, 2021; Hasan et al., 2020; Raheem & Al-Juhaishi, 2025; Zubaidi et al., 2019).

Another important issue is related to population data uncertainty. Different population datasets may provide different absolute values for the same city because they are based on different methods, spatial definitions, and modelling approaches. For this reason, comparing multiple population sources is useful for obtaining a more reliable interpretation of demographic growth (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.).

1.3 Aim and Objectives of the Study

The main aim of this thesis is to analyze urban spatial growth and population change in Baghdad and to interpret their possible implications for urban water management.

To achieve this aim, the thesis follows these objectives:

1. To analyze the temporal evolution of built-up area in Baghdad using GHSL built-up data (Pesaresi & Politis, 2023).
2. To examine population growth using GHS-POP, UN-Habitat, and WorldPop datasets (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.).
3. To compare population estimates from different data sources and evaluate their differences.
4. To calculate urban indicators such as population density and built-up area per capita.
5. To interpret how built-up expansion and population growth may contribute to increasing pressure on urban water-management systems.
6. To provide recommendations for integrated urban and water-resource planning in Baghdad.

1.4 Research Questions

Based on the aim and objectives, the thesis addresses the following research questions:

1. How has the built-up area of Baghdad changed during the analyzed period?
2. How has Baghdad's population changed according to different population datasets?
3. How do population estimates differ among GHS-POP, UN-Habitat data, and WorldPop?
4. Is population growth faster than built-up area expansion in Baghdad?
5. What do these spatial and demographic trends suggest about urban water-management pressure in the city?

1.5 Scope of the Study

This study focuses on Baghdad as the main spatial unit of analysis. It uses spatial and demographic datasets to evaluate built-up area expansion, population growth, population density, and built-up area per capita (Bondarenko et al., 2025; Pesaresi & Politis, 2023; Schiavina et al., 2023; UN-Habitat, n.d.). The main comparison between built-up growth and population datasets focuses especially on the recent period from 2015 to 2025, where GHS-POP, UN-Habitat data, and WorldPop can be compared.

The thesis does not perform a detailed hydraulic simulation of Baghdad's water distribution network. It also does not calculate actual household water consumption, since such an analysis would require detailed operational data, pipe network information, pressure measurements, and consumption records. Instead, the thesis provides a spatial and demographic interpretation of urban water-management pressure. This approach is useful as a planning-oriented analysis that connects urban expansion with population-based indicators.

1.6 Thesis Structure

This thesis is organized into seven main chapters.

Chapter 1 introduces the research context, problem statement, objectives, research questions, scope, and structure of the thesis.

Chapter 2 presents the study area, with attention to Baghdad's geographical location, urban context, and relevance to water-management issues.

Chapter 3 reviews the literature related to urban expansion, remote sensing, population growth, water demand, water supply infrastructure, and Tigris River flow conditions in relation to Baghdad.

Chapter 4 describes the data and methodology used in the thesis. It explains the spatial datasets, population datasets, data preprocessing, R-based workflow, built-up area analysis, population comparison, and derived indicators.

Chapter 5 presents the results of the analysis, including built-up area expansion, population growth, comparison of population datasets, density, built-up area per capita, and the relationship between urban growth and demographic pressure.

Chapter 6 discusses the meaning of the results and connects them with previous studies on Baghdad's urban growth, water demand, infrastructure pressure, and broader water-resource constraints.

Chapter 7 provides the main conclusions, recommendations, and suggestions for future work.

CHAPTER 2:

Study Area

Baghdad is the capital city of Iraq and the administrative center of Baghdad Governorate. It is located in central Iraq along the Tigris River, within the alluvial plain of Mesopotamia. The city has historically developed around the Tigris, which represents the main surface-water source for urban, agricultural, and economic activities. Baghdad's generally flat terrain has supported urban expansion, but it also makes the city sensitive to land-use change and water-management challenges (Encyclopaedia Britannica, n.d.; Mahal et al., 2022).



Figure 1. Tigris River flowing through Baghdad, July 2016. Source: Dominique A. Pineiro / U.S. Department of Defense, public domain.

In this study, the spatial extent is defined using the Baghdad Governorate administrative boundary obtained from the GADM database, version 4.1. The boundary was extracted from the level-1 administrative layer and used as the main spatial mask for the analysis (GADM, n.d.). The extracted boundary was checked in QGIS by overlaying it with OpenStreetMap layers to verify its spatial alignment with the urban area and major geographic features (OpenStreetMap contributors, n.d.). This ensured that the built-up and population datasets used in the analysis were processed within a consistent study-area boundary.

Baghdad has a hot and dry climate, especially during summer, while rainfall is limited and mainly concentrated in the winter and early spring months. Previous studies describe the city as having high summer temperatures, low precipitation, and dry climatic conditions, which can increase pressure on water availability and urban environmental conditions (Mahal et al., 2022). These climatic characteristics are relevant to this thesis because they influence both water demand and the vulnerability of the city to drought and reduced river flow.

The city has also experienced strong population growth and rapid urban expansion during recent decades. Population increase; internal migration, housing demand, weak planning control, and unplanned development have contributed to the conversion of agricultural and green areas into built-up land (Kadhim & Abbas, 2021; Mahal et al., 2022; Waleed & Al-Bakri, 2024). This expansion has increased pressure on urban services, including water supply, energy, transportation, and other basic infrastructure. Therefore, Baghdad provides a suitable case for analyzing how spatial urban growth can affect urban water-management needs.

Baghdad's water-management challenge is also connected to its dependence on the Tigris River. The city's water availability is influenced not only by local population growth and urban demand, but also by wider hydrological pressures along the Tigris basin, including upstream water-resource development and drought conditions (Al-Ali, 2025; Asaad & Abed, 2020; Torabi Haghighi et al., 2023). At the same time, the urban water supply system depends on treatment plants, reservoirs, pipelines, and distribution zones that require continuous monitoring and planning (Al-Mukhtar & Mutar, 2021; Hasan et al., 2020; Raheem & Al-Juhaishi, 2025). For this reason, Baghdad is an appropriate case study for investigating the relationship between urban spatial growth, population distribution, and urban water management.

CHAPTER 3:

Literature Review

3.1 Urban Spatial Growth and Land-Use Change in Baghdad

Urban expansion in Baghdad has been widely discussed as one of the main processes affecting land use, green areas, agricultural land, and the urban environment. Several studies indicate that the city has expanded rapidly during recent decades, particularly after 2003. This expansion has been linked to population growth, internal migration, housing demand, weak planning control, and increasing pressure on available land.

Kadhim and Abbas (2021) examined unplanned urbanization and agricultural land degradation in Baghdad between 2003 and 2017. Their study argued that rapid population increase, rural-to-urban migration, weak legislation, and limited commitment to the master plan encouraged the conversion of agricultural land into residential areas. This work is useful for understanding the social and planning context behind urban sprawl in Baghdad. However, its quantitative results should be interpreted carefully, since the analysis relies mainly on municipal data, regression analysis, and GIS-based illustrative maps rather than detailed satellite classification.

Remote sensing studies provide stronger spatial evidence for the physical expansion of the city. Waleed and Al-Bakri (2024) used Google Earth Engine and Landsat imagery to investigate land-cover changes in Baghdad between 2004 and 2021. Their results show a clear shift from vegetated land toward built-up surfaces. Urbanized areas increased from 835 km² in 2004 to 2694 km² in 2021, while vegetation cover decreased from 3476 km² to 1368 km² during the same period. The study also found that the highest land surface temperatures were concentrated in open and built-up areas, whereas cooler zones were mainly located near water bodies and vegetation. These findings suggest that urban growth in Baghdad is not only a land-use issue, but also an environmental problem connected with vegetation loss and local warming.

Similar findings were reported by Mahal et al. (2022), who analyzed land-use and land-cover change in Baghdad between 2001 and 2020 using Landsat, Sentinel-2A, NDVI, NDBI, land surface temperature, supervised classification, and GIS tools. Their results showed that built-up areas increased from about 863 km² in 2001 to 1469 km² in 2020, while vegetation classes decreased during the same period. The study also reported that land surface temperature increased from 26–47°C in July 2001 to 32–56°C in July 2020,

with the highest temperatures mainly located in built-up areas and zones with limited vegetation. These results support the relationship between urban expansion, vegetation degradation, and the development of urban heat island conditions in Baghdad.

A longer historical perspective was provided by Moussa and Alwehab (2022), who analyzed urban growth in Baghdad over four periods from 1981 to 2021. Their results indicate that urban cover increased from 37.10% during 1981–1990 to 85.90% during 2011–2021, while green cover decreased from 62.90% to only 14.10%. The study also suggests that this change was associated with variations in climatic elements, including temperature, humidity, atmospheric pressure, wind speed, rainfall, and solar radiation. However, this study should be used with some caution, since it mainly shows correlation between urban expansion and climate variables rather than proving direct causation. Taken together, these studies confirm that Baghdad has experienced strong spatial growth, loss of green and agricultural areas, and increasing environmental stress.

3.2 Remote Sensing and GIS Applications for Urban and Environmental Monitoring

Remote sensing and GIS have become important tools for monitoring urban growth, water bodies, vegetation cover, and environmental change in Baghdad. These methods are especially useful because they make it possible to analyze spatial patterns over long time periods and across large urban areas. In the case of Baghdad, satellite-based indices such as NDVI, NDWI, NDBI, and land surface temperature have been used to examine vegetation loss, built-up expansion, water availability, and local climate conditions (Ghanbari et al., 2025; Mahal et al., 2022; Waleed & Al-Bakri, 2024).

Ghanbari et al. (2025) used Google Earth Engine, Landsat, and Sentinel-2 imagery to analyze surface water distribution in Baghdad from 2012 to 2023 using the Normalized Difference Water Index. Their study shows that web-based mapping and satellite indices can support the monitoring of water bodies, moisture conditions, and drought-related patterns over time. The results indicated that water surface coverage varied considerably during the study period, with lower values in some years and higher values in wetter years such as 2020. This study is relevant because it demonstrates how remote sensing can improve the spatial understanding of water availability and environmental change in Baghdad.

The use of remote sensing is also central in the work of Waleed and Al-Bakri (2024) and Mahal et al. (2022), who applied satellite imagery and spectral indices to detect urban expansion, vegetation decline, and land surface temperature patterns. These studies show that spatial datasets can reveal environmental effects that may not be visible through population or administrative statistics alone. For example, increases in built-up land can be compared with reductions in vegetation and increases in land surface temperature, helping to explain how urban growth changes the physical environment of the city.

GIS methods have also been applied to Baghdad's water supply system. Hasan et al. (2020) used GIS, remote sensing, GPS, LiDAR data, and records from the Baghdad Water Department to map and evaluate water supply facilities, including treatment plants, reservoirs, pipelines, and supply zones. Their work shows that geospatial tools can support the planning and monitoring of urban water infrastructure. This is important for the present thesis because the relationship between urban growth and water management is not only about total population or total water demand. It is also related to where people, built-up areas, and infrastructure are located. Therefore, remote sensing and GIS provide a useful framework for linking urban spatial growth with water-management challenges.

3.3 Urban Water Demand and Water Resource Management in Baghdad

Water demand in Baghdad is strongly influenced by population growth, urban expansion, climate conditions, and the reliability of water supply from the Tigris River. Al-Mukhtar and Mutar (2021) investigated future water supply and demand in Baghdad using the Water Evaluation and Planning model under several development scenarios. Their study showed that Baghdad's population is expected to continue growing, which will increase future water demand. Since the city depends mainly on the Tigris River as its primary water source, reductions in river inflow combined with population growth may intensify future shortages. The study reported unmet water demand under all simulated future scenarios, highlighting the need for long-term planning, sustainable water allocation, and integrated urban water management.

Short-term water demand forecasting has also been studied at the treatment-plant scale. Zubaidi et al. (2019) proposed a hybrid forecasting approach based on Singular Spectrum Analysis and an Autoregressive model to predict municipal water demand using monthly consumption data from Al-Wehda water treatment plant for the period 2006–2015. Their work is relevant because it shows that water consumption data in Baghdad can be affected by climatic conditions, population changes, and social instability, making demand forecasting more difficult. The study found that applying signal pre-processing improved model performance and helped predict short-term municipal water demand with high accuracy. This supports the need for reliable forecasting tools in water supply planning and decision-making.

Together, these studies show that Baghdad's water-management problem is not limited to present supply capacity. It is also a planning issue linked to future demand, demographic growth, and uncertainty in water availability. For this reason, urban water management should be studied together with spatial growth and population distribution, rather than only through general city-level water statistics.

3.4 Water Supply Infrastructure and Distribution Challenges

The performance of Baghdad's water supply infrastructure is another important part of urban water management. Even when water is available from the Tigris River, the reliability of supply depends on treatment plants, reservoirs, pumping systems, pipelines, pressure conditions, and distribution networks. Hasan et al. (2020) mapped Baghdad's water supply system using geospatial techniques and showed that the city depends on several treatment plants, compact units, reservoirs, pipelines, and distribution zones. The study also noted that long pipeline distances, pressure losses, weather conditions, and power outages can affect water flow and contribute to a gap between water supply and demand. This indicates that infrastructure location and operational conditions are important when analyzing water-management challenges in Baghdad.

Raheem and Al-Juhaishi (2025) provided a more detailed hydraulic evaluation of two water distribution networks in Al-Rashid Municipality using Water-CAD integrated with QGIS. Their study analyzed pressure heads and flow velocities under peak and low-demand conditions. The results showed that many network junctions operated

below acceptable pressure levels, especially during peak demand periods. In some locations, negative pressure values were recorded, indicating insufficient supply and possible service deficiencies. The authors concluded that both networks suffered from inadequate hydraulic performance, suggesting that operational conditions and supply limitations play an important role in network efficiency.

Hydraulic problems are also related to river water levels. Asaad and Abed (2020) examined the flow characteristics of the Tigris River within Baghdad using a one-dimensional steady-flow HEC-RAS model. Their study focused on a 49 km reach from Al-Muthana Bridge to the confluence with the Diyala River. The results showed that low river discharge can reduce water levels below the minimum operational requirements of several water supply projects along the riverbanks. This is important because it connects regional water scarcity with local infrastructure operation. The study tested engineering solutions such as barrages, inflatable weirs, and obstructions, and suggested that inflatable weirs may be a practical option for maintaining required water levels during drought conditions. These studies show that Baghdad's water supply challenge is both a network-management problem and a river-level problem.

3.5 Tigris River Flow, Drought, and Surface Water Availability

Baghdad's water resources are closely connected to the hydrological conditions of the Tigris River. Local water demand and infrastructure performance cannot be fully understood without considering river discharge, drought, water levels, and upstream regulation. Asaad and Abed (2020) showed that reduced Tigris discharge within Baghdad can lower water levels below the operational needs of water supply projects. This finding is directly relevant to urban water management because it shows that even if treatment plants and distribution networks exist, their performance may be affected when river levels fall during drought periods.

Al-Ali (2025) assessed the water budget of the Tigris River between Baghdad and Al-Amara using climate records from 1990 to 2020, together with discharge and water-quality indicators. The study reported low rainfall, high evaporation, and a dominant water-deficit regime. Baghdad showed a water deficit of about 64.26%, while Al-Amara recorded a deficit of about 67.7%. The study also showed that river discharge decreased downstream from an average of about 535.9 m³/s in Baghdad to 231.8 m³/s in Al-

Amara. This reduction was associated with higher total dissolved solids, suggesting that lower flow, evaporation, groundwater interaction, and human activities can worsen water quality downstream. Although this study does not directly examine urban growth, it is useful for understanding the broader hydroclimatic stress affecting Baghdad and southern Iraq.

At the basin scale, Torabi Haghighi et al. (2023) assessed the impact of Turkey's water-resource development on the flow regime of the Tigris River in Iraq by analyzing key gauges at Cizre, Mosul, Baiji, Baghdad, and Kut. The study reconstructed natural flow conditions and compared them with different irrigation-development scenarios in Turkey. The results suggest that before major Turkish regulation, severe hydrological impacts were mainly concentrated downstream of the Samarra Barrage, especially around Baghdad and Kut. However, under future irrigation scenarios, drought conditions may extend across most of the Iraqi Tigris corridor. This article is particularly important because it shows that Baghdad's water-resource challenges are shaped not only by local urban demand, but also by upstream water withdrawals and transboundary river regulation.

Remote sensing adds another perspective to the analysis of water availability. Ghanbari et al. (2025) used NDWI and web-mapping techniques to examine surface water changes in Baghdad between 2012 and 2023. Their results show that water surface coverage varied between years, supporting the idea that water availability should be monitored spatially and temporally. Overall, these studies show that Baghdad's water security depends on a combination of local demand, infrastructure capacity, drought conditions, river water levels, and upstream hydrological pressures.

3.6 Research Gap and Contribution of the Present Study

The reviewed literature shows that many studies have examined separate aspects of Baghdad's urban and water-management challenges. Some studies focused on urban growth, land-use change, agricultural land degradation, green-cover loss, and urban heat island effects. Other studies analyzed water demand forecasting, water-resource planning, infrastructure mapping, hydraulic performance, river water levels, drought conditions, and transboundary flow reduction. Remote sensing and GIS have also been widely used to monitor built-up growth, vegetation change, water bodies, and water

supply infrastructure (Al-Mukhtar & Mutar, 2021; Ghanbari et al., 2025; Hasan et al., 2020; Kadhim & Abbas, 2021; Mahal et al., 2022; Raheem & Al-Juhaishi, 2025; Waleed & Al-Bakri, 2024).

However, the existing literature remains fragmented. Urban expansion studies often focus on land-cover change and environmental impacts, but they do not always connect these changes to water demand or water supply infrastructure. Water-resource studies often focus on river discharge, drought, or future demand, but they do not always include the spatial pattern of urban growth. Infrastructure studies provide useful information about treatment plants, reservoirs, pipelines, and network performance, but they are usually limited to specific systems or districts. Therefore, there is a need for an integrated spatial approach that links urban growth, population distribution, and urban water-management pressure in Baghdad.

The present thesis contributes to this gap by analyzing Baghdad's urban spatial growth using consistent geospatial datasets and connecting the results with population trends and water-management challenges. By combining administrative boundaries, built-up area data, and population datasets, the study aims to provide a clearer understanding of how urban expansion may influence future water demand and pressure on water supply planning. In addition, the proposed workflow is reproducible and can be applied to other urban areas where comparable spatial and demographic datasets are available. This approach does not replace detailed hydraulic or hydrological modelling, but it provides a spatial planning perspective that can support integrated urban and water-resource management in Baghdad.

CHAPTER 4:

Data and Methodology

This chapter describes the spatial and demographic datasets used in the thesis and explains the workflow adopted to analyze urban spatial growth and population change in Baghdad. The methodology is based on the integration of administrative boundary data, built-up area datasets, and population datasets. The main objective is to identify the spatial expansion of Baghdad and compare population estimates from different sources in order to support the assessment of urban water-management pressure.

4.1 Administrative Boundary

The administrative boundary of Baghdad used in this study was obtained from the GADM database, version 4.1. GADM provides global administrative boundaries in shapefile format and is widely used in spatial analysis. The Iraq shapefile was downloaded from the GADM website, and the Baghdad Governorate boundary was extracted from the level-1 administrative layer (GADM, n.d.).

The extracted shapefile was imported into QGIS Desktop 3.40.12 for preprocessing and visualization (QGIS Development Team, 2026). Since this boundary was used as the main spatial extent of the study, its position and extent were checked carefully. The Baghdad polygon was overlaid on OpenStreetMap layers in QGIS to visually verify its alignment with the urban area and major geographic features (OpenStreetMap contributors, n.d.). The coordinate reference system of the dataset was WGS84 (EPSG:4326). After verification, the boundary was used as a spatial mask for clipping raster datasets, ensuring that all calculations were restricted to the Baghdad study area.



Figure 2. Administrative boundary of Baghdad used as the study area.

4.2 Available Datasets Considered

Before selecting the final datasets, different data sources were reviewed to evaluate their relevance to the objectives of this thesis. The selected datasets had to satisfy three main requirements: spatial coverage of Baghdad, availability for multiple time periods, and suitability for analyzing urban growth and population change. Table 1 summarizes the main datasets considered in the study.

Table 1. Overview of datasets considered in the study. Source: Author's elaboration based on Global Human Settlement Layer (GHSL) product documentation, European Commission Joint Research Center.

Dataset Name	Description	Resolution	Coordinate systems	Epochs
Multi-temporal built-up layers (epochs)				
GHS-BUILT-S	Total built-up surface and the component of non-residential (NRES) built-up surface (m2); The spatial raster dataset depicts the distribution of built-up surfaces, expressed as number of square meters. The data report about the total built-up surface and the built-up surface allocated to dominant non-residential (NRES) uses.	100m; 1km	Mollweide; WGS84	1975-2030
GHS-POP	Resident population grid (inhabitants); The spatial raster dataset depicts the distribution of population, expressed as the number of people per cell.	100m; 1km; 3 arcsec; 30 arcsec	Mollweide; WGS84	1975-2030
GHS-SMOD	Settlement classification by the UN; recommended methodology "degree of urbanization"; The layers present the application of the Degree of Urbanization stage I methodology recommended by UN Statistical Commission to	1 km	Mollweide	1975-2030

Dataset Name	Description	Resolution	Coordinate systems	Epochs
	the global population grid generated by the JRC in the epochs 1975-2030 (5 years timestep)			
GHS-BUILT-V	Total built-up volume and the component of non-residential (NRES) built-up volume (m3); The spatial raster dataset depicts the distribution of built-up volumes, expressed as number of cubic meters. The data reports about the total built-up volume and the built-up volume allocated to dominant non-residential (NRES) uses.	100m; 1km; 3 arcsec; 30 arcsec	Mollweide; WGS84	1975-2030
Global urban centers database and building footprints				
GHS-UCDB	Urban Centre Database UCDB R2024A; The most comprehensive and updated dataset for world cities, with a coverage of 11,000 urban centers and 15 thematic domains (Human Settlement Baseline, Geography, Temporal Trajectory, Land Use Land Cover, Infrastructure, Socioeconomic, Exposure, Hazard and Risk, Vegetation, Water, Natural Systems, SDGs, Climate, Health, Emissions), resulting in 473 indicators, and 2602 attributes ranging between 1975 and 2030			2025
Global baselines for policy indicators_Short-range projections				
GHS-DUC	GHS Degree of Urbanization Classification, application of the Degree of Urbanization methodology (stage II) to GADM 4.1 layer,			1975-2030

Dataset Name	Description	Resolution	Coordinate systems	Epochs
	multitemporal (1975-2030); This dataset contains the Global Degree of Urbanization Classification of administrative units delineated by the Global Administrative layer version 4.1 (GADM41) according to the application of stage II of the Degree of Urbanization			
GHS-FUA	GHS functional urban areas, derived from GHS-UCDB R2019A (2015)_ Spatial entities called “Functional Urban Areas” delineated as those areas in which at least 15% of the population is commuting to the main Urban Centre of the area.	1km	Mollweide	2015
Other thematic and regional products Global				
GHS-LAND	Land fraction as derived from Sentinel2 image composite (2018) and OSM data	10m; 100m; 1km	Mollweide	2018

The review of available datasets showed that GHSL, UN-Habitat demographic data, and WorldPop are the most relevant sources for the objectives of this thesis (Bondarenko et al., 2025; Pesaresi & Politis, 2023; Schiavina et al., 2023; UN-Habitat, n.d.). GHSL provides globally consistent spatial datasets for built-up area and population distribution. UN-Habitat data provide urban agglomeration population estimates, while WorldPop offers gridded population estimates that can be compared with GHSL population data. Therefore, the final analysis focuses on GHS-BUILT-S for built-up growth and on GHS-POP, UN-Habitat data, and WorldPop for population comparison.

4.3 Selected Datasets for the Analysis

4.3.1 Built-Up Area Dataset: GHS-BUILT-S

The Global Human Settlement Layer (GHSL), developed by the European Commission Joint Research Centre, provides open-access spatial datasets describing built-up surfaces, population distribution, and settlement patterns. In this study, the GHS-BUILT-S dataset was selected as the main source for built-up area analysis (Pesaresi & Politis, 2023).

GHS-BUILT-S represents built-up surface as the number of square meters of built-up area within each raster cell. This dataset is suitable for the thesis because it provides a consistent spatial representation of built-up surfaces over different time periods. As a result, it allows the temporal expansion of urban areas in Baghdad to be analyzed using the same data structure and methodology across all selected epochs.

Although other GHSL products were reviewed, GHS-BUILT-S was selected as the primary built-up dataset because it directly measures built-up surface. Products such as GHS-BUILT-V, GHS-SMOD, GHS-UCDB, GHS-DUC, GHS-FUA, and GHS-LAND were considered useful for broader settlement or urban classification studies, but they were not directly required for the present analysis.

4.3.2 Population Datasets: GHS-POP, UN-Habitat Data, and WorldPop

Population data were analyzed using three different sources: GHS-POP, UN-Habitat urban agglomeration data, and WorldPop (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.). The use of three population datasets allows the demographic trend of Baghdad to be evaluated from different perspectives. Since each source represents population using a different method and spatial definition, comparing them helps assess whether the overall population-growth pattern is consistent across independent datasets.

GHS-POP provides gridded resident population data and is useful for spatial analysis because population is distributed across raster cells. This allows the population data to be clipped to the Baghdad boundary and compared spatially with built-up growth. UN-Habitat demographic data provide population estimates for urban agglomerations and

are useful as an official demographic reference, although they are not spatial raster datasets. WorldPop provides gridded population estimates and can be used as an additional source to compare with GHS-POP.

Table 2. Overview Table of GHS-POP Data. Source: Schiavina et al. (2023).

Dataset Name	Description	Resolution	Coordinate systems	Epochs
GHS-POP	Resident population grid (inhabitants); The spatial raster dataset depicts the distribution of population, expressed as the number of people per cell.	100m; 1km; 3 arcsec; 30 arcsec	Mollweide; WGS84	1975-2030

Table 3. Overview Table of UN Demography Data. Source: UN-Habitat (n.d.).

Dataset Name	Description	Epochs
Population in Urban Agglomerations 2000 - 2035 (Thousands)	Total estimated population for urban agglomerations which had a population of 300,000 or more in 2018. "Urban agglomeration" as the unit of measurement follows a diversity of concepts.	2000-2035
Urban Population at Mid-year by country 2000-2050 (Thousands)	Total estimated population living in urban areas based on national urban definitions.	2000-2050

Among the available UN-Habitat demographic datasets, urban agglomeration population estimates were adopted. The comparison was carried out at the “Baghdad urban area / agglomeration” reporting level.

Table 4. Overview Table of WorldPop Data. Source: Bondarenko et al. (2025).

Dataset Name	Description	Epochs
Global mosaics 2015-2030 (1km Resolution) R2025 A v1	Mosaiced 1km resolution global datasets using 100m resolution population count datasets.	2015-2030
Individual countries 2015-2030 (100m Resolution) R2025 A v1	Constrained estimates of 2015-2030 total number of people per grid square at a resolution of 3 arc (approximately 100m at the equator) R2025A version v1. This	2015-2030

Dataset Name	Description	Epochs
	work is part of the WorldPop Global Demographic Data project enabled through funding from the Bill and Melinda Gates Foundation (BMGF), grant number INV-045237. The projection is Geographic Coordinate System, WGS84. The units are number of people per pixel. The mapping approach is Random Forest-based dasymetric redistribution.	
Individual countries 2015-2030 (1km Resolution) R2025 A v1	Constrained estimates of 2015-2030 total number of people per grid square at a resolution of 30 arc (approximately 1km at the equator) R2025A version v1. This work is part of the WorldPop Global Demographic Data project enabled through funding from the Bill and Melinda Gates Foundation (BMGF), grant number INV-045237. The projection is Geographic Coordinate System, WGS84. The units are number of people per pixel. The mapping approach is Random Forest-based dasymetric redistribution.	2015-2030
Bespoke methods for individual countries (WOPR)	The WorldPop Open Population Repository (WOPR) provides access to gridded population estimates and related data created using bespoke methods for individual countries, including final products as well as early experimental results.	

For the present analysis, the WorldPop Individual countries – 1 km resolution (R2025A v1) dataset was used. Global mosaics and 100 m datasets were reviewed but were not employed in the current workflow.

Because these datasets use different spatial definitions and modelling approaches, their population values are not expected to be exactly identical. GHS-POP and WorldPop are raster-based population grids, while UN-Habitat are reported at the urban agglomeration level. Therefore, the comparison focuses mainly on the general trend, magnitude, and consistency of population growth, rather than expecting identical values from all sources.

4.4 Data Preprocessing

All spatial datasets were prepared in QGIS Desktop 3.40.12 before analysis (QGIS Development Team, 2026). The first step was to import the Baghdad administrative boundary obtained from GADM and verify its alignment using OpenStreetMap (GADM, n.d.; OpenStreetMap contributors, n.d.). The boundary was then used as the spatial reference area for the analysis.

Raster datasets were checked for coordinate reference system, spatial resolution, and geographic coverage. When necessary, datasets were reprojected or aligned to ensure consistency. The Baghdad boundary was used to clip built-up and population raster layers so that only the cells located inside the study area were included in the calculations.

The preprocessing workflow included the following steps:

1. Downloading the Baghdad administrative boundary from GADM.
2. Importing the boundary into QGIS.
3. Checking the boundary alignment using OpenStreetMap.
4. Downloading built-up and population datasets from GHSL and WorldPop.
5. Preparing UN-Habitat urban agglomeration population data.
6. Checking coordinate reference systems and spatial coverage.
7. Clipping raster datasets to the Baghdad boundary.
8. Extracting built-up area and population values.
9. Comparing population estimates from GHS-POP, UN-Habitat data, and WorldPop.
10. Interpreting the results in relation to urban water-management pressure.

4.5 Built-Up Area Analysis

The built-up area analysis was carried out using the GHS-BUILT-S dataset (Pesaresi & Politis, 2023). After clipping the raster layers to the Baghdad boundary, the built-up surface values were extracted for each selected time period. Since GHS-BUILT-S reports built-up surface in square meters, the total built-up area was calculated by

summing the built-up surface values inside the study area and converting the result into square kilometers when required.

The purpose of this step was to measure how the built-up area of Baghdad changed over time. The extracted values were used to identify the overall growth trend and to support the interpretation of spatial urban expansion. The built-up area analysis therefore provides the physical urban-growth component of the thesis.

The general calculation can be expressed as:

Total built-up area = sum of built-up surface values within the Baghdad boundary

The built-up growth between two periods was then calculated as:

Built-up growth = built-up area in later year – built-up area in earlier year

This calculation allowed the expansion of built-up surfaces to be evaluated and related to population growth and possible pressure on urban water services.

4.6 Population Data Comparison

The population analysis was based on the comparison of GHS-POP, UN-Habitat urban agglomeration data, and WorldPop (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.). The aim was not to determine that one dataset is fully correct and the others are incorrect. Instead, the purpose was to evaluate whether the datasets show a similar population-growth pattern for Baghdad.

For GHS-POP and WorldPop, raster layers were clipped to the Baghdad boundary, and the total population was calculated by summing the population values of all cells within the study area. For UN-Habitat data, the reported Baghdad urban agglomeration population values were extracted directly from the tabular dataset. Since the UN-Habitat dataset follows the concept of urban agglomeration, while the raster datasets are clipped to the administrative boundary, exact values may differ. For this reason, the comparison was interpreted carefully.

The comparison focused on three points:

1. Whether all datasets show population growth over time.
2. Whether the estimated population values are within a comparable range.
3. Whether differences between datasets may be explained by different spatial definitions, modelling methods, and reporting units.

This comparison is important because population growth is one of the main drivers of urban water demand. If the datasets show a similar upward trend, this strengthens the interpretation that Baghdad is facing increasing demographic pressure, which may affect future urban water-management needs.

4.7 Linking Urban Growth and Population Change to Water Management

After analyzing built-up growth and population change, the results were interpreted in relation to urban water management. The main assumption is that spatial urban expansion and population growth can increase pressure on water supply systems by increasing demand, extending service areas, and creating new infrastructure needs.

This thesis does not attempt to replace detailed hydraulic modelling or water-demand simulation. Instead, it provides a spatial planning perspective. By identifying where and how Baghdad has expanded, and by comparing population estimates from different datasets, the study can support a better understanding of how urban growth may influence water-management challenges.

The interpretation framework is based on the following logic:

- Urban expansion increases built-up surfaces and extends the urban footprint.
- Population growth increases domestic water demand and pressure on public services (Al-Mukhtar & Mutar, 2021; Zubaidi et al., 2019).
- Expansion of built-up areas may require extension of water supply infrastructure.
- Dependence on the Tigris River makes Baghdad sensitive to upstream flow reduction, drought, and water-level decline (Al-Ali, 2025; Asaad & Abed, 2020; Torabi Haghighi et al., 2023).

Therefore, urban spatial growth and population distribution should be considered together in urban water-management planning.

4.8 Implementation of the R-Based Processing Workflow

The spatial and demographic analyses in this thesis were implemented using an R version 4.5.2 (R Core Team, 2025). The purpose of this workflow was to ensure that the built-up area, population datasets, and derived indicators were processed in a consistent and reproducible way. The complete scripts are provided in the Appendix, while the most important code sections are reported here with brief methodological explanations.

4.8.1 Import of Spatial Data and Study Area Preparation

The first step of the workflow consisted of importing the GHSL built-up raster data and the Baghdad administrative boundary (GADM, n.d.; Pesaresi & Politis, 2023). The raster data were imported using the terra package, while the administrative boundary was loaded as a vector layer.

```
library(terra)
r1975    <- rast(raster_1975_path)
baghdad  <- vect(boundary_path)
```

Before performing spatial analysis, the coordinate reference systems of the raster and vector datasets were checked. If the datasets had different coordinate systems, the Baghdad boundary was reprojected to match the raster layer. This step was necessary to ensure correct spatial overlay during cropping and masking.

```
if (crs(r1975) != crs(baghdad)) {
  baghdad <- project(baghdad, crs(r1975))
}
```

The raster was then cropped and masked using the Baghdad boundary. Cropping reduced the raster to the spatial extent of the study area, while masking retained only the pixels located inside the Baghdad administrative boundary.

```
r1975_crop <- crop(r1975, baghdad)
r1975_mask <- mask(r1975_crop, baghdad)
```

This step ensured that the built-up area calculations were performed only within the selected study area.

4.8.2 Automated Multi-Year Processing of GHSL Built-Up Data

To analyze built-up area change over time, the GHSL built-up raster files were processed using an automated multi-year workflow (Pesaresi & Politis, 2023). Instead of selecting each raster manually, all relevant files were detected from the dataset folder using a filename pattern.

```
ghsl_folder <- "Data/GHSL_Built"

raster_files_all <- list.files(
  ghsl_folder,
  pattern = "GHS_BUILT_S_E[0-9]{4}.*3ss.*\\.tif$",
  full.names = TRUE,
  recursive = TRUE
)
```

The reference year of each raster was extracted automatically from the filename. A structured table was then created to associate each raster file with its corresponding year. Duplicate years were removed, and the datasets were ordered chronologically to ensure correct time-series analysis.

```
years_all <- as.integer(sub(".*GHS_BUILT_S_E([0-9]{4}).*", "\\1",
                           basename(raster_files_all)))

df_files <- data.frame(
  year = years_all,
  file = raster_files_all,
  stringsAsFactors = FALSE
)

df_unique <- df_files[!duplicated(df_files$year), ]

ord <- order(df_unique$year)
raster_files <- df_unique$file[ord]
years <- df_unique$year[ord]
```

This step transformed the collection of raster files into an organized temporal dataset.

The core analysis was performed using a loop-based procedure. For each year, the corresponding raster was loaded, cropped and masked to the Baghdad boundary, and summary indicators were calculated.

```
baghdad <- aggregate(baghdad)
baghdad_area_m2 <- expanse(baghdad, unit = "m")[1]

results <- data.frame(
  year      = years,
  sum_m2    = NA_real_,
  mean_m2   = NA_real_,
  ratio_sum = NA_real_
)

for (i in seq_along(raster_files)) {
  r <- rast(raster_files[i])

  r_crop <- crop(r, baghdad, snap = "out")
  r_mask <- mask(r_crop, baghdad, touches = TRUE)

  s_sum  <- global(r_mask, "sum", na.rm = TRUE)[1,1]
  s_mean <- global(r_mask, "mean", na.rm = TRUE)[1,1]

  results$sum_m2[i]      <- s_sum
  results$mean_m2[i]     <- s_mean
  results$ratio_sum[i]   <- s_sum / baghdad_area_m2
}
```

In this workflow, `sum_m2` represents the total built-up surface within the Baghdad boundary, while `ratio_sum` represents the proportion of built-up surface relative to the total study area. The built-up area was then converted from square meters to square kilometers to improve readability in the Results chapter.

```
results$built_km2 <- results$sum_m2 / 1e6
```

The final built-up indicators were exported in both CSV and Excel formats for further analysis, visualization, and inclusion in the thesis.

```
write.csv(results, "Output/Built_Baghdad_terra.csv", row.names =
FALSE)
```

```
write.xlsx(results, "Output/Built_Baghdad_terra.xlsx")
```

4.8.3 Processing of Population Datasets

Population data were processed from three different sources: GHS-POP, UN-Habitat data, and WorldPop (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.). The use of multiple population datasets allowed comparison between different estimates and reduced dependence on a single data source.

For the UN-Habitat dataset, the relevant Baghdad urban agglomeration records were selected and reorganized into a time-series structure. Since the original values were reported in thousands of inhabitants, they were converted into absolute population values.

```
baghdad_pop <- un_pop_agglom %>%
  filter(country == "Iraq",
         grepl("Baghdad", agglomeration, ignore.case = TRUE)) %>%
  pivot_longer(
    cols = all_of(year_cols),
    names_to = "colname",
    values_to = "pop_thous"
  ) %>%
  mutate(
    year = years_vec[match(colname, year_cols)],
    UN_pop = pop_thous * 1000
  ) %>%
  select(year, UN_pop) %>%
  arrange(year)
```

WorldPop and GHS-POP were processed as raster datasets. For each raster file, the data were cropped and masked to the Baghdad boundary, and the total population was obtained by summing the cell values inside the study area.

```
r_crop <- crop(r, baghdad)
r_mask <- mask(r_crop, baghdad)

pop_total <- global(r_mask, "sum", na.rm = TRUE)[1,1]
```

This procedure converted the raster population datasets into population totals for each selected year, allowing them to be compared with the UN-Habitat dataset.

4.8.4 Integration of Built-Up and Population Data

After the built-up and population datasets were processed, they were integrated using the year as a common temporal reference. This made it possible to analyze the relationship between physical urban expansion and population growth (Bondarenko et al., 2025; Pesaresi & Politis, 2023; Schiavina et al., 2023; UN-Habitat, n.d.).

```
built <- read.xlsx("Output/Built_Baghdad_terra.xlsx")

built <- built %>%
  mutate(
    built_km2 = sum_m2 / 1e6,
    built_ratio = ratio_sum
  )
```

The integrated dataset was then used to calculate the main indicators used in the Results chapter.

```
comparison <- built %>%
  left_join(GHS_Data, by = "year") %>%
  left_join(UN_Data, by = "year") %>%
  left_join(WP_Data, by = "year")
```

For population density, the same method used in the Results chapter was adopted. Density was calculated by dividing the population estimate by the fixed Baghdad study-area extent. This ensured that the density values were comparable across datasets and years.

```
area_km2 <- 861.6952

comparison$GHS_density <- comparison$GHS_pop / area_km2
comparison$UN_density <- comparison$UN_pop / area_km2
comparison$WP_density <- comparison$WP_pop / area_km2
```

Built-up area per capita was calculated by dividing the total built-up surface by the population estimate. Since built-up area was expressed in square kilometers, it was first converted to square meters using the factor 1e6.

```

comparison$built_per_capita_GHS <- comparison$built_km2 * 1e6 /
comparison$GHS_pop
comparison$built_per_capita_UN <- comparison$built_km2 * 1e6 /
comparison$UN_pop
comparison$built_per_capita_WP <- comparison$built_km2 * 1e6 /
comparison$WP_pop

```

The built-up area per capita indicator was expressed in m²/person and was used to evaluate how the available built-up surface changed in relation to population growth.

4.8.5 Comparison between Population Sources

To compare population estimates from GHS-POP, UN-Habitat, and WorldPop, the analysis was restricted to common benchmark years (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.). In this thesis, the common comparison years were 2015, 2020, and 2025.

```

common_years <- c(2015, 2020, 2025)

comparison_common <- comparison %>%
  filter(year %in% common_years) %>%
  arrange(year)

```

Absolute and percentage differences were calculated to evaluate how GHS-POP differed from the UN and WorldPop estimates.

```

comparison_common$diff_GHS_UN_abs <- comparison_common$GHS_pop -
comparison_common$UN_pop
comparison_common$diff_GHS_UN_pct <-
  (comparison_common$GHS_pop - comparison_common$UN_pop) /
comparison_common$UN_pop * 100

comparison_common$diff_GHS_WP_abs <- comparison_common$GHS_pop -
comparison_common$WP_pop
comparison_common$diff_GHS_WP_pct <-
  (comparison_common$GHS_pop - comparison_common$WP_pop) /
comparison_common$WP_pop * 100

```

These indicators were used to assess the difference between the population datasets. Negative percentage values indicate that GHS-POP produced lower population estimates than the corresponding comparison dataset.

Population growth between consecutive benchmark years was also calculated for each dataset.

```
comparison_common$GHS_growth <- c(  
  NA,  
  diff(comparison_common$GHS_pop) /  
    head(comparison_common$GHS_pop, -1) * 100  
)
```

```
comparison_common$UN_growth <- c(  
  NA,  
  diff(comparison_common$UN_pop) /  
    head(comparison_common$UN_pop, -1) * 100  
)
```

```
comparison_common$WP_growth <- c(  
  NA,  
  diff(comparison_common$WP_pop) /  
    head(comparison_common$WP_pop, -1) * 100  
)
```

These values represent growth between consecutive benchmark periods, rather than annualized growth rates.

4.8.6 Normalized Growth and Comparative Indicators

To compare population growth patterns independently from differences in absolute population size, the population series were normalized using 2015 as the baseline year. After normalization, the value in 2015 becomes 1, and later values represent relative growth compared with that baseline.

```
comparison_common$GHS_norm <- comparison_common$GHS_pop /  
  comparison_common$GHS_pop[comparison_common$year == 2015]  
  
comparison_common$UN_norm <- comparison_common$UN_pop /
```

```
comparison_common$UN_pop[comparison_common$year == 2015]

comparison_common$WP_norm <- comparison_common$WP_pop /
  comparison_common$WP_pop[comparison_common$year == 2015]
```

This allowed direct comparison of relative growth trends across the three population datasets.

For visualization, the comparison table was reshaped from wide format to long format. This format allowed the three datasets to be plotted together in a single figure.

```
norm_long <- pivot_longer(
  comparison_common,
  cols = c(GHS_norm, UN_norm, WP_norm),
  names_to = "Dataset",
  values_to = "Normalized_value"
)
```

The same restructuring logic was also used for population, density, growth-rate, and built-up-area-per-capita comparison figures.

4.8.7 Generation of Maps and Figures

The workflow also included the generation of maps and figures used in the Results chapter. For the built-up maps, a fixed classification scheme was applied to all years to ensure that the maps were visually comparable.

```
breaks <- c(seq(0, 7) * 1000, Inf)

classes <- c(
  "0 - 1000", "1000 - 2000", "2000 - 3000",
  "3000 - 4000", "4000 - 5000", "5000 - 6000",
  "6000 - 7000", ">7000"
)

pal <- brewer.pal(8, "YlOrRd")
```

For each year, the masked raster was plotted using the same classification intervals and color palette. The Baghdad boundary was added to clearly identify the study area.

```

plot(r_mask,
     col = pal,
     breaks = breaks,
     axes = FALSE,
     legend = FALSE,
     main = paste("Baghdad - Built-up area", yr))

plot(baghdad, add = TRUE, border = "black", lwd = 2)

legend("right",
      inset = 0.02,
      legend = classes,
      fill = pal,
      title = "Built m2 per pixel",
      bty = "n",
      cex = 0.8)

```

In addition to maps, time-series plots and comparative figures were produced for built-up area, population growth, population density, normalized growth, and built-up area per capita. These figures supported the interpretation of the numerical results and were exported in high resolution for inclusion in the thesis.

Overall, the R-based workflow allowed the analysis to move from raw spatial and demographic datasets to structured indicators, tables, maps, and figures. This improved the reproducibility of the analysis and ensured that urban expansion and population growth were evaluated using a consistent methodological framework.

4.9 Methodological Limitations

Several limitations must be considered in this methodology. First, the datasets used in this study have different spatial resolutions, temporal coverage, and modelling approaches. Therefore, direct comparison between them must be done carefully. Second, the Baghdad administrative boundary may not perfectly match the functional urban area or the UN urban agglomeration boundary. This means that population values from raster-based datasets and UN-Habitat data may differ because they refer to different spatial concepts (Bondarenko et al., 2025; GADM, n.d.; Schiavina et al., 2023; UN-Habitat, n.d.).

Third, GHS-POP and WorldPop population datasets are model-based estimates, not direct census counts (Bondarenko et al., 2025; Schiavina et al., 2023). Therefore, they are useful for spatial analysis and trend comparison, but they should not be interpreted as exact population counts. Fourth, GHS-BUILT-S represents built-up surface, but it does not directly describe building height, water demand, income level, household size, or infrastructure condition. Finally, this study links urban growth and population change to water-management pressure conceptually and spatially. A full assessment of water distribution performance would require detailed hydraulic network data, water consumption records, and operational information from the water authority.

Despite these limitations, the selected methodology is suitable for the objective of the thesis because it provides a consistent spatial framework for analyzing Baghdad's urban growth and comparing population trends using multiple data sources. Moreover, the same methodological approach could also be applied at the sub-city level, either to specific districts or sectors of Baghdad or to comparable urban areas in other cities, provided that suitable spatial boundaries and local data are available.

CHAPTER 5:

Results

This chapter presents the results obtained from the spatial and demographic analysis of Baghdad. The results are organized according to the main components of the study: built-up area expansion, population growth, comparison of population datasets, population density, built-up area per capita, and the relationship between urban expansion and population pressure. The aim is not only to describe the numerical changes, but also to interpret how these changes may be connected to urban water-management challenges in Baghdad.

5.1 Built-Up Area Expansion in Baghdad

The first part of the results focuses on changes in built-up area within the Baghdad study boundary. The built-up surface values were extracted from the GHS-BUILT-S dataset and clipped to the administrative boundary of Baghdad (GADM, n.d.; Pesaresi & Politis, 2023). The results show a clear increase in built-up area between 2000 and 2025, indicating continuous spatial expansion of the city.

As shown in Figure 3 and Table 5, the built-up area increased from 160.31 km² in 2000 to 187.18 km² in 2025. This represents an overall increase of approximately 26.86 km² during the analyzed period. The built-up ratio also increased from 0.186 in 2000 to 0.217 in 2025, showing that the proportion of built-up surface within the study area became larger over time. The strongest growth occurred between 2000 and 2020, when the built-up area increased steadily from 160.31 km² to 186.11 km². After 2020, the rate of increase became slower, reaching 187.18 km² in 2025.

These results show that Baghdad experienced continuous urban expansion during the study period. The increase in built-up area can be associated with population growth, housing demand, and the gradual conversion of open or non-built land into urban surfaces. From an urban water-management perspective, this expansion is important because new built-up areas may require additional water supply infrastructure, wider distribution networks, and higher service capacity. Therefore, the built-up area trend provides the spatial basis for understanding how urban growth may contribute to pressure on Baghdad's water-management system.

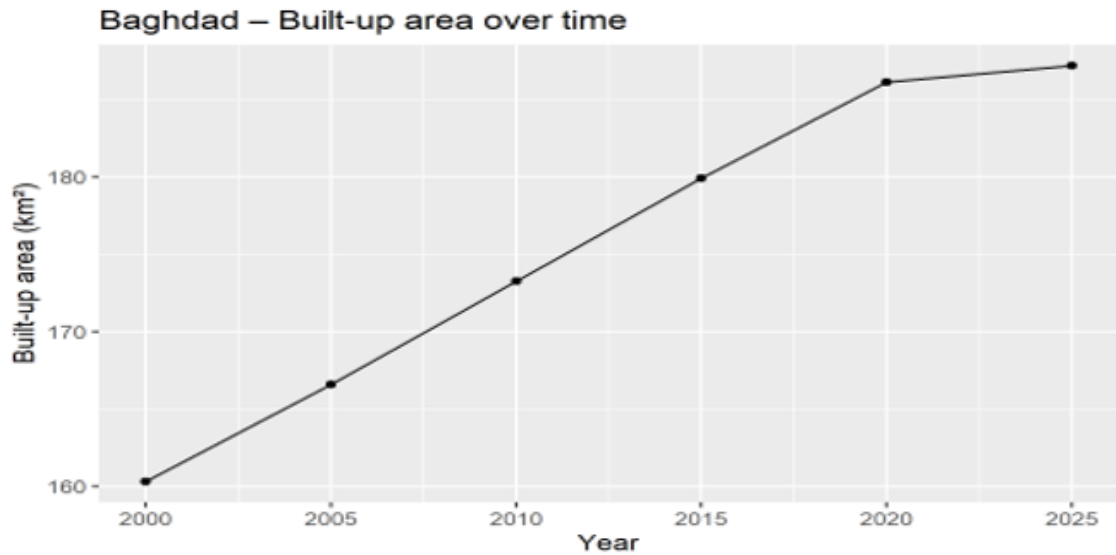


Figure 3. Built-up area growth in Baghdad based on the GHS-BUILT-S dataset.

Table 5. Built-up area and population base data for Baghdad.

Year	Built-up area (km²)	Built-up ratio	GHS-POP pop.	UN pop.	WorldPop pop.	GHS-POP built-up per capita(m²/person)	UN built-up per capita(m²/person)	WorldPop built-up per capita(m²/person)
2000	160.31	0.186	4,089,733	5,199,948	N/A	39.20	30.83	N/A
2005	166.58	0.193	4,236,432	5,327,261	N/A	39.32	31.27	N/A
2010	173.27	0.201	4,542,758	5,651,654	N/A	38.14	30.66	N/A
2015	179.90	0.209	5,111,021	6,351,400	5,917,296	35.20	28.32	30.40
2020	186.11	0.216	5,824,778	7,144,260	6,647,371	31.95	26.05	28.00
2025	187.18	0.217	6,508,322	8,141,119	7,427,081	28.76	22.99	25.20

5.2 Population Growth Based on GHS-POP

The second part of the results examines population growth in Baghdad using the GHS-POP dataset (Schiavina et al., 2023). Unlike the UN and WorldPop datasets, which are used later for comparison, this section focuses only on GHS-POP population estimates. The population values were extracted from the gridded GHS-POP dataset for the Baghdad study area and analyzed over time to identify the main demographic trend.

As shown in Figure 4 and Table 6, the GHS-POP results indicate a continuous increase in Baghdad's population between 1975 and 2025. The estimated population increased from approximately 2.08 million in 1975 to 6.51 million in 2025. This means that the population increased by about 4.43 million people over the 50-year period, more than tripling according to this dataset. The increase was gradual from 1975 to 2000, rising from 2.08 million to about 4.09 million. After 2000, the population continued to grow, reaching 4.54 million in 2010, 5.11 million in 2015, 5.82 million in 2020, and 6.51 million in 2025.

This trend is important because population growth is one of the main drivers of urban water demand. As the number of inhabitants increases, the need for domestic water supply, service coverage, and infrastructure capacity also increases. In Baghdad, this demographic growth occurred together with the spatial expansion of built-up areas. Therefore, the GHS-POP results provide an important population-based indication of increasing pressure on urban water-management systems.

The results also show that population growth was not a short-term fluctuation, but a long-term and continuous trend. This suggests that water-management planning in Baghdad should not only consider current demand, but also the cumulative effect of long-term demographic growth. For this reason, the GHS-POP population trend is used as an important basis for the following comparison with UN and WorldPop population estimates.

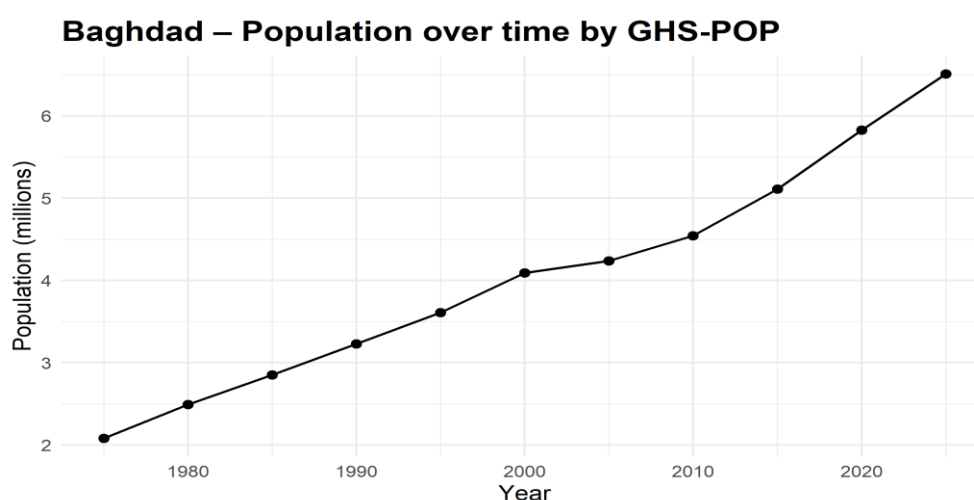


Figure 4. Population growth in Baghdad based on the GHS-POP dataset.

Table 6. *GHS-POP population estimates for Baghdad*

Year	GHS-POP population
1975	2,082,132
1980	2,492,966
1985	2,852,704
1990	3,228,758
1995	3,607,578
2000	4,089,733
2005	4,236,432
2010	4,542,758
2015	5,111,021
2020	5,824,778
2025	6,508,322

5.3 Comparison of Population Estimates from GHS-POP, UN-Habitat Data, and WorldPop

After analyzing the population trend based on GHS-POP, the next step was to compare population estimates from three different sources: GHS-POP, UN-Habitat urban agglomeration data, and WorldPop (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.). The comparison was carried out for the common years 2015, 2020, and 2025, because all three datasets provide values for these years. The aim of this comparison is not to identify one dataset as completely correct, but to understand how different population sources represent the demographic trend of Baghdad.

As shown in Figure 5 and Table 7, all three datasets indicate a clear increase in population between 2015 and 2025. However, the estimated values differ. The UN-Habitat dataset gives the highest population estimates, increasing from 6.35 million in 2015 to 8.14 million in 2025. WorldPop provides intermediate values, increasing from about 5.92 million to 7.43 million during the same period. GHS-POP reports the lowest values, increasing from 5.11 million in 2015 to 6.51 million in 2025.

The difference between GHS-POP and the other datasets is important. In 2015, the GHS-POP estimate was about 1.24 million lower than the UN-Habitat estimate, corresponding to a difference of approximately 19.5%. In 2025, this difference

increased to about 1.63 million, or approximately 20.1%. Compared with WorldPop, GHS-POP was about 806,000 lower in 2015 and about 919,000 lower in 2025, corresponding to differences of about 13.6% and 12.4%, respectively. This shows that GHS-POP consistently provides lower population estimates than both UN-Habitat and WorldPop during the common comparison period.

Despite these differences in absolute values, the general trend is consistent across all datasets. All sources show population growth, confirming that Baghdad experienced increasing demographic pressure during the analyzed period. The difference between datasets is expected because each source uses a different spatial definition and modelling approach. UN-Habitat data represent the Baghdad urban agglomeration, while GHS-POP and WorldPop are gridded population datasets. For this reason, the comparison should be interpreted mainly in terms of trend and relative magnitude, rather than exact equality between values.

This result is important because it shows that the conclusion of population growth does not depend on a single dataset. Even though the three datasets report different population totals, they all confirm an increasing population trend. This strengthens the interpretation that Baghdad's urban water-management system is facing growing demographic pressure. Therefore, population growth should be considered together with built-up area expansion when assessing future water demand and infrastructure needs.

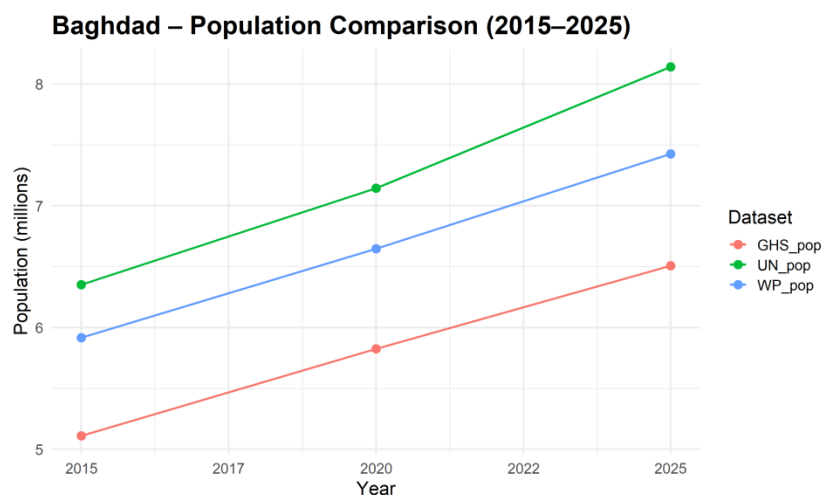


Figure 5. Population comparison for Baghdad based on GHS-POP, UN data, and WorldPop for 2015–2025.

Table 7. Comparison of GHS-POP, UN, and WorldPop population estimates for Baghdad.

Year	GHS-POP pop.	UN pop.	WorldPop pop.	GHS-POP – UN difference	GHS- POP – UN differe nce (%)	GHS-POP – WorldPop difference	GHS- POP – World Pop differe nce (%)	GHS- POP growt h (%)	UN growt h (%)	World Pop growt h (%)
2015	5,111,021	6,351,400	5,917,296	- 1,240,379	-19.53	-806,275	-13.63	N/A	N/A	N/A
2020	5,824,778	7,144,260	6,647,371	- 1,319,482	-18.47	-822,593	-12.37	13.96	12.48	12.34
2025	6,508,322	8,141,119	7,427,081	- 1,632,797	-20.06	-918,759	-12.37	11.73	13.95	11.73

5.4 Population Density and Spatial Pressure

Population density was analyzed to better understand how demographic pressure changed within the Baghdad study area. While total population values show the overall increase in inhabitants, population density gives a clearer indication of how concentrated this growth is within the spatial boundary of the study area. This is important because higher density can increase pressure on urban services, including the water supply system.

As shown in Figure 6, all three datasets indicate an increase in population density between 2015 and 2025. The UN-based density values are the highest, followed by WorldPop, while GHS-POP gives the lowest density estimates. This pattern is consistent with the population comparison presented in the previous section, where UN-Habitat data reported the highest population values and GHS-POP reported the lowest. Despite the differences between datasets, the general trend is the same: population density increased continuously during the analyzed period.

The increase in density suggests that Baghdad is not only expanding spatially, but is also experiencing stronger demographic pressure within its urban area. From a water-management perspective, this is important because denser areas usually require more reliable water supply, higher network capacity, and stronger pressure management. If

population density increases without sufficient improvement in infrastructure, the risk of service shortages and unequal distribution may also increase. Therefore, the density comparison supports the main argument of this thesis: urban water management in Baghdad should be analyzed not only in relation to total population growth, but also in relation to the spatial concentration of people within the city.

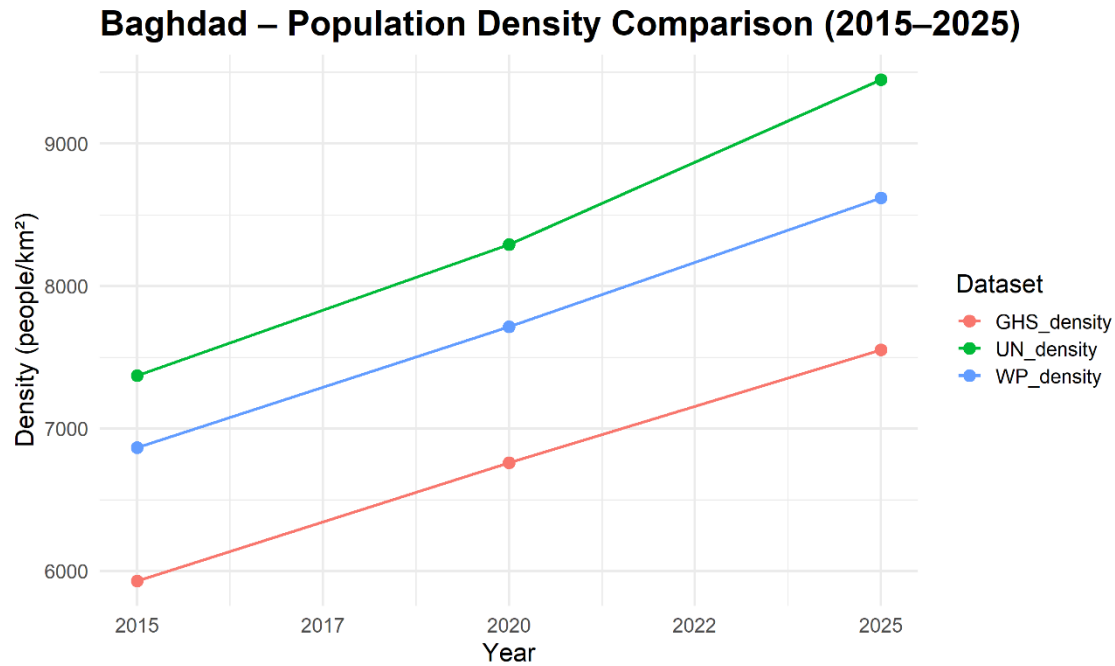


Figure 6. Population density comparison for Baghdad based on GHS-POP, UN data, and WorldPop for 2015–2025.

5.5 Built-Up Area per Capita

Built-up area per capita was analyzed to understand the relationship between urban land expansion and population growth. This indicator shows how much built-up surface is available per person and helps evaluate whether urban land expansion is increasing faster or slower than population growth. In this study, the indicator was compared using population estimates from GHS-POP, UN-Habitat data, and WorldPop for the common period 2015–2025 (Bondarenko et al., 2025; Pesaresi & Politis, 2023; Schiavina et al., 2023; UN-Habitat, n.d.).

As shown in Figure 7, the built-up area per capita decreased in all three datasets between 2015 and 2025. Although the absolute values differ depending on the population dataset used, the general trend is consistent. The GHS-POP-based estimate

remains the highest, decreasing from about 35 m²/person in 2015 to around 29 m²/person in 2025. The WorldPop-based estimate shows an intermediate pattern, decreasing from about 30 m²/person to about 25 m²/person. The UN-based estimate is the lowest, declining from about 28 m²/person to nearly 23 m²/person during the same period.

This decreasing trend indicates that population growth was faster than the increase in built-up area during the analyzed period. In other words, although Baghdad continued to expand spatially, the amount of built-up surface available per inhabitant became smaller. This suggests increasing urban pressure and a more intensive use of the existing urban area.

From the perspective of urban water management, this result is important because a reduction in built-up area per capita may indicate greater concentration of demand within urbanized zones. Higher population pressure within the built-up area can increase the need for reliable water distribution, stronger infrastructure capacity, and better service planning. Therefore, the built-up area per capita indicator supports the argument that urban growth in Baghdad should be evaluated together with demographic pressure, not only by looking at built-up expansion alone.

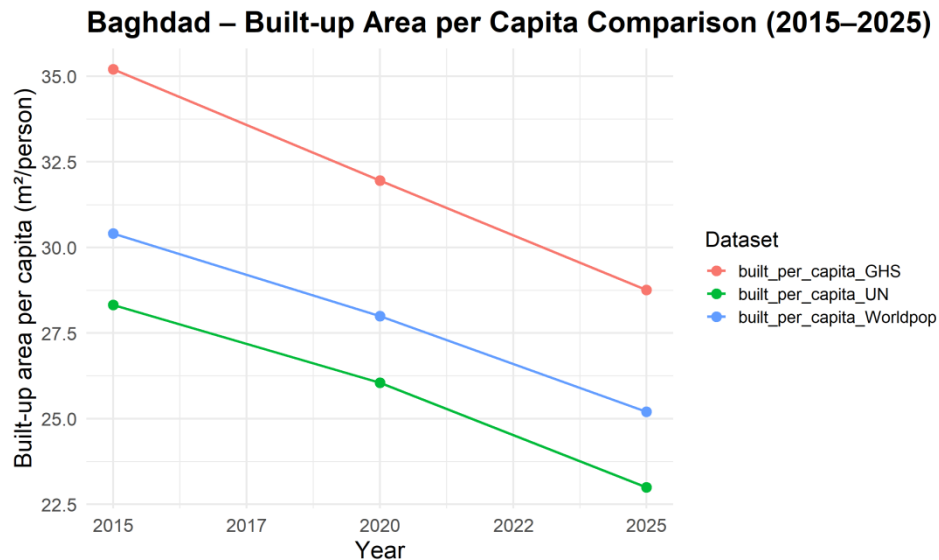


Figure 7. Built-up area per capita comparison for Baghdad based on GHS-POP, UN data, and WorldPop for 2015–2025.

5.6 Comparison Between Urban Growth and Population Growth

The next step compares the increase in built-up area with the increase in population between 2015 and 2025. This comparison is important because urban water-management pressure is influenced not only by how much the city expands physically, but also by how fast the population grows within the same period.

As shown in Table 8, the built-up area of Baghdad increased from 179.90 km² in 2015 to 187.18 km² in 2025. This represents an increase of about 7.28 km², equal to approximately 4.0% over the ten-year period. In comparison, population growth was much stronger in all three population datasets. According to GHS-POP, the population increased from 5.11 million in 2015 to 6.51 million in 2025, corresponding to an increase of about 27.3%. The UN-Habitat dataset increased from 6.35 million to 8.14 million, equal to about 28.2%, while WorldPop increased from 5.92 million to 7.43 million, equal to about 25.5%.

These results show that population growth was considerably faster than built-up area expansion. While the built-up surface increased only slightly after 2015, the number of inhabitants continued to rise strongly. This difference suggests that Baghdad experienced increasing population pressure within the existing and slowly expanding urban area. In other words, the city did not expand spatially at the same rate as its population increased.

This result indicates that future water-management challenges may be driven more by demographic pressure than by physical expansion alone. A faster-growing population can increase domestic water demand, network load, and pressure on treatment and distribution systems, even when the built-up area grows more slowly. Therefore, the comparison between built-up growth and population growth supports the need to consider both spatial expansion and demographic increase when evaluating urban water-management pressure in Baghdad.

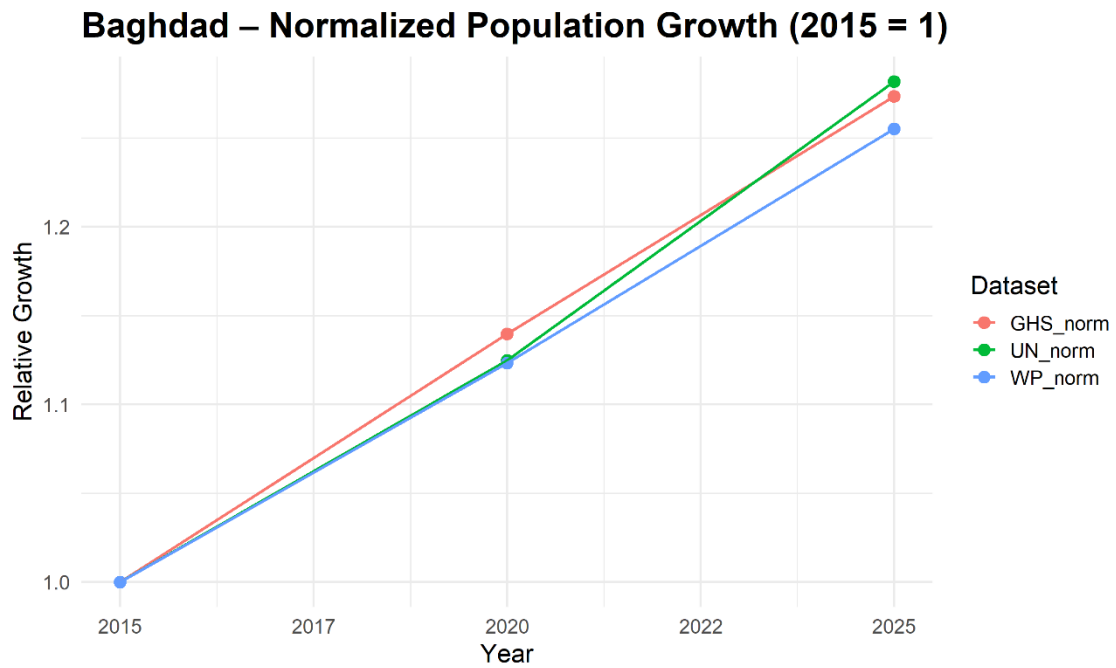


Figure 8. Normalized population growth for Baghdad using 2015 as the reference year.

Table 8. Built-up area and population comparison for Baghdad between 2015 and 2025.

Year	Built-up area (km ²)	GHS-POP pop.	UN pop.	WorldPop pop.
2015	179.90	5,111,021	6,351,400	5,917,296
2020	186.11	5,824,778	7,144,260	6,647,371
2025	187.18	6,508,322	8,141,119	7,427,081

5.7 Interpretation of Urban Expansion in Relation to Water-Management Pressure

The previous results show that Baghdad experienced both built-up expansion and population growth between 2015 and 2025. However, the comparison between these two trends indicates that population increased faster than the built-up area. This relationship is important because urban water-management pressure is influenced not only by the physical expansion of the city, but also by the number of people living within the urbanized area.

As shown in Figure 9, the built-up area increased only slightly from about 179.90 km² in 2015 to 187.18 km² in 2025, while population increased more strongly in all three population datasets. This means that the same urban system had to accommodate a larger population within a built-up area that expanded at a much slower rate. The result suggests increasing pressure on urban services, especially water supply, because more people require access to water within a relatively limited increase in built-up surface.

The built-up maps for 2015 and 2025, shown in Figures 10 and 11, provide a spatial view of this change. The maps show that built-up surfaces are concentrated mainly in the central and already urbanized parts of Baghdad, with additional development visible around existing built-up clusters. The general pattern suggests that urban growth occurred through both expansion and intensification of existing urban areas, rather than through a completely new isolated pattern of development.

From a water-management perspective, this is important for two reasons. First, expansion around existing urban areas may require extension of water distribution networks, pumping capacity, and service coverage. Second, population increase within already built-up zones may raise demand without necessarily creating a large visible increase in built-up area. This can lead to higher pressure on treatment plants, reservoirs, pipelines, and distribution networks (Al-Mukhtar & Mutar, 2021; Hasan et al., 2020; Raheem & Al-Juhaishi, 2025; Zubaidi et al., 2019).

Therefore, the results suggest that Baghdad's water-management challenges should be understood as a combined effect of spatial growth and demographic pressure. Built-up expansion shows where the urban footprint is growing, while population growth and density indicators show how demand may be increasing within that footprint. This supports the main argument of the thesis: urban water planning in Baghdad should consider both the spatial pattern of urban expansion and the population pressure associated with it.

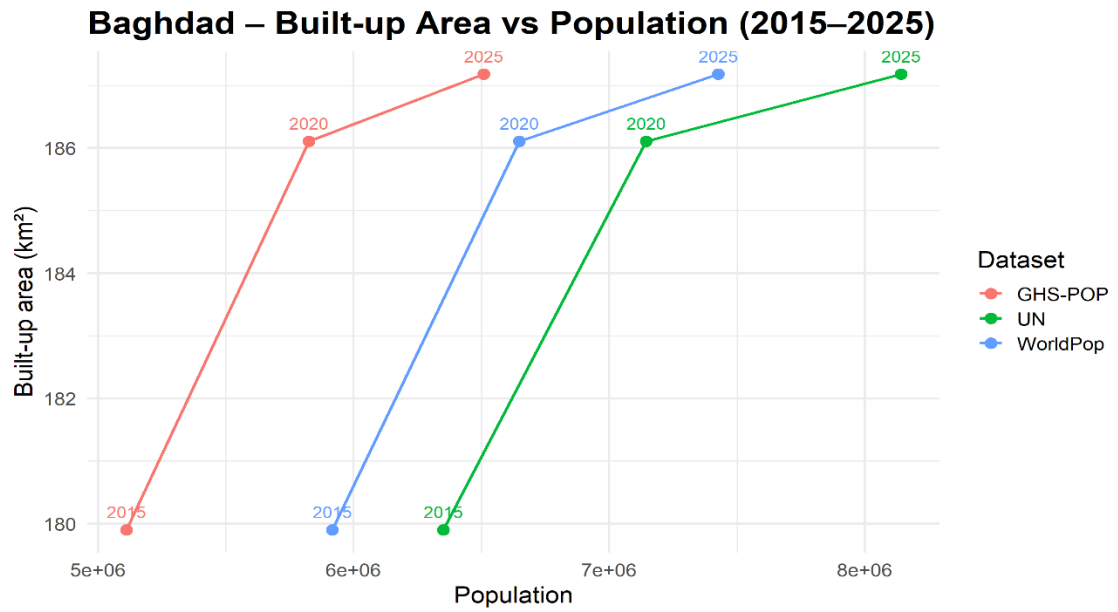


Figure 9. Relationship between built-up area and population in Baghdad for 2015–2025.

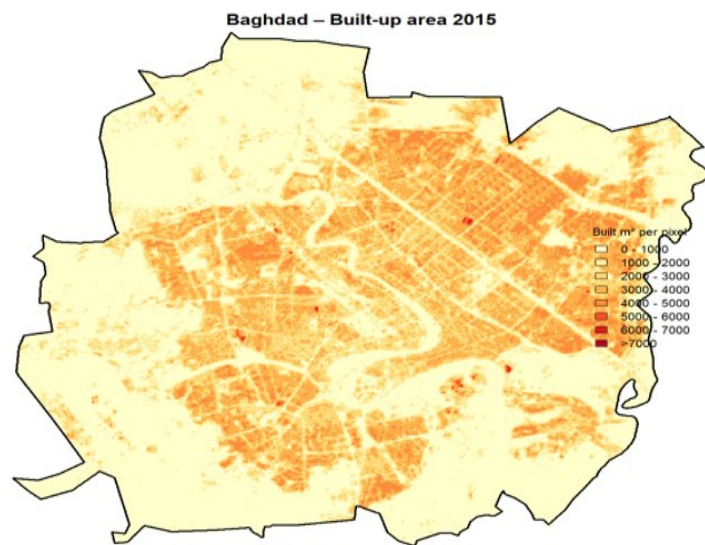


Figure 10. Spatial distribution of built-up area in Baghdad in 2015 based on GHS-BUILT-S dataset.

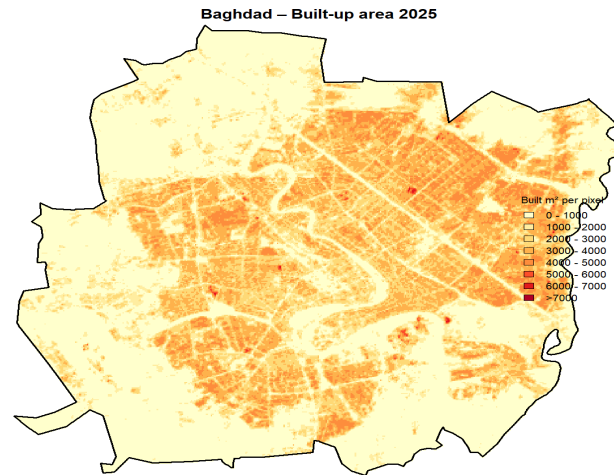


Figure 11. Spatial distribution of built-up area in Baghdad in 2025 based on GHS-BUILT-S dataset.

5.8 Summary of Main Results

The results of this chapter show that Baghdad experienced continuous urban and demographic growth during the analyzed period. The built-up area increased from 179.90 km² in 2015 to 187.18 km² in 2025, showing that the city continued to expand spatially. However, this increase was relatively limited compared with the population growth observed during the same period.

The population analysis showed a clear upward trend in all datasets. Based on GHS-POP, the population increased from 5.11 million in 2015 to 6.51 million in 2025. The UN-Habitat dataset reported higher values, increasing from 6.35 million to 8.14 million, while WorldPop showed an increase from 5.92 million to 7.43 million. Although the three datasets produced different absolute values, they all confirmed the same general trend of population growth.

The comparison between built-up expansion and population increase showed that population grew faster than the built-up area. This was also reflected in the decrease in built-up area per capita between 2015 and 2025. In practical terms, this means that Baghdad's urban area had to accommodate a larger population without an equivalent increase in built-up surface. This result suggests increasing demographic pressure within the urban system.

From the perspective of urban water management, these findings are important. The results indicate that Baghdad's water-management challenges are likely influenced by both spatial expansion and population concentration. Built-up growth may require extension of water supply networks, while population growth can increase demand within already urbanized areas. Therefore, the results support the need for integrated urban and water-resource planning that considers both land development and demographic pressure.

CHAPTER 6:

Discussion

6.1 Interpretation of Built-Up Area Expansion in Baghdad

The results show that Baghdad experienced a continuous increase in built-up area during the analyzed period. Between 2015 and 2025, the built-up area increased from 179.90 km² to 187.18 km². Although this increase is relatively limited compared with the total size of the study area, it still confirms that the urban footprint of Baghdad continued to expand. This expansion is important because built-up growth usually reflects the conversion of open, agricultural, or non-urban land into residential, commercial, or service areas.

This finding is consistent with previous studies that describe Baghdad as a city affected by long-term urban growth and unplanned expansion. Kadhim and Abbas (2021) linked this process to population growth, migration, housing demand, and weak planning control. Similarly, Waleed and Al-Bakri (2024), Mahal et al. (2022), and Moussa and Alwehab (2022) showed that the expansion of built-up areas in Baghdad has been accompanied by the loss of vegetation, agricultural land, and green cover. Therefore, the built-up trend identified in this thesis fits within the wider pattern reported in the literature.

However, the results of this thesis also show that built-up growth between 2015 and 2025 was slower than population growth. This means that Baghdad's urban challenge cannot be understood only by measuring spatial expansion. It is also necessary to consider how many people are living within the existing and gradually expanding built-up area.

6.2 Population Growth and Differences between Population Datasets

The population results show a clear increase in Baghdad's population. Based on GHS-POP, the population increased from 5.11 million in 2015 to 6.51 million in 2025. The UN-Habitat dataset reported higher values, increasing from 6.35 million to 8.14 million, while WorldPop showed an increase from 5.92 million to 7.43 million. Although the exact population values differ between the datasets, all three sources show the same general trend of population growth (Bondarenko et al., 2025; Schiavina et al., 2023; UN-Habitat, n.d.).

The differences between the datasets are expected because each source uses a different method and spatial definition. UN-Habitat data refer to the urban agglomeration, while GHS-POP and WorldPop are gridded population datasets. For this reason, the values should not be interpreted as identical measurements of the same spatial unit. Instead, they should be used to compare the general trend and relative magnitude of population increase.

The fact that all three datasets show population growth strengthens the reliability of the main interpretation. Even if the exact population total changes depending on the dataset, the general conclusion remains the same: Baghdad is facing increasing demographic pressure. This is important for urban water management because population growth is directly related to domestic water demand, service coverage, and pressure on water supply infrastructure.

6.3 Population Density, Built-Up Area per Capita, and Urban Pressure

The density and built-up area per capita results provide a more detailed understanding of urban pressure. Population density increased between 2015 and 2025 in all three datasets, while built-up area per capita decreased. This means that population increased faster than built-up area. In practical terms, Baghdad had to accommodate more people without an equivalent increase in built-up surface.

This result suggests a process of increasing urban pressure. A lower built-up area per capita can indicate that more people are concentrated within the available urban land. This may create pressure on housing, public services, roads, and water supply systems. In relation to water management, higher population concentration can increase demand on existing water networks, treatment plants, reservoirs, and distribution systems (Al-Mukhtar & Mutar, 2021; Hasan et al., 2020; Raheem & Al-Juhaishi, 2025; Zubaidi et al., 2019).

The result also shows why built-up area alone is not sufficient to understand urban water-management pressure. A city may expand slowly in spatial terms, but if its population grows quickly, water demand may still increase strongly. Therefore, the combination of population density and built-up area per capita provides a better interpretation of urban pressure than built-up area alone.

6.4 Relationship between Urban Growth and Urban Water-Management Pressure

The results suggest that Baghdad's water-management pressure is shaped by two connected processes: spatial expansion and population growth. Built-up expansion can require the extension of water supply networks to new or growing urban areas. At the same time, population growth can increase demand within already urbanized areas. These two processes may affect the water system in different ways.

If urban growth occurs at the edge of the city, new infrastructure may be needed to connect these areas to the water supply network. If population growth occurs mainly inside already built-up areas, existing infrastructure may face higher pressure without a large visible increase in urban surface. Both conditions are important for Baghdad because the city already depends on a complex system of treatment plants, reservoirs, pipelines, and distribution zones.

This interpretation is supported by previous studies on Baghdad's water supply system. Hasan et al. (2020) showed that geospatial methods can help map treatment plants, reservoirs, pipelines, and supply zones. Raheem and Al-Juhaishi (2025) found pressure and hydraulic performance problems in selected water distribution networks. Asaad and Abed (2020) also showed that low Tigris River levels during drought can affect the operation of water supply projects. Together, these studies support the idea that Baghdad's water-management challenge is not only about total water availability, but also about infrastructure performance and the spatial distribution of demand.

6.5 Comparison with Previous Studies on Baghdad

The findings of this thesis are generally consistent with previous studies. The observed built-up expansion supports the conclusions of Kadhim and Abbas (2021), who argued that unplanned urbanization and agricultural land conversion have been important features of Baghdad's development. The results also agree with remote sensing studies by Waleed and Al-Bakri (2024) and Mahal et al. (2022), which found that urban expansion in Baghdad has been associated with vegetation decline and environmental stress.

The population-growth results also support the conclusions of studies focused on water demand and planning. Al-Mukhtar and Mutar (2021) showed that future population growth may increase water demand and create unmet demand under different future scenarios. Zubaidi et al. (2019) also emphasized the importance of demand forecasting for improving water supply planning in Baghdad. The present thesis supports these studies by showing that population growth is visible across different datasets and should be considered together with spatial urban growth.

At the hydrological scale, the discussion is also supported by Al-Ali (2025) and Torabi Haghighi et al. (2023). These studies show that Baghdad's water situation is affected by broader Tigris River conditions, including water deficit, discharge reduction, and upstream water-resource development. This means that local urban growth is occurring in a context where water availability may also be under pressure. Therefore, Baghdad's future water-management problem should be understood as the combined result of urban demand, infrastructure limitations, and wider river-basin constraints.

6.6 Implications for Urban and Water-Resource Planning

The results have important implications for planning. First, urban growth should not be analyzed only through land expansion. Population growth and population density must also be included because they directly influence water demand. Second, water supply planning should consider where urban expansion is occurring and whether existing infrastructure can support growing demand in those areas.

Third, the comparison between datasets shows that using only one population source may give an incomplete picture. Since GHS-POP, UN-Habitat data, and WorldPop provide different values but similar growth trends, planners should be careful when using population data for water-demand estimation. Comparing several sources can provide a more reliable understanding before making planning decisions.

Finally, the results suggest that Baghdad needs integrated urban and water-resource planning. This means that urban expansion, population distribution, water infrastructure, and Tigris River water availability should be studied together. Such an approach can help identify areas where future growth may create stronger pressure on the water supply system.

6.7 Limitations of the Study

This study has several limitations. First, the datasets used in the analysis have different spatial definitions and modelling approaches. GHS-POP and WorldPop are gridded datasets, while UN-Habitat data refer to the urban agglomeration. Therefore, the population values are useful for comparison, but they should not be treated as perfectly equivalent.

Second, the built-up analysis is based on GHS-BUILT-S, which measures built-up surface but does not provide detailed information about building height, land-use type, household size, income level, or actual water consumption. As a result, the study can identify spatial growth, but it cannot directly calculate detailed water demand at the household or district level.

Third, the study links urban growth and population pressure to water management mainly through spatial interpretation. It does not include a full hydraulic simulation of the water distribution network or a detailed water-demand model. Such analyses would require additional data, including network layout, pipe characteristics, pressure records, consumption data, and operational information from water authorities.

Despite these limitations, the study provides a useful spatial planning perspective. It shows that Baghdad's built-up area and population are increasing, and that population growth is faster than physical urban expansion. This supports the need to consider spatial and demographic indicators together when discussing urban water-management pressure.

6.8 Summary of Discussion

The discussion shows that Baghdad's urban water-management challenge is linked to both spatial and demographic change. Built-up area increased between 2015 and 2025, but population increased at a faster rate. This led to higher population density and lower built-up area per capita, suggesting increasing pressure within the urban system.

The findings are consistent with previous studies on Baghdad's urban expansion, vegetation loss, water demand, infrastructure limitations, and Tigris River flow pressures. The main contribution of this thesis is that it brings these issues together

through a spatial analysis of built-up growth and population datasets. The results suggest that future water-management planning in Baghdad should consider not only water availability, but also where and how the city is growing.

CHAPTER 7:

Conclusions and Recommendations

7.1 Conclusions

This thesis investigated the relationship between urban spatial growth, population increase, and urban water-management pressure in Baghdad, Iraq. The study used spatial datasets, population datasets, and R-based data processing to analyze changes in built-up area and demographic indicators over time. The main purpose was to understand how physical urban expansion and population growth may contribute to increasing pressure on urban water-management systems.

The analysis showed that Baghdad experienced continuous built-up area expansion during the analyzed period. Between 2015 and 2025, the built-up area increased from 179.90 km² to 187.18 km². Although this increase was not very large in absolute terms, it confirmed that the urban footprint of Baghdad continued to expand. The spatial maps also showed that built-up areas remained concentrated mainly around already urbanized zones, with additional growth occurring around existing built-up clusters.

The population analysis showed a stronger growth trend. According to GHS-POP, Baghdad's population increased from 5.11 million in 2015 to 6.51 million in 2025. The UN-Habitat dataset reported higher values, increasing from 6.35 million to 8.14 million, while WorldPop increased from 5.92 million to 7.43 million. Although the datasets produced different population totals, they all showed the same general trend of continuous population growth.

The comparison between built-up area and population growth showed that population increased faster than the physical built-up area. This was also reflected in the decline of built-up area per capita between 2015 and 2025. This result suggests that Baghdad's urban system is experiencing increasing demographic pressure, where more people are being accommodated within a built-up area that is expanding more slowly.

From a water-management perspective, the results indicate that Baghdad's challenges should not be understood only as a problem of urban expansion. Population growth, increasing density, and decreasing built-up area per capita are also important because they can increase water demand and pressure on existing infrastructure. Even if the built-up area grows slowly, domestic water demand may continue to rise because of population increase.

The use of multiple population datasets was also important. GHS-POP, UN-Habitat data, and WorldPop produced different absolute values, but they supported the same general conclusion. This shows that the choice of dataset can influence numerical estimates, but the overall trend remains consistent. Therefore, comparing more than one population source can provide a more reliable interpretation of demographic pressure.

Overall, the thesis shows that Baghdad's urban water-management pressure is linked to the combined effect of spatial expansion and population growth. Built-up area data help identify where the city is physically expanding, while population indicators help explain how demand and pressure may be increasing within the urban system. For this reason, urban planning and water-resource planning should be considered together.

7.2 Recommendations

Based on the findings of this thesis, several recommendations can be proposed.

First, urban water-management planning should consider both built-up expansion and population growth. Planning based only on physical urban growth may underestimate future water demand, especially when population increases faster than built-up area.

Second, population datasets should be used carefully in water-demand and urban-planning studies. Since different population datasets may produce different absolute values, it is recommended to compare multiple population sources before making planning decisions. This can help reduce uncertainty and provide a more balanced understanding of demographic pressure.

Third, water supply planning should give special attention to areas where urban expansion and population concentration occur together. These areas may require improvements in water distribution capacity, network extension, storage facilities, and service coverage.

Fourth, spatial data and GIS-based monitoring should be used regularly to support urban water management. Remote sensing datasets such as GHSL can help track built-up expansion over time and provide useful information for planning authorities.

Fifth, future planning should integrate urban growth analysis with water infrastructure data. Built-up and population indicators are useful, but they become more powerful when combined with information about water treatment plants, reservoirs, pipelines, pressure zones, and actual consumption records.

Finally, urban growth should be managed through stronger coordination between land-use planning and water-resource planning. If urban expansion continues without considering water infrastructure capacity, pressure on the water supply system may become more severe in the future.

7.3 Future Work

This thesis provides a spatial and demographic interpretation of urban water-management pressure in Baghdad, but further research can improve and extend the analysis.

Future studies could include district-level or neighborhood-level analysis to identify which parts of Baghdad are experiencing the strongest urban and demographic pressure. This would provide a more detailed understanding than city-level analysis.

Another important future step would be to include actual water consumption data. This would allow a more direct connection between population growth, built-up expansion, and water demand.

Hydraulic modelling of the water distribution network could also be added in future research. Such modelling would require data on pipe networks, reservoirs, pumping stations, pressure records, and operational conditions. This would make it possible to evaluate whether the existing water infrastructure can support current and future demand.

Future research could also combine urban growth analysis with climate and hydrological data, especially Tigris River discharge, drought conditions, and water availability. This would help connect local urban demand with broader water-resource constraints.

Finally, future work could compare Baghdad with other large Iraqi or Middle Eastern cities facing similar urban growth and water-management challenges. This would make it possible to understand whether the patterns observed in Baghdad are part of a wider regional trend.

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Appendix

Appendix A – R Scripts Used for Spatial and Demographic Analysis

This appendix presents the R scripts used to process the spatial and demographic datasets in this thesis. The scripts support the methodology described in Chapter 4 and were used to generate the built-up area indicators, population comparisons, maps, figures, and tables presented in the Results chapter.

The complete R files are included here to improve transparency and reproducibility. Some scripts contain preliminary tests or exploratory calculations, while the final interpretation in the thesis is based on the harmonized indicators described in the main methodology and results sections. In particular, population density in the thesis was interpreted using the fixed Baghdad study-area extent, while any alternative density calculation appearing in earlier exploratory code should be considered only as part of the development process.

A.1 Initial GHSL Built-Up Raster Test

This script was used as an initial test for importing the GHSL built-up raster and the Baghdad administrative boundary. It includes the main spatial preprocessing steps, such as loading raster and vector data, checking the coordinate reference system, reprojecting the boundary when needed, cropping and masking the raster to the study area, and calculating preliminary built-up statistics for a single year.

```
# 01_builtup_baghdad_terra.R
library(terra)
getwd()
raster_1975_path <- "Data/GHSL_Built/Iraq
Tile/1975/GHS_BUILT_S_E1975_GLOBE_R2023A_4326_3ss_V1_0_R6_C23.tif"
boundary_path    <-
"Data/Boundaries/Border/Baghdad_OSM_boundary/Baghdad_OSM_boundary.shp"
r1975    <- rast(raster_1975_path)
baghdad <- vect(boundary_path)
crs(r1975)
crs(baghdad)
if (crs(r1975) != crs(baghdad)) {
```

```

    baghdad <- project(baghdad, crs(r1975))
  }
  r1975_crop <- crop(r1975, baghdad)
  r1975_mask <- mask(r1975_crop, baghdad)
  sum_built_1975 <- global(r1975_mask, "sum", na.rm = TRUE)[1,1]
  mean_built_1975 <- global(r1975_mask, "mean", na.rm = TRUE)[1,1]
  baghdad_area_m2 <- expanse(baghdad, unit = "m")[1]
  ratio_1975 <- sum_built_1975 / baghdad_area_m2
  cat("Year: 1975\n")
  cat("Total built-up area (m^2):", sum_built_1975, "\n")
  cat("Mean built-up per pixel (m^2):", mean_built_1975, "\n")
  cat("Baghdad area (m^2):", baghdad_area_m2, "\n")
  cat("Built ratio 1975 (sum / area):", ratio_1975, "\n")

```

A.2 Multi-Year GHSL Built-Up Area Extraction

This script represents the main built-up area extraction workflow. It automatically identifies GHSL built-up raster files, extracts the reference year from filenames, removes duplicate years, orders the datasets chronologically, and processes each year using a loop-based procedure. For each year, the raster is cropped and masked to the Baghdad boundary, and built-up indicators such as total built-up area, mean built-up value, and built-up ratio are calculated.

```

# 02_builtup_baghdad_all_years.R

library(terra)

library(openxlsx)

getwd()

ghsl_folder <- "Data/GHSL_Built"

raster_files_all <- list.files(

  ghsl_folder,

  pattern = "GHS_BUILT_S_E[0-9]{4}.*3ss.*\\.tif$",

  full.names = TRUE,

```

```

recursive = TRUE

)

if (length(raster_files_all) == 0) {

  stop("No GHSL 3ss .tif files found. Check ghsl_folder or pattern.")

}

years_all <- as.integer(sub(".*GHS_BUILT_S_E([0-9]{4}).*", "\\1",

                           basename(raster_files_all)))

df_files <- data.frame(year = years_all,

                       file = raster_files_all,

                       stringsAsFactors = FALSE)

df_unique <- df_files[!duplicated(df_files$year), ]

raster_files <- df_unique$file

years      <- df_unique$year

ord <- order(years)

raster_files <- raster_files[ord]

years      <- years[ord]

cat("Files actually used (one per year):\n")

print(data.frame(year = years, file = raster_files))

boundary_path <-
"Data/Boundaries/Border/Baghdad_OSM_boundary/Baghdad_OSM_boundary.shp"

baghdad <- vect(boundary_path)

r_test <- rast(raster_files[1])

if (crs(baghdad) != crs(r_test)) {

```

```

    baghdad <- project(baghdad, crs(r_test))

}

baghdad <- aggregate(baghdad)

baghdad_area_m2 <- expanse(baghdad, unit = "m")[1]

results <- data.frame(

  year      = years,

  sum_m2     = NA_real_,

  mean_m2    = NA_real_,

  ratio_sum  = NA_real_

)

for (i in seq_along(raster_files)) {

  cat("Processing year", years[i], "...\\n")

  r <- rast(raster_files[i])

  r_crop <- crop(r, baghdad, snap = "out")

  r_mask <- mask(r_crop, baghdad, touches = TRUE)

  s_sum <- global(r_mask, "sum", na.rm = TRUE)[1,1]

  s_mean <- global(r_mask, "mean", na.rm = TRUE)[1,1]

  results$sum_m2[i] <- s_sum

  results$mean_m2[i] <- s_mean

  results$ratio_sum[i] <- s_sum / baghdad_area_m2

}

cat("Final results:\\n")

```

```

print(results)

if (!dir.exists("Output")) dir.create("Output")

write.csv(results,

          file = "Output/Built_Baghdad_terra.csv",

          row.names = FALSE)

write.xlsx(results,

           file = "Output/Built_Baghdad_terra.xlsx")

cat("Saved clean results (1 row per year) to
Output/Built_Baghdad_terra.csv and .xlsx\n")

```

A.3 Built-Up Area Map Generation

This script was used to generate the built-up area maps for Baghdad. It applies a consistent classification scheme and color palette across all years, allowing direct visual comparison of the spatial distribution of built-up areas over time. The Baghdad boundary is overlaid on each map to clearly identify the study area.

```

# 03_maps_baghdad_ghsl.R

library(terra)

library(RColorBrewer)

getwd()

ghsl_folder <- "Data/GHS1_Built"

raster_files_all <- list.files(

  ghsl_folder,

  pattern = "GHS_BUILT_S_E[0-9]{4}.*3ss.*\\.tif$",

  full.names = TRUE,

  recursive = TRUE

```

```

)

if (length(raster_files_all) == 0) {

  stop("No GHSL 3ss .tif files found. Check ghsl_folder or pattern.")

}

years_all <- as.integer(sub(".*GHS_BUILT_S_E([0-9]{4}).*", "\\1",

                           basename(raster_files_all)))

df_files <- data.frame(year = years_all,

                       file = raster_files_all,

                       stringsAsFactors = FALSE)

df_unique <- df_files[!duplicated(df_files$year), ]

raster_files <- df_unique$file

years      <- df_unique$year

ord <- order(years)

raster_files <- raster_files[ord]

years      <- years[ord]

cat("Will create maps for years:\n")

print(years)

boundary_path <-
"Data/Boundaries/Border/Baghdad_OSM_boundary/Baghdad_OSM_boundary.shp"

baghdad <- vect(boundary_path)

r_test <- rast(raster_files[1])

if (crs(baghdad) != crs(r_test)) {

  baghdad <- project(baghdad, crs(r_test))

```

```

}

baghdad <- aggregate(baghdad)

breaks <- c(seq(0, 7) * 1000, Inf)

classes <- c(

  "0 - 1000", "1000 - 2000", "2000 - 3000",

  "3000 - 4000", "4000 - 5000", "5000 - 6000",

  "6000 - 7000", ">7000"

)

pal <- brewer.pal(8, "YlOrRd")

out_folder <- "Output/Maps"

if (!dir.exists(out_folder)) dir.create(out_folder)

for (i in seq_along(raster_files)) {

  yr <- years[i]

  cat("Creating map for year", yr, "...\\n")

  r <- rast(raster_files[i])

  r_crop <- crop(r, baghdad, snap = "out")

  r_mask <- mask(r_crop, baghdad, touches = TRUE)

  png_file <- file.path(out_folder, paste0("Baghdad_GHSL_built_", yr,
".png"))

  png(png_file, width = 1200, height = 1200, res = 150)

  par(mar = c(4, 4, 4, 6))

  plot(r_mask,

    col = pal,

```

```

        breaks = breaks,

        axes    = FALSE,

        legend  = FALSE,

        main    = paste("Baghdad - Built-up area", yr))

plot(baghdad, add = TRUE, border = "black", lwd = 2)

legend("right",

       inset  = 0.02,

       legend = classes,

       fill   = pal,

       title  = "Built m2 per pixel",

       bty    = "n",

       cex    = 0.8)

dev.off()

}

cat("All maps saved in Output/Maps as PNG files.\n")

```

A.4 United Nations Population Data Processing

This script was used to process United Nations population data. It extracts the records related to Baghdad, reorganizes the dataset into a time-series format, converts population values into absolute numbers when needed, and prepares the data for comparison with spatial indicators.

```

library(readxl)

library(dplyr)

```

```

un_pop_country <- read_excel("Data/UN/Urban_Population_at_Mid-
Year_by_Country,_2000-2050_(thousands).xlsx")

un_pop_agglom <-
read_excel("Data/UN/Population_in_Urban_Agglomerations.xlsx")

head(un_pop_country)

head(un_pop_agglom)

names(un_pop_agglom)

head(un_pop_agglom)

library(readxl)

library(dplyr)

library(tidyr)

library(openxlsx)

getwd()

un_pop_agglom <-
read_excel("Data/UN/Population_in_Urban_Agglomerations.xlsx")

year_cols <- c("Population in Urban
Agglomerations", "...5", "...6", "...7", "...8", "...9", "...10", "...11")

years_vec <- c(2000, 2005, 2010, 2015, 2020, 2025, 2030, 2035)

baghdad_pop <- un_pop_agglom %>%

  filter(

    `...1` == "Iraq",

    grepl("Baghdad", `...2`, ignore.case = TRUE)

  ) %>%

  pivot_longer(

    cols      = all_of(year_cols),

```

```

    names_to = "colname",

    values_to = "pop_thous"

  ) %>%

  mutate(

    year = years_vec[ match(colname, year_cols) ],

    pop = pop_thous * 1000

  ) %>%

  select(year, pop_thous, pop) %>%

  arrange(year)

baghdad_pop

library(openxlsx)

built <- read.xlsx("Output/Built_Baghdad_terra.xlsx")

head(built)

built <- built %>%

  mutate(

    built_km2 = sum_m2 / 1e6,    # total built-up area in km2

    built_ratio = ratio_sum

  )

baghdad_merged <- built %>%

  inner_join(baghdad_pop, by = "year") %>%

  mutate(

    density_pop_per_km2 = pop / built_km2,    # persons per km2 of
built-up area

```

```

    built_per_capita_m2 = sum_m2 / pop      # built-up surface per
person (m2)

) %>%

arrange(year)

baghdad_merged

if (!dir.exists("Output/Tables")) dir.create("Output/Tables",
recursive = TRUE)

write.xlsx(baghdad_merged,

          file = "Output/Tables/Baghdad_Built_and_Pop_UN.xlsx")

write.csv(baghdad_merged,

          file = "Output/Tables/Baghdad_Built_and_Pop_UN.csv",

          row.names = FALSE)

cat("Merged Baghdad built-up + population saved in Output/Tables.\n")

install.packages("ggplot2")

library(ggplot2)

p_built <- ggplot(baghdad_merged, aes(x = year, y = built_km2)) +

  geom_line() +

  geom_point() +

  labs(

    title = "Baghdad - Built-up area over time",

    x = "Year",

    y = "Built-up area (km2)"

  )

p_pop <- ggplot(baghdad_merged, aes(x = year, y = pop / 1e6)) +

```

```

geom_line() +

geom_point() +

labs(

  title = "Baghdad - Population over time",

  x = "Year",

  y = "Population (millions)"

)

p_percap <- ggplot(baghdad_merged, aes(x = year, y =
built_per_capita_m2)) +

geom_line() +

geom_point() +

labs(

  title = "Baghdad - Built-up area per capita",

  x = "Year",

  y = "Built-up area per person (m2/person)"

)

ggsave("Output/Figures/Fig1_Baghdad_Builtup.png",

  plot = p_built,

  width = 6, height = 4, dpi = 300)

ggsave("Output/Figures/Fig2_Baghdad_Population.png",

  plot = p_pop,

  width = 6, height = 4, dpi = 300)

ggsave("Output/Figures/Fig3_Baghdad_Builtup_perCapita.png",

```

```

plot = p_percap,

width = 6, height = 4, dpi = 300)

```

A.5 WorldPop Population Raster Extraction

This script was used to process WorldPop raster datasets. The raster population layers were cropped and masked to the Baghdad boundary, and the total population within the study area was calculated by summing the raster cell values. The resulting values were exported for later comparison with other population sources.

```

# WorldPop (Iraq, 1km R2025A) -> Baghdad extraction (terra)

rm(list = ls())

library(terra)

library(dplyr)

library(writexl)

boundary_path <-
"Data/Boundaries/Border/Baghdad_OSM_boundary/Baghdad_OSM_boundary.shp"

wp_dir <- "Data/WorldPop/Iraq_1km_R2025A"

wp_files <- c(

  "irq_pop_2015_CN_1km_R2025A_UA_v1.tif",

  "irq_pop_2020_CN_1km_R2025A_UA_v1.tif",

  "irq_pop_2025_CN_1km_R2025A_UA_v1.tif",

  "irq_pop_2030_CN_1km_R2025A_UA_v1.tif"

)

baghdad <- vect(boundary_path)

extract_wp_sum <- function(tif_path, year) {

  r <- rast(tif_path)

```

```

    baghdad_proj <- baghdad

    if (!same.crs(r, baghdad_proj)) {

        baghdad_proj <- project(baghdad_proj, crs(r))

    }

    r_crop <- crop(r, baghdad_proj)

    r_mask <- mask(r_crop, baghdad_proj)

    total_pop <- global(r_mask, fun = "sum", na.rm = TRUE)[1, 1]

    data.frame(

        year = year,

        worldpop_total = as.numeric(total_pop)

    )

}

results <- bind_rows(lapply(wp_files, function(f) {

    year <- as.integer(sub(".*_(\\d{4})_.*", "\\1", f))

    extract_wp_sum(file.path(wp_dir, f), year)

})))

out_csv <- "Output/Tables/Baghdad_WorldPop_2015_2030.csv"

out_xlsx <- "Output/Tables/Baghdad_WorldPop_2015_2030.xlsx"

write.csv(results, out_csv, row.names = FALSE)

write_xlsx(results, out_xlsx)

print(results)

cat("\nSaved:\n", out_csv, "\n", out_xlsx, "\n")

```

A.6 Comparison between UN and WorldPop Population Data

This script compares population estimates derived from United Nations data and WorldPop. It merges the datasets by year, calculates differences between the population estimates, and prepares the comparison outputs for interpretation and visualization.

```
rm(list = ls())

library(dplyr)

library(readr)

library(readxl)

library(writexl)

wp_path <- "Output/Tables/Baghdad_WorldPop_2015_2030.xlsx"

un_path <- "Output/Tables/Baghdad_Built_and_Pop_UN.xlsx"

wp <- read_excel(wp_path) %>%

  rename(worldpop_pop = worldpop_total)

un <- read_excel(un_path)

possible_pop_cols <- c("population", "pop", "pop_total",
  "un_population", "population_total")

pop_col <- possible_pop_cols[possible_pop_cols %in% names(un)][1]

if (is.na(pop_col)) {

  stop(paste(

    " UN population column not found. Available columns are:\n",

    paste(names(un), collapse = ", ")

  ))

}

un2 <- un %>%
```

```

  rename(un_pop = all_of(pop_col)) %>%

  select(year, un_pop)

cmp <- wp %>%

  inner_join(un2, by = "year") %>%

  mutate(

    diff_abs = worldpop_pop - un_pop,

    diff_pct = 100 * diff_abs / un_pop

  ) %>%

  arrange(year)

out_xlsx <- "Output/Tables/Baghdad_UN_vs_WorldPop.xlsx"

out_csv <- "Output/Tables/Baghdad_UN_vs_WorldPop.csv"

write_xlsx(cmp, out_xlsx)

write_csv(cmp, out_csv)

print(cmp)

cat("\nSaved:\n", out_xlsx, "\n", out_csv, "\n")

```

A.7 Integration of Built-Up Area and Population Indicators

This script integrates built-up area indicators with population datasets using the year as the common reference. It was used to calculate combined indicators such as population density and built-up area per capita. In the final thesis interpretation, population density was considered using the fixed Baghdad study-area extent to maintain consistency across population datasets and years.

```

rm(list = ls())

library(dplyr)

library(readxl)

```

```

library(writexl)

un_path <- "Output/Tables/Baghdad_Built_and_Pop_UN.xlsx"

wp_path <- "Output/Tables/Baghdad_WorldPop_2015_2030.xlsx"

un <- read_excel(un_path)

wp <- read_excel(wp_path) %>%

  rename(worldpop_pop = worldpop_total)

possible_pop_cols <- c("population", "pop", "pop_total",
"un_population", "population_total", "un_pop")

pop_col <- possible_pop_cols[possible_pop_cols %in% names(un)][1]

if (is.na(pop_col)) {

  stop(paste(

    "UN population column not found. Columns are:\n",

    paste(names(un), collapse = ", ")

  ))

}

if (!("built_km2" %in% names(un))) {

  stop(paste(

    "built_km2 column not found. Columns are:\n",

    paste(names(un), collapse = ", ")

  ))

}

un2 <- un %>%

  rename(un_pop = all_of(pop_col))

```

```

merged <- un2 %>%

  left_join(wp, by = "year") %>%

  mutate(

    density_un = un_pop / built_km2,

    density_worldpop = worldpop_pop / built_km2,

    built_per_capita_un = (built_km2 * 1e6) / un_pop,

    built_per_capita_worldpop = (built_km2 * 1e6) / worldpop_pop

  ) %>%

  arrange(year)

out_xlsx <- "Output/Tables/Baghdad_Built_and_Pop_UN_WorldPop.xlsx"

write_xlsx(merged, out_xlsx)

print(merged)

cat("\nSaved:\n", out_xlsx, "\n")

```

A.8 UN and WorldPop Indicator Plots

This script was used to produce comparison plots based on United Nations and WorldPop indicators. These visualizations supported the interpretation of population density and built-up area per capita derived from different population sources.

```

rm(list = ls())

library(dplyr)

library(readxl)

library(ggplot2)

in_path <- "Output/Tables/Baghdad_Built_and_Pop_UN_WorldPop.xlsx"

df <- read_excel(in_path)

```

```

df2 <- df %>%

  filter(!is.na(worldpop_pop)) %>%

  select(year,

         density_un, density_worldpop,

         built_per_capita_un, built_per_capita_worldpop)

p_density <- ggplot(df2, aes(x = year)) +

  geom_line(aes(y = density_un, linetype = "UN")) +

  geom_point(aes(y = density_un, shape = "UN")) +

  geom_line(aes(y = density_worldpop, linetype = "WorldPop")) +

  geom_point(aes(y = density_worldpop, shape = "WorldPop")) +

  labs(

    title = "Baghdad - Population density (UN vs WorldPop)",

    x = "Year",

    y = "Population density (people per km2 built-up area)",

    linetype = "Dataset",

    shape = "Dataset"

  )

p_bpc <- ggplot(df2, aes(x = year)) +

  geom_line(aes(y = built_per_capita_un, linetype = "UN")) +

  geom_point(aes(y = built_per_capita_un, shape = "UN")) +

  geom_line(aes(y = built_per_capita_worldpop, linetype = "WorldPop"))
+

  geom_point(aes(y = built_per_capita_worldpop, shape = "WorldPop")) +

```

```

labs(

  title = "Baghdad - Built-up area per capita (UN vs WorldPop)",

  x = "Year",

  y = "Built-up area per capita (m2/person)",

  linetype = "Dataset",

  shape = "Dataset"

)

out1 <- "Output/Figures/Fig_WorldPop_vs_UN_Density.png"

out2 <- "Output/Figures/Fig_WorldPop_vs_UN_BuiltPerCapita.png"

ggsave(out1, p_density, width = 9, height = 5, dpi = 300)

ggsave(out2, p_bpc, width = 9, height = 5, dpi = 300)

print(p_density)

print(p_bpc)

cat("\nSaved:\n", out1, "\n", out2, "\n")

```

A.9 Initial GHS-POP Raster Test

This script was used as an initial test for processing GHS-POP raster data. Similar to the built-up raster workflow, the population raster was cropped and masked to the Baghdad boundary, and the total population within the study area was extracted.

```

library(terra)

pop1975 <- rast("GHS_POP_E1975_GLOBE_R2023A_4326_3ss_V1_0_R6_C23.tif")

plot(pop1975)

plot(pop1975, xlim=c(43,45), ylim=c(32,34))

global(pop1975, "max", na.rm=TRUE)

```

```

baghdad <- vect("Baghdad_OSM_boundary.shp")

baghdad

pop1975_crop <- crop(pop1975, baghdad)

plot(pop1975_crop)

lines(baghdad, col="red", lwd=2)

pop1975_mask <- mask(pop1975_crop, baghdad)

plot(pop1975_mask)

lines(baghdad, col="red", lwd=2)

pop_total_1975 <- global(pop1975_mask, "sum", na.rm = TRUE)

pop_total_1975

pop_total_1975_num <- as.numeric(pop_total_1975[1,1])

result_1975 <- data.frame(

  Year = 1975,

  GHS_pop = pop_total_1975_num

)

result_1975

```

A.10 Multi-Year GHS-POP Population Extraction

This script represents the main GHS-POP processing workflow. It automatically processes multiple GHS-POP raster datasets, extracts the corresponding years, calculates total population values within the Baghdad boundary, orders the results chronologically, and prepares the GHS-POP time series for analysis.

```
library(terra)
```

```

baghdad <-
vect("D:/thesis/Data/Boundaries/Border/Baghdad_OSM_boundary/Baghdad_OS
M_boundary.shp")

crs(baghdad)

files <- list.files(

  "D:/thesis/Data/GHS-POP",

  pattern = "\\\\.tif$",

  recursive = TRUE,

  full.names = TRUE

)

files

results <- data.frame(

  Year = integer(),

  GHS_pop = numeric()

)

for (f in files) {

  year <- as.numeric(gsub(".*E([0-9]{4}).*", "\\1", f))

  r <- rast(f)

  r_crop <- crop(r, baghdad)

  r_mask <- mask(r_crop, baghdad)

  pop <- global(r_mask, "sum", na.rm = TRUE)[1, 1]

  results <- rbind(

    results,

```

```

data.frame(

  Year = year,

  GHS_pop = pop

)

)

}

results <- results[order(results$Year), ]

results$GHS_pop <- round(results$GHS_pop)

results

output_folder <- "D:/thesis/Output/Tables"

write.csv(results,

          file = file.path(output_folder,
"Baghdad_Population_GHS.csv"),

          row.names = FALSE)

library(writexl)

write_xlsx(results,

          path = file.path(output_folder,
"Baghdad_Population_GHS.xlsx"))

library(ggplot2)

results$pop_million <- results$GHS_pop / 1e6

fig_folder <- "D:/thesis/Output/Figures"

p <- ggplot(results, aes(x = Year, y = pop_million)) +

  geom_line(color = "black", linewidth = 1) +

  geom_point(color = "black", size = 3) +

```

```

labs(title = "Baghdad - Population over time by GHS-POP",

      x = "Year",

      y = "Population (millions)") +

theme_minimal(base_size = 16) +

theme(plot.title = element_text(size = 24, face = "bold"),

      axis.title = element_text(size = 18),

      axis.text = element_text(size = 14))

ggsave(filename = file.path(fig_folder, "Baghdad_Population_Growth by
GHS-POP.png"),

      plot = p,

      width = 10, height = 6, dpi = 300)

results$growth_rate <- c(NA, diff(results$GHS_pop) /
head(results$GHS_pop, -1) * 100)

fig_folder <- "D:/thesis/Output/Figures"

p_growth <- ggplot(results, aes(x = Year, y = growth_rate)) +

  geom_line(color = "black", linewidth = 1) +

  geom_point(color = "black", size = 3) +

labs(title = "Baghdad - Population Growth Rate by GHS-POP",

      x = "Year",

      y = "Growth rate (%)") +

theme_minimal(base_size = 16) +

theme(plot.title = element_text(size = 24, face = "bold"),

      axis.title = element_text(size = 18),

      axis.text = element_text(size = 14))

```

```

ggsave(filename = file.path(fig_folder, "Baghdad_Growth_Rate.png"),

        plot = p_growth,

        width = 10, height = 6, dpi = 300)

area_km2 <- expanse(baghdad, unit = "km")

results$density <- results$GHS_pop / area_km2

p_density <- ggplot(results, aes(x = Year, y = density)) +

  geom_line(color = "black", linewidth = 1) +

  geom_point(color = "black", size = 3) +

  labs(title = "Baghdad - Population Density over time by GHS-POP",

        x = "Year",

        y = "Density (people/km2)") +

  theme_minimal(base_size = 16) +

  theme(plot.title = element_text(size = 24, face = "bold"),

        axis.title = element_text(size = 18),

        axis.text = element_text(size = 14))

ggsave(filename = file.path(fig_folder,

"Baghdad_Population_Density.png"),

        plot = p_density,

        width = 10, height = 6, dpi = 300)

```

A.11 Final Comparison Plots and Result Figures

This script was used to generate the main comparison figures and result plots used in the thesis. It includes comparisons between GHS-POP, UN-Habitat, and WorldPop datasets, as well as plots related to population growth, normalized growth, density, built-up area per capita, and the relationship between built-up area and population.

```

UN_Data <-
read.csv("D:/thesis/Output/Tables/Baghdad_UN_vs_WorldPop.csv")

Worldpop_Data <-
read.csv("D:/thesis/Output/Tables/Baghdad_WorldPop_2015_2030.csv")

GHS_Data <-
read.csv("D:/thesis/Output/Tables/Baghdad_Population_GHS.csv")

head(UN_Data)

head(Worldpop_Data)

UN_compare <- UN_Data[, c("year", "worldpop_pop", "un_pop")]

names(UN_compare) <- c("Year", "WP_pop", "UN_pop")

head(UN_compare)

head(GHS_Data)

comparison <- merge(GHS_Data, UN_compare, by = "Year", all = TRUE)

comparison

comparison$diff_GHS_UN_abs <- comparison$GHS_pop - comparison$UN_pop

comparison$diff_GHS_UN_pct <- (comparison$GHS_pop - comparison$UN_pop)
/ comparison$UN_pop * 100

comparison$diff_GHS_WP_abs <- comparison$GHS_pop - comparison$WP_pop

comparison$diff_GHS_WP_pct <- (comparison$GHS_pop - comparison$WP_pop)
/ comparison$WP_pop * 100

comparison

out_folder <- "D:/thesis/Output/Tables"

write.csv(comparison,

          file = file.path(out_folder,
"Comparison_GHS_UN_WorldPop.csv"),

```

```

    row.names = FALSE)

library(writexl)

out_folder <- "D:/thesis/Output/Tables"

write_xlsx(comparison,

            path = file.path(out_folder,
                              "Comparison_GHS_UN_WorldPop.xlsx"))

library(ggplot2)

GHS_Data$abs_increase <- c(NA, diff(GHS_Data$GHS_pop))

fig_folder <- "D:/thesis/Output/Figures"

GHS_abs <- GHS_Data[!is.na(GHS_Data$abs_increase), ]

p_abs <- ggplot(GHS_abs, aes(x = Year, y = abs_increase / 1e6)) +

  geom_line(color = "black", linewidth = 1) +

  geom_point(color = "black", size = 3) +

  labs(title = "Baghdad - Absolute Population Increase by GHS-POP",

        x = "Year",

        y = "Increase (millions)") +

  theme_minimal(base_size = 16) +

  theme(plot.title = element_text(size = 24, face = "bold"),

        axis.title = element_text(size = 18),

        axis.text = element_text(size = 14))

ggsave(filename = file.path(fig_folder,
                              "Baghdad_Absolute_Population_Increase_GHS.png"),

        plot = p_abs,

        width = 10, height = 6, dpi = 300)

```

```

p_abs

GHS_Data$norm_growth <- GHS_Data$GHS_pop / GHS_Data$GHS_pop[1]

p_norm <- ggplot(GHS_Data, aes(x = Year, y = norm_growth)) +

  geom_line(color = "black", linewidth = 1) +

  geom_point(color = "black", size = 3) +

  labs(title = "Baghdad - Normalized Population Growth (1975 = 1)",

        x = "Year",

        y = "Relative Growth") +

  theme_minimal(base_size = 16) +

  theme(plot.title = element_text(size = 24, face = "bold"),

        axis.title = element_text(size = 18),

        axis.text = element_text(size = 14))

ggsave(file.path("D:/thesis/Output/Figures",

                  "Baghdad_Normalized_Growth_GHS.png"),

        plot = p_norm,

        width = 10, height = 6, dpi = 300)

p_norm

comparison$GHS_growth <- c(NA, diff(comparison$GHS_pop) /
head(comparison$GHS_pop, -1) * 100)

comparison$UN_growth <- c(NA, diff(comparison$UN_pop) /
head(comparison$UN_pop, -1) * 100)

comparison$WP_growth <- c(NA, diff(comparison$WP_pop) /
head(comparison$WP_pop, -1) * 100)

```

```

library(reshape2)

comp_long <- melt(comparison[, c("Year", "GHS_growth", "UN_growth",
"WP_growth")],

                id.vars = "Year")

p_comp_growth <- ggplot(comp_long, aes(x = Year, y = value, color =
variable)) +

  geom_line(linewidth = 1) +

  geom_point(size = 2) +

  labs(title = "Baghdad - Growth Rate Comparison (GHS vs UN vs
WorldPop)",

        x = "Year",

        y = "Growth rate (%)",

        color = "Dataset") +

  theme_minimal(base_size = 16) +

  theme(plot.title = element_text(size = 22, face = "bold"))

ggsave("D:/thesis/Output/Figures/Comparison_Growth_Rate.png",

        plot = p_comp_growth,

        width = 10, height = 6, dpi = 300)

p_comp_growth

common_years <- c(2015, 2020, 2025)

comparison_common <- comparison[comparison$Year %in% common_years, ]

comparison_common

comparison_common_clean <- comparison_common[, c(

  "Year", "GHS_pop", "WP_pop", "UN_pop",

```

```

    "diff_GHS_UN_abs", "diff_GHS_UN_pct",

    "diff_GHS_WP_abs", "diff_GHS_WP_pct",

    "GHS_growth", "UN_growth", "WP_growth"

  )]

comparison_common_clean <-
comparison_common_clean[order(comparison_common_clean$Year), ]

out_folder <- "D:/thesis/Output/Tables"

write.csv(comparison_common_clean,

          file = file.path(out_folder,
"Comparison_Common_Years_2015_2025.csv"),

          row.names = FALSE)

library(writexl)

write_xlsx(comparison_common_clean,

           path = file.path(out_folder,
"Comparison_Common_Years_2015_2025.xlsx"))

comparison_common_clean

library(tidyr)

library(ggplot2)

comp_long_pop <- pivot_longer(

  comparison_common_clean,

  cols = c(GHS_pop, WP_pop, UN_pop),

  names_to = "Dataset",

  values_to = "Population"

)

```

```

comp_long_pop$Population <- comp_long_pop$Population / 1e6

p_pop_comp <- ggplot(comp_long_pop, aes(x = Year, y = Population,
color = Dataset)) +

  geom_line(linewidth = 1) +

  geom_point(size = 3) +

  labs(

    title = "Baghdad - Population Comparison (2015-2025)",

    x = "Year",

    y = "Population (millions)",

    color = "Dataset"

  ) +

  theme_minimal(base_size = 16) +

  theme(plot.title = element_text(size = 22, face = "bold"))

ggsave("D:/thesis/Output/Figures/Comparison_Population_2015_2025.png",

  plot = p_pop_comp,

  width = 10, height = 6, dpi = 300)

p_pop_comp

library(terra)

baghdad <-
vect("D:/thesis/Data/Boundaries/Border/Baghdad_OSM_boundary/Baghdad_OS
M_boundary.shp")

area_km2 <- expanse(baghdad, unit = "km")

area_km2

area_km2 <- 861.6952

```

```

    comparison_common_clean$GHS_density <-
comparison_common_clean$GHS_pop / area_km2

    comparison_common_clean$UN_density  <- comparison_common_clean$UN_pop
/ area_km2

    comparison_common_clean$WP_density  <- comparison_common_clean$WP_pop
/ area_km2

    library(tidyr)

    library(ggplot2)

    comp_long_density <- pivot_longer(

    comparison_common_clean,

    cols = c(GHS_density, UN_density, WP_density),

    names_to = "Dataset",

    values_to = "Density"

    )

p_density_comp <- ggplot(comp_long_density, aes(x = Year, y = Density,
color = Dataset)) +

    geom_line(linewidth = 1) +

    geom_point(size = 3) +

    labs(

        title = "Baghdad - Population Density Comparison (2015-2025)",

        x = "Year",

        y = "Density (people/km2)",

        color = "Dataset"

    ) +

    theme_minimal(base_size = 16) +

```

```

    theme(plot.title = element_text(size = 22, face = "bold"))

ggsave("D:/thesis/Output/Figures/Comparison_Density_2015_2025.png",

    plot = p_density_comp,

    width = 10, height = 6, dpi = 300)

p_density_comp

library(tidyr)

library(ggplot2)

built_long <- pivot_longer(

    built_data,

    cols = c(built_per_capita_un, built_per_capita_worldpop),

    names_to = "Dataset",

    values_to = "Built_per_capita"

)

p_built_capita <- ggplot(built_long, aes(x = year, y =
Built_per_capita, color = Dataset)) +

    geom_line(linewidth = 1) +

    geom_point(size = 3) +

    labs(

        title = "Baghdad - Built-up Area per Capita (UN vs WorldPop)",

        x = "Year",

        y = "Built-up area per capita (m2/person)",

        color = "Dataset"

    ) +

```

```

theme_minimal(base_size = 16) +

theme(plot.title = element_text(size = 22, face = "bold"))

ggsave("D:/thesis/Output/Figures/Comparison_BuiltUp_perCapita_2015_202
5.png",

      plot = p_built_capita,

      width = 10, height = 6, dpi = 300)

p_built_capita

library(ggplot2)

built_long_common <- built_long[built_long$year >= 2015, ]

p_built_capita_common <- ggplot(built_long_common,

                                aes(x = year, y = Built_per_capita,
color = Dataset)) +

  geom_line(linewidth = 1) +

  geom_point(size = 3) +

  labs(

    title = "Baghdad - Built-up Area per Capita Comparison (2015-
2025)",

    x = "Year",

    y = "Built-up area per capita (m2/person)",

    color = "Dataset"

  ) +

theme_minimal(base_size = 16) +

theme(

  plot.title = element_text(size = 22, face = "bold"),

```

```

    axis.title = element_text(size = 18),

    axis.text = element_text(size = 14)

)

ggsave(

  filename =
"D:/thesis/Output/Figures/Comparison_BuiltUp_perCapita_Common_2015_202
5.png",

  plot = p_built_capita_common,

  width = 10,

  height = 6,

  dpi = 300

)

p_built_capita_common

library(ggplot2)

p_scatter <- ggplot(built_data, aes(x = worldpop_pop, y =
built_km2)) +

  geom_point(size = 3, color = "black") +

  geom_smooth(method = "lm", se = FALSE, color = "red", linewidth =
1) +

  labs(

    title = "Baghdad - Built-up Area vs Population (WorldPop)",

    x = "Population (WorldPop)",

    y = "Built-up area (km2)"

  ) +

  theme_minimal(base_size = 16) +

```

```

theme(

  plot.title = element_text(size = 22, face = "bold"),

  axis.title = element_text(size = 18),

  axis.text = element_text(size = 14)

)

ggsave(

  filename =
"D:/thesis/Output/Figures/Scatter_Built_vs_Population_WorldPop.png",

  plot = p_scatter,

  width = 10,

  height = 6,

  dpi = 300

)

p_scatter

built_scatter_long <- rbind(

  data.frame(pop = built_data$un_pop, built = built_data$built_km2,
Dataset = "UN"),

  data.frame(pop = built_data$worldpop_pop, built =
built_data$built_km2, Dataset = "WorldPop")

)

p_scatter_compare <- ggplot(built_scatter_long, aes(x = pop, y =
built, color = Dataset)) +

  geom_point(size = 3) +

  geom_smooth(method = "lm", se = FALSE, linewidth = 1) +

  labs(

```

```

    title = "Baghdad - Built-up Area vs Population (UN vs WorldPop)",

    x = "Population",

    y = "Built-up area (km2)",

    color = "Dataset"

) +

theme_minimal(base_size = 16) +

theme(plot.title = element_text(size = 22, face = "bold"))

ggsave(

  filename =

"D:/thesis/Output/Figures/Scatter_Built_vs_Population_Comparison.png",

  plot = p_scatter_compare,

  width = 10,

  height = 6,

  dpi = 300

)

p_scatter_compare

library(readxl)

built_data <-
read_excel("D:/thesis/Output/Tables/Baghdad_Built_and_Pop_UN_WorldPop.
xlsx")

comparison <-
read_excel("D:/thesis/Output/Tables/Comparison_GHS_UN_WorldPop.xlsx")

scatter_data <- merge(

  built_data[, c("year", "built_km2")],

  comparison[, c("Year", "GHS_pop", "UN_pop", "WP_pop")],

```

```

    by.x = "year",

    by.y = "Year",

    all = FALSE

)

scatter_data

scatter_common <- scatter_data[scatter_data$year %in% c(2015, 2020,
2025), ]

scatter_common

write.csv(

    scatter_common,

    "D:/thesis/Output/Tables/Scatter_Common_2015_2025.csv",

    row.names = FALSE

)

library(writexl)

write_xlsx(

    scatter_common,

    "D:/thesis/Output/Tables/Scatter_Common_2015_2025.xlsx"

)

library(ggplot2)

scatter_long <- rbind(

    data.frame(year = scatter_common$year,

               built_km2 = scatter_common$built_km2,

               Population = scatter_common$GHS_pop,

```

```

        Dataset = "GHS-POP"),

data.frame(year = scatter_common$year,

          built_km2 = scatter_common$built_km2,

          Population = scatter_common$UN_pop,

          Dataset = "UN"),

data.frame(year = scatter_common$year,

          built_km2 = scatter_common$built_km2,

          Population = scatter_common$WP_pop,

          Dataset = "WorldPop")

)

p_scatter_all <- ggplot(scatter_long,

                        aes(x = Population, y = built_km2, color =
Dataset)) +

geom_point(size = 3) +

geom_line(aes(group = Dataset), linewidth = 1) +

labs(

  title = "Baghdad - Built-up Area vs Population (2015-2025)",

  x = "Population",

  y = "Built-up area (km2)",

  color = "Dataset"

) +

theme_minimal(base_size = 16) +

theme(

```

```

    plot.title = element_text(size = 22, face = "bold"),

    axis.title = element_text(size = 18),

    axis.text = element_text(size = 14)

  )

  ggsave(

    filename =
"D:/thesis/Output/Figures/Scatter_Built_vs_Population_All_2015_2025.png",

    plot = p_scatter_all,

    width = 10,

    height = 6,

    dpi = 300

  )

  p_scatter_all

  library(readxl)

  library(tidyr)

  library(ggplot2)

  built_compare <-
read_excel("D:/thesis/Output/Tables/Scatter_Common_2015_2025.xlsx")

  built_compare$built_per_capita_GHS <- built_compare$built_km2 *
1e6 / built_compare$GHS_pop

  built_compare$built_per_capita_UN <- built_compare$built_km2 *
1e6 / built_compare$UN_pop

  built_compare$built_per_capita_Worldpop <-
built_compare$built_km2 * 1e6 / built_compare$WP_pop

```

```

    built_long_all <- pivot_longer(

    built_compare,

    cols = c(built_per_capita_GHS, built_per_capita_UN,
    built_per_capita_Worldpop),

    names_to = "Dataset",

    values_to = "Built_per_capita"

)

    p_built_capita_all <- ggplot(

    built_long_all,

    aes(x = year, y = Built_per_capita, color = Dataset)

) +

    geom_point(size = 3) +

    geom_line(aes(group = Dataset), linewidth = 1) +

    labs(

        title = "Baghdad - Built-up Area per Capita Comparison (2015-
2025)",

        x = "Year",

        y = "Built-up area per capita (m2/person)",

        color = "Dataset"

) +

    theme_minimal(base_size = 16) +

    theme(

        plot.title = element_text(size = 22, face = "bold"),

        axis.title = element_text(size = 18),

```

```

    axis.text = element_text(size = 14)

  )

  ggsave(

    filename =
"D:/thesis/Output/Figures/Comparison_BuiltUp_perCapita_All_2015_2025.png",

    plot = p_built_capita_all,

    width = 10,

    height = 6,

    dpi = 300

  )

p_built_capita_all

library(ggplot2)

library(tidyr)

comparison <-
read_excel("D:/thesis/Output/Tables/Scatter_Common_2015_2025.xlsx")

comparison$diff_GHS_UN_pct <- (comparison$GHS_pop -
comparison$UN_pop) / comparison$UN_pop * 100

comparison$diff_GHS_WP_pct <- (comparison$GHS_pop -
comparison$WP_pop) / comparison$WP_pop * 100

diff_long <- pivot_longer(

comparison,

cols = c(diff_GHS_UN_pct, diff_GHS_WP_pct),

names_to = "Comparison",

values_to = "Difference_pct"

```

```

)

p_diff <- ggplot(diff_long,

                  aes(x = year, y = Difference_pct, color =
Comparison)) +

geom_point(size = 3) +

geom_line(aes(group = Comparison), linewidth = 1) +

labs(

  title = "Baghdad - Population Difference (GHS vs UN vs
WorldPop)",

  x = "Year",

  y = "Difference (%)",

  color = "Comparison"

) +

theme_minimal(base_size = 16) +

theme(

  plot.title = element_text(size = 22, face = "bold")

)

ggsave(

"D:/thesis/Output/Figures/Difference_GHS_vs_UN_WP.png",

plot = p_diff,

width = 10,

height = 6,

dpi = 300

)

```

```

p_diff

library(ggplot2)

library(tidyr)

comparison <-
read_excel("D:/thesis/Output/Tables/Scatter_Common_2015_2025.xlsx")

comparison$GHS_growth <- c(NA, diff(comparison$GHS_pop) /
head(comparison$GHS_pop, -1) * 100)

comparison$UN_growth <- c(NA, diff(comparison$UN_pop) /
head(comparison$UN_pop, -1) * 100)

comparison$WP_growth <- c(NA, diff(comparison$WP_pop) /
head(comparison$WP_pop, -1) * 100)

comparison_growth <- comparison[-1, ]

growth_long <- pivot_longer(

comparison_growth,

cols = c(GHS_growth, UN_growth, WP_growth),

names_to = "Dataset",

values_to = "Growth_rate"

)

p_growth_clean <- ggplot(growth_long,

aes(x = year, y = Growth_rate, color =
Dataset)) +

geom_point(size = 3) +

geom_line(aes(group = Dataset), linewidth = 1) +

labs(

```

```

    title = "Baghdad - Population Growth Rate Comparison (2015-
2025)",

    x = "Year",

    y = "Growth Rate (%)",

    color = "Dataset"

) +

theme_minimal(base_size = 16) +

theme(

  plot.title = element_text(size = 22, face = "bold")

)

ggsave(

"D:/thesis/Output/Figures/Growth_Comparison_2015_2025.png",

plot = p_growth_clean,

width = 10,

height = 6,

dpi = 300

)

p_growth_clean

library(ggplot2)

library(tidyr)

library(readxl)

comparison <-

read_excel("D:/thesis/Output/Tables/Scatter_Common_2015_2025.xlsx")

```

```

    comparison$GHS_norm <- comparison$GHS_pop /
comparison$GHS_pop[comparison$year == 2015]

    comparison$UN_norm <- comparison$UN_pop /
comparison$UN_pop[comparison$year == 2015]

    comparison$WP_norm <- comparison$WP_pop /
comparison$WP_pop[comparison$year == 2015]

    norm_long <- pivot_longer(

comparison,

cols = c(GHS_norm, UN_norm, WP_norm),

names_to = "Dataset",

values_to = "Normalized_value"

)

    p_norm <- ggplot(norm_long,

                      aes(x = year, y = Normalized_value, color =
Dataset)) +

    geom_point(size = 3) +

    geom_line(aes(group = Dataset), linewidth = 1) +

    labs(

      title = "Baghdad - Normalized Population Growth (2015 = 1)",

      x = "Year",

      y = "Relative Growth",

      color = "Dataset"

    ) +

    theme_minimal(base_size = 16) +

    theme(

```

```

    plot.title = element_text(size = 22, face = "bold")
  )

  ggsave(

"D:/thesis/Output/Figures/Normalized_Growth_2015_2025.png",

plot = p_norm,

width = 10,

height = 6,

dpi = 300

)

p_norm

library(ggplot2)

library(readxl)

library(dplyr)

built_compare <-
read_excel("D:/thesis/Output/Tables/Scatter_Common_2015_2025.xlsx")

scatter_long <- bind_rows(

data.frame(

  year = built_compare$year,

  pop = built_compare$GHS_pop,

  built = built_compare$built_km2,

  Dataset = "GHS-POP"

),

data.frame(

```

```

    year = built_compare$year,

    pop = built_compare$UN_pop,

    built = built_compare$built_km2,

    Dataset = "UN"

),

data.frame(

    year = built_compare$year,

    pop = built_compare$WP_pop,

    built = built_compare$built_km2,

    Dataset = "WorldPop"

)

)

p_efficiency <- ggplot(scatter_long,

                        aes(x = pop, y = built, color = Dataset)) +

geom_point(size = 3) +

geom_line(aes(group = Dataset), linewidth = 1) +

geom_text(aes(label = year), vjust = -1, size = 4, show.legend =
FALSE) +

labs(

    title = "Baghdad - Built-up Area vs Population (2015-2025)",

    x = "Population",

    y = "Built-up area (km2)",

    color = "Dataset"

```

```

) +

theme_minimal(base_size = 16) +

theme(

  plot.title = element_text(size = 22, face = "bold")

)

ggsave(

"D:/thesis/Output/Figures/Urban_Efficiency_Improved.png",

plot = p_efficiency,

width = 10,

height = 6,

dpi = 300

)

p_efficiency

```

Note on Density Calculation

During the development of the analysis, different exploratory indicators were tested. For the final thesis Results chapter, population density was interpreted using the fixed Baghdad study-area extent. This approach was adopted to ensure that density values remained comparable across GHS-POP, UN-Habitat, and WorldPop datasets. Any alternative density calculation appearing in earlier scripts should be understood as exploratory and not as the main density definition used in the final interpretation.

Appendix B – Additional Figures, Maps, and Tables

This appendix includes additional visual and tabular materials generated during the spatial and demographic analysis of Baghdad. These materials were not all included in

the main Results chapter in order to keep the thesis body clear and focused. However, they are provided here to support transparency, reproducibility, and a more complete understanding of the analytical outputs.

B.1 – Additional Built-Up Area Maps

This section presents the additional GHSL built-up area maps generated for Baghdad. While selected maps were used in the main Results chapter to support the interpretation of urban expansion, the complete map series provides a broader visual overview of how the spatial distribution of built-up areas evolved across the analyzed years.

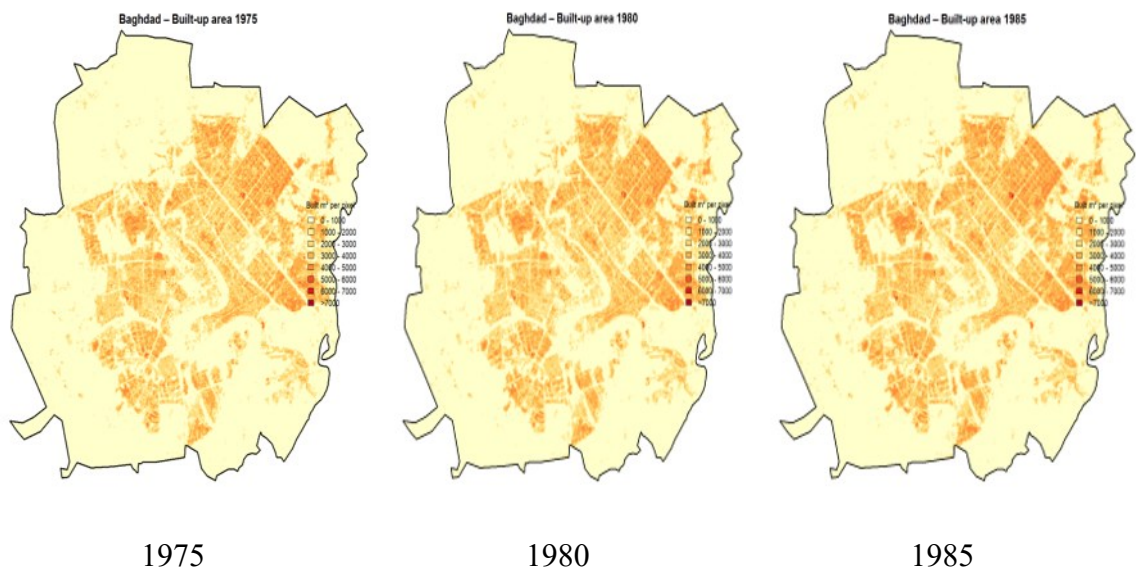


Figure 12. Spatial distribution of built-up area in Baghdad in 1975, 1980 and 1985 based on the GHS-BUILT-S dataset.

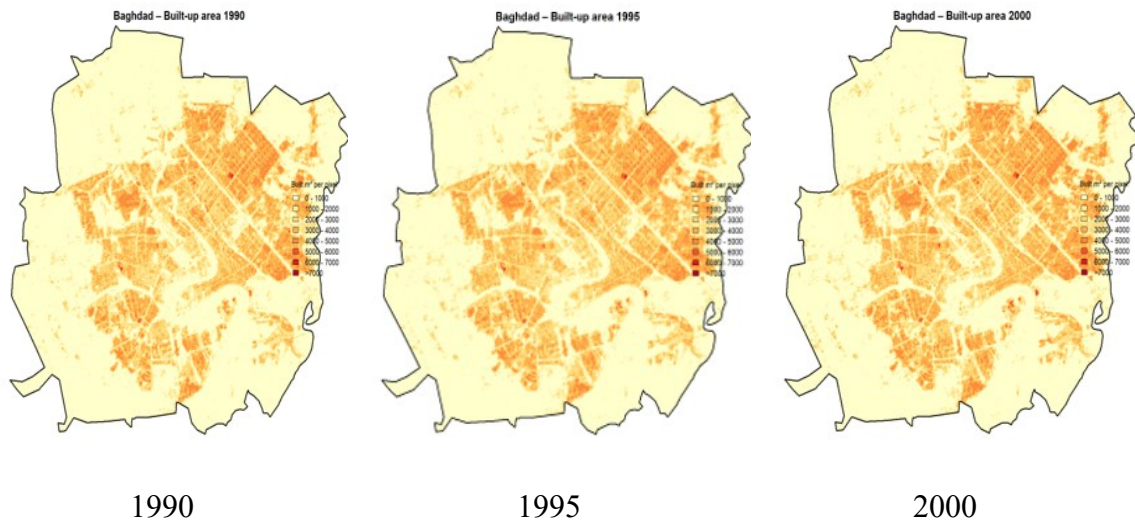


Figure 13. Spatial distribution of built-up area in Baghdad in 1990, 1995 and 2000 based on the GHS-BUILT-S dataset.

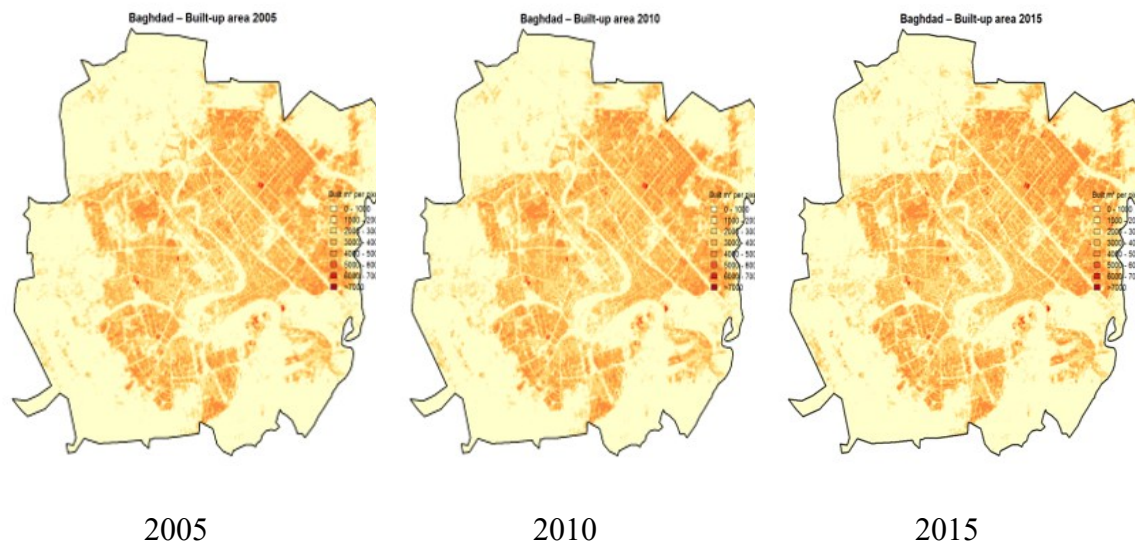


Figure 14. Spatial distribution of built-up area in Baghdad in 2005, 2010 and 2015 based on the GHS-BUILT-S dataset.

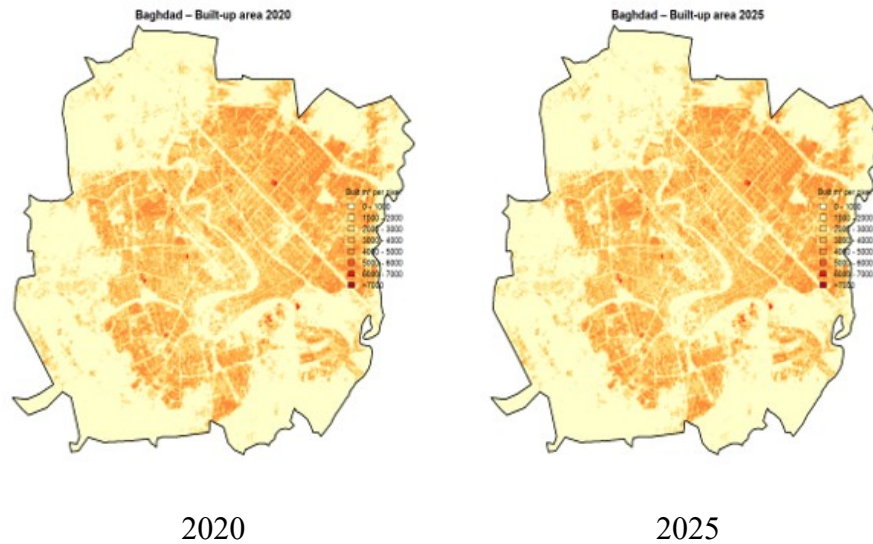


Figure 15. Spatial distribution of built-up area in Baghdad in 2020 and 2025 based on the GHS-BUILT-S dataset.

The built-up area maps reveal a clear temporal evolution of urban development in Baghdad between 1975 and 2025, characterized by both spatial expansion and increasing built-up density.

During the early period (1975–1990), built-up areas are mainly concentrated in the central parts of the city, with relatively low built-up density in peripheral zones. Urban development appears compact, with limited outward expansion.

From the mid-1990s to 2010, a noticeable expansion of built-up areas toward the outskirts of Baghdad is observed. This period is characterized by both horizontal expansion and infilling of previously low-density areas, leading to a more continuous urban fabric.

In the most recent years (2015–2025), high built-up density values become more widespread across the city. Urban growth appears increasingly characterized by densification rather than extensive spatial expansion, suggesting a more mature stage of urban development.

B.2 – Supporting Built-Up Area and Population Figures

Appendix B.2 presents supporting figures derived from the GHS-POP dataset. These figures complement the main Results chapter by showing additional demographic indicators, including absolute population increase, growth rate, population density, and

normalized population growth. They are included as supplementary material to provide a broader view of Baghdad's long-term demographic evolution, while the main interpretation remains focused on the selected figures and comparisons presented in Chapter 5.

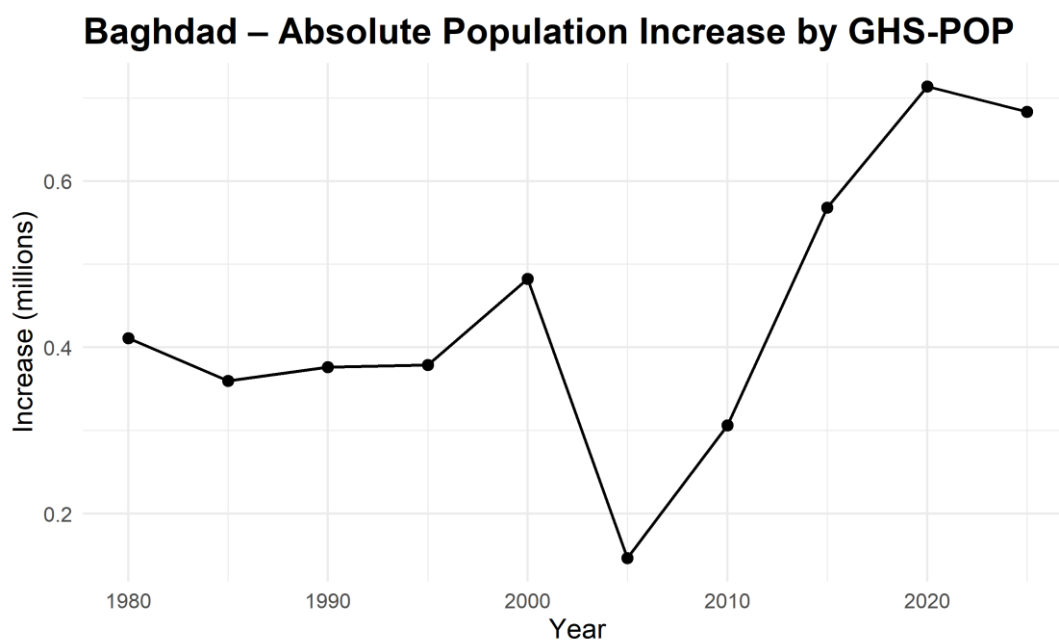


Figure 16. Absolute population increase in Baghdad based on GHS-POP estimates.

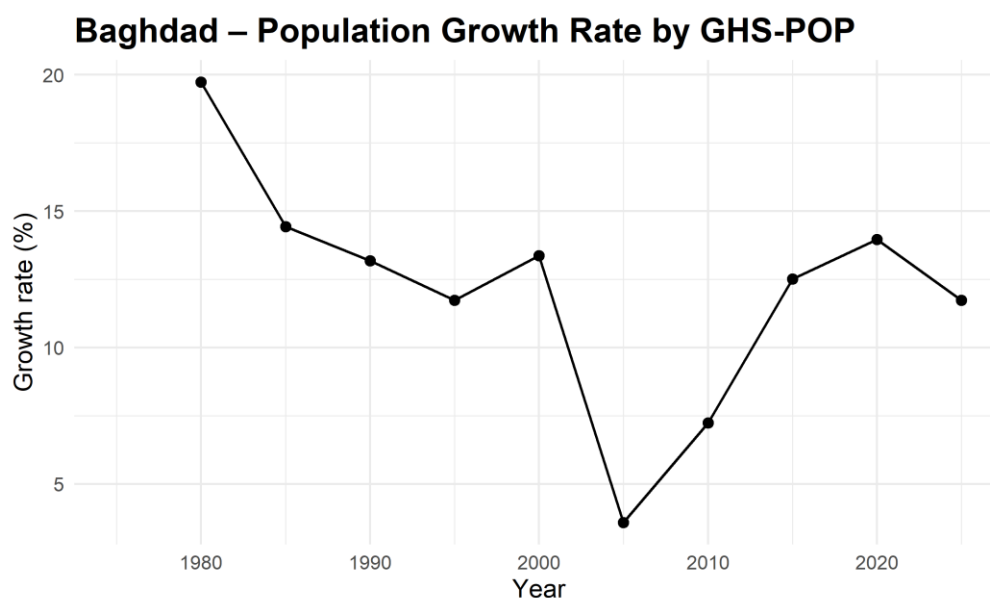


Figure 17. Population growth rate in Baghdad based on GHS-POP estimates.

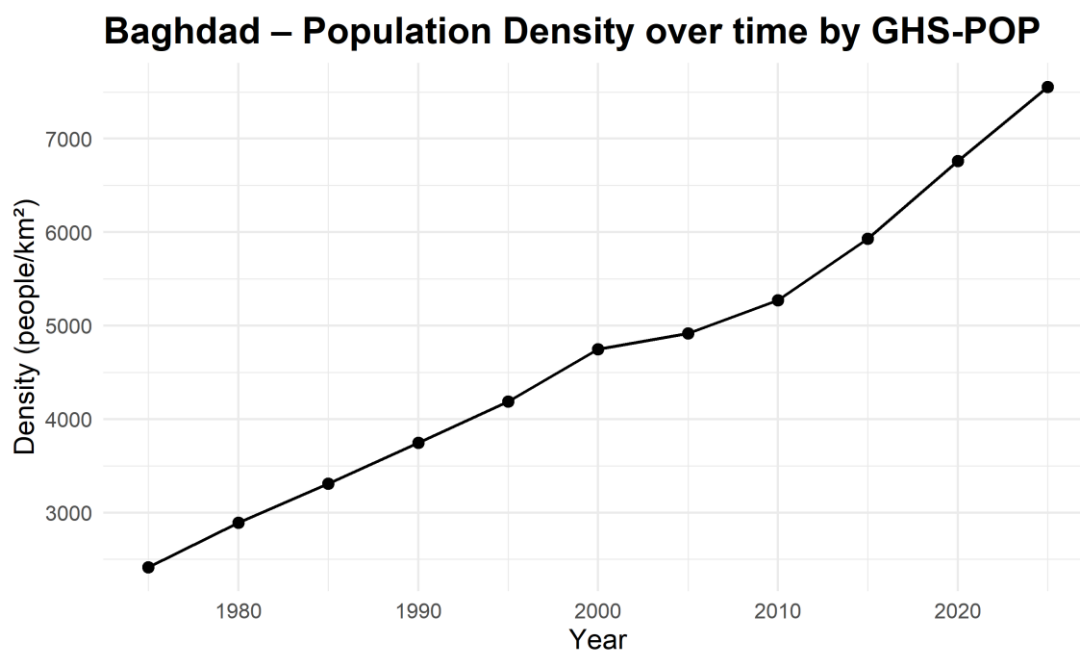


Figure 18. Population density trend in Baghdad based on GHS-POP estimates.

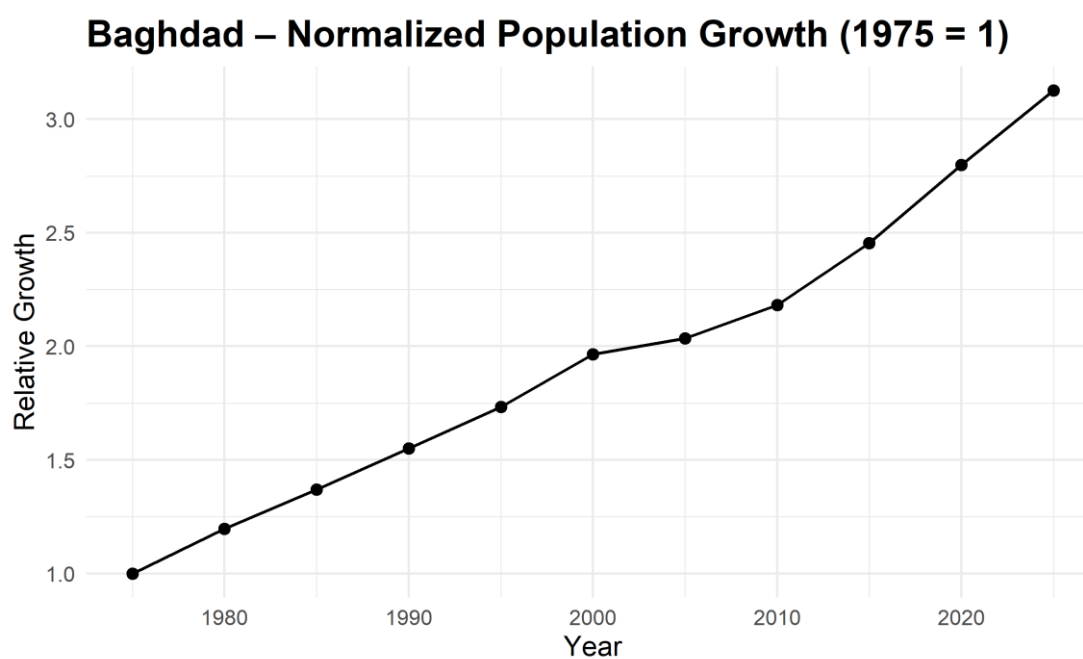


Figure 19. Normalized population growth in Baghdad based on GHS-POP, using 1975 as the reference year.

B.3 – Additional Dataset Comparison Figures

Appendix B.3 presents additional comparison figures used to support the interpretation of population dataset differences. These figures show how GHS-POP differs from UN-Habitat and WorldPop estimates, how population growth rates vary between the common comparison years, and how the relationship between built-up area and population changes depending on the population source used. These figures are included as supplementary material, while the main interpretation remains based on the selected comparison figures presented in Chapter 5.

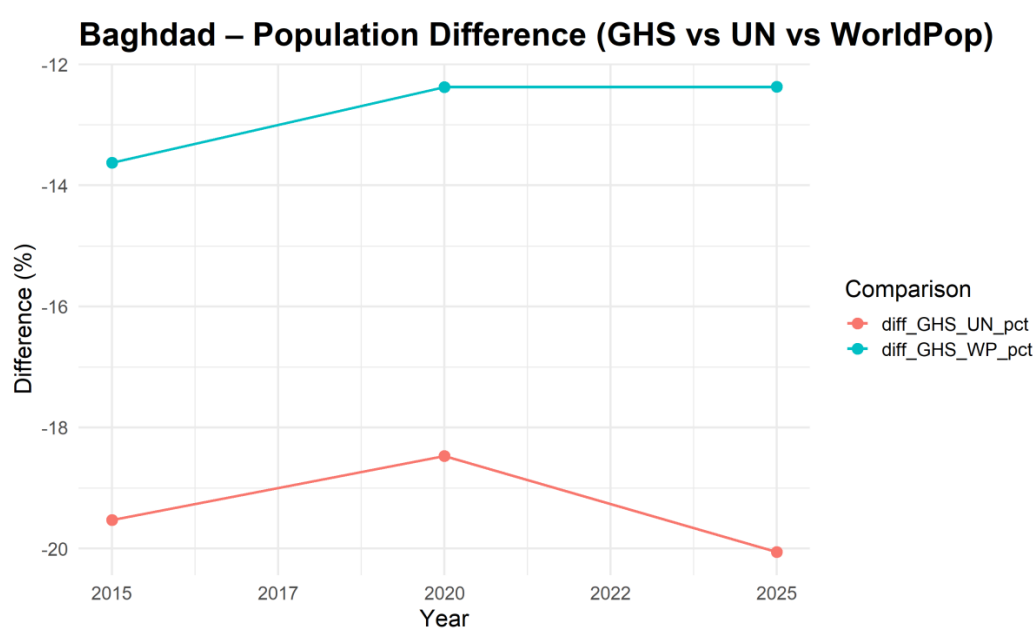


Figure 20. *Percentage difference between GHS-POP and the UN and WorldPop population estimates for Baghdad.*

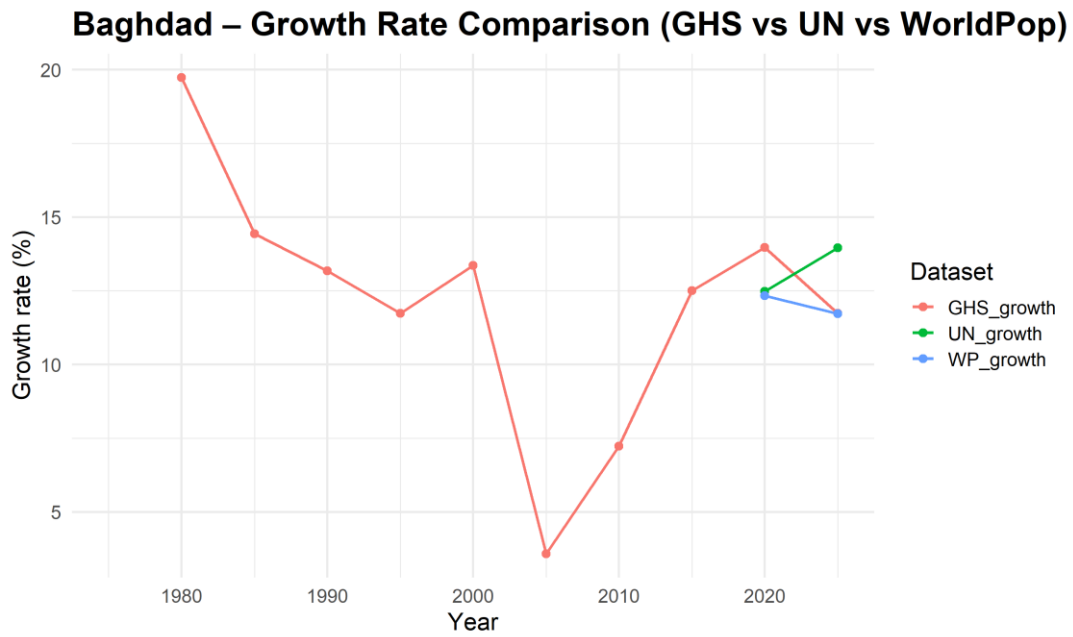


Figure 21. Population growth-rate comparison for Baghdad based on available GHS-POP, UN data, and WorldPop.

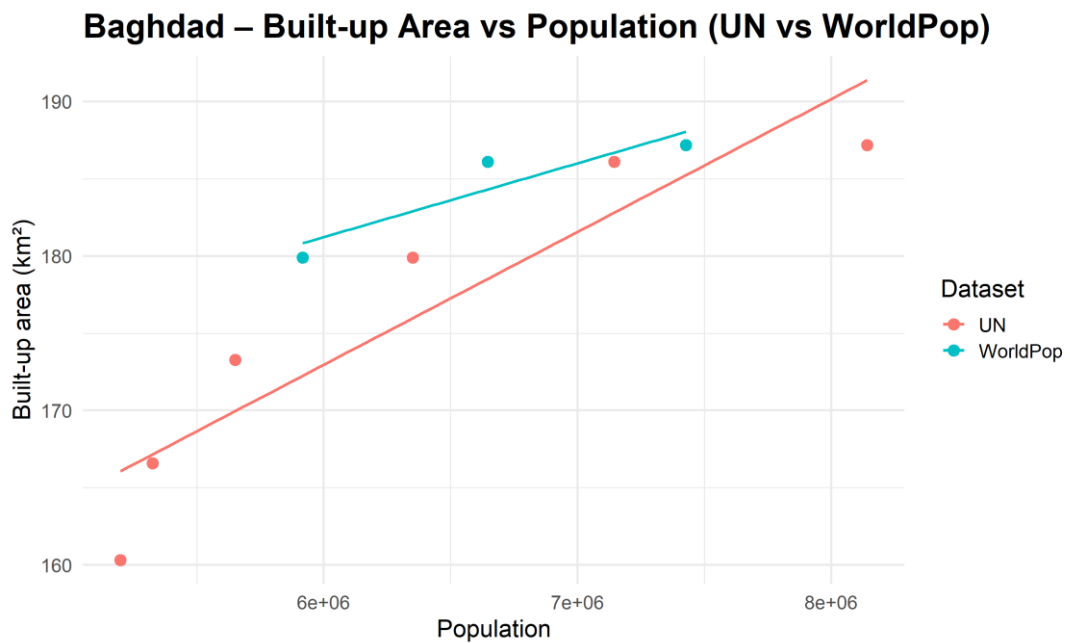


Figure 22. Relationship between built-up area and population in Baghdad based on UN and WorldPop estimates.

B.4 – Full and Supporting Tables

Appendix B.4 presents supporting tables generated during the analysis. These tables provide the complete population comparison dataset and additional comparison indicators used to support the Results chapter. They are included as supplementary material to show the intermediate and supporting values behind the population dataset comparison.

Tables that include exploratory or intermediate indicators are not used for the main interpretation unless they follow the same definitions adopted in the Results chapter.

Table 9. Full population comparison dataset for Baghdad based on GHS-POP, UN data, and WorldPop.

Year	GHS-POP pop.	WorldPop pop.	UN pop.	GHS-POP – UN diff. (persons)	GHS-POP – UN diff. (%)	GHS-POP – WorldPop diff. (persons)	GHS-POP – WorldPop diff. (%)
1975	2,082,132	N/A	N/A	N/A	N/A	N/A	N/A
1980	2,492,966	N/A	N/A	N/A	N/A	N/A	N/A
1985	2,852,704	N/A	N/A	N/A	N/A	N/A	N/A
1990	3,228,758	N/A	N/A	N/A	N/A	N/A	N/A
1995	3,607,578	N/A	N/A	N/A	N/A	N/A	N/A
2000	4,089,733	N/A	N/A	N/A	N/A	N/A	N/A
2005	4,236,432	N/A	N/A	N/A	N/A	N/A	N/A
2010	4,542,758	N/A	N/A	N/A	N/A	N/A	N/A
2015	5,111,021	5,917,296	6,351,400	-1,240,379	-19.53	-806,275	-13.63
2020	5,824,778	6,647,371	7,144,260	-1,319,482	-18.47	-822,593	-12.37
2025	6,508,322	7,427,081	8,141,119	-1,632,797	-20.06	-918,759	-12.37

Table 10. Supporting comparison between WorldPop and UN population estimates for Baghdad.

Year	WorldPop population	UN population	WorldPop – UN difference (persons)	WorldPop – UN difference (%)
2015	5,917,296	6,351,400	-434,104	-6.83
2020	6,647,371	7,144,260	-496,889	-6.96
2025	7,427,081	8,141,119	-714,038	-8.77

B.5 – Notes on Supplementary Materials

The figures, maps, and tables included in this appendix were used as supporting material during the analysis. They complement the Results chapter by providing a more complete view of the intermediate and final outputs. The main interpretation of the thesis remains based on the selected figures and tables presented in Chapter 5, while Appendix B serves as additional documentation of the analytical process.