A guideline to support the monitoring of SDG 11

Using open geospatial data extracted by Earth observation and Machine Learning

ZAHRA TORABI DASHTI

July 2022

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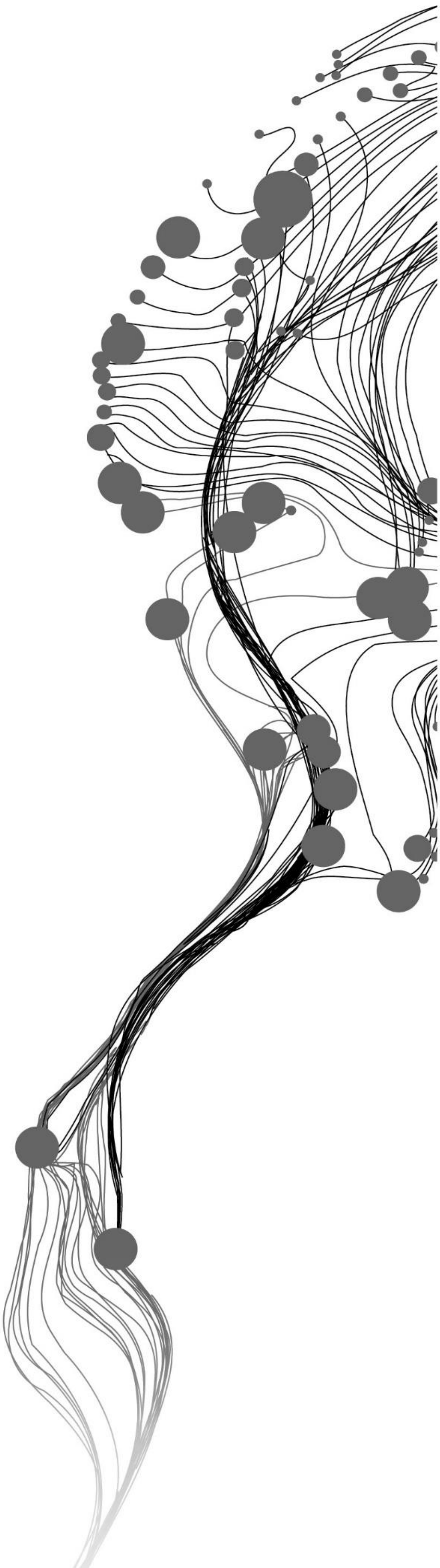

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Using open geospatial data extracted by Earth observation and Machine Learning

ZAHRA TORABI DASHTI

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ABSTRACT

Agenda 2030 have defined Sustainable Development Goal 11 to make cities and human settlements inclusive, safe, resilient, and sustainable. There are also specified targets of SDG11 to help cities overcome their challenges, grow, and thrive. 15 indicators have been defined for monitoring the achievement towards the targets. But, due to poor access to open and standardized data and the lack of institutions for comprehensive data collection, monitoring the progress toward these goals becomes difficult which makes it hard to accomplish them. This study proposes a guideline for monitoring the three SDG indicators; access to public transport, land use efficiency, and access to public spaces, with the aim of solving the problem of obtaining required data to evaluate them for the city of Tehran (whose organizations and institutions face data restrictions). For assessing the access to public transport, the walking distance to the public transport stations has been set as a criteria. This criterion is used for determining the service area of public transport system. For calculating this indicator, data for stations and roads are captured from Open Street Map and analyzed through the Network Analysis tool in ArcMap. Since the monitoring of the indicator progress needs the calculation of indicator in a past date, historical data of public transport stations and roads were collected from the Tehran municipality dataset. Land use efficiency is assessed by computing the land consumption rate per population growth rate. For calculating the land consumption rate data of built-up areas of two different times are captured from the World Settlement Footprint layer. The population data of the Tehran municipality statistical year book is used for computing population growth rate. Access to public spaces is assessed by calculation of the share of the people within its service area, which is defined by the 400-meter walking distance toward them. Data on the open/green spaces are captured through Sentinel-2 imageries. The CART algorithm in Google Earth Engine (GEE) platform is used for land cover classification. The Street network for this analysis is captured from OSM. In the next step, the results of the computation are analyzed, considering the context of the city of Tehran and in the two defined times to monitor the progress of SDG indicators. Finally, the guideline for the evaluation and monitoring of SDG11 indicators is formed by organizing the whole process. The guideline consists of all available data sources, the methods for extracting required data, and the ways of computation of indicators which is useful for relevant stakeholders in evaluating and monitoring SDG indicators. The guideline can fill the gap of data restriction and helps to analyze data with minimal manual interaction and at the lowest cost and in the shortest time. Although there are some limitations to applying the guideline; It is not addressed social and economic conditions, and some aspects of indicators cannot be observed by EO tools. There could be an improvement in assessing and interpreting the result of monitoring indicators by accompanying the other auxiliary data such as demographic, social, and economic data in future studies.

Keywords: Sustainable development goals, SDG indicators monitoring, Earth Observation, Open geospatial data

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1. INTRODUCTION

1.1. Background and justification

During the last decades, urban expansion exceeded the urban populations growth rate throughout the world (Nicolau & Caetano, 2019). The expansion of cities is, on average, twice their population growth rates (Angel et al., 2011). Urban expansion has led to several negative consequences. It has affected ecosystem functioning and services locally to the global scale (Wu et al., 2015). Increased transport-related emissions, loss of open spaces, and adverse effects on human health are consequences of these changes (Guastella et al., 2019). Then, the rapid urban transition is a current challenge for most of the cities in the world.

Cities should be a place of opportunities for all the residents to have access to basic services, energy, housing, transportation, and more (United Nations, 2018). Understanding the spatial growth of cities and providing the required facilities, services, and policy and legal frameworks ahead of development are requirements that should be met by city authorities for pro-active planning of the city and lead it to sustainable urbanization (United Nations, 2018). To reach this goal, the 2030 Agenda include Sustainable Development Goal 11 (SDG 11) as a goal exclusively focus on cities and human settlements to make them inclusive, safe, resilient, and sustainable (UN Habitat, 2017). To help cities to overcome their challenges, grow, and thrive the United Nations has specified ten targets for SDG 11. Specific targets of SDG 11 are around the most critical urban and development issues: housing, public transport, spatial and demographic urbanization, participation in decision making, culture, disasters, waste management, and air quality, open and green spaces and urban policies, and linkages of settlements (UN habitat 2021). To provide universal access to safe, inclusive, and accessible, green and public spaces, enhance inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning, and provide access to safe, affordable, accessible, and sustainable transport systems for all are some major targets of SGD 11. For tracking the achievement of these targets, 15 indicators have been defined (United Nations, 2018).

Nevertheless, little progress has been achieved toward reaching the sustainable and inclusive urbanization targets, despite all these efforts and the adoption of the Sustainable Development Goals in 2015 and the New Urban Agenda (NUA) in 2016. The difficulty of monitoring progress toward these goals contributes to the current failure to accomplish them (Hsu et al., 2020). The main challenges of monitoring SDG 11 are poor access to open and standardized data, the lack of institutions for comprehensive data collection, and localization that specify SDG application for different cities by diverse actors (Klopp & Petretta, 2017). Even in high-income countries and developed economies, data gaps frequently indicate a conflict between the expenses of monitoring progress toward the SDGs and the usually under-resourced local administrations in most parts of the world (Wong, 2006; Simon and Arfvidsson, 2015; Arfvidsson et al., 2017 as cited in Hsu et al., 2020).

UN Data Revolution report emphasizes "Too many countries still have poor data, data arrives too late, and too many issues are still barely covered by existing data" (Data Revolution Group, 2014). To speed up the monitoring of urbanization to track indicators in case of physical transition, new technologies can populate and support the SDG indicators (Stokes et al., 2019). New methods can replace costly traditional methods like surveys and provide real-time and repeated coverage information. Earth Observation (EO) is one of these innovative and affordable approaches to addressing challenges in obtaining data (Andries et al., 2019). EO technology has the potential to contribute to "track progress towards targets through monitoring indicators; supporting coherence in SDG processes and international comparability across indicator outputs; and, driving sustainable development policies and management strategies"(Kavvada et al., 2020a, p. 1). The emergence of EO satellite missions (such as the Copernicus Sentinels and the Landsat family) offers policymakers and urban planners the opportunity to characterize urban settlement patterns in spatial detail (GEO, 2017).

Urban spatio-temporal changes could be detected and analyzed with the help of Earth Observation in combination with Machine Learning (ML). EO helps to monitor the SDGs by having free and open data (through specific satellite missions), data on all scales from local to national, regional, and even global, and measurement of dozens of geophysical parameters (GEO, 2017). EO datasets can not only be used to directly monitor some specific Indicators of SDGs, but they can also be complementary to traditional statistical methods for monitoring them (GEO, 2017). Furthermore, the combination of EO and machine learning-based methods makes these advantages that urban dynamics can be mapped from the historical dataset and trained on their own. Also, different image features can be included as part of the model; therefore, the model can be trained and validated repeatedly to optimize predictive accuracy, and ultimately improve decisions (Gómez as cited in Chaturvedi et al., 2020). Using ML algorithms improves data analysis and image classification automation, advances using big data, decreases human analysis errors, and saves time (The Parliamentary Office of Science and Technology, 2020).

The information extracted by EO and ML will be used to assess and benchmark conditions and trends across space and time and monitor progress toward goals (Klopp & Petretta, 2017). Therefore, combining open data with the use of EO and the ML can be a practical step in processing the data needed to evaluate sustainable development goals. These freely accessible tools and data allow us to evaluate goals at different time intervals, thus facilitating the conditions for monitoring them regularly.

SDG11 ranks third in the sorting among the SDGs that have the most direct connections with EO (Kavvada et al., 2020b). An analysis by Group on Earth Observations (GEO) and the Committee on Earth Observation Satellites (CEOS) indicates the SDG indicators that can use existing EO systems to generate data. The following SDG11 indicators can be fully or partially derived from EO data:

- 11.1.1 Proportion of urban population living in slums, informal settlements, or inadequate housing

- 11.2.1 Proportion of population that has convenient access to public transport, by sex, age, and persons with disabilities

- 11.3.1 Ratio of land consumption rate to population growth rate

- 11.6.2 Annual mean levels of fine particulate matter in cities

- 11.7.1 Average share of the built-up area of cities that is open space for public use for all, by sex, age, and persons with disabilities (GEO, 2017).

On the other hand, Inter-agency and Expert Group on SDG Indicators (IAEG-SDGs) has classified SDG indicators into three tiers based on their level of methodological development and the availability of data. Based on IAEG-SDGs classification, Tier II, which is related to this study, includes "indicators that are conceptually clear have an internationally established methodology and standards are available, but data are not regularly produced by countries"(IAEG-SDGs, 2019, p. 3). These SDG11 indicators are among the Tier II classification:

- 11.2.1 Proportion of population that has convenient access to public transport, by sex, age, and persons with disabilities
- 11.3.1 Ratio of land consumption rate to population growth rate.

- 11.3.2 Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically.
- 11.4.1 Total per capita expenditure on the preservation, protection, and conservation of all cultural and natural heritage, by source of funding, type of heritage, and level of government.
- 11.5.2 Direct economic loss attributed to disasters in relation to global gross domestic product (GDP).
- 11.6.1 Proportion of municipal solid waste collected and managed in controlled facilities out of total municipal waste generated, by cities.
- 11.7.1 Average share of the built-up area of cities that is open space for public use for all, by sex, age, and persons with disabilities.
- 11.7.2 Proportion of person victims of physical or sexual harassment, by sex, age, disability status, and place of occurrence (IAEG-SDGs, 2019).

What the two categories mentioned above have in common are indicators that are not reported by countries but can be obtained through Earth Observation. This study focuses on these indicators that monitor physical aspects of the city can be obtained through open data and EO, also categorized as Tier II. These selected indicators are:

- Indicator 11.2.1: The proportion of the population with convenient access to public transport. This indicator is calculated in two steps; For low-capacity public transport systems (such as bus and BRT systems) by computing of estimated share of urban population who can access a public transport stop within walking distance of 500 meters along with the street network and 1000 meters for high capacity public transport systems (such as metro system) (UN-Habitat, 2019).

- Indicator 11.3.1: Ratio of land consumption rate to the population growth rate. Indicator 11.3.1 is defined as the ratio of the land consumption rate (LCR) to the population growth rate (PGR), which requires the evaluation of the surface occupied by urban areas and its inhabitants at different temporal instants and will test land-use efficiency (Nicolau & Caetano, 2019).

- Indicator 11.7.1 uses earth observations and geospatial information techniques to measure spatial/distribution elements of open spaces and share the population within 400 meters of walking distance to open public spaces (UN-Habitat, 2020).

The selected indicators are directly related to urban development plans. This means that the physical decisions making in urban development plans regarding the built-up area, land uses, and street networks directly impact these indicators. The purpose of selecting these indicators is to show how EO and ML in combination with open geospatial data can overcome the data lack challenges that prevent regular assessment of sustainable development in cities.

1.2. Research problem

Despite the opportunity of open reference data and open EO data for monitoring SDG11, most countries do not know or do not have the leverage to utilize them (Kavvada et al., 2020b). Iran is among the countries that face challenges in data collection and statistics. These challenges consist of conflicting statistical reports between agencies and a lack of partnerships of the private sector in data collection because of financial issues (Tabnak, 2015). On the other hand, monitoring SDGs in Iran is facing financial problems. Due to the report of the Iran Plan and Budget Organization to the Iran parliament, the budget for implementing the agenda 2030 has been suspended since 2020 (Donya-e-eqtesad, 2020). In the last two years, the annual reporting on SDGs has been stopped and became out of the agenda of this organization. Therefore, the affiliated organizations have also faced difficulties in carrying out activities aimed at monitoring SDGs.

Also, the report of Iran Voluntary National Review (VNR) indicates the challenges that Iran faces with monitoring SDG indicators as; "the inconsistency of the many indicators with the existing national monitoring and evaluation frameworks and (b) the lack of scientifically credible and/or reliable data and information for a large number of the identified targets and indicators"(The Islamic Republic of Iran, 2017, p.1). Therefore, there is a need for a practical guide to solve the difficulty of accessing and updating data and also to monitor SDG indicators in Iran. This study tries to fill the gap in guidance of using EO and open geospatial data by proposing a guideline to support monitoring SDG 11 indicators. This guideline is based on internationally established methodology and standards of the metadata repository for SDG indicators to also fill the gap of the inconsistency of the many indicators with the existing national monitoring in Iran. This guideline can solve the problem of periodic information shortage, monitor selected indicators of SDG 11, and provide the required information to the relevant authorities. The guideline can also be used to prepare the required information for the Tehran report on Voluntary Local Review[1] which uses to track and report on SDG progress. It also can cover the information that is missed for indicators 11.2.1, 11.3.1, and 11.7.1 in Sustainable Development Report[2] which tracks progress and trends in achieving the Sustainable Development Goals.

1.3. Research objectives

1.3.1. General objective

The general objective of this study is:

Exploring the potential of open geospatial data and Earth Observation to make a guideline in monitoring three indicators of SDG 11

1.3.2. Specific objectives and corresponding research questions

- To identify metrics and geospatial data that is required for monitoring the three indicators of SDG11

  a. Which metrics can be used to monitor the indicators?

  b. Which free geospatial data sources can be used?

- To evaluate and monitor the SDGs' indicators over time in Tehran

  a. How are the indicators change over time in Tehran?

  b. Which parts of the city have considered progress according to the three indicators?

- Providing a guideline for regular SDG monitoring in Tehran

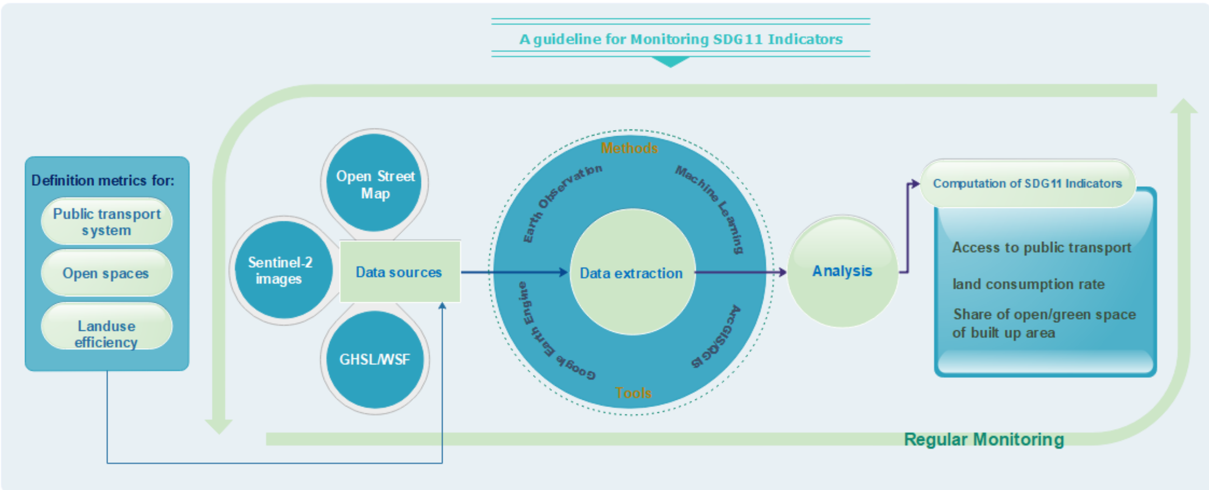
  a. How can the guideline fill the gaps in data capturing and SDG monitoring in Tehran?

[1] https://unhabitat.org/topics/voluntary-local-reviews#:~:text=Voluntary%20Local%20Reviews%20(VLRs)%20and,to%20support%20VLRs%20and%20VSRs.
[2] https://dashboards.sdgindex.org/profiles/iran-islamic-rep

1.4. Conceptual framework

There are five major components in the research conceptual framework. The first component is defining metrics for each indicator that need to be measured. The Second component is determining the source of required data for each indicator. The primary geospatial data can be extracted from satellite images and open street maps. WSF and GHSL are among the open-source data that can be used in the study. The third component includes the methods and tools that are used in extracting data. The fourth component includes analyzing the data obtained in the previous component. In the fifth component, the values of sustainable development indicators are computed to be evaluated. These major components can be seen in light green color in the figure below. The relations of the components are shown by arrows that determine the sequences of components in achieving the main goal of the study. This evaluation of SDG11 indicators at regular time intervals helps to monitor indicators over time. Regular monitoring helps urban decision-makers see their decisions' impact on the city's sustainable development. Through the constant communication of these components, we will have a comprehensive guideline that can help us regularly assess the three mentioned physical indicators of SDG11.

Figure 1. Conceptual framework; Making a guideline for regular monitoring of SDG 11 indicators



1.5. Thesis structure

The thesis is organized into six chapters that are described below:

Chapter 1: Introduction

In this chapter, first, the background and justification of the research and then the research problem is clarified. The generic objective, specific objectives, and corresponding research questions are identified. The conceptual framework is presented based on the main components of research and their sequences and relations.

Chapter 2: Literature review

This chapter reviews the main concepts of research which are sustainable development goals, earth observation, and the role of it in combination with auxiliary data in capturing and analyzing data for SDG monitoring.

Chapter3: Methodology

This chapter introduces the overall methodology of the research and the study area. It follows by data preprocessing of each indicator which includes the identification of data sources, the methods and tools for extracting them, and data analysis.

Chapter 4: Results

The outputs of the computation of each indicator are presented as the results in this chapter followed by maps and explanations of the evaluation of each indicator.

Chapter 5: Discussion

A discussion of the obtained results is presented in this chapter.

Chapter 6: Conclusion and recommendations

This chapter presents remarks on the research as the conclusion and recommendations for further studies.

1.6. Summary

The background of the study and the research gaps are elaborate in this chapter, followed by the research objective and questions. Also, a conceptual framework illustrates the main components of the research. In summary, the study aims to explore the potential of free geospatial data and EO to make a guideline for monitoring three indicators of SDG 11 to be used in cities with data restrictions.

2. LITERATURE REVIEW

2.1. Sustainable development goals

In the 2030 Agenda for Sustainable Development, 17 Sustainable Development Goals (SDGs) with 169 global targets and nearly 234 indicators are adopted based on the three pillars of sustainable development, which are economic, social, and environmental.

Figure 2. The global goals for sustainable development

Source: www.globalgoals.org

Based on the 2030 Agenda, "governments have the primary responsibility for follow-up and review, at the sub-national and national levels, in relation to the progress made in implementing the Goals and targets"(Page 2). Then, to have high-quality, obtainable, convenient, and reliable disaggregated data to estimate the national and sub-national progress, Countries are expected to set regular and inclusive review processes and develop new systems (UN-Human-Settlement-Programme, 2018).

Among all these goals, SDG 11 is specified for cities to make cities and human settlements inclusive, safe, resilient, and sustainable. New and intelligent urban planning is needed to develop safe, affordable, and resilient cities with green and inclusive living conditions to accommodate, survive, and prosper everyone in the fast-growing cities in the world (Mispy et al., 2018). If SDG concerns the local level, its assessment, from starting point to quantifying the targets and indicating the public policies, should also be arranged at this level, with municipal data and characteristics (Martínez-Córdoba et al., 2021). Martínez-Córdoba, Amor-Esteban, Benito and García-Sánchez (2021) considered that it is necessary to evaluate the commitment of local governments with the implementation of SDG 11. They analyzed the commitment of Spanish local governments to SDG11 by using the X-STATIS study technique, which showed a positive trend toward achieving SDG11.

2.2. The application of Earth observation in combination with auxiliary data in monitoring SDG indicators

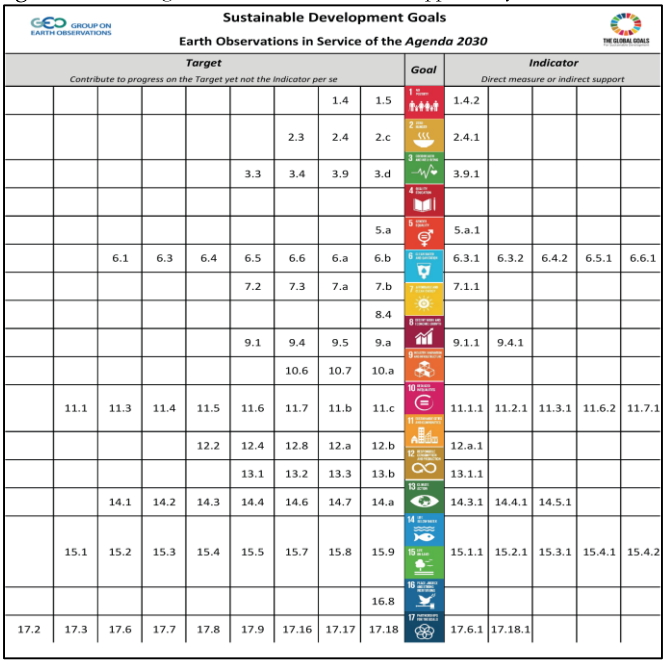
Although new technologies replace the expensive traditional approaches like replacing surveys with more affordable methods to support SDG, there are still significant challenges in acquiring data with sufficient quality, specifically in developing countries. These countries have poor data, acquiring data for them needs time, and data arrive too late. Using Earth Observation(EO) via satellites is one option to help provide the required data for the SDG indicators (Andries et al., 2019).

Monitoring and reporting SDGs by using Earth observation and geospatial information can be more viable when the government and city authorities face resources limitation. It also decreases the cost of preparation and monitoring of these data significantly (GEO, 2017). For example Space agencies such as ESA and NASA offers free historical and current access to EO data for more than ten years (Andries et al., 2019). "Satellite imagery has significant potential to provide a more timely statistical output, to reduce the frequency of surveys, to reduce respondent burden and other costs, and to provide data at a more disaggregated level for informed decision making"(UN Global Working Group on Big Data, 2022).

UN agencies and Conventions are custodians of specific SDG indicators that are relevant to their thematic expertise and/or mandate (Kavvada et al., 2020b). In this role, they have responsibility for compiling and validating country data and metadata; developing monitoring guidelines, including definitions and standards, to enable comparability across country data on SDG indicators; strengthening national statistical capacities; and, supporting countries in national monitoring and reporting efforts (Kavvada et al., 2020b). There is an opportunity to use EO technologies to contribute more to achieving the 2030 agenda. Using EO help to track the progress towards targets through monitoring indicators. Also, there will be coherence in SDG procedures and the ability to compare the international result of indicators and related policies and strategies. Also, by speeding up the use of these technologies by international agencies and regional commissions for monitoring and reporting the SDGs on different scales (local, sub-national/national, regional, and global), the assurance of geospatial information, and EO data gain acceleration (Kavvada et al., 2020). "Earth Observation data can make a major contribution to 15 indicators, partially contribute to 40 indicators, provide weak support to 25 indicators" (Andries et al., 2019, P. 17).

Since many SDG indicators have a geographic dimension, countries can be assisted by high-quality geospatial information to measure and monitor improvement in their economic, social, and environmental sustainability (Kavvada et al., 2020). In the following picture, SDG targets and indicators that can be supported by Earth Observation are shown:

Figure 3. SDG targets and indicators that can be supported by Earth Observation



GEO GROUP ON EARTH OBSERVATIONS

Sustainable Development Goals

Earth Observations in Service of the *Agenda 2030*

THE GLOBAL GOALS

Target *Contribute to progress on the Target yet not the Indicator per se*									Goal	Indicator *Direct measure or indirect support*				
							1.4	1.5		1.4.2				
						2.3	2.4	2.c		2.4.1				
					3.3	3.4	3.9	3.d		3.9.1				
								5.a		5.a.1				
		6.1	6.3	6.4	6.5	6.6	6.a	6.b		6.3.1	6.3.2	6.4.2	6.5.1	6.6.1
					7.2	7.3	7.a	7.b		7.1.1				
								8.4						
					9.1	9.4	9.5	9.a		9.1.1	9.4.1			
						10.6	10.7	10.a						
	11.1	11.3	11.4	11.5	11.6	11.7	11.b	11.c		11.1.1	11.2.1	11.3.1	11.6.2	11.7.1
				12.2	12.4	12.8	12.a	12.b		12.a.1				
					13.1	13.2	13.3	13.b		13.1.1				
		14.1	14.2	14.3	14.4	14.6	14.7	14.a		14.3.1	14.4.1	14.5.1		
	15.1	15.2	15.3	15.4	15.5	15.7	15.8	15.9		15.1.1	15.2.1	15.3.1	15.4.1	15.4.2
								16.8						
17.2	17.3	17.6	17.7	17.8	17.9	17.16	17.17	17.18		17.6.1	17.18.1			

Source: EO4SDGs/CEOS

It can be seen that 5 indicators of SDG 11: Making cities inclusive, safe, resilient, and sustainable, can be supported by EO. EO satellite missions such as the Copernicus Sentinels and the Landsat family proposes a unique opportunity to illustrate urban settlement patterns worldwide with frequent global observations at the high spatial resolution, long-term continuity, and open and free data policies (GEO, 2017).

EO data can address urban challenges by identifying characteristics of interest, which has often been seen as a classification problem using techniques that are mostly based on Machine Learning (ML) (Ferreira et al., 2020). ML will improve the storage, processing, analysis, and application of EO data and contain unique characteristics in classification, modelling and forecasting to monitor progress toward environmental targets (Ferreira et al., 2020; London Ec, 2018). Machine learning, as a branch of Artificial Intelligence (AI), can help experts automatically and efficiently analyse remote sensing data and understand complex environmental systems like land, ocean, and atmosphere (The Parliamentary Office of Science and Technology, 2020). Its algorithms reduce the level of human intervention by learning and improving through the experience and training data (Hutson, 2017). There are storage and computational needs for processing the EO data using machine learning. Google Earth Engine (GEE) provides cloud EO access, storage, and computing of the most common remote sensing data (e.g., Landsat, Sentinel, and MODIS) (Sudmanns et al., 2020). Also, there is a need to collect train and test data whose amounts depend on the complexity of the problem and can come from higher resolution remote sensing data (Brownlee, 2017; Holloway et al., 2018). Generally, 75% of training data are used to train the model and 25% are used to validate the model (Pantazi, X. E. et al., 2016 as cited in The Parliamentary Office of Science and Technology, 2020). The algorithm used in ML is chosen based on purpose, data availability, and proof of concept (The Parliamentary Office of Science and Technology, 2020).

Many machine learning algorithms can be applied for land use classification like SVM (Support Vector Machine) and RF (Random Forest), etc. (Sang et al., 2019). Classification And Regression Trees (CART) as a Machine Learning algorithm is a single tree decision classifier for building a decision tree based on Gini's impurity index to split each non-terminal node into two child nodes, repeatedly (Breiman, 1984; Choi, 2017; Praticò et al., 2021). The final decision is made by choosing the attribute with the higher value of normalized information gain (Praticò et al., 2021). The algorithm is a simple to use data mining technique and the decision process is like human decision-making (Choi, 2017). It allows combinations of input data like numerical and categorical variables to develop a tree-like set of rules to determine the final class, making it flexible enough to use in diverse applications (Choi, 2017). For land use classification, the CART algorithm uses a randomly selected sample of remote sensing to construct a binary tree, then prune it with the test sample (Sang et al., 2019). The simplicity of using the model and at the same time its ability to solve complex problems as well as its wide application in land use classification makes it used in this research to extract green and open spaces.

Open Street Map (OSM) is a georeferenced, crowdsourced product of geospatial open data that can be used for monitoring SDG indicators (Borkowska & Pokonieczny, 2022; Van Den Hoek et al., 2021). OSM stores a significant amount of data on infrastructure and place-specific services collected through interpretation of remotely sensed aerial or satellite imagery (Van Den Hoek et al., 2021). Since identifying feature data of amenities and public services through EO could be complex, OSM data surpass at obtaining features and have global coverage (Hoek et al., 2019)

Borkowska & Pokonieczny, 2022 have done an analysis of OSM data quality and indicate that OSM geospatial data with relatively high data quality can support other spatial data to support monitoring some SDG indicators.

Kavvada et al., (2020) discuss the need to promote the operationalization of EO solutions for implementing the 2030 Agenda. The analysis introduces EO systems that are available to capture data and their characteristics and present the factors that impede countries' use of EO technologies. Mudau et al., (2020) assess Indicator 11.3.1, Ratio of Land Consumption Rate to Population Growth Rate (LCRPGR) for four cities in South Africa. The Landsat 5 TM and SPOT 2&5 satellite images are used to map the built-up area in 1996, 2001 and 2011. Aguilar & Kuffer, 2020 present a cloud computation-based method to map open spaces. The spatial pattern of open spaces for the city of Kampala, Uganda, is mapped by a proposed method that accesses the multi-temporal high-resolution imagery repository of Planet.

The studies mentioned above emphasize the importance of using Earth Observation, but they use Very-High-Resolution data that are available for commercial rates. The education and Research Program[1], that provide access to PlanetScope and RapidEye imagery for students and researchers, is not in line with the purpose of this study because it wants to provide a guideline for the use of free sources to be applicable for using of all stakeholders.

2.3. Summary

In this chapter, relevant concepts to the purpose of the research are reviewed and prior researches conducted in this field are studied. Also, the importance of using new technologies and Earth Observation in combination with other auxiliary data has in monitoring SDG indicators been emphasized.

[1] https://www.planet.com/markets/education-and-research/

3. METHODOLOGY

3.1. Study area

Tehran, Iran's capital, is one of the world's fast-growing cities. It would be one of the new megacities in witnessing rapid population growth and area extension, which accelerated after 1960 (Hosseini et al., 2016). Based on the vision expressed in the Tehran master plan, Tehran will be a green, beautiful, livable city with wide and diverse public spaces (Tehran Development Agency, 2008 as cited in Ziari et al., 2018)

The location of Iran in the world and the location of Tehran in Iran are illustrated, in figure 4. Tehran is located in north-central Iran and is divided into 22 municipal regions, each of which has its administrative center (Madanipour, 2021). Tehran is bounded by the Alborz mountain range in the Northern part (Madanipour, 2021). It is also bounded in the east by the mountains of Rey and Bibi Shahrbanu and the flat plains of Shahriyar and Varamin in the south. The mountains in the north and east and the desert in the south constrain the growth of urban fabric to only expand to the west (Madanipour, 1999). The slope of Tehran is from north to south, and the average slope of the city is estimated at 3 to 5 percent.

A clear core-periphery distinction is Tehran's urban layout (Madanipour, 2021). With an approximate 8,992,000 population, Tehran is the largest city in Iran and one of the most populous cities in the world (Tehran Information and Statistics Office, 2021). It is also the biggest market and hub of economic activity in Iran (Madanipour, 1999). Air pollution is one of the big problems in Tehran. The main contributor to air pollution in Tehran is the transport sector which makes it among the most polluted in the world (Heger & Sarraf, 2018).

The reason for choosing Tehran as a case study is its rapid growth as a capital. Failure to pay attention to the indicators of sustainable development in the growth of this city may lead to problems in the near future in terms of livability, resilience and inclusiveness. Regular monitoring of the SDG11 indicators helps the city's decision-makers to continuously consider their performance in order to achieve the SDG11. One of the main issues to monitor the sustainable development of the city is the lack of information. Restrictions on access to sufficient, up-to-date, and free information prevent urban experts from properly assessing the city's sustainability. This study tries to provide a guideline for assessing the sustainability of the three physical indicators mentioned for the city of Tehran, which allows the use of required information with the help of open data and EO tools. This guideline will help urban authorities and local governments assess their actions and find the problems that prevent improvements toward sustainable development.

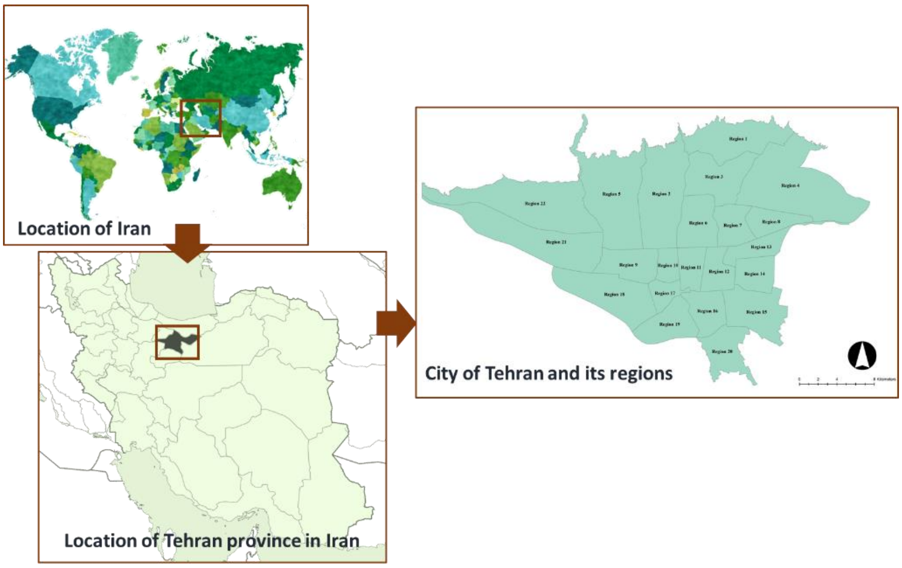


Figure 4. Location of the study area

3.2. Overall methodology

The methodological approach in this study comprises four steps that can be seen in figure 5. In the first step, the metrics should be defined for each indicator. Based on these metrics, the next stage is to detect data sources and extract data. The required data for this study can be obtained from sources like open street maps and open sources satellite imagery (Sentinel-2 images). Since we want to monitor SDG indicators progress, data for each indicator is collected at two different times. In the figure, different time indicated by T_1 as initial time and T_2 as the final time.

For indicator 11.3.1, the land consumption rate is computed by input data extracted from multitemporal satellite imagery, which in this study, the World Settlement Footprint[1] layer is used. Also, high-resolution satellite imagery can extract open/green spaces for indicator 11.7.1. CART as a Machine Learning method is used for this image classification. First trained data for the land cover classification is introduced to the model. Then the trained model is used to classify open/green spaces and the built-up area in Tehran. Google Earth Engine (GEE) is used as a cloud-based processing system in this step. The required data for indicator 11.2.1 is the street network, and the location of public transport stops, which can come from Open Street Map or city administration (IRENA, & OECD. 2021).

Population data is required for computing all these three indicators. Statistical sources like censuses are needed for population data and computation of the population growth rate. These data should be disaggregated to the smallest unit possible (UN-Habitat, 2021a). In this study, population data at the city block level is used.

The third step includes analyzing extracted data to be used for computing each indicator. In the fourth step, each indicator is computed and evaluated based on its metrics. The value of each indicator is computed at two different times to reveal the change of the indicator's value during the specified time. Therefore, it could be possible to monitor the progress toward achieving the indicator. At the end a comprehensive guideline is made that brings all the previous steps together to provide a regular SDG indicators evaluation tool.

[1] https://geoservice.dlr.de/web/maps/eoc:wsf

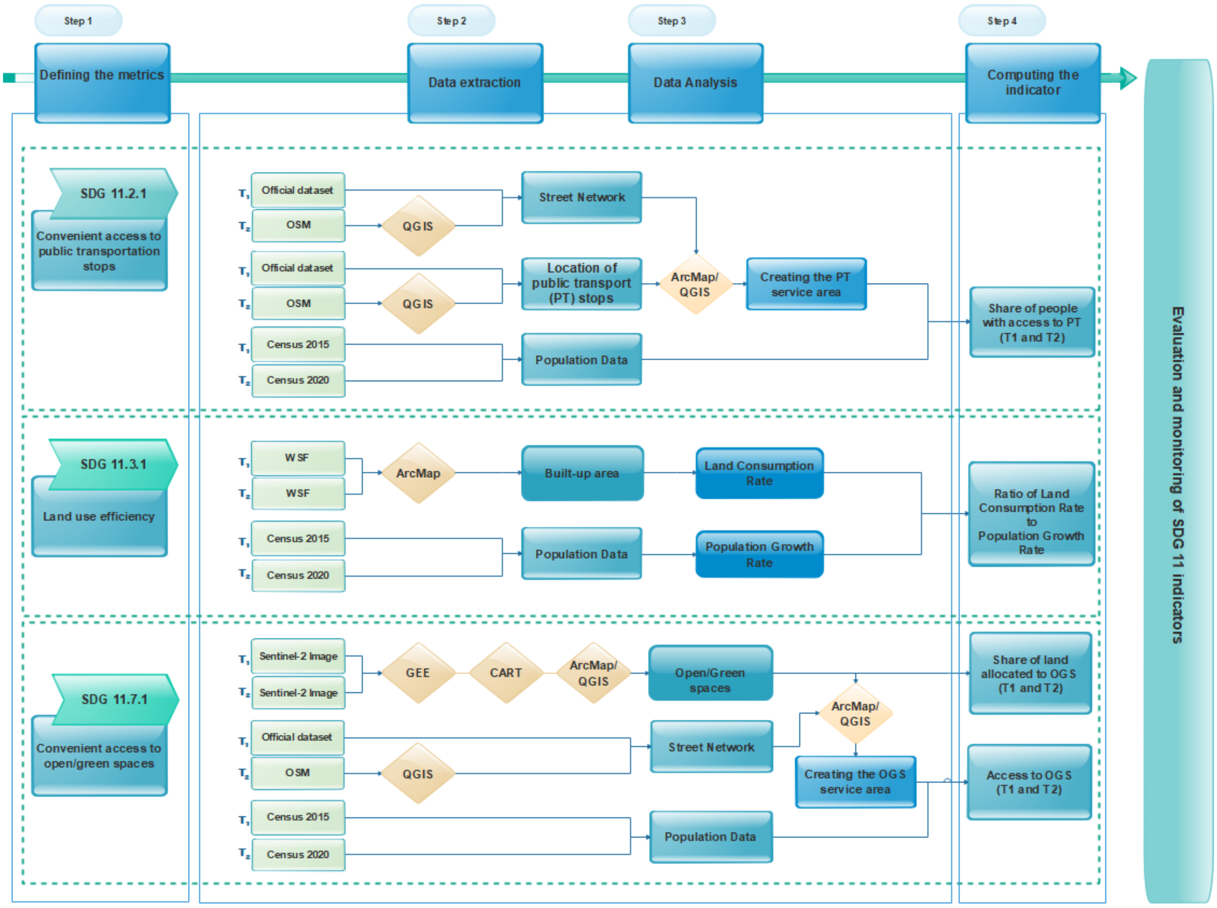


Figure 5. Research workflow

3.3. Selected SDG11 indicators

In this research indicators 11.2.1, 11.3.1, and 11.7.1 will be assessed with the support of earth observation tools. Three targets and three indicators are selected to be monitored in this research and can be found in table 1:

Table 1. Targets and indicators of the research

Targets	Indicators
11.2 By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	11.2.1 Proportion of population that has convenient access to public transport for all
11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management in all countries	11.3.1 Ratio of land consumption rate to population growth rate
11.7 By 2030, provide universal access to safe, inclusive, and accessible, green and public spaces, in particular for women and children, older persons, and persons with disabilities	11.7.1 Average share of the built-up area of cities that is open space for public use for all

3.3.1. Indicator 11.2.1: The proportion of the population with convenient access to public transport

Moving away from car-based travel to public transportation is mandatory for having more inclusive safe, and sustainable cities. Adequate and low-cost public transportation with good inter-modal connectivity provides access to essential services like health care, educational centers, jobs, and other public goods, helps to reduce urban deprivation and inequalities, and improves economic development (UN-Habitat, 2019).

The public transport accessibility also affects the environmental impacts related to urban mobility pollution-related sources. Several factors influence population accessibility to public transport:

- Number of available public transport stops
- The distribution of public transport stops
- The clustering of the population in proximity to the stops
- Distribution of the street network (UN-Human-Settlement-Programme, 2018).

Monitoring this indicator is needed for having a systemic approach to the city with clear policy implications based on collecting accurate, timely, disaggregated data and information. With this approach, city authorities and decision-makers can implement the most acceptable policies and actions and adapt them based on the regular monitoring of their performance. This regular monitoring also, accelerate progress against the target and goal 11.

3.3.2. Indicator 11.3.1: Ratio of land consumption rate to population growth rate

Indicator 11.3.1. measures a ratio of the rate that cities consume land versus the rate of population growth to see if the cities utilize land efficiently. City authorities and decision-makers need to predict the shape of city growth and its direction which helps them to provide needed services and facilities for future development. This foresighted planning is a requirement for sustainable urbanization which resulted in convenient access for the plurality of the city residents to economic and social opportunities and essential services (UN-Habitat, 2018c).

Cities that are compact consume less energy and increase the advantages of agglomeration because they make the better condition for accessing public goods and services which means they use land more efficiently (UN-Human-Settlement-Programme, 2018). In non-compact cities, the cost of providing basic services and infrastructure is high because they experience increased demand for mobility, energy consumption, and environmental degradation (UN-Human-Settlement-Programme, 2018).

Measuring this indicator helps city authorities to calculate the need for public services, determine newly developed areas and supply sufficient infrastructure and amenities for the improvement of living conditions for all (UN-Human-Settlement-Programme, 2018).

Generation of data on this indicator helps to understand the spatial expansion of an urban area versus its rate of population change, the urban growth dynamics, and the nature of human settlements growth which has substantial importance on the demand for and cost of providing services, as well as on environmental protection and preservation which is the core for stimulating sustainable urbanization (UN-Habitat, 2018c). Efficient land use calculated by this indicator shows by the value below one. The ideal value of this indicator would be one that implies an accepted ratio of land consumption to population growth rate. Obviously, a value higher than one indicates insufficient land use (UN-Habitat, 2018a).

Essential and timely information that city authorities and stakeholder needs to accelerate progress towards improved inclusive and sustainable urbanization can be provided by monitoring SDG indicator 11.3.1 (UN-Habitat, 2018c).

3.3.3. Indicator 11.7.1: Average share of the built-up area of cities that is open space for public use for all

As a common good, open public spaces improve the quality of life by realizing human rights and giving opportunities to all especially youth and women to participate in the city's social life. Also, increasing mobility and access to market and public services and improving urban productivity influence by considering public space infrastructure in urban planning (UN-Habitat, 2018e). Good urban planning and designing establish, organize and facilitate public space usage to improve a sense of belonging in a city. It also makes the ideal opportunities for the cooperation of all citizens, ensuring their diverse interests in collaborative practices (UN-Habitat, 2018e).

This indicator measures the share of land allocated to public spaces and the total population access to these spaces. For assessing the shared prosperity of a city, the size, allocation, and quality of its public space is a good indicator. So, SDG 11 provides the platform to monitor this indicator (UN-Habitat, 2018b). Decision-makers and stakeholders will access the essential and timely information by monitoring this indicator to accelerate progress toward organizing access to safe and inclusive public and green spaces for all citizens (UN-Habitat, 2018e).

3.4. Data processing

The first step in defining a guideline to use EO and open data is identifying the required data and making them ready for analysis. This section describes the steps of pre-processing the required data, which include collecting the initial data and preparing them for use in computing the desired SDG11 Indicators. Since different data are needed to calculate each indicator, the progress of capturing and preparing them for the analysis is described as follows.

One of this research's objectives is to monitor progress against SDG11 indicators. Regular indicators monitoring can be done every five years (UN-Habitat, 2018e). To do that, data for each indicator was captured in two different years. However, the initial year and final year for each indicator might be different due to the source availability.

The defined area for this study is the administrative boundary of Tehran and its regions which can be seen in figure 6. The boundary of Tehran has been extracted from OSM and adjusted according to the maps available on the website of Tehran Municipality. This computation will be performed for each indicator at the regional level to monitor the progress of each region.

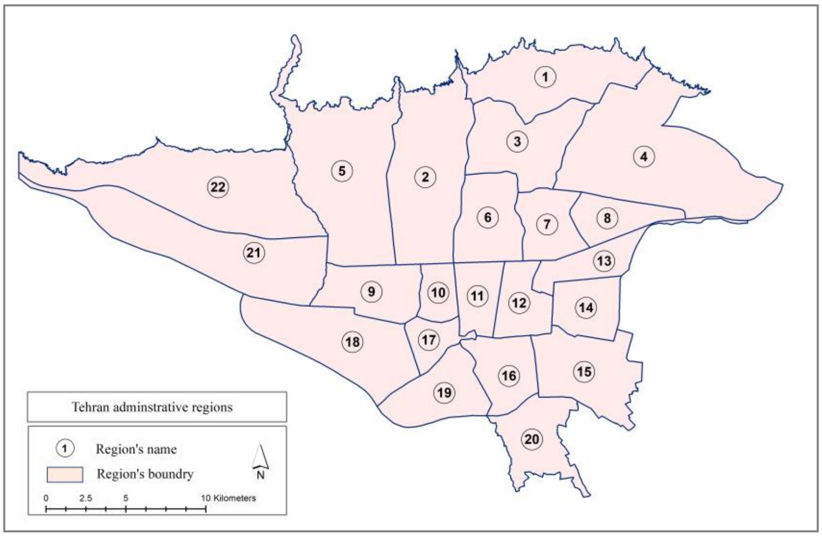


Figure 6. Tehran administrative regions

3.4.1. Access to public transportation

This indicator refers to the proportion of the population with convenient access to public transport. Public transport in this study includes bus, BRT (Bus rapid transit), and metro. Based on the UN-Habitat Metadata repository, metro service is considered a high-capacity transport system because of their large carriers and large terminus infrastructure requirement (UN-Habitat, 2018d). They operate along metro-lines as their dedicated infrastructure and work at higher speeds than low-capacity systems (UN-Habitat, 2018d). Bus and BRT (Bus rapid transit) services are considered as low capacity systems since they have smaller size carriers and smaller area needs for stopping-dropping-picking passengers so their stops can be closer to each other (UN-Habitat, 2021a).

Access to bus and BRT systems as low-capacity systems is convenient when the nearest stop is located at 500 m distance from a reference point like home, workplace, or market through the street network, while for accessing the metro as a high-capacity transport system, this distance is 1 km (UN-Habitat, 2021a). So, convenient access has two different definitions in terms of transport system capacity, which means that people can walk a longer distance to access mass transport systems such as metro stops/stations than low-capacity systems (UN-Habitat, 2018d). High-capacity transport systems have a more significant area of influence than low-capacity systems (UN-Habitat, 2021a).

For monitoring this indicator, data on two aspects of public transport are required: public transport stops and population data (UN-Habitat, 2021a). This indicator is evaluated in Tehran by three steps;

- Identifying public transport stops in 2015 and 2020
- Creating service areas for each stop (Metro, BRT, and, bus stops)
- Estimating the number of people within the service areas by overlaying the service area with population data layers

To make it possible to detect changes in access to public transportation, a 5-year monitoring interval is proposed for this indicator. In the continuation of this section, these steps are explained for capturing the data for 2015 and 2020.

3.4.1.1. Identifying public transport stops

- **Low capacity system; Bus and BRT stops**

- **Bus stops**

The most important source for detecting and extracting bus stations in Tehran is Open Street Map data. This resource has been used to extract information for 2020. OSM uses tags to illustrates physical features on the ground. OSM basic data structure (its nodes, ways and relations) is shown by each tag describing a geographic attribute of the feature (OpenStreetMap Wiki Contributors, 2021). Most features are described by their type and classification tag. For extracting data of public transport features, public transport tag can be used. For example, the tag Public Transport (Legacy)/Bus Station is used for showing bus station feature. The public transport data can be captured through Quantum GIS using QuickOSM tool that helps to extract physical features from OSM. This tool uses tags for its query to load OSM data and represent them as point, lines or polygons. After extracting the bus stop points from the OSM, the data is randomly checked according to the Google Earth image for validation. For the data of the year 2015, due to the lack of access to this data in OSM, the information archived by the Tehran Municipality Statistical Systems[1] is used.

[1] https://tuo.tehran.ir

- **BRT stations**

Tehran Bus Rapid Transit has been officially inaugurated in 2008 to facilitate the motor traffic (Parvizi & Mohammadi, 2011). To extract data for the year 2020 related to BRT stations, Open Street Map is used as a source. The QuickOSM tool in QGIS is used again to capture the features from OSM using the tag highway/Bus stop and filtering the name of BRT station.

For the year 2015, the free information available on the Tehran Municipality website and field observation were used to provide the data. The Tehran Municipality[1] website provided information that specifies the name and operation date of each station. This information was used to identify stations that were operating in 2015.

- **High capacity system**

- **Metro stations**

The metro transportation system is worked as a high-capacity system in Tehran. The metro project's first operational activities and the construction of metro stations were launched in 1987. Since then, part of the network is gradually completed by adding more lines. (Tehran urban & suburban railway operation Co., 2022).

Required data for the location of Tehran metro stations for the year 2020 is acquired from Google Street Maps. The QuickOSM tool and query Transport/Railway/Subway tag in Tehran is used for capturing the data. Since the operation time of the metro station and metro line is on the website of the Tehran metro[2], this information has been used to identify the metro stations that operated in 2015. Based on this information, a map of metro stations in 2015 and 2020 has been drawn.

3.4.1.2. The identification of service areas

For identification of public transportation service area, in this step service area for each stop is created. Service area is typically achieved by calculating the walking distance to each stop on a network using the Network Analyst tool (in ArcMap)[3]. A network service area covers all the accessible areas within a specified distance via a street network, considering the presence of any impediments preventing direct access to public transport stations (UN-Habitat, 2021a).

Service Area, for a low capacity system which is bus and BRT for Tehran, is defined as the area served by public transport within 500 m walking distance and 1 km to a high-capacity system which is metro for Tehran, based on the street network.

- **Low capacity system; Bus and BRT service area**

For creating 500 meters service areas around each bus stop and BRT station, we need to create a street network dataset. Streets data that is required for this step is acquired from Open Street Map for the year 2020. Under the tag of Highway the different categories of roads can be extracted using the QuickOSM tool in QGIS.

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[1] https://Tehran.ir

[2] https://metro.tehran.ir/

[3] QGIS as a free platform can be used, too.

The street network for 2015 is provided by the Tehran Municipality Statistical Systems[1] because of the lack of access to the year 2015 on OSM maps. However, the comparison of street networks in 2015 and 2020 does not show much change. Most of these changes have taken place in the western part of the city, where the city is currently growing.

- **High capacity system; Metro service area**

For the metro transportation system, 1 km walking distance threshold is applied for running service area analysis. The same street network dataset has been used for the calculation of metro service area.

3.4.1.3. Estimating the number of people within the service areas

After identifying the public transportation service area, the number of people living in these areas should be calculated. It will demonstrate the population with convenient access to public transport.

High-resolution population data is required to accurately determine the total population within the service areas. This data is obtained from the Statistical Center of Iran[2] at the block level for two different years (2015 and 2020), which is the smallest statistical unit prepared for research.

In this step, the service area created in the previous step is overlaid with the population data at the block level. For estimating the number of people who has access to public transport, the number of people living in the blocks within the service area is summed up. To better understand the performance of this indicator, calculations have been performed on the scale of Tehran regions. Thus, the level of access to public transportation in each region has been measured according to the service area and its population. Therefore, the changes in this indicator from 2015 to 2020 can be measured. Since the population data existed based on the gender in block level, the public transport accessibility was also calculated for women and men in each region of Tehran.

3.4.1.4. Computing the indicator 11.3.1

The last step is computing the share of the population with access to public transport. The equation below is used for the computation:

$$\%\ with\ access\ to\ public\ transport = [(Population\ with\ convenient\ access\ to\ public\ transport)/(population\ of\ the\ region)] * 100$$

Source: (UN-Habitat, 2018a)

3.4.2. Land consumption rate

For computing land consumption rate, image analysis for two different times is required which helps to understand the effect of land consumption by cities on urban sustainability. To detect the land cover change multi-year monitoring interval from openly available satellite imagery with reasonable accuracy is needed (UN-Habitat, 2021b). For computing, this indicator in this study, World Settlement Footprint (WSF) layer which is 10 m resolution (0.32 arcsec) global map of human settlements on Earth is used. Duo to existing of World Settlement Footprint layer for the years 2015 and 2019, monitoring of this indicator is done considering these two year.

The WSF 2019 outlining the current global settlement extent derived by joint exploits of multitemporal Sentinel-1 and Sentinel-2 imagery with a 10m resolution (Marconcini et al., 2021). The WSF 2015 is also

[1] https://tuo.tehran.ir
[2] https://www.amar.org.ir/

outlining the extent of human settlements globally derived by means of 2014-2015 multitemporal Landsat-8 and Sentinel-1 imagery (Marconcini et al., 2020).

First, land consumption per capita as a secondary indicator is calculated in every 22 regions of Tehran to show the changes during the time and the difference in performance between the regions. This indicator estimates how efficiently cities use land, which is measured as a ratio of the rate at which regions spatially consume land against the rate at which their populations grow (UN-Habitat, 2021b). It represents how much is the average amount of land that each person in each region occupies in the specified year. Two inputs are required for computing this indicator in each region of Tehran;

- The total built-up area in each region in 2015 and 2019
- The total population data in each region in 2015 and 2019

The WSF map is used for calculating the built-up area. The WSF consists of two values; value 255 as settlements and value 0 as other pixel. Since only the settlement value is needed, the other pixel as non-built-up area is deleted from the raster file by setting this value as null. To determine the sum of built-up areas in each region Zonal Statistics as Table (statistic type; SUM) tool is used in ArcMap[1]. The result shows the amount of built-up area in each region.

The population data for each region is acquired from Tehran Municipality Statistical Year Book[2] for 2015 and 2019. For computing Land consumption per capita (LCPC) the total built-up area in each region is divided by the total population of each region, using the formula below. This formula is used twice for computing LCPC for each year.

$$LCPC_{t1} = \frac{Urb_{t1}}{Pop_{t1}}$$

Urb_{t1}: the total built-up area within each region

Pop_{t1}: the total population within each region

Source: (UN-Habitat, 2021b)

Based on the results from this analysis, for measuring the change in land consumption per capita between analysis years, the following formula is used.

$$Change\ in\ LPCP_{(t1,t2)} = (LPCP_{t2} - LPCP_{t1} / LPCP_{t1}) * 100$$

Source: (UN-Habitat, 2021b)

For calculating the main indicator; land consumption rate to population growth rate (LCRPGR), these data are needed:

- The total urbanized area in 2015 and 2019
- The total population within regions in 2015 and 2019

The first step is measuring land consumption rate (LCR) between 2015 and 2019. The total urbanized area for each year is computed before. The data is used here in the following formula;

[1] The process also can be done in QGIS.

[2] https://amar.thmporg.ir/

$$LCR = LN(Urb_{t2} - Urb_{t1}) / Y$$

Urb_{t1}: the total urbanized area in the initial year t1;
Urb_{t2}: the total urbanized area in the final year t2;
Y: the number of years between t1 and t2

Source: (UN-Habitat, 2021b)

The second step is computing the population growth rate (PGR) using this formula;

$$PGR = LN(Pop_{t2} - Pop_{t1}) / Y$$

Pop_{t1}: the total population within the urban area in the initial year t1
Pop_{t2}: the total population within the urban area in the final year t2
Y: the number of years between t1 and t2

Source: (UN-Habitat, 2021b)

The final step is computing land consumption rate to population growth rate (LCRPGR) by dividing the calculated land consumption and population growth rates;

$$LCRPGR = LCR / PGR$$

Source: (UN-Habitat, 2021b)

3.4.3. Access to open/green spaces

The importance of open spaces is promoted by SDG indicator 11.7.1, which evaluates the "average share of the built-up area of cities that is open space for public use for all, by sex, age, and persons with disabilities." Public open spaces are defined as "all places publicly owned or of public use, accessible and enjoyable by all for free and without a profit motive." It includes unstructured land or land with very minimal or no structures (UN-Habitat, 2021c).

Based on the definition of UN-Habitat, open and green spaces and streets that are significant places for interaction are defined as open spaces in this study.

- Open/green space: A freely accessible land to the public that has recreational areas and improves the quality of neighborhoods. Public open spaces can be categorized from small parklets and small areas of nature that service the recreation needs of the immediate residential population, to larger spaces that accommodate activities, such as recreation, sporting, and natural features conservation, regional open space, larger city parks, and national/metropolitan open public spaces(UN-Habitat, 2018e).

- Street: The main purpose of a street is to facilitate intra-city connections and links city spaces and enable public interaction (UN-Habitat, 2018b). Also, it is defined as an open space with social and economic functions that have residential houses, retail, and other structures on one or each side (UN-Habitat, 2021c). while the UN-Habitat metadata repository mentions "streets, avenues, and boulevards, pavements, passages and galleries, bicycle paths, sidewalks, traffic island, tramways and roundabouts"(UN-Habitat, 2018b) as the street space elements and excludes "plots (either built-up), open space blocks, railways, paved space within parking lots and airports and individual industries"(UN-Habitat, 2018b) from street space.

As this indicator compares the total built-up area with the open/green area, to compute this indicator, the amount of built-up area, open spaces, and street area are needed. Although the data of this indicator support local planning, health, and environmental policies, the needed data are not readily available globally and at the metropolitan scale (Aguilar & Kuffer, 2020). Earth observations and geospatial information techniques are newly employed to measure the entire area and extract streets and open public spaces data. In the following parts, these techniques are used to extract the data that are needed for computing this indicator. In this research, the potential of Sentinel-2 satellite imagery and OpenStreetMap (OSM) data is used for mapping the green/open spaces, as open and globally available datasets.

There are two elements of SDG indicator 11.7.1 that should be measured:

- Spatial (distribution) component: Share of the area of cities that is open space.
- Socio-demographic (access) component: Share of population with access to open/green spaces.

This indicator needs regular monitoring and reporting. Then two-time intervals are selected for monitoring the changes. The image of Sentinel-2 has been available since 2016, this monitoring will be done in 2016 and 2020.

3.4.3.1. Share of the area of cities allocated to public space

To measure the share of cities occupied by streets and public open spaces these data are measured; Amount of land allocated to streets (LAS), Amount of land occupied by open/green spaces (OGS).

- **Amount of land occupied by Open/Green Spaces (OGS)**

For extracting the open/green spaces data, high-resolution satellite imagery is used. European Space Agency (ESA) is in charge of satellite missions that execute terrestrial observations of the earth and deliver imagery that can be used for land cover changes monitoring. Sentinel-2 imagery is downloaded from the Copernicus Open Access Hub[1] (UN-Habitat, 2018e).

The processing of the images and mapping of open/green spaces are carried out within Google Earth Engine (GEE). The first step for mapping open spaces is to classify land cover in Tehran from Sentinel-2 images for the years 2016 and 2020. The period that is considered for the classification was from May to August. For land cover classification of the images, these classes are defied; Built-up, Green area, Water body, and Street considering four bands B2 (Blue), B3 (Green), B4 (Red), And B8 (NIR). The Classification And Regression Tree (CART) algorithm as a predictive model is used for the classification. The prediction of outcome variable values in the CART model is based on other values. Therefore, training samples have been generated for the classification of the images. Eighty percent of samples are used for training the model, and 20 percent are used for testing the model. An erosion followed by a dilation operation is performed to remove small objects from the classified image and smooth the border of large objects (MathWorks, 2019). In the end, a confusion matrix has been made to check the model's accuracy. The overall accuracy of the model has been calculated as 90%[2].

In the next step, the classified images are imported to ArcMap for processing. The focus here is on the green area and water body classes as the main classes that can reveal the open/green areas. Since we want to determine the open spaces, the first step is to exclude the areas that are not public. Based on the OSM land use data, the functions that have green areas but are not public have been deleted from the maps.

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[1] https://scihub.copernicus.eu/dhus/#/home

[2] The codes are provided in the annex.

Functions such as the universities, militaries, stadiums, embassies, and non-public entertainment venues have been removed from the green area class. Also, the base map "imagery with labels" was added to the project in ArcMap to detect the spaces with a specific function to check their publicity. Also, the size of the areas was determined as a characteristic of open spaces. The average residential area in Tehran is 400 square meters, according to municipal regulations, only 40% of it should be allocated to the building and the rest is used as a yard. To distinguish these residential areas from open and green spaces, buildings smaller than 400 meters have been removed from the data.

Based on the data of these maps, the share of land allocated to open/green spaces can be computed using this formula for each region:

$$Share\ of\ the\ land\ allocated\ to\ OGS = \frac{Total\ area\ coverd\ by\ open-green\ spaces}{Total\ area\ of\ region} * 100$$

Source=(UN-Habitat, 2021c)

- **Amount of Land Allocated to Streets (LAS)**

This indicator shows how much of the city is covered by streets. So, the requirement for calculating this indicator is street area. For this calculation, street length and width should be considered. Municipality database and OSM data can help to figure it out. But there are streets that do not have this information. Road length can be easily calculated in ArcMap by calculating geometry. The width of the streets that do not have this information can be estimated through the following steps:

- Checking the type of roads and referring to Street Design Regulations[1] which indicate the width of the street based on their type.
- Using a base map in ArcMap that offers imagery, imagery with labels, and street layers to check the width of streets and manually add them to the database.

After determining the width and length of the streets, it is possible to calculate their area by multiplying their width and length. Then, the area of the streets has been calculated for both 2016 and 2020. These data are used to calculate the amount of land allocated by street by using this formula:

$$LAS = \frac{Total\ area\ coverd\ by\ street\ in\ each\ region}{Total\ area\ of\ region} * 100$$

Source=(UN-Habitat, 2021c)

- **The proportion of land allocated to public spaces**

This formula can be used to calculate the share of land allocated to public spaces. By combining the area of OGS and LAS, the total area of the public spaces can be obtained.

$$\textbf{Share of land } \text{of } \textbf{region allocated to public} = \frac{Total\ area\ coverd\ by\ OGS}{Total\ area\ of\ region} * 100$$

Source=(UN-Habitat, 2021c)

3.4.3.2. Share of population with access to open/green spaces

The second element (socio-demographic (access)) of indicator 11.7.1, share of population with access to open public spaces, goes beyond identifying the population within 400 meters of walking distance to the

[1] Iran Research Center of Road Housing and Urban Development. (2020). *Street Design Regulations*. Publications of Iran's Road Housing and Urban Development Research Center.

spaces. The street network is included as an input in the delineation of the service areas for each open public space.

The first step for computation of this indicator is converting the polygons of OGS to points, which can be done by using the Feature Vertices To Points tool in ArcMap. Then, we can use the points to create the service area for each space. For creating the service area, the Network Analysis extension in ArcMap is used. The OGS points are defined as facilities for creating the service area. The service area is computed by setting 400 m break that is defined for walking distance toward the OGS.

Estimating the number of people with access to OGS is the next step. The OGS service area layer is overlaid with population data. The smallest statistical unit that can be used for this research is population data at the block level obtained from the statistical center of Iran. In this way, statistical blocks that are within the service area of OGS are identified. By aggregating the population in these blocks, the number of populations that have access to OGS is determined. Then, we can estimate the share of the population that has convenient access to OGS by dividing the calculated population by the total population of the area. This calculation has been done on the scale of Tehran regions to determine the performance of each region in accessing to OGS. Also, according to the demographic information of the statistical blocks and the separation of the male and female population living in each block, access to OGS can be determined by gender.

3.5. Summary

In this chapter, the overall methodology to accomplish the research objectives is explained. The city of Tehran as the study area is introduced. Selected indicators are presented to identify the metrics required for the research. In the data processing section, the data sources are identified, and the methods for capturing the data are elaborated, and finally, data is extracted based on the identified metrics. Also, the equations for computing the indicators are determined.

4. RESULTS

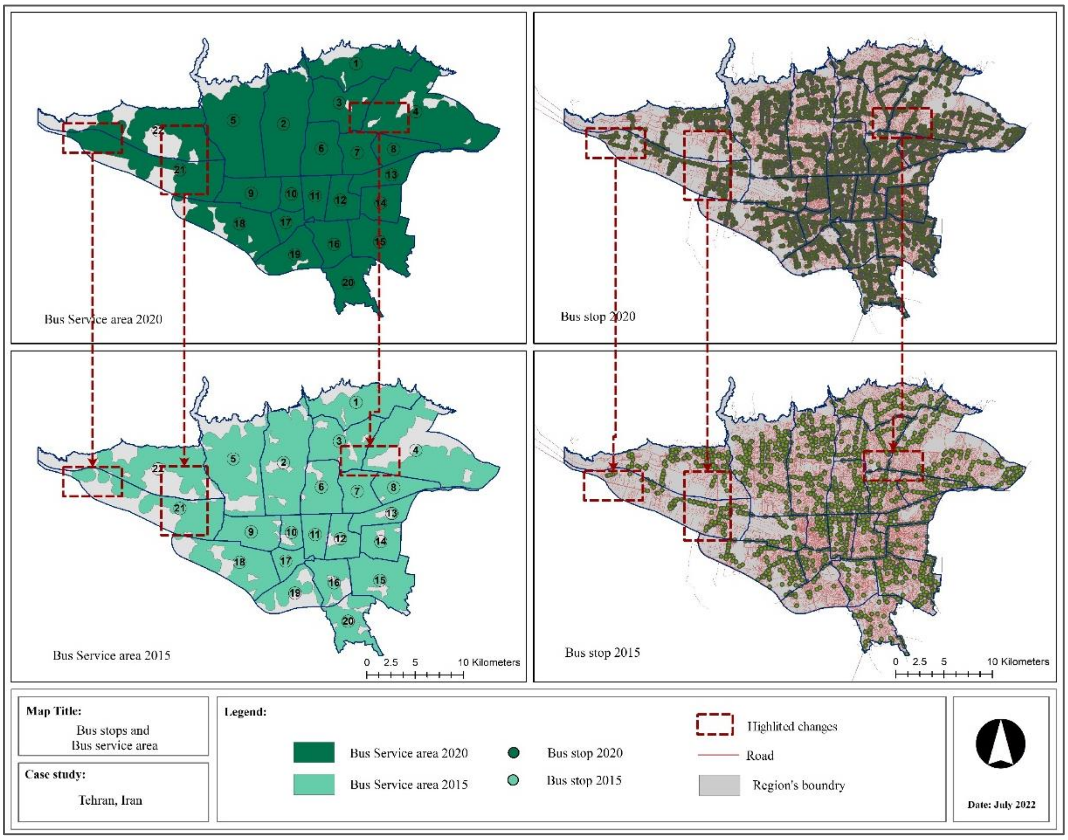
After processing the required data for computing each indicator, in this section, the results of computation of indicators are presented and analyzed.

4.1. Result of computing indicator 11.2.1; Access to public transport

As previously explained, the public transportation system in Tehran consists of three sections: metro, BRT, and bus. According to the explanations related to the evaluation of this indicator, buses and BRT are considered low-capacity transportation systems, and the metro is considered a high-capacity transportation system. In this part, first, the maps of extracted data for each of the transportation systems are presented. Then, the result of computing the indicator 11.2.1 is provided. Data for each system was extracted in 2015 and 2020.

- **Public transport stations:**
  - **Bus stations:**

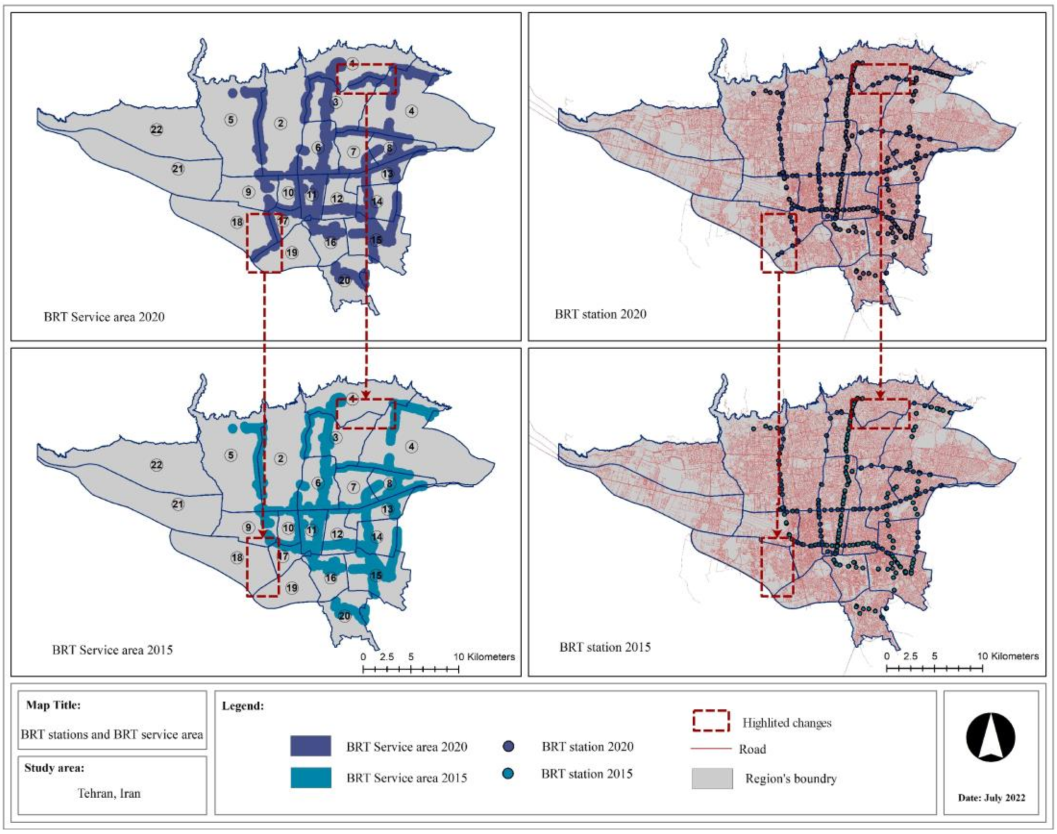
Considering 500 m walking distance toward bus stations shows that the bus service area increases from 2015 to 2020. The number of active stations has increased throughout Tehran. This has caused that in addition to the central regions, the surrounding regions also have adequate access to the bus system. In map 1, the location of bus stops and their service area in these two years can be seen. The highlighted areas show some locations where the number of bus stops increased in 2020 compared to 2015. The number of stations has increased in most of the main streets of the regions and has increased access to public transport within the regions.



Map 1. The service area of bus stops in the years 2015 and 2020

- **BRT stations:**

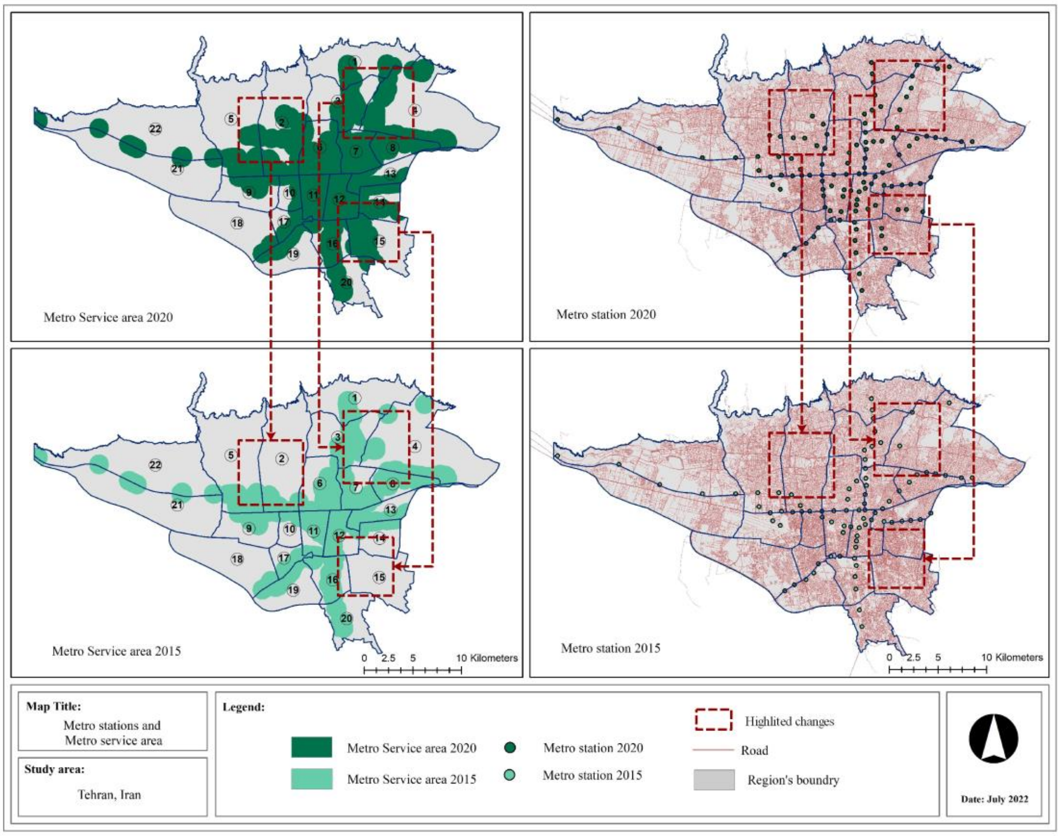
Extracting the BRT stations feature from OSM, their location can be found in the following maps for 2015 and 2020. In 2015, 400 BRT stations were active in Tehran. This number reached 450 stations in 2020. An increase in the number of BRT stations can be seen on the border of region 4 and 5 in the north and 18 and 19 in the south of Tehran. The location of the new stations can be seen on map 2. Taking into account the walking distance of 500 meters, the service area of these stations has been determined. The map shows that with the increase in the number of stations, their service area has also increased in the northern and southwestern parts of the city.



Map 2. The service area of BRT stations in the years 2015 and 2020

- **Metro stations**

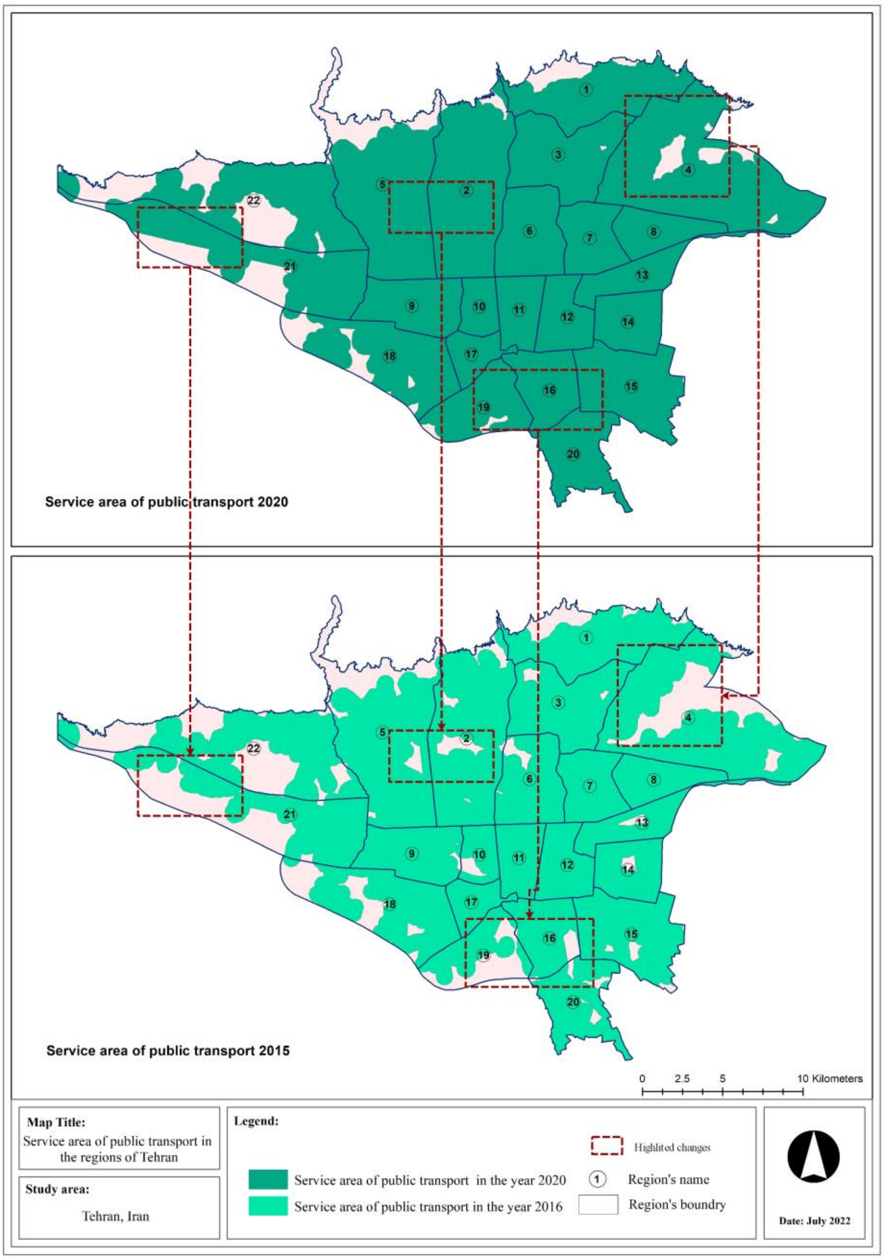
The data extracted from OSM show that the number of metro stations in Tehran has increased from 83 stations in 2015 to 117 stations in 2020. As can be seen in the map below, the number of metro stations in areas 4 and 7 in the northeast, 14 and 15 in the south, 10 in the center, and 2 and 5 in the west of the city has increased from the year 2015 to the year 2020. Increasing the number of these stations has improved access to the metro in the northeastern and southeastern parts, as well as the northwestern part of the city. The location of metro stations and their service areas in 2015 and 2020 have been illustrated in map 3.



Map 3. The service area of metro stations in the years 2015 and 2020

- **Public transportation service area:**

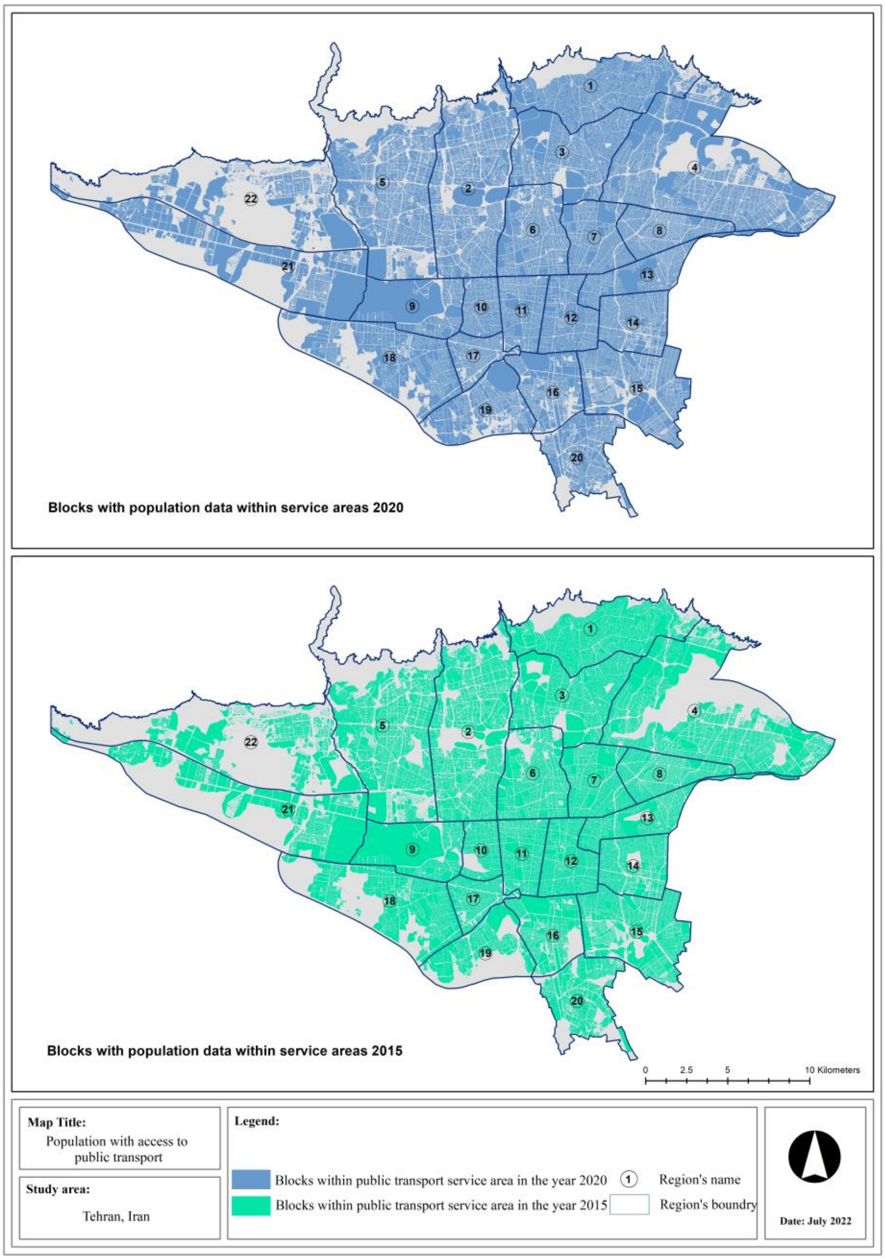
After identifying the service area for all of the public transportation modes in Tehran, all individual service areas are merged to create a continuous service area polygon. Calculating the public transport service area in Tehran shows an increase of service area from 82.5% to 89.7% from the year 2015 to the year 2020. The service area of the public transportation system in Tehran in these two years can be seen in map 4. According to the maps, all central regions of the city have convenient access to public transport in 2020. There is a significant increase in the service areas in the northern and southern parts of the city. Looking again at the service areas of each of the transportation systems in Tehran, it can be seen that this increase in the northeastern and southern regions has been influenced by the expansion in services of all three modes of public transportation in these areas. Then, monitoring the progress of this indicator shows that these areas have performed well in order to improve indicator 11.2.1.



Map 4. The service area of public transportation system in Tehran

- **Estimating the number of people within the service areas**

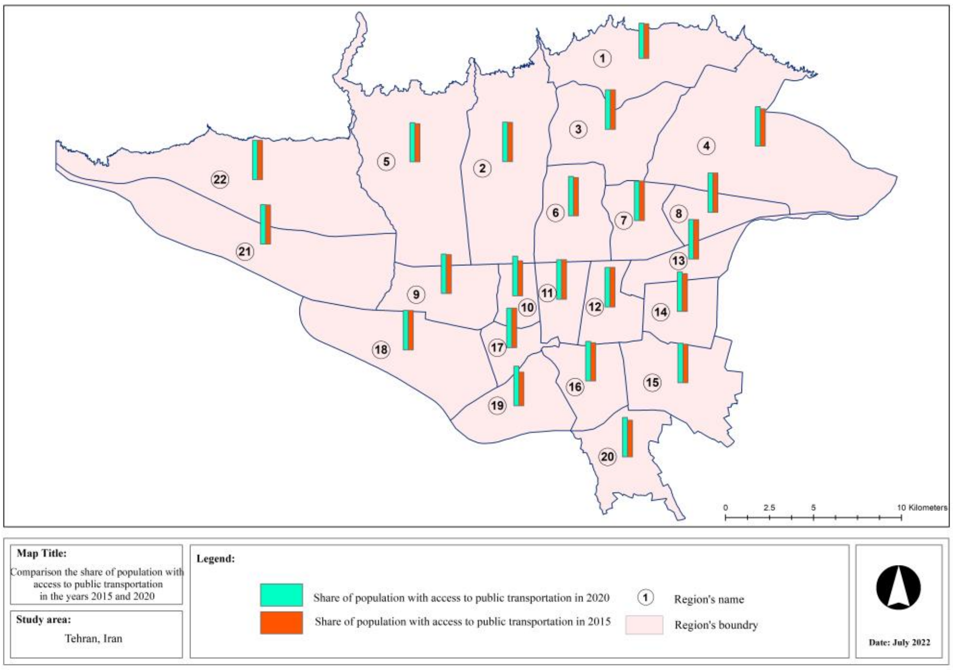
Map 5 shows the result of overlaying the population layer with the public transport service area layer. It presents the blocks that have access to public transportation.



Map 5. Population with access to public transport in the years 2015 and 2020

- **Estimating the access to public transport**

The results of the evaluation of access to the public transportation indicator in the regions of Tehran show a significant increase in the share of people with convenient access to public transport over the last five years. Based on the definition of convenient access to public transport, most areas have 100% access to public transportation. The main reason is the increase in bus, metro, and BRT stations in the city in 2020. However, in two western areas and one northern area of the city, there is still a need to improve access to public transportation. The speed of construction in these regions is much higher than the providing services like public transportation. Because of that newly constructed parts don't have suitable access to this service. The result of computation and the changes in accessibility from 2015 to 2020 can be seen in map 6.



Map 6. Comparison of public transport accessibility in regions of Tehran in the years 2015 and 2020

Figure 7 shows the share of population with convenient access to public transport in regions of Tehran. The changes in the value of the indicator also can be seen. Most improvements in accessibility are for regions 3, 10, 14, 19, and 20.

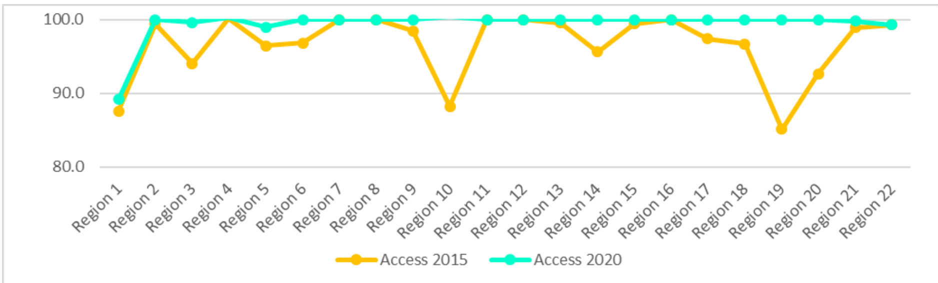


Figure 7. Comparison of public transport accessibility in regions of Tehran in 2015 and 2020

The result of access to public transport for different gender is more or less similar to the previous results. It can be said that the male and female groups have convenient access to public transportation in most Tehran regions. There is also a need to improve access to public transport in the western part of the city. The result of computation for access to public transport indicator based on gender is presented in the following maps.

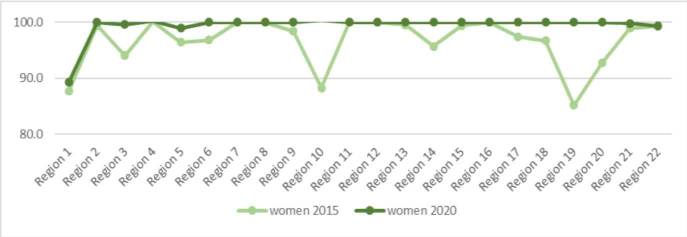


Figure 8. Share of women with access to public transport

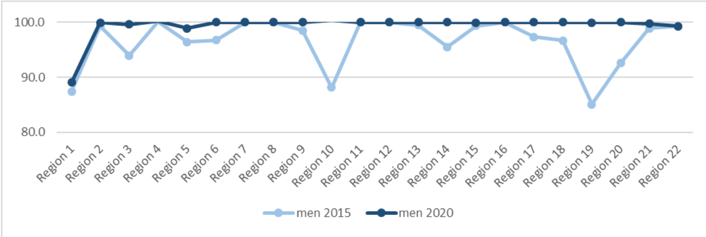
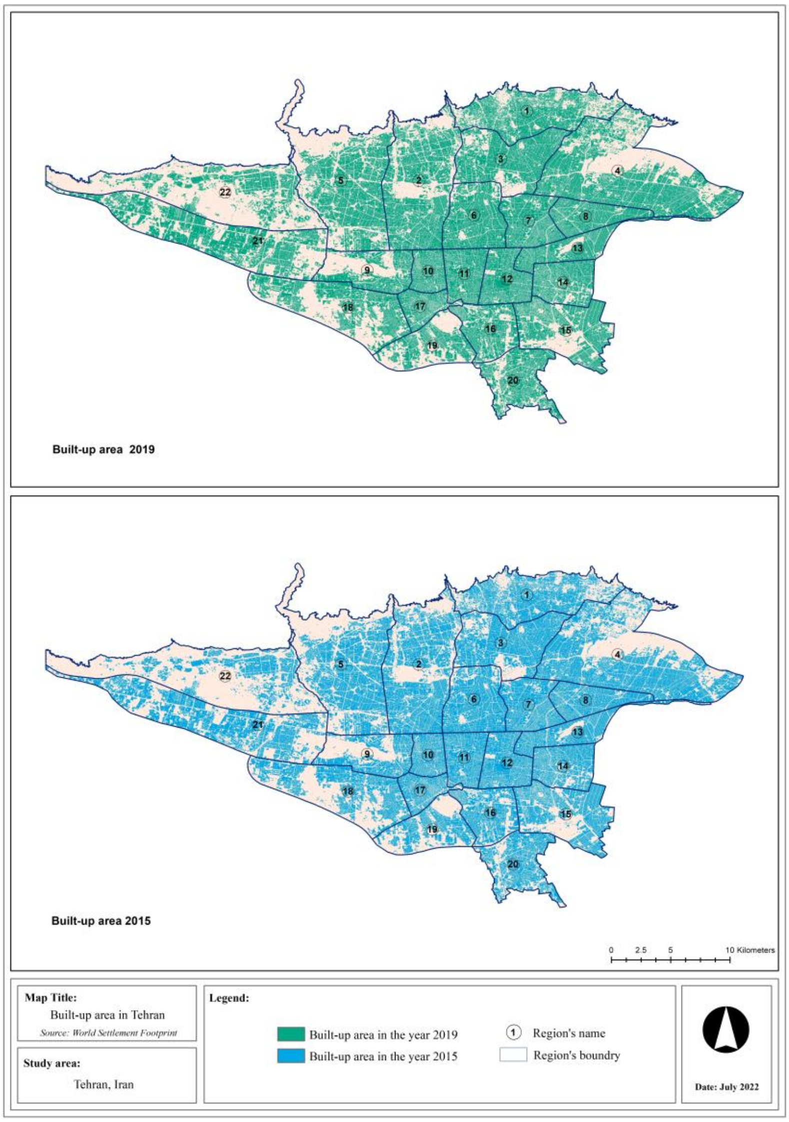


Figure 9. Share of men with access to public transport

It is important to note that this indicator only assesses access to public transport and does not take into account the quality of the transportation system, its speed, and its costs. Also, the 500 meters distance to the station is considered assuming that most users walk to their desired station. This distance does not regard factors such as the path's slope or the presence of stairs on the path. Considering the north-south slope of Tehran, which is very high in some areas, this factor can affect the people's access to stations.

4.2. Result of computing indicator 11.3.1; Land consumption

The World Settlement Footprint layer gives an overview of Tehran's urban structures in 2015 and 2019. Estimation of the built-up area based on WSF data in the city of Tehran shows an increase from 301286888 km^2 in the year 2015 to 307204603 km^2 in the year 2019. Map 7 shows the built-up area of Tehran.



Map 7. Built-up area in Tehran in the years 2015 and 2019

- **Land consumption per capita**

The estimated built-up area is used to observe the changes in land consumption per capita. The calculation of LCR shows the amount of land each person occupies in 2015 and 2019 in each region. Detecting the changes among the regions shows a decrease in the indicator from the year 2015 to the year 2019. In figure 10, we can see that region 21 and 22 has the higher LCR, and Region 10 and 14 has the lower LCR among other regions. It can be inferred that in the central regions of Tehran, the amount of land consumption per capita is much lower than in the western regions.

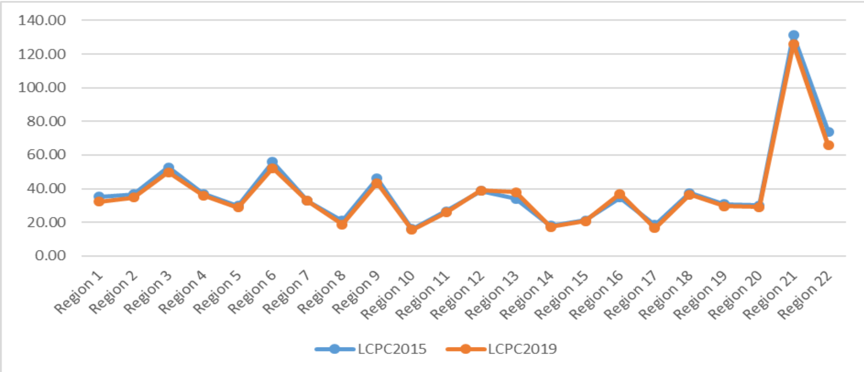


Figure 10. The changes of land consumption per capita in each region of Tehran

The percentage change in land consumption per capita between 2015 and 2019 is presented in table 2. Estimation of this indicator in Tehran shows about 3.41% decrease in the amount of space occupied by each person between 2015 and 2019. It implies a declining trend in land consumption per capita value which means the city is moving towards compactness.

Table 2. Changes in land consumption rate per capita in the region of Tehran

Name of regions	LCPC2015	LCPC2019	Percentage change in LCPC
Region 1	35.12	32.25	-8.16
Region 2	36.66	34.60	-5.63
Region 3	52.59	49.63	-5.62
Region 4	36.98	35.88	-2.96
Region 5	29.75	28.71	-3.50
Region 6	55.97	52.09	-6.92
Region 7	32.86	32.85	-0.02
Region 8	20.97	18.82	-10.24
Region 9	45.93	43.33	-5.66
Region 10	16.10	15.59	-3.21
Region 11	26.68	25.91	-2.87
Region 12	38.73	38.99	0.69
Region 13	34.04	37.82	11.11
Region 14	18.05	17.28	-4.23
Region 15	21.12	20.74	-1.77
Region 16	34.69	36.89	6.35
Region 17	18.36	16.40	-10.66
Region 18	37.54	36.40	-3.03
Region 19	30.66	29.53	-3.71
Region 20	30.11	28.97	-3.78
Region 21	131.20	126.14	-3.86
Region 22	73.77	65.71	-10.92
All	34.71	33.53	-3.41

- **Land consumption rate to population growth rate**

Table 3 shows the computation of the land consumption rate to population growth rate (LCRPGR) indicator for each region of Tehran. When LCPPGR is almost equal to 1, it indicates that the rate of land conversion from other uses to urban uses is equal to the rate of population growth. LCPPGR for most of the regions is closer to 0 which means the rate of population growth is higher than the new developments rate. For some regions, the indicator is negative because of declining in population growth rate.

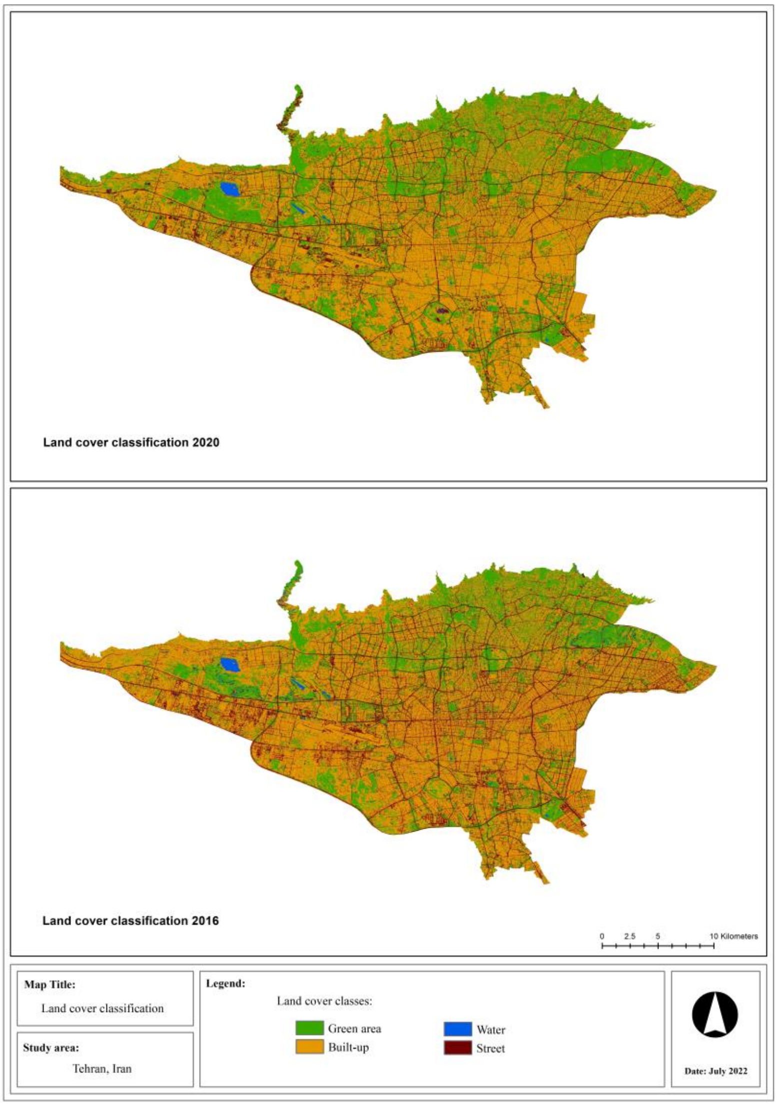
Table 3. Computation of land consumption rate to population growth rate (LCRPGR) indicator for regions of Tehran

Name of region	Built-up area 2015	Population 2015	Built-up area 2019	Population 2019	LCR	PGR	LCRPGR
Region 1	17344702	493889	17523078	543311	0.0030	0.024	0.11
Region 2	25390598	692579	25719207	743408	0.0030	0.018	0.18
Region 3	17355346	330004	17478887	352155	0.0020	0.016	0.11
Region 4	33915820	917261	34519978	962073	0.0040	0.012	0.37
Region 5	25483334	856565	25982901	905056	0.0050	0.014	0.35
Region 6	14034171	250753	14123279	271107	0.0020	0.02	0.08
Region 7	10251250	312002	10285925	313115	0.0010	0.001	0.95
Region 8	8912941	425044	8922296	474056	0.0000	0.027	0.01
Region 9	7997754	174115	8267818	190793	0.0080	0.023	0.36
Region 10	5264367	326885	5266866	337883	0.0000	0.008	0.01
Region 11	8221369	308176	8242175	318082	0.0010	0.008	0.08
Region 12	9329288	240909	9344287	239635	0.0000	-0.001	-0.3
Region 13	8612879	253054	8722146	230645	0.0030	-0.023	-0.14
Region 14	8826576	489101	8852784	512232	0.0010	0.012	0.06
Region 15	13925952	659468	14019253	675837	0.0020	0.006	0.27
Region 16	9285097	267678	9385172	254409	0.0030	-0.013	-0.21
Region 17	5110263	278354	5127681	312619	0.0010	0.029	0.03
Region 18	15738506	419249	16118645	442798	0.0060	0.014	0.44
Region 19	7835666	255533	8045493	272472	0.0070	0.016	0.41
Region 20	11067169	367600	11218531	387281	0.0030	0.013	0.26
Region 21	24444766	186319	25473899	201952	0.0100	0.02	0.51
Region 22	12939075	175398	14564301	221631	0.0300	0.058	0.51
All	301286888	8679936	307204604	9162550	0.0050	0.014	0.36

The value of LCRPGR for Tehran is 0.36. As previously mentioned, a value below one means efficient land use and compactness, and a value above one indicates inefficient land use. Value 0.36 for Tehran shows it is becoming compact over time. At the same time, it implies higher population growth than land consumption growth. However, this compactness does not look suitable for the central areas because it demonstrates congestion and inadequate living environments. The value of some central regions of Tehran, such as districts 10 and 11, implies high compactness. This value for region 7 is close to one, which indicates the balance between the spatial growth of urban areas and their populations. Regions 12, 13, and 16 have reported negative growth as their population decreased over the analysis period. However, the compactness is beneficial for the western regions (regions 21 and 22) because it prevents the expansion of built-up areas to surrounding agricultural lands. Also, the cost of providing services and infrastructure decreases, especially for the newly built-up area in the western part of the city.

4.3. Result of computing indicator 11.7.1; Public spaces

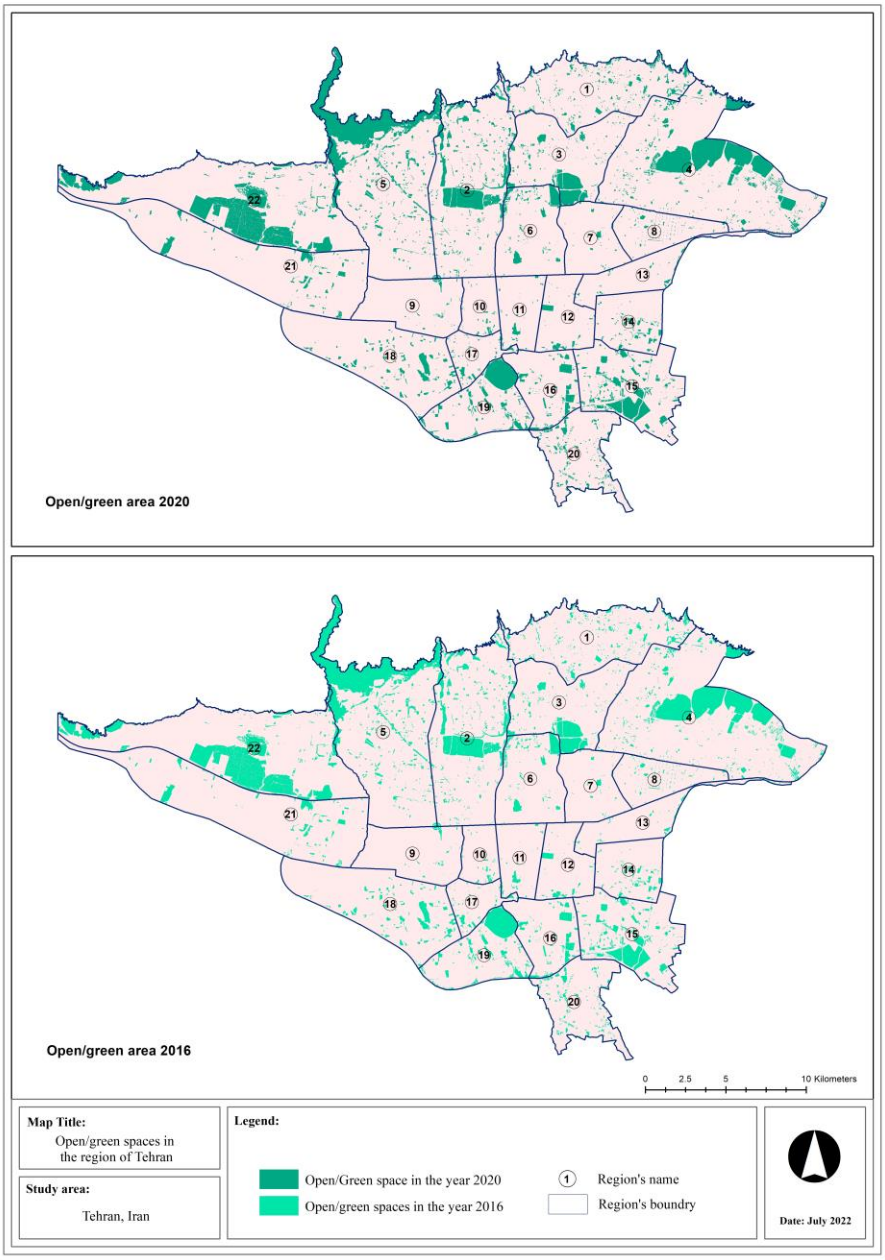
There are two elements of SDG indicator 11.7.1 that are measured; share of the area of the city that is public spaces, and share of population with access to open/green spaces. For both of them, it needs to have data extracted from land cover classification in Tehran for two different times. The land cover classification for 2016 and 2020 extracted from Sentinel-2 images are provided in map 8.



Map 8. Tehran land cover classification in the years 2016 and 2020

- **First element: Share of the area of the city that is public space**
  - **Estimating the area of open/green spaces**

After processing the land cover classification maps, the maps of Tehran's open/green spaces in 2016 and 2020 can be produced. The Map shows these spaces extracted from the classification maps. The assessment demonstrates that the share of land allocated to OPS in Tehran was 12.5 percent in 2016 and 12.9 percent in 2020, which indicates a slight increase during these years.



Map 9. Open/Green spaces in Tehran in the years 2016 and 2020

In table 4, the share of OGS in each region for the years 2016 and 2020 is provided. Region 5, 19, and 22 have the highest share of OGS. The values for the central regions, such as regions 10 and 11 are low. Considering this issue and the compactness of these areas, which was interpreted in the previous section, it can be confirmed that these areas are congested.

Table 4.Share of the area of regions that is open space in 2016 and 2020 (percentage)

Name of region	Share of open/green area 2016
Region 1	7.4
Region 2	14.7
Region 3	12.9
Region 4	18.0
Region 5	24.1
Region 6	8.3
Region 7	1.7
Region 8	3.4
Region 9	1.4
Region 10	3.0
Region 11	3.1
Region 12	4.4
Region 13	2.6
Region 14	5.7
Region 15	16.7
Region 16	10.8
Region 17	6.4
Region 18	5.8
Region 19	21.4
Region 20	5.9
Region 21	3.8
Region 22	23.8
All	12.5

Name of region	share of open/green area 2020
Region 1	8.7
Region 2	15.6
Region 3	13.2
Region 4	18.3
Region 5	24.3
Region 6	8.6
Region 7	1.8
Region 8	3.4
Region 9	1.6
Region 10	3.2
Region 11	3.2
Region 12	4.4
Region 13	2.9
Region 14	6.0
Region 15	17.5
Region 16	11.1
Region 17	6.8
Region 18	6.0
Region 19	22.2
Region 20	6.9
Region 21	3.9
Region 22	24.4
All	12.9

Figure 11 compares the changes in the share of open/green spaces in each region with other regions of Tehran. It can also be seen which areas have the largest share of open/green spaces.

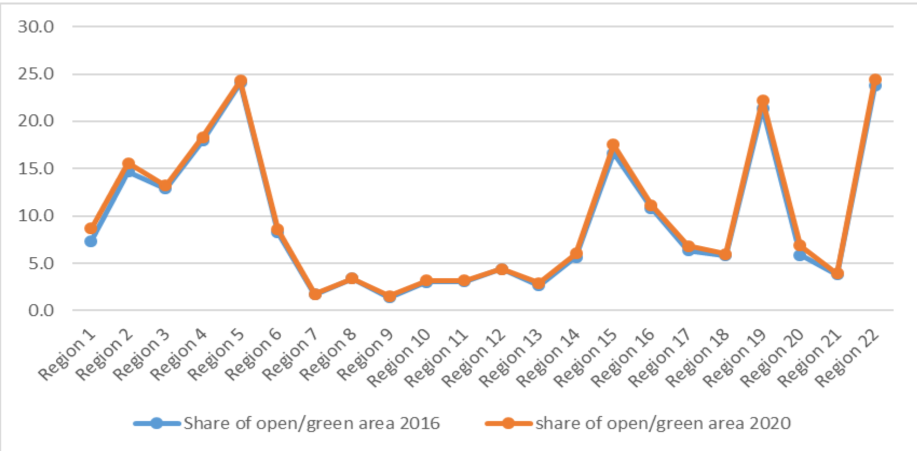


Figure 11. Share of the area of regions that is open space in 2016 and 2020 (percentage)

The images in figure 12 are captured from Google Earth Pro which shows emerging OGS during 2016-2020 in different parts of Tehran.

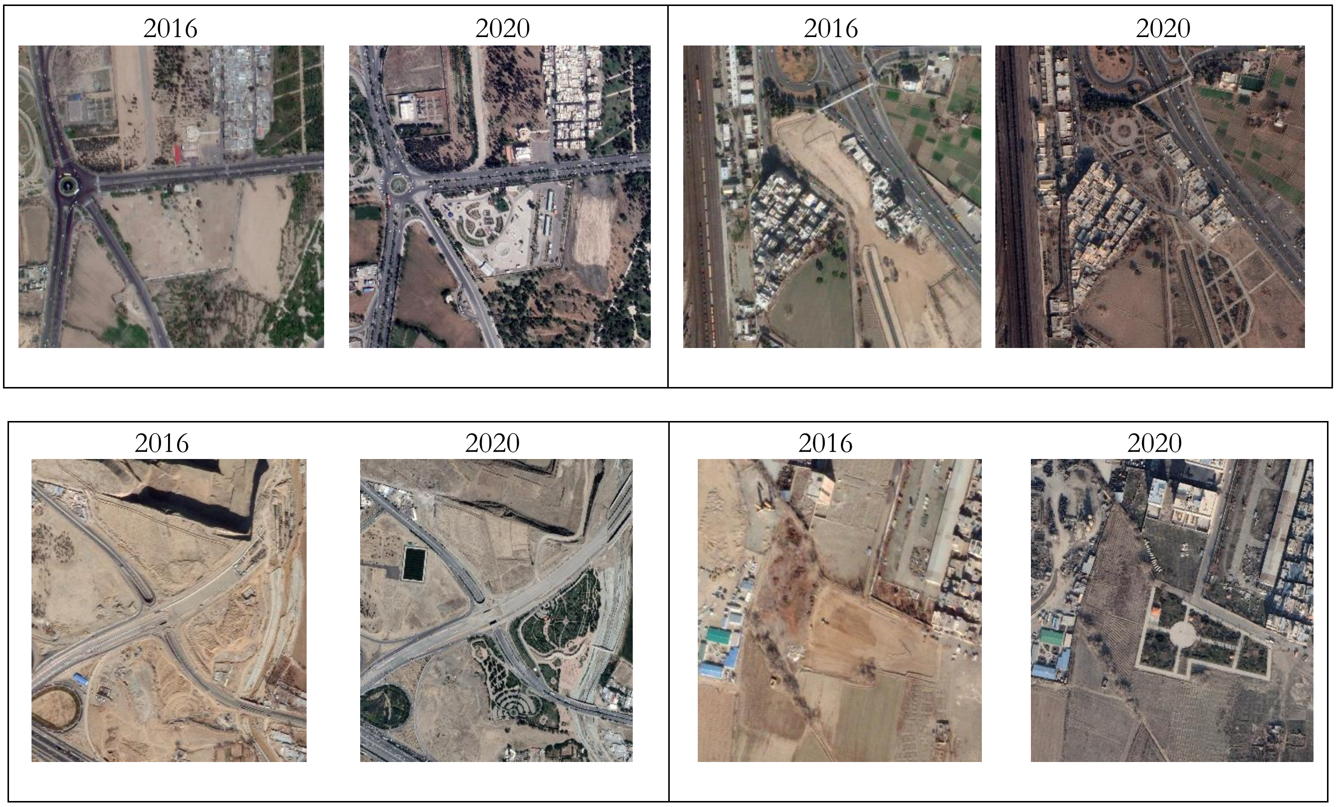


Figure 12. Land cover changes to green spaces detected from Google Earth images

- **Estimating the area of streets**

In tables 5 and 6, street areas and share of land allocated to streets show for each region in Tehran. Comparing the values for 2016 and 2020 shows that the area allocated to streets has increased slightly in 2020 due to the addition of new streets to regions 18, 22, and 21 after 2016.

Table 5. Share of land of region allocated to streets 2016

Name	Road area 2016	Region area	Share of land allocated to streets (percentage)
Region 1	6103471	34539805	17.7
Region 2	9500488	49564092	19.2
Region 3	5725053	29380892	19.5
Region 4	12073539	72434723	16.7
Region 5	8124299	59011222	13.8
Region 6	4400210	21443176	20.5
Region 7	3675493	15368236	23.9
Region 8	4038789	13239392	30.5
Region 9	2401687	19554123	12.3
Region 10	3033509	8059985	37.6
Region 11	3299512	11866392	27.8
Region 12	3788107	13560355	27.9
Region 13	3378688	13885781	24.3
Region 14	4541317	14559952	31.2
Region 15	6383896	28455352	22.4
Region 16	3725760	16449826	22.6
Region 17	2794422	8274247	33.8
Region 18	5029185	38147936	13.2
Region 19	3053627	20546014	14.9
Region 20	4596860	20282802	22.7
Region 21	5121378	51959995	9.9
Region 22	5257528	61401976	8.6
All	110046817	621986273	17.7

Table 6. Share of land of region allocated to streets 2020

Name	street area 2020	Region area	Share of land allocated to streets (percentage)
Region 1	6103471	34539805	17.7
Region 2	9500488	49564092	19.2
Region 3	5725053	29380892	19.5
Region 4	12013159	72434723	16.6
Region 5	8124299	59011222	13.8
Region 6	4400210	21443176	20.5
Region 7	3675493	15368236	23.9
Region 8	4038789	13239392	30.5
Region 9	2401687	19554123	12.3
Region 10	3033509	8059985	37.6
Region 11	3299512	11866392	27.8
Region 12	3788107	13560355	27.9
Region 13	3378688	13885781	24.3
Region 14	4541317	14559952	31.2
Region 15	6383896	28455352	22.4
Region 16	3725760	16449826	22.6
Region 17	2794422	8274247	33.8
Region 18	5081248	38147936	13.3
Region 19	3053627	20546014	14.9
Region 20	4596860	20282802	22.7
Region 21	5172878	51959995	10.0
Region 22	5610931	61401976	9.1
All	110443404	621986273	17.8

The images provided below show the road instruction in different parts of Tehran during 2016-2020.

Figure 13. Land cover changes to roads detected from Google Earth images

- **Total area of public spaces**

Table 7 shows the total area of public spaces in each area, obtained by aggregating the area of open/green spaces and streets. The share of public spaces for each region in 2016 and 2020 can also be seen. Comparing all these changes shows that the share of public spaces in Tehran in 2020 compared to 2016 has increased slightly. The share of open/green spaces in 2016 was about 30.14%, which in 2020 reached 30.67%. Most of these changes are related to the western part of the city which are the expansion zones. Along with the addition of public green space in this part, new streets have been built in them.

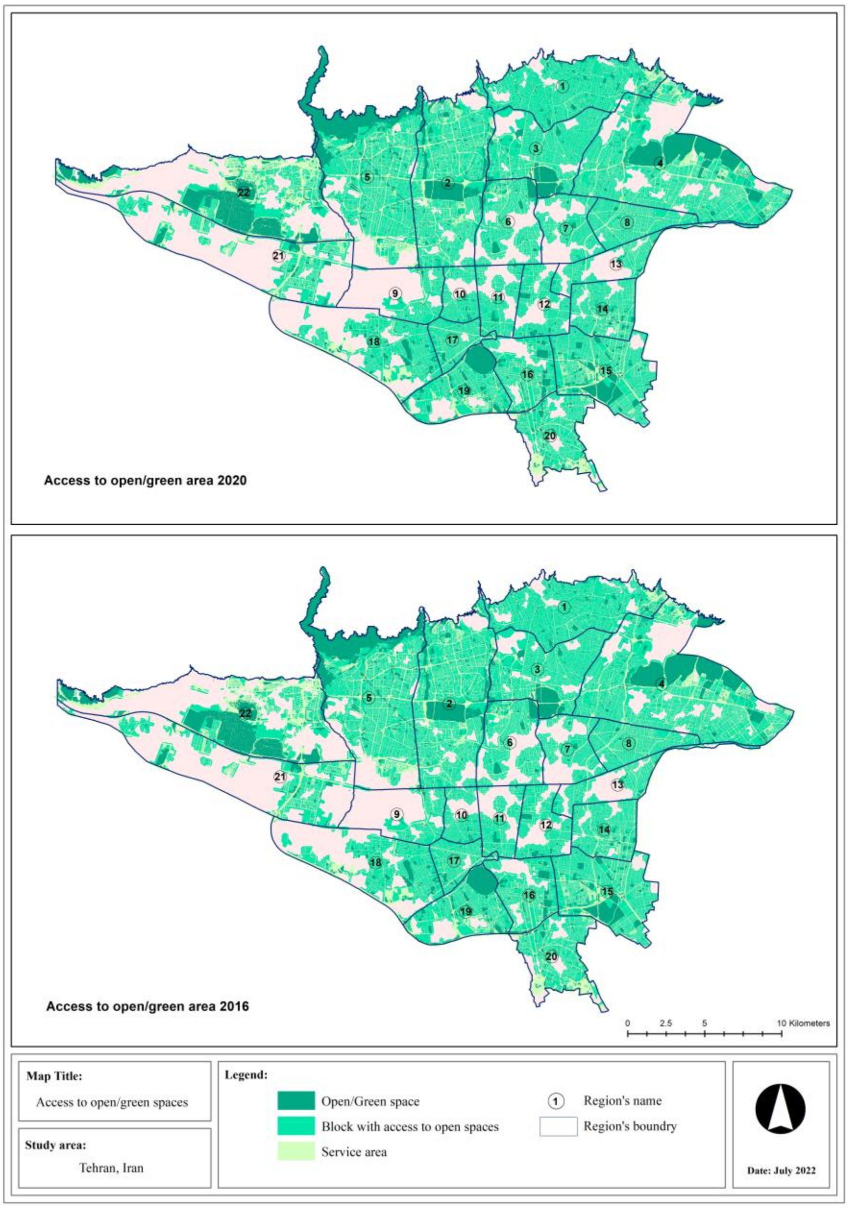
Despite the increase in the area of public spaces, the value of the indicator is still far from UN-Habitat's recommendation which is 45-50% of urban land allocation to streets and open/green spaces (UN-Habitat, 2018c). It includes 30 - 35% for streets and 15 - 20% for open green spaces which is for Tehran is 17.8% For streets and 12.9% for open green spaces.

Table 7.The share of public spaces for each region in 2016 and 2020

Region	OGS 2016	OGS 2020	Road 2016	Road 2020	Area of region	Total OGS 2016	Total OGS 2020	Share of OGS 2016	Share of OGS 2020
Region 1	2546600	3002517	6103471	6103471	34539805	8650071	9105988	25.04	26.36
Region 2	7283335	7720376	9500488	9500488	49564092	16783823	17220864	33.86	34.74
Region 3	3795257	3882837	5725053	5725053	29380892	9520310	9607891	32.40	32.70
Region 4	13010112	13284630	12073539	12013159	72434723	25083651	25297789	34.63	34.92
Region 5	14213630	14341755	8124299	8124299	59011222	22337929	22466054	37.85	38.07
Region 6	1774039	1843686	4400210	4400210	21443176	6174249	6243897	28.79	29.12
Region 7	259702	270486	3675493	3675493	15368236	3935195	3945980	25.61	25.68
Region 8	449580	452911	4038789	4038789	13239392	4488369	4491699	33.90	33.93
Region 9	275726	303485	2401687	2401687	19554123	2677414	2705172	13.69	13.83
Region 10	244501	257423	3033509	3033509	8059985	3278010	3290933	40.67	40.83
Region 11	365119	381009	3299512	3299512	11866392	3664630	3680521	30.88	31.02
Region 12	594061	597803	3788107	3788107	13560355	4382168	4385910	32.32	32.34
Region 13	366384	403322	3378688	3378688	13885781	3745072	3782010	26.97	27.24
Region 14	824199	878209	4541317	4541317	14559952	5365516	5419527	36.85	37.22
Region 15	4738026	4992677	6383896	6383896	28455352	11121922	11376573	39.09	39.98
Region 16	1779430	1833616	3725760	3725760	16449826	5505190	5559376	33.47	33.80
Region 17	527558	566332	2794422	2794422	8274247	3321979	3360753	40.15	40.62
Region 18	2222512	2291681	5029185	5081248	38147936	7251697	7372929	19.01	19.33
Region 19	4394244	4567708	3053627	3053627	20546014	7447870	7621335	36.25	37.09
Region 20	1189159	1394880	4596860	4596860	20282802	5786019	5991740	28.53	29.54
Region 21	1989150	2045259	5121378	5172878	51959995	7110528	7218138	13.68	13.89
Region 22	14600506	14981632	5257528	5610931	61401976	19858035	20592562	32.34	33.54
All	77442829	80294235	110046817	110443404	621986273	187489646	190737639	30.14	30.67

- **Second element: Share of population with access to open/green spaces**

Map 10 shows the network analysis to define the service area of OGS. The service area of these spaces is determined by taking 400 meters of walking towards them. The maps show that most of northern regions of the city have convenient access to OGS. In the central regions, there are some populated blocks that do not have convenient access to OGS. Due to the compactness of these regions, there is a necessity to provide more green spaces in them. There is also a need to allocate more OGS in region 22, for providing OGS accessibility for all its population, which should be considered in development projects in this region. In region 21, however, existing OGSs cover a large portion of residential blocks.



Map 10. Open/green spaces service area in Tehran in the years 2016 and 2020

Tables 8 and 9 provide the share of all total population and women and men population with access to OGS for each region in 2016 and 2020. The evaluation of the indicator access to open/green spaces shows its relative improvement in accessibility over the past years. The evaluation of access to OGS shows that the population living in most areas of Tehran has convenient access to these spaces. It shows the appropriate distribution of these spaces in the city of Tehran. Monitoring this indicator indicates progress in access to OGSs in many regions between 2016 and 2020.

Table 8.Share of all population (total, women and men) with access to OGS in the year 2016

Name of region	Total population 2016	Women 2016	Men 2016
Region 1	98.8	98.8	98.8
Region 2	95.4	95.5	95.3
Region 3	97.3	97.4	97.2
Region 4	96.0	96.0	96.0
Region 5	96.3	96.4	96.3
Region 6	85.3	85.0	85.6
Region 7	76.4	76.6	76.3
Region 8	98.4	98.3	98.4
Region 9	96.5	96.6	96.5
Region 10	78.9	78.9	78.9
Region 11	78.3	78.7	77.9
Region 12	84.7	84.9	84.5
Region 13	78.6	78.8	78.4
Region 14	94.9	94.9	94.8
Region 15	97.7	97.7	97.7
Region 16	95.6	95.6	95.6
Region 17	96.3	96.3	96.4
Region 18	87.3	87.3	87.2
Region 19	98.4	98.3	98.4
Region 20	93.2	93.4	93.1
Region 21	93.7	93.8	93.7
Region 22	77.8	78.0	77.6

Table 9.Share of all population (total, women and men) with access to OGS in the year 2020

Name of region	Total population 2020	Women 2020	Men 2020
Region 1	98.9	98.9	98.9
Region 2	95.4	95.3	95.5
Region 3	98.3	98.2	98.3
Region 4	94.8	94.8	94.9
Region 5	96.3	96.3	96.4
Region 6	86.2	86.5	85.9
Region 7	77.2	77.1	77.3
Region 8	98.5	98.6	98.5
Region 9	96.2	96.2	96.1
Region 10	79.8	79.9	79.8
Region 11	83.2	82.9	83.5
Region 12	87.0	86.8	87.2
Region 13	78.4	78.2	78.6
Region 14	94.5	94.5	94.6
Region 15	97.6	97.6	97.7
Region 16	95.2	95.3	95.2
Region 17	97.2	97.3	97.2
Region 18	90.0	89.9	90.0
Region 19	98.8	98.8	98.8
Region 20	94.5	94.4	94.6
Region 21	93.7	93.7	93.8
Region 22	84.0	83.9	84.1

4.4. The recommended guideline to evaluate SDG indicators

In the processing, results, and discussion sections, the steps of evaluating desired indicators of SDG 11 were presented. In the processing section, the required data were defined and extracted through the specified tools and processed for use in the next step. Then, these data were converted into the formats needed for the indicators' computation. In the results section, outputs and indicators computation are presented. Finally, the estimation of these results and the evaluation of each indicator are discussed.

In all these steps, we have tried to use open resources and tools to access, extract and analyze data. Therefore, it provides a general guideline for data acquisition, extraction, and analysis so that organizations can perform these steps with the least cost and in the shortest time. This guideline is presented for each indicator in the following part. They consist of three steps:

- First: Data capturing and processing
  - the source of data is determined. They are mostly open sources.
  - The tools for extracting data are introduced. The software and platforms are QGIS and Google Earth Engine. Both of them are freely accessible[1].
  - The output of this step is data prepared for the analysis step.
- Second: data analysis

[1] The codes are provided in the annex.

- The data analysis method is defined according to the desired indicator.
- The appropriate platforms for analysis are introduced.
- The output is presented as data ready for computation.

▪ Third: Computation

- The indicator is computed based on the defined formula.

These guidelines can be helpful for companies working on local and urban development projects, NGOs focusing on improving low-income neighbourhoods, and municipal-related organizations working on operational projects. By observing the mentioned indicators, these institutions can evaluate the impact of their performance on the situation of SDGs. They can review their performance, identify weaknesses and deficiencies, and take steps to improve it.

This guideline can be used for other cities in Iran. Knowing that Tehran is the largest and most populous city in Iran and its data must be collected at a more significant level and volume, the preparation of data at the level of other cities can be done efficiently and with less time. However, these steps are accompanied by limitations, which will be addressed in the next section.

Figure 14. The guideline for computing indicator 11.2.1: Access to public transportation

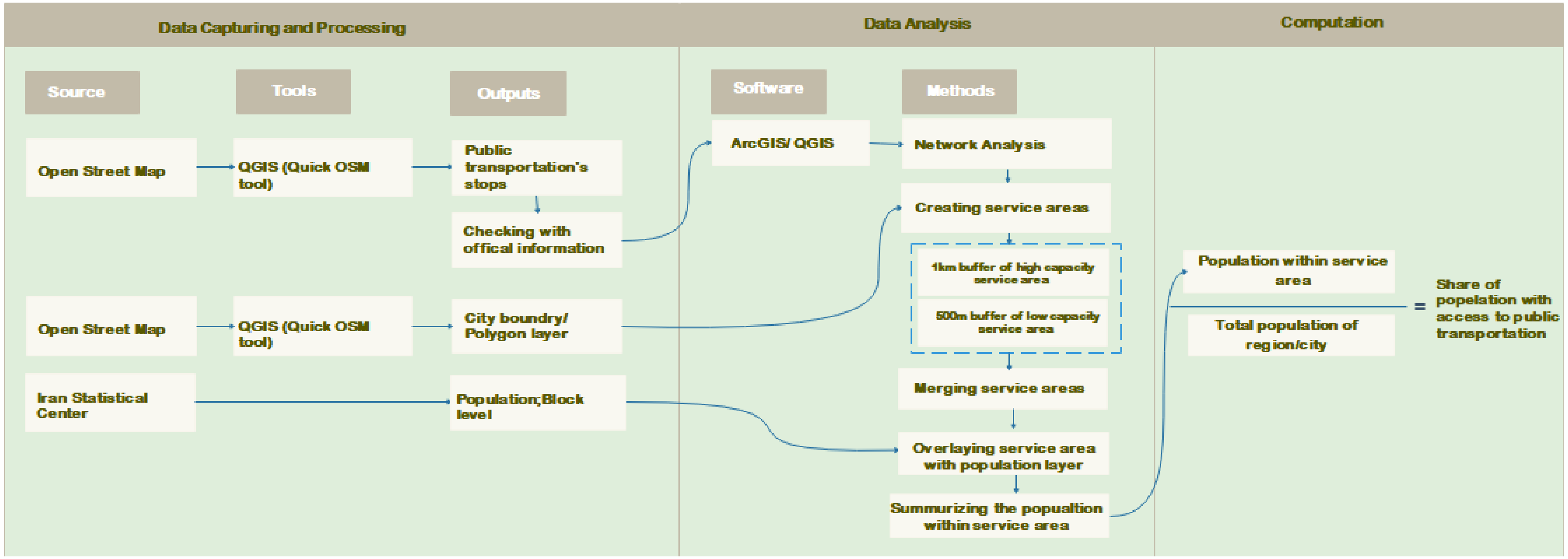


Figure 15. The guideline for computing indicator 11.3.1: Land Consumption

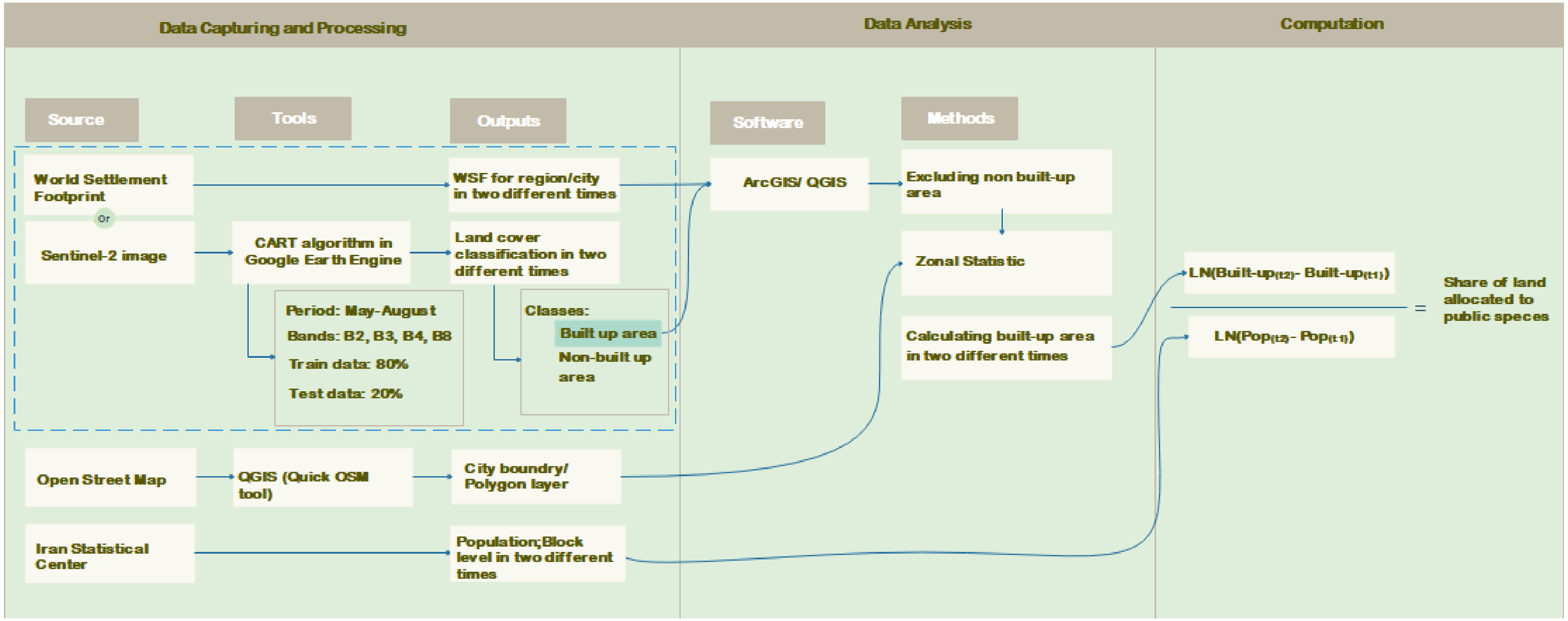
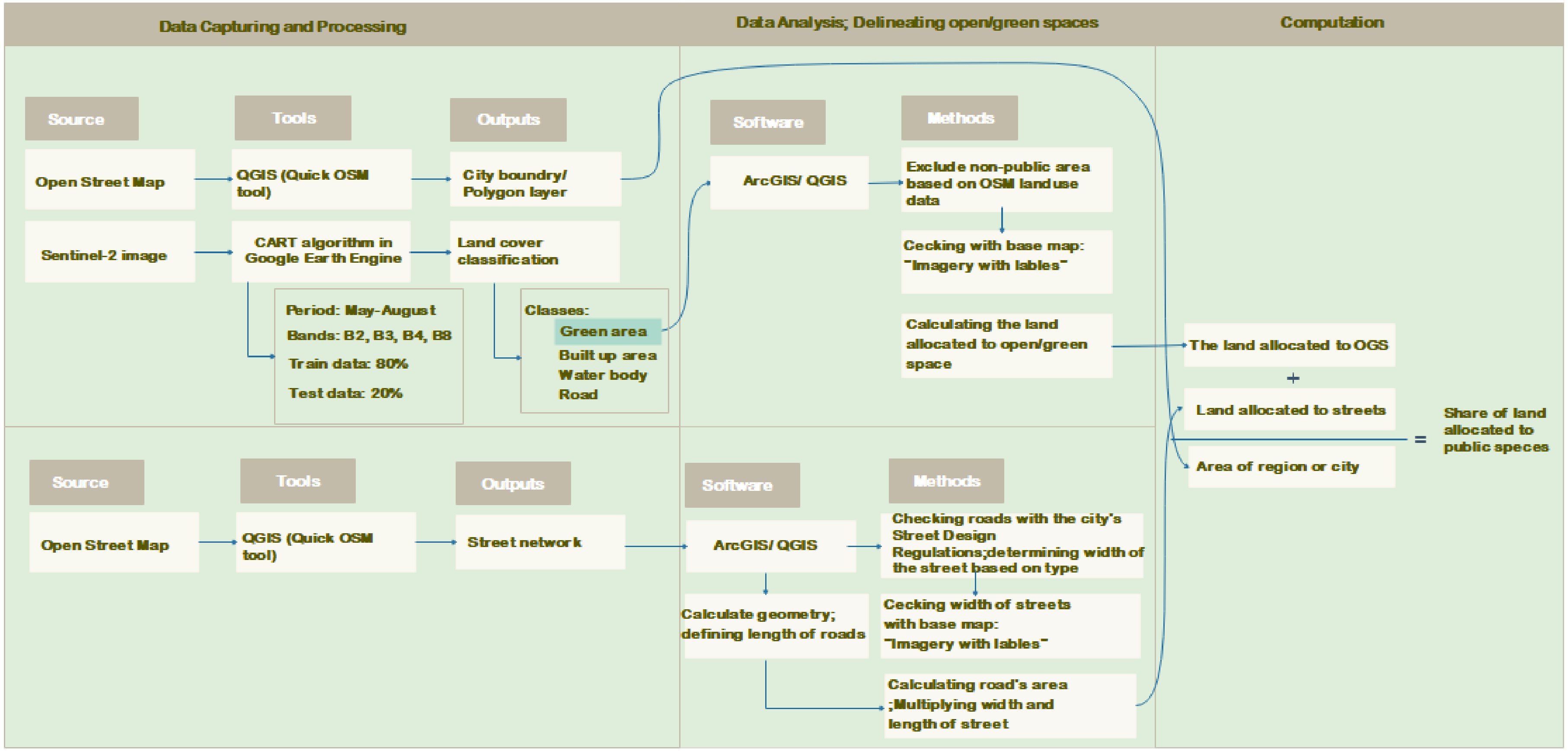


Figure 16. The guideline for computing indicator 11.7.1: access to public spaces



4.5. Summary

In this chapter, the results of the computation of each indicator are presented. The results are analyzed based on their changes during the time and among the Tehran regions. Based on that the progress of each indicator is evaluated. In the last section, the guidelines for monitoring SDG11 indicators are presented.

5. DISCUSSION AND LIMITATIONS

5.1. Discussion

This research took advantage of Earth observation and open geospatial data to take a step forward in monitoring SDG11 indicators. Using the benefit of these data combined with free access platforms (GEE and QGIS) has led to the development of a practical guideline to regular monitoring of these indicators in Tehran, Iran. Regarding the requirements and limitations in data collection and analysis in cases like Tehran, the proposed guideline can substitute traditional methods in the monitoring and decision-making process.

The guideline can be applied by the companies and institutions involved in urban development which normally obtain their required data from government departments and agencies' databases. Issues like doing a lot of correspondence with these departments, consuming lots of time and cost to capture data, and lack of access to some data considered confidential, could be solved by using open-source data and platforms. This guideline helps the companies and institutions to capture these data and determine the best algorithmic method and statistical applications for the use of EO data. As such, facilitating monitoring through this guideline provides information to decision-makers to make informed decisions, assess their performance, and accelerate progress toward achieving SDG11. Using this guideline for three selected indicators can be effective in deciding on physical changes in the city:

- Indicator 11.2.1; access to public transport

Regular monitoring of access to public transport, show the changes (increase or decrease) in its service area over a period of time. It helps urban decision-makers prepare appropriate plans to improve access to public transportation and see its consequences on Tehran's land-use changes, especially for parts that faced rapid growth in recent years. The progress toward achieving this indicator also positively affects other indicators of sustainable development, such as reducing air pollution. Given Tehran's pollution situation, monitoring this indicator could help experts assess the impact of their transportation plans on changes in air pollution.

- Indicator 11.3.1; land use efficiency

Monitoring land-use efficiency shows compactness in the case of Tehran. Compactness in some parts of Tehran could be led to congestion. This congestion, which can be identified through the Land consumption per capita indicator, can be lessened through other urban development programs related to access to public/green spaces and access to public transportation. Considering all these programs for Tehran, compactness has positive consequences like decreased demand for mobility, less energy consumption per capita, and less GHG emission per capita. Therefore, using this guideline to monitor all three indicators can help to check the trend of transformations in compactness along with changes in access to green space and public transportation.

- Indicator 11.7.1; access to public spaces

Monitoring changes in the share of OGS and access to them helps decision-makers observe the impact of their action plans. Based on regular monitoring, they can provide required spaces in the areas that do not have proper access to the OGS. Also, allocating green spaces to areas with high LCRPGR will help improve the quality of their living space. Progress in achieving this indicator through the proper and hierarchical distribution of OGSs in the city and its regions, creating a well-designed street network, and paying attention to the accessibility of these spaces for everyone promote its inclusiveness, create a sense of belonging, and social interactions for Tehran.

Due to the free access to the required resources and platforms, this guideline can be used for other cities in Iran. However, its adaptation to the geographical, economic, and demographic conditions of the city is needed. In addition, interpreting the results requires some knowledge of the city. Therefore, the adjusted version of this guideline can be helpful for monitoring sustainable development indicators.

5.2. Limitations

There are limitations to using the guideline:

- This guideline provides an overview of the status of sustainable development indicators. More critical decisions need to be evaluated more accurately and in detail. Changes in indicators may be due to various social and economic conditions that are not addressed in this guideline. Tehran, as the capital, is witnessing rapid changes due to the country's economic conditions, international decisions, immigration, etc. Indeed, these cases affect the city's growth, its compactness or dispersion, and the way urban transportation services and green/open spaces are provided, which are beyond the scope of this guideline.

- Convincing organizations to use free data could be an issue. Because there is still no complete confidence in the accuracy of this data and replacing it with data that is obtained manually, for example, with fieldwork.

- Data collection can also be challenging at the beginning because organizations need to update themselves with sufficient knowledge to use the data sources. There are also restrictions on access to historical data. In order to evaluate the indicators through free data, it is necessary to collect data for several consecutive years so that evaluation can be done in future years. In this study, official data was used in some cases due to the lack of access to information in the initial year of evaluation. Also, when the data were unavailable in the desired year, the data were collected in the closest possible year.

- Since the purpose of this study is to use open data, Sentinel-2 Imagery is used as the data mining source for the 11.7.1 indicator. Due to the resolution of this image, some mapped open/green spaces are coarse, and the smaller ones may not have been correctly detected or omitted from land cover classification.

- Open street map is used as a resource for extracting required data for indicator 11.2.1. Although it is a useful resource, it may provide not fully accurate data. The data should be checked with high-resolution imageries or fieldwork data.

- Some aspects of indicators cannot be observed by EO tools. Accessibility to public transport and public spaces cannot be assessed for all, regardless of age and level of mobility (as mentioned in the indicators). Statistical data with details such as age and data such as station facilities (like facilities for all levels of mobility) are needed for better analysis. Accurate identification of open spaces that have public access also requires ancillary data such as cadastral records. Also, the data on characteristic of open space to check if it is suitable for all by sex, age, and persons with disabilities should be collected by fieldwork (Using KoBo Toolbox[17]).

[17] https://www.kobotoolbox.org/

- Depending on the city, there may also be restrictions on data acquisition. This constraint may arise, for example, in calculating the access to public transport. In some cities, the public transport system could be different. In many of them, there is no metro as a high-capacity system. In some, using other kinds of public transportation is common, and collecting data may require a different method.

6. CONCLUSION AND RECOMMENDATION

6.1. Reflection to research objectives and questions

The following objectives followed by their research questions were answered to achieve the generic goal.

- To identify metrics and geospatial data that are required for monitoring the three indicators of SDG11

   a. Which metrics can be used to monitor the indicators?

The indicators' metrics are set for evaluating them according to UN-Habitat's definitions. These metric for the 11.2.1 indicator is the service area of transport stations. This service area is determined based on the walking distance to the stations. This distance varies according to the capacity of the public transport systems. A distance of 500 meters is set for access to the low-capacity transport system, and a distance of 1 km is set for access to the high-capacity transport system. Therefore, the population within the service area has convenient access to public transportation. For indicator 11.3.1, the land use efficiency is considered. The amount of land allocated to the built-up must be estimated. This rate is measured according to demographic changes to estimate city compactness. The 11.7.1 indicator estimates the share of land allocated to OGS. Open/green spaces are defined based on their free accessibility, greenness, and area. Also, the service area of OGS is one of the criteria for proper access to them. This service area is set at a walking distance of 400 meters.

   b. Which free geospatial data sources can be used?

The required data for assessing the 11.2.1 indicator includes public transport stations and street networks. Open Street Map has been used as a source from which this data can be extracted as a feature. Indicator 11.3.1 needs to calculate the built-up area. The free source for extraction of built-up is the World Settlement Footprint layer. Also, the data has been produced in the years close to this research's desired time. Satellite imagery is a proper source for extracting data for indicator 11.7.1. The best source for downloading free and high-resolution satellite imagery is Copernicus Open Access Hub. Sentinel-2 images can be used for extracting Tehran land cover and delineating OGS.

- To evaluate and monitor the SDGs' indicators over time in Tehran

   a. How are the indicators change over time in Tehran?

Data of two different years were collected with an interval of 5 years to investigate the changes in the study area. Initially, the years 2015 and 2020 were considered to calculate all indicators. However, due to the limitations of the sources from which the data for 11.3.1 and 11.7.1 indicators were extracted, the period for these two indicators was reduced to 4 years. The indicators in each of these years were calculated using data from two different years, and their changes in the specified period were evaluated. The result of the access to public transport indicator shows an increase of about 3% in accessibility to public transport stations. The value of the land consumption rate indicator, calculated by computing land-use changes and population changes, is estimated at 0.36, indicating the tendency to compactness in Tehran. The evaluation of the access to public spaces indicator shows that the share of land allocated to public spaces in Tehran has increased by about 0.53%. However, access to public spaces has also risen by 6.5 percent.

   b. Which parts of the city have considered progress according to the three indicators?

The city of Tehran has been selected as a study area, but in order to better interpret the changes in the indicators, this area has been divided into smaller regions based on the boundaries of Tehran's administrative districts. The indicators are calculated for each region in two different years. The comparison of indicators in the two years shows their change in each region. On the other hand, comparing regions in terms of performance in both years is feasible. This comparison shows that the central regions of Tehran are in a better position regarding access to public transportation and open/green space. However, they are more compact, and some of them encounter congestion. In the western areas of Tehran, which are in the city's growth zone, the land consumption per capita is higher, and the rate of compactness is less. Access to public transport should be increased in these regions, and due to the existence of large open/green spaces, access to public spaces is convenient.

- Providing a guideline for regular SDG monitoring in Tehran

    a. How can the guideline fill the gaps in data capturing and SDG monitoring in Tehran?

Data restriction is one of the most critical challenges city decision-makers face in Iran. Typically, they use traditional methods such as surveys, which consume a lot of time and energy. Also, SDG monitoring has been suspended due to the lack of budget in Iran. Gaps in data capturing and SDG11 indicators monitoring are filled by proposing guidance to use open geospatial data and EO by utilizing free platforms.

6.2. Conclusions

This study explored the potential of open geospatial data and Earth Observation in monitoring three indicators of SDG11. It highlights the importance of these data for monitoring progress on the SDGs. A guideline was proposed based on open imagery, cloud computation, and open data. This guideline aimed to monitor SDG11 indicators with minimal manual interaction and at the lowest cost and in the shortest time to fill the gap in data acquisition in Tehran. However, limited access to the high-resolution source can influence the method's accuracy. OSM Data may be accompanied by errors. Also, due to the 10-meter resolution of Sentinel-2 images, the data received from land cover classification may miss some information. There is also a need for auxiliary data for a better interpretation of the indicators.

However, the obtained results can fill the information gaps in the Sustainable Development Report for Iran on selected indicators and could be helpful for preparing information to report for Voluntary Local Reviews not only for Tehran but also for other cities in Iran. It could also help city decision-makers to review the result of their plans in order to make progress toward achieving SDG11 indicators.

6.3. Recommendations for further studies

Based on current research, there are some recommendations for future research:

Due to the time limitation, three indicators of SDG11 have been selected for monitoring. For a better understanding of the progress toward SDG11, other remaining SDG11 indicators that can be observed through EO could be added to this study's guideline. It will make a more comprehensive guideline to monitor SDG11. These indicators are; the proportion of urban population living in slums, informal settlements, or inadequate housing and the annual mean levels of fine particulate matter in cities

More complex machine learning models are recommended in future studies to produce more accurate data. For example, data on public transportation systems in different years can be extracted, or green spaces' boundaries can be delineated more accurately through these models. Choosing a smaller area can be more practical for data collection. It can be more comfortable to check the extracted data with the samples on the ground to determine the accuracy of the data. On the other hand, it makes more sense to use the KoBoToolbox for field data collection to determine ownership, and characteristics of open spaces in smaller areas. Data collected at lower levels can be aggregated together to produce a dataset for the city that can be used to evaluate the indicator.

The inclusion of this study with the social and economic studies of the city can provide a better interpretation of the results. A comprehensive study can better explain the reasons for the changes in the indicators and analyze their effects on the city structure.

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APPENDIX

Annex 1:

Codes for land cover classification used in Google Earth Engine:

```
// ROI
Map.addLayer(Tehranlimit);
Map.centerObject(Tehranlimit);

//Load SentinelData
var image = ee.ImageCollection("COPERNICUS/S2")
.filterDate('2020-05-30', '2020-08-30')
.filter(ee.Filter.lt('CLOUDY_PIXEL_PERCENTAGE', 20))
.filterBounds(Tehranlimit)
.median();

// Visualization
var visParamsTrue = {bands: ['B8', 'B3', 'B2'], min: 0, max: 2500, gamma:1.1};
Map.addLayer(image.clip(Tehranlimit), visParamsTrue, 'Sentinel_2020');
Map.centerObject(Tehranlimit);

//creat training data
var training = water.merge(building).merge(green).merge(roads);
print(training);

var lable = 'class';
var bands = ['B2', 'B3', 'B4', 'B8'];
var input = image.select(bands);

 //overlay the points on the imagry to get training
var trainImage = input.sampleRegions({
  collection: training,
  properties: [lable],
  scale: 30
});

var trainingData = trainImage.randomColumn();
var trainset = trainingData.filter(ee.Filter.lessThan('random', 0.8));
var testset = trainingData.filter(ee.Filter.greaterThanOrEquals('random', 0.8));
var classifier = ee.Classifier.smileCart().train(trainset, lable, bands);

//Classify the image
var classified = input.classify(classifier);

//define a palette for classification
var landcoverPalette = [
  '24C248', //water (3)
```

```
  'FFC133', //building (2)
  '3364FF', //green (1)
  '975B1E', //roads(4)
  ];

// Define a kernel.
var kernel = ee.Kernel.circle({radius: 5});

// Perform an erosion followed by a dilation, display.
var opened = classified.clip(Tehranlimit)
          .focalMin({kernel: kernel, iterations: 2})
          .focalMax({kernel: kernel, iterations: 2});
    Map.addLayer(opened, {palette: landcoverPalette, min:1, max:4 }, 'Classification CART');

//Acuracy assessment
var confusionMartix = ee.ConfusionMatrix(testset.classify(classifier)
.errorMatrix({
  actual: 'class',
  predicted: 'classification'
}));

print('Confusion Matrix:', confusionMartix)
print('Overall Accuracy:', confusionMartix.accuracy());

//export classified map to Google Drive
Export.image.toDrive({
  image: classified.clip(Tehranlimit),
  description: 'Sentinel_2_CART',
  scale: 10,
  region: Tehranlimit,
  maxPixels: 1e13,
   });
```