
**EO Clinic** project:

# Infrastructure Projects Implementation and Economic Outcomes in Armenia

*Work Order Report*

Support requested by:
Asian Development Bank (ADB)

Reference: EOC0013_WOR_v01.1
Date: 2021 December 8

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# ABOUT THIS DOCUMENT

This publication was prepared in the framework of the EO Clinic (Earth Observation Clinic, see below), in partnership between ESA (European Space Agency), the Asian Development Bank (ADB), Central West Regional Department (CWRD), Urban Development and Water Division (CWUW) and team of service providers contracted by ESA: GeoVille GmbH (Austria) and CLS (France).

This Work Order Report (WOR) is structured as in the following:

- **Section 1** describes the context of the ADB activities on Infrastructure Projects Implementation and Economic Outcomes in Armenia, as well as the objectives of ESA EO Clinic support.
- **Section 2** highlights the applied work logic and responsibilities among the EO Clinic service providers.
- **Section 3** describes the services, their specifications, methods and outcomes.

# ABOUT THE EO CLINIC

The EO Clinic (Earth Observation Clinic) is an ESA (European Space Agency) initiative to create a rapid-response mechanism for small-scale and exploratory uses of satellite EO information in support of a wide range of International Development projects and activities. The EO Clinic consists of "on-call" technically pre-qualified teams of EO service suppliers and satellite remote sensing experts in ESA member states. These teams are ready to demonstrate the utility of satellite data for the development sector, using their wide range of geospatial data skills and experience with a large variety of satellite data types.

The support teams are ready to meet the short delivery timescales often required by the development sector, targeting a maximum of 3 months from request to solution.

The EO Clinic is also an opportunity to explore more innovative EO products related to developing or improving methodologies for deriving socio-economic and environmental parameters and indicators.

The EO Clinic was launched in March 2019 and is open to support requests by key development banks and agencies during the project duration.

# AUTHORS

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# ACKNOWLEDGEMENTS

The following colleagues provided valuable inputs, insights and evaluation feedback on the work performed: Maria Pia Ancora (Senior Urban Development Specialist, Asian Development Bank), Paolo Manunta (ESA Resident Support to ADB, Manilla, Philippines), Armen Nurbekyan (Head of Macroeconomic Directorate, Central Bank of Armenia), Rajesh Chandy (Academic Director, Wheeler Institute for Business and Development), Erik Vardanyan (Researcher, Central Bank of Armenia), Giorgio Chiovelli (Assistant Professor, Universidad de Montevideo), Vardan Karapetyan (Senior Project Officer, Asian Development Bank), and Zoltan Bartalis (ESA Coordinator and Technical Officer).

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| For further information | Please contact Sébastien Delbour, Project Manager, CLS (sdelbour@group-cls.com) with copy to Zoltan.Bartalis@esa.int if you have questions or comments with respect to content or if you wish to obtain permission for using the material in this report.<br>Visit the ESA EO Clinic: https://eo4society.esa.int/eo_clinic. |

# 1 DEVELOPMENT CONTEXT AND BACKGROUND

We firstly present in this section a concise and comprehensive description of the demographic trends correlated with Armenia urban development. Then, we describe the objectives of the ESA EO Clinic service.

## 1.1 Armenia urban development

Armenia has moved from a centrally planned economy to a market economy, with new economic, social, and territorial priorities. The country faces constraints on regional and global integration, economic risks, and governance problems[1].

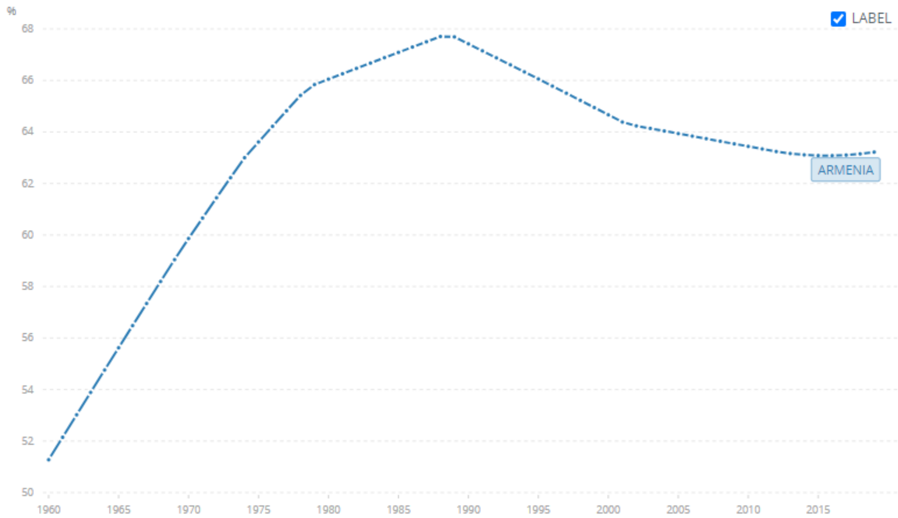



FIGURE 1: URBAN POPULATION (% OF TOTAL POPULATION) IN ARMENIA - *SOURCE: WORLD BANK DATA*

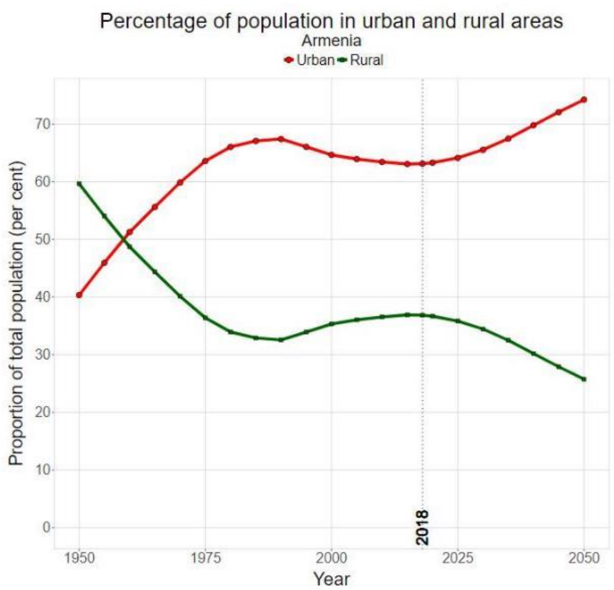



FIGURE 2: PERCENTAGE OF POPULATION IN URBAN AND RURAL AREAS - *SOURCE: UNITED NATIONS - DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS*

[1] ADB, *Armenia's transformative urban future*, December 2019 (https://www.adb.org/sites/default/files/institutional-document/546036/armenia-national-urban-assessment.pdf)

Due to low birth rates and to emigration, Armenia's population has declined in the 1990's, in particularity in urban areas as FIGURE 1 shows. After this observed decrease of population in the country, the trend seems to be reversing with a significant increase in the urban population, especially in the next 30 years, as can be seen in FIGURE 2.

These trend at a country scale is accentuated by a discrepancy between the capital city and the other towns of the country. Yerevan hosts over a third of the national population. The two other biggest cities are Gyumri with a population of 121,976 people and Vanadzor with 86,199 inhabitants (2011 census). The main obstacles to the development of secondary towns are well known such as limited fiscal capacities, insufficient transport connectivity and low value-added production. Therefore, this supportive study on "Infrastructure projects implementation and Economic outcomes in Armenia" seems to be a necessary reflection for the future of the country in an unstable world situation.

## 1.2 Objectives

A team composed by ADB Armenia Resident Mission, ADB Headquarters, the Central Bank of Armenia, and the London Business School is pursuing an assessment on the impact of multiannual investments in Armenia. ADB Armenia Resident Mission has requested Technical Assistance from the ESA EO Clinic to support in this assessment. Therefore, the service aims at identifying areas of permanent change in the physical urban and peri-urban landscape reflecting changes in the economic activity, as observed via EO data.

More precisely, the following information services have been requested:

- **Services 1 & 2:** Indicators of permanent change in the economy spanning from the 90s until present for the three largest urban of the country, namely Yerevan, Gyumri and Vanadzor.
- **Service 3:** Concept note on a possible platform to support investment prioritisation providing a brief technical description of such a proposed platform, together with technical requirements and a cost estimate for its deployment. A separate cost estimate of extending the services 1 & 2 to the other main urban areas of Armenia shall also be provided.

# 2 WORK LOGIC FOR EO-BASED SOLUTIONS

The overall work logic and organisation between GeoVille (coordinator of EO-Clinic framework contract, interface towards ESA and ADB, and service provider) and CLS/ex-SIRS (service provider) is presented in FIGURE 3. GeoVille has acted as focal point towards ESA as the contracting authority and ADB.

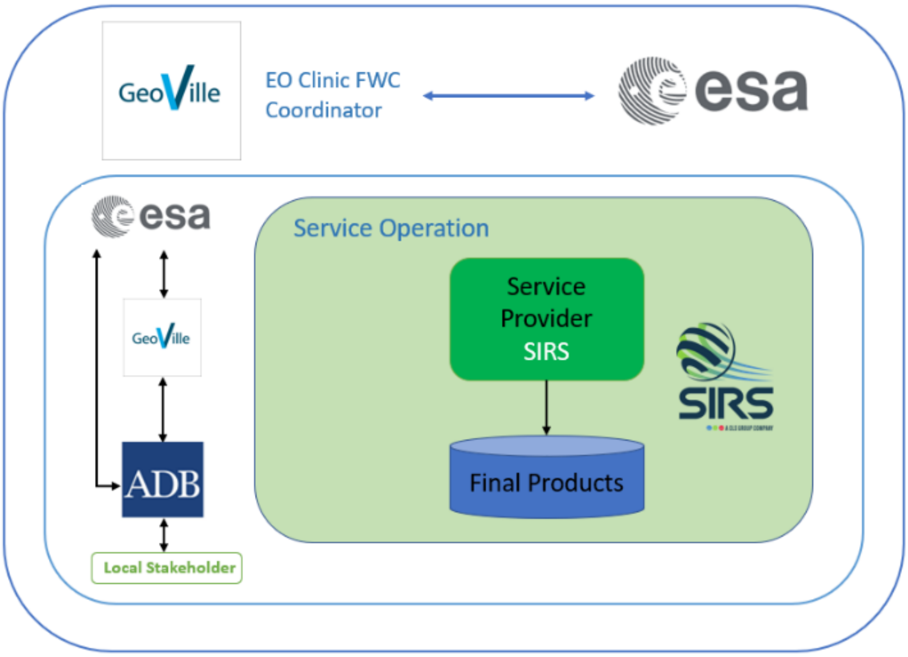



FIGURE 3: OVERALL WORK LOGIC AND INTERACTION BETWEEN ORGANISATIONS AND SERVICES

During the implementation phase the following stakeholder representatives were involved:

- Maria Pia Ancora (Senior Urban Development Specialist, Asian Development Bank)
- Armen Nurbekyan (Head of Macroeconomic Directorate, Central Bank of Armenia)
- Rajesh Chandy (Academic Director, Wheeler Institute for Business and Development)
- Erik Vardanyan (Researcher, Central Bank of Armenia)
- Giorgio Chiovelli (Assistant Professor, Universidad de Montevideo)
- Vardan Karapetyan (Senior Project Officer, Asian Development Bank)

All the requested services were implemented by CLS. This work has been initially planned over a tight period with a Work Completion Deadline (WCD) for all three services of 8 weeks from the issuing of the Work Order (WO). Due to delays in input data delivery the main service related to the provision of indicators of permanent change was partially completed on April 1, 2021 (product delivery for Gyumri). Feedback collected during the Progress Meeting on April 13 implied to perform further analysis on satellite images with higher spatial resolution. Consequently, the WO implementation was put on hold in agreement with all stakeholders while the additional service provision required is more precisely defined and an amendment to the contract between ESA and the service providers is drawn up. Implementation finally started again shortly after reception of the Contract Change Notice No. 1 (CCN1) on October 7, 2021 and WCD was extended to end of November 2021.

The time plan for implementing the WO is summarised in TABLE 1.

TABLE 1: WORK ORDER IMPLEMENTATION TIMELINE

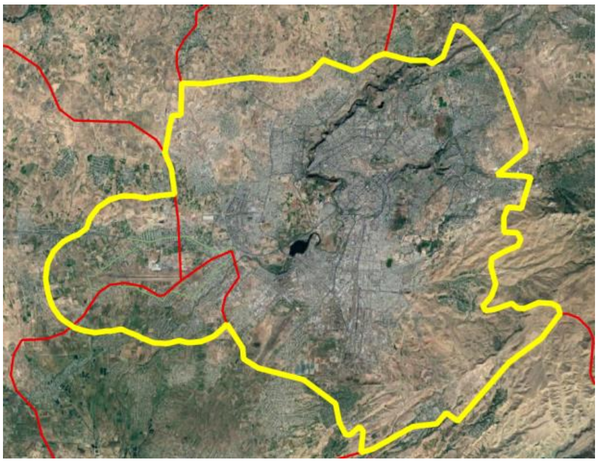
| Item | Date |
|---|---|
| **Request for Proposal issued by ESA** | **18.09.2020** |
| **Submission of Technical and Financial Proposal** | **14.10.2020** |
| **Start of Work Order** | **18.12.2020** |
| First call with representatives of ADB to discuss time schedule of implementation | 22.12.2020 |
| **Kick-Off Meeting with the stakeholders** | **27.01.2021** |
| Input data provision by the Cadastre Committee and used for defining Areas of Interest | 12.02.2021 |
| Information provision by ADB representative about the epochs of observation | 18.02.2021 |
| Population census data provision by ADB/CBA representatives | 25.03.2021 |
| **Delivery of first EO-based data package (referring to services 1 & 2) for Gyumri** | **01.04.2021** |
| **Progress Meeting** | **13.04.2021** |
| **ADB request for additional image analysis / WO implementation put on hold** | **21.04.2021** |
| CLS proposal for additional service provision | 12.05.2021 |
| Formal agreement from ESA Resident Support to ADB | 21.06.2021 |
| **Contract Change Notice No.1 (CCN1) emitted by ESA** | **07.10.2021** |
| **Restart of WO implementation considering CCN1** | **18.10.2021** |
| Information provision by CBA representative about urban projects from the last decade | 22.10.2021 |
| Delivery of EO-based data package (referring to services 1 & 2 + CCN1) | 19.11.2021 |
| **Delivery of final EO-based data package (referring to services 1 & 2 + CCN1)** | **29.11.2021** |
| **WOR submission (covering all services + CCN1)** | **02.12.2021** |

# 3 DELIVERED EO-BASED PRODUCTS AND SERVICES

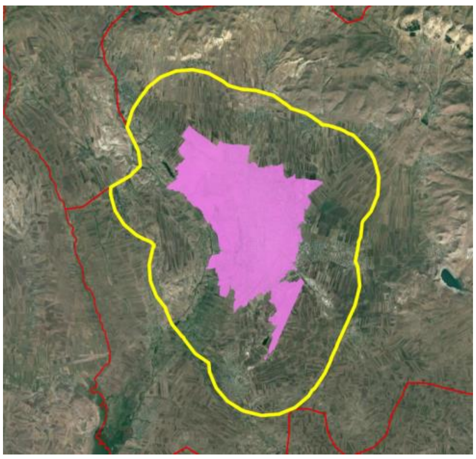
## 3.1 Indicators of permanent change in the economy

The service aims at identifying areas of permanent change in the physical urban and peri-urban landscape reflecting changes in the economic activity, as observed via EO data. **Urban extent and land use / land cover (LULC) changes have been mapped accordingly and used as main input to derive geospatial indicators.**

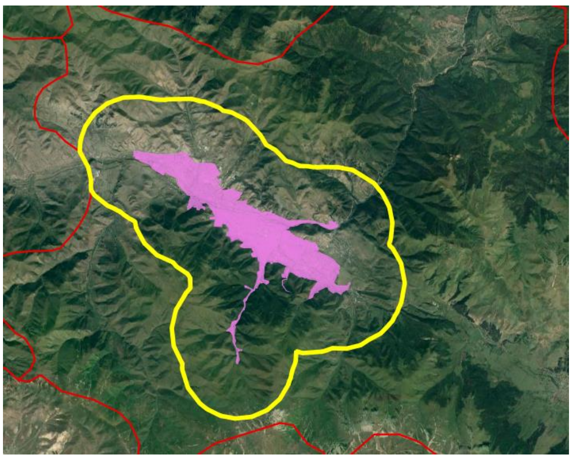
**Areas of interest (AOIs) are the three largest cities of Armenia, namely Yerevan, Gyumri and Vanadzor**, including the city itself and the suburbs with high proportion of daily commuting. Considering the lack of administrative level 3 (municipal community) boundaries and commuting data between localities, it was not possible to implement the approach recommended by the DG REGIO from the European Commission[1]. Therefore, a simplified method was applied. Administrative level 2 boundaries (source: UN OCHA) were used in the case of Yerevan which resulted in an AOI of 275 km², while information layers provided by the Armenian Cadastre Committee were used for the other cities to define the municipality boundary, then completed by a 3-km buffer application to include the surroundings. It resulted an AOI of 208 km² for Gyumri and 188 km² for Vanadzor, as shown in FIGURE 4. **The overall observation period is 25 years, from 1995 to 2020, considering analysis every 5 years.** Both AOIs and observation periods have been defined in cooperation with ADB and its project partners prior starting the service implementation.



**YEREVAN**



**GYUMRI**



**VANADZOR**

FIGURE 4 : AREAS OF INTEREST DEFINED FOR EACH CITY

[1] European Commission - Cities in Europe - The new OECD-EC definition (https://ec.europa.eu/regional_policy/fr/information/publications/regional-focus/2012/cities-in-europe-the-new-oecd-ec-definition)

The products delivered are vector geospatial datasets (urban extent and LULC change areas) derived from EO analysis and geospatial indicators derived from those datasets and ancillary ones when necessary. The following sections provide all the relevant information from the product specifications to the outputs and their usage, limitations and constraints.

### 3.1.1 Definition of key concepts

Clearly defined and commonly agreed key concepts and terms are considered as a prerequisite of the service.

**Land cover** refers to surface type on the ground like vegetation, urban infrastructure, water, bare soil, etc. (used as baseline information for activities like thematic mapping and change detection analysis), while **land use** describes how people use the land for socio-economic activities (residential, industrial, commercial, recreational, wildlife habitat, or agriculture). **Land Use / Land Cover (LULC)** mapping offers spatial descriptive information about both physical description and use of the Earth surface.

**No single international standard definition exists for the following topics of interest.**

**Built-up area** is defined for example by the Organisation for Economic Co-operation and Development (OECD) as the presence of buildings (roofed structures). This definition largely excludes other parts of urban environments or human footprint such as paved surfaces (roads, parking lots), commercial and industrial sites (ports, landfills, quarries, runways) and urban green spaces (parks, gardens).

However, **built-up area** can also refer to all artificial structures including buildings, roads and parking lots, all constructions of infrastructure and other artificially sealed or paved areas. This definition is directly linked to the surface imperviousness and the one applied in the study.

**Urban area extent** consequently considers all surfaces with a dominant human influence but without agricultural land use. These areas include all artificial structures (built-up areas) and their associated non-sealed and vegetated surfaces, functionally related to human activities except agriculture.[1]

**Urban change areas** will correspond to any land that was classified as urban at one time but was not at the previous time, and vice versa, or any urban land which evolved through the time.

### 3.1.2 Specifications

#### *3.1.2.1 Input data*

<u>EO data</u>

High resolution (HR) optical satellite images from Landsat and Sentinel-2 missions (pixel size between 10 and 30m) freely available were the primary input data used for mapping urban area extent at all epochs. TABLE 2 provides the details.

TABLE 2: EO HR INPUT DATA USED FOR THE SERVICE IMPLEMENTATION

| **HR optical satellite data (covering all cities)** | | | |
|---|---|---|---|
| **1995** | Landsat 5 | 30m | Images from 02/06/1994 to 27/09/1996 |
| **2000** | Landsat 5 & 7 | 30m | Images from 15/05/1999 to 17/11/2000 |
| **2005** | Landsat 5 | 30m | Images from 25/03/2004 to 12/12/2006 |
| **2010** | Landsat 5 | 30m | Images from 19/02/2009 to 21/11/2010 |
| **2015** | Landsat 8 | 30m | Images from 17/02/2014 to 23/12/2016 |
| **2020** | Sentinel 2 | 10m | Images from 16/02/2020 to 13/12/2020 |

[1] Copernicus European Urban Atlas mapping guide (https://land.copernicus.eu/local/urban-atlas)

Very high resolution (VHR) optical satellite images from Pleiades & WorldView missions (pixel size between 0.3 and 5m) were also procured for supporting urban LULC change detection and characterization, but only for the reference years 2010, 2015 and 2020 considering the [RD-2] and [RD-4]. TABLE 3 provides the complete list of VHR scenes used for covering each city.

TABLE 3: EO VHR INPUT DATA USED FOR THE SERVICE IMPLEMENTATION

| VHR optical data (per city) | | | |
|---|---|---|---|
| | **2010** | **2015** | **2020** |
| **Yerevan** | **WorldView 2** (0.3m) from 24/06/2010<br>**Spot 5** (5m) from 27/07/2010 | **Spot 6** (1.5m) from 30/07/2016 | **Pléiades 1A** (0.5m) from 11/10/2020 |
| **Gyumri** | **Spot 5** (5m) from 08/02/2010 | **Spot 6** (1.5m) from 04/08/2016 | **Pléiades 1B** (0.5m) from 25/08/2020 |
| **Vanadzor** | **Spot 5** (5m) from 14/11/2010 | **Spot 6** (1.5m) from 30/07/2015 | **WorldView 3** (0.3m) from 15/09/2020 |

Ancillary data

Some ancillary data were used in addition to the EO data selected from open and global sources, namely:

- Open Street Map (OSM) database, especially for selecting samples to be considered as ground truth/training data for the classification algorithm, considering buildings, roads and traffic area features as described in detail in section 3.1.2.2
- Global Human Settlement Layer (GHSL)[1] providing human presence and built-up areas, a reference dataset also used for selecting samples to be considered as ground truth/training data for the classification algorithm, considering built-up areas as described in section 3.1.2.2
- Wikimapia, and virtual globes such as Google Earth and Bing Maps
- In situ information about urban projects implemented over the last decade provided by the CBA.

#### *3.1.2.2 Method*

The methodological approach to generate the geospatial datasets was implemented in three main steps:

1. **Built-up area mapping** by automated HR image classification based on Geographic Object-Based Image Analysis (GEOBIA) which relies on two main components:
    - Feature extraction based on tree representation & attribute profiles using NDVI & texture indices,
    - Semi-supervised classification using a robust machine learning algorithm, namely the random forest classifier that combines multiple decision trees.
2. **Urban area extent mapping** by manual refinement of the previous result including also the associated non-sealed and vegetated surfaces by visual interpretation of both HR and 2020 VHR images
3. **Urban change detection and characterisation** in terms of LULC over the whole period still by means of visual interpretation using both HR and 2020 VHR images, as well as ancillary data
4. **Additional intra-urban change detection and characterisation over 2010-2020** by means of visual interpretation using VHR images acquired in the second phase of the service implementation

[1] https://ghsl.jrc.ec.europa.eu/

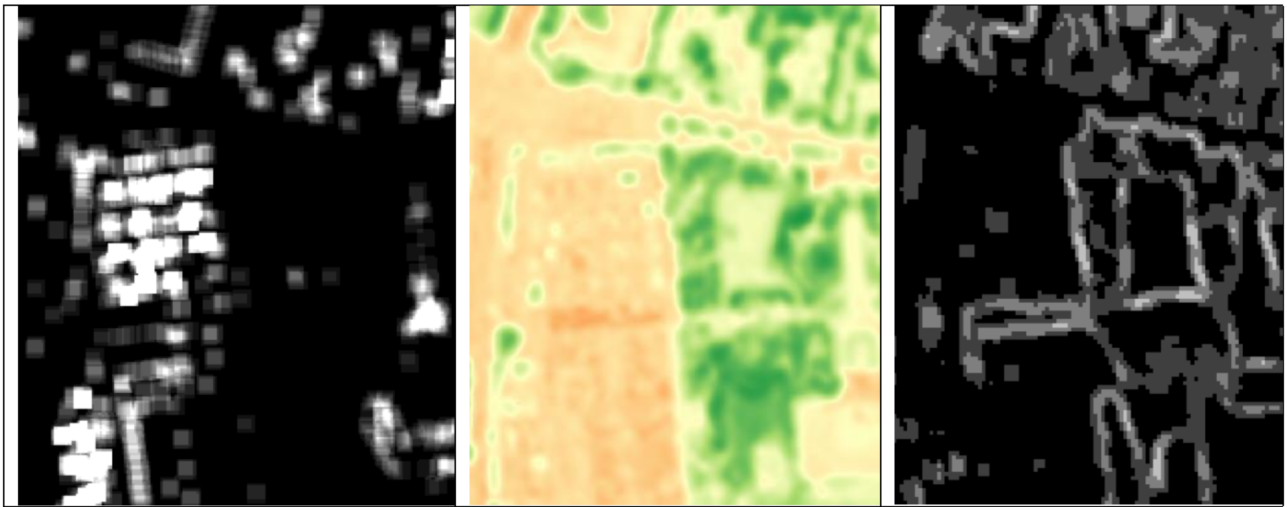
Built-up area mapping

**Step 1: Input EO data preparation**

To take full advantage of the Sentinel-2 and Landsat time series, no date selection in terms of season or vegetation phenology was performed and all available and cloud-free scenes were considered. Only the choice of the sensor to be used for each epoch was made depending on availability and led to a specific methodology.

To ensure the spatial and temporal homogeneity of the optical satellite time series, the data were pre-processed using appropriate tools for a Top of Canopy conversion of all the selected data. A single date approach was applied, using ESA Sen2Cor[1] processor that aims at removing inhomogeneous image effects from different atmospheric, illumination and topography-related conditions, presence of clouds and cloud shadows. Especially cloud and cloud shadow detection was crucial to ensure as less as possible artefacts in classifier learning process and classification results.

Spectral indices and biophysical variables were then calculated as part of pre-processing steps. Many of them have been defined in the past three decades. Some have been and are still widely used, such as the Normalized Difference Vegetation Index (NDVI) to highlight vegetation cover, while others have been proposed as alternatives only in the recent years. Thus, the Pantex textural index is now known to bring interesting results in order to study built-up areas (Pesaresi et al., 2013[2]). An effective detection could also require texture and morphological indices such as Sobel operator and the Haar wavelets (see FIGURE 5) which consist in extracting information on the spatial arrangement of pixels.



| *Pantex Index* | *NDVI* | *Sobel* |
|---|---|---|

FIGURE 5: FEATURE EXTRACTION FROM SATELLITE IMAGERY

**Step 2: Training data preparation and integration**

As input for the algorithm, a specific set of training data considered as ground truth was required for the detection of the built-up areas. The training data selected must therefore be representative of the whole study area in order to cover all the reflectance variations of the classes, as well as to go further and consider the local variability of the environmental classes due to the soil type, moisture, etc. The training sites must be exempt from anomalies and must be a suitable statistical representation of the area with a meaningful population.

[1] http://step.esa.int/main/third-party-plugins-2/sen2cor/

[2] Pesaresi, M., G. Huadong, X. Blaes, D. Ehrlich, S. Ferri, L. Gueguen, M. Halkia, M. Kauffmann, T. Kemper, L. Lu, M. A. Marin-Herrera, G. K. Ouzounis, M. Scavazzon, P. Soille, V. Syrris & L. Zanchetta (2013) A Global Human Settlement Layer From Optical HR/VHR RS Data: Concept and First Results. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 6, 2102-2131.

Thus, the OSM database was used as training data for the buildings (houses, apartments, offices, public, industrial, commercial, administrative buildings, etc.), roads (sealed roads) and traffic areas (parking, dams, service areas, etc). The GHSL dataset was also used as training data for built-up features in complement to OSM. In order to best reflect the different urban features, an automated random point sampling was applied. Samples in non-urban areas were also selected in different classes such as rocks, bare soils or agricultural fields for example to obtain background training samples. The visual analysis of the selected VHR (including Google Earth) and HR EO data allowed the consolidation of the collection of calibration/training data.

**Step 3: Built-up area mapping for the reference epochs**

The methodology is based on GEOBIA which relies on two main components which are feature extraction based on tree representation and attribute profiles, and a semi-supervised classification using random forest algorithm. The first step thus consisted in the computation of predefined indices from each spectral band of the original HR multispectral image, as described in Step 1.

Among the different supervised classifiers available, we made use of the random forest classifier that combines multiple decision trees to increase the robustness of the overall classification process. Furthermore, it comes with parallel, scalable, open-source implementations such as the Shark library for the machine learning classification. The general workflow of the foreseen methodology is illustrated in FIGURE 6.

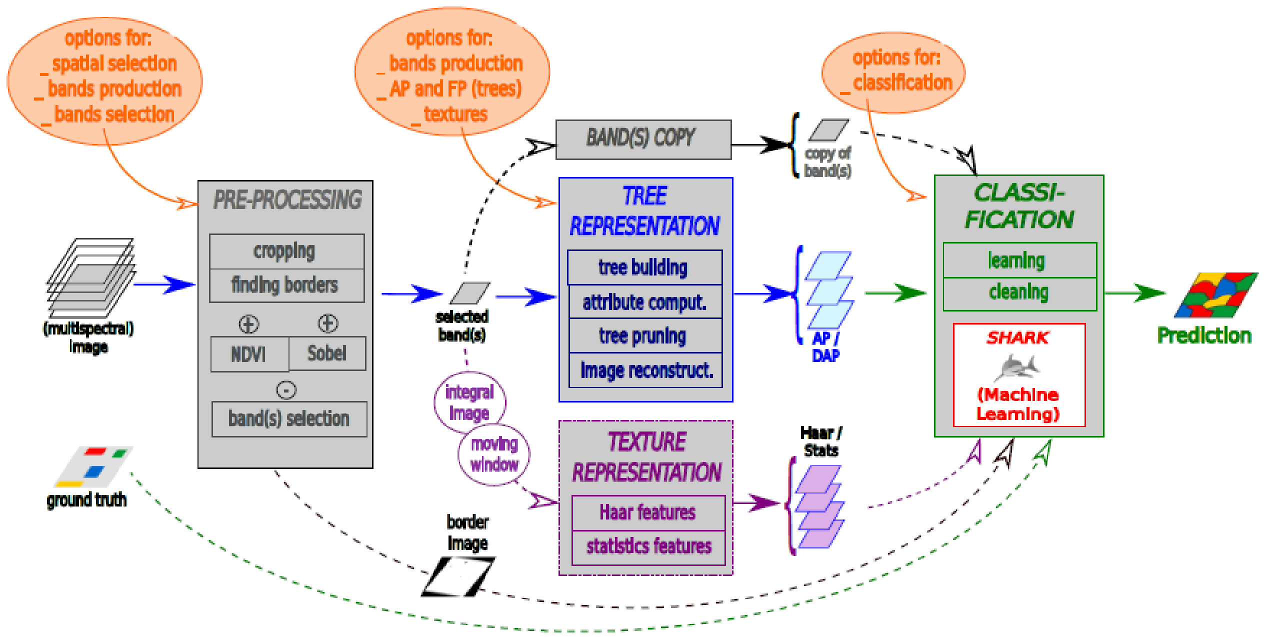



FIGURE 6: GENERAL WORKFLOW OF THE CLASSIFICATION METHODOLOGY

Using this methodology, urban area classifications for the reference years were computed based on HR EO data covering the cities of interest. A single date approach was implemented, i.e. all the HR images were classified individually and then fused to obtain the final classification for each epoch (1995 to 2020).

Then, post-classification was applied through Post-Classification Comparison (PCC) which implies post-processing of the layers to be spatially consistent including:

- Spatial and temporal consistency based on the reference data. The purpose was to ensure the temporal and spatial consistency and comparability between the different date to prevent problems related to the differences in terms of acquisition, geometry between the two periods.
- Post-processing filtering generally used in global urban map. Indeed, there was a significant portion of noise due to single or isolated pixels (small, aggregated group of pixels), which were most likely misclassifications. Such noises have to be reduced/removed with post-classification filtering approaches based on the selected Minimum Mapping Unit (MMU).

- Contextual analysis based on change probability. The aim was to consider the probability of a pixel to be classified in a given theme for both epochs as a basis to establish a probability map of changes. The analysis describes each cell's relationship/membership to a source, or a set of sources based on probabilities.

Urban area extent mapping

Knowing that urban extent product should include both built-up areas and their associated non-sealed and vegetated surfaces, i.e. functionally related to human activities except agriculture, the previous result was checked and manually refined by means of visual interpretation using both HR and 2020 VHR images.

Urban change detection and characterisation

Changes impacting urban extent between two reference epochs were easily and automatically extracted using simple GIS analysis tool from Urban Extent products resulting from the automated classifications with PCC and manual refinement as previously described. The changes detected were then characterised manually by means of visual interpretation of HR optical images used for the urban extent classification and 2020 VHR optical images, the latter being necessary for the artificial areas. In-house tools to optimize navigation and data collection supported this task in order to improve the efficiency. This manual approach was preferred to an automatic method because of the area to be covered and the specifications defined for characterising the LULC changes.

**In addition to change detection occurring in the urban fringe over the whole period 1995-2020, ADB and its partners requested for further analysis about the intra-urban dynamics. Therefore, additional change detection and characterisation were also performed over the cities for the last decade 2010-2020 by means of visual interpretation of VHR optical satellite images at a second stage, with the support of in situ information about urban projects implemented over the last decade as provided by the CBA representative.**

#### *3.1.2.3 Mapping outputs*

LULC datasets such as the European Urban Atlas[1], one of the Copernicus land monitoring services, were originally developed to support better planning decisions and assess the impact of infrastructural investment by the European Regional Development Fund. Several studies were developed by DG Regio based on the European Urban Atlas (UA) to compare the requirements of European cities in terms of access to public transportation[2] and green areas[3], as examples among others. The European UA provides harmonised mapping specifications of LULC across Europe for all cities above 50,000 inhabitants. Therefore, thematic classification nomenclature applied for this study has been adapted from this reference dataset.

The primary status layers define the extent of the urban areas for each city and each epoch. Secondly, the urban change area layers provide the location, extent and type of any LULC changes involving artificial areas at least in one point in time. Change area characterisation was carried out in compliance with UA-like LULC nomenclature. Hierarchical level-2/3 classes have been selected for artificial areas (urban fabric units with predominant residential use, industrial and commercial units, transportation network and associated spaces, green, recreational or other areas), while level-1 classes only for non-artificial ones. TABLE 4 shows the LULC nomenclature used for characterising change areas at each epoch.

[1] https://land.copernicus.eu/local/urban-atlas
[2] https://ec.europa.eu/regional_policy/sources/docgener/work/2015_01_publ_transp.pdf
[3] https://ec.europa.eu/regional_policy/sources/docgener/work/2018_01_green_urban_area.pdf

TABLE 4: LULC STATUS NOMENCLATURE USED FOR CHARACTERISATION OF URBAN CHANGE AREAS

| | *Artificial area classes* | RGB Code |
|---|---|---|
| 111 | **Continuous urban fabric units (soil sealing level above 80%)** | **128,0,0** |
| 112 | **Discontinuous dense urban fabric units (soil sealing level 40% - 80%)** | **191,0,0** |
| 113 | **Discontinuous low density urban fabric units (soil sealing level below 40%)** | **255,64,64** |
| 121 | **Industrial, commercial, public, military and private units** | **104,77,242** |
| 122 | **Roads, railways and associated land** | **179,179,179** |
| 123 | **Airports** | **230,204,230** |
| 131 | **Mineral extraction, dump sites and construction sites** | **115,77,55** |
| 132 | **Land without current use and brownfields** | **135,69,69** |
| 140 | **Green urban areas, sports and leisure facilities** | **140,220,0** |
| | ***Non-artificial area classes (agricultural and natural)*** | **RGB Code** |
| 200 | **Agricultural areas (arable land, permanent crops, pastures, complex and mixed cultivation patterns)** | **255,255,168** |
| 300 | **Forests and semi-natural/natural areas** | **0,140,0** |
| 400 | **Wetlands** | **166,166,255** |
| 500 | **Water** | **128,242,230** |

TABLE 5 presents the LULC change matrix providing all combinations possible of LULC classes and the result in terms of LULC change class between two reference epochs of observation.

TABLE 5: LULC CHANGE MATRIX

| LULC Class - Epoch 1 | LULC Class – epoch 2 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **111** | **112** | **113** | **121** | **122** | **123** | **131** | **132** | **140** | **200** | **300** | **400** | **500** |
| **111** | 30* | 21 | 21 | 22 | 23 | 23 | 24 | 25 | 26 | 41 | 42 | 42 | 42 |
| **112** | 21 | 30* | 21 | 22 | 23 | 23 | 24 | 25 | 26 | 41 | 42 | 42 | 42 |
| **113** | 21 | 21 | 30* | 22 | 23 | 23 | 24 | 25 | 26 | 41 | 42 | 42 | 42 |
| **121** | 21 | 21 | 21 | 30* | 23 | 23 | 24 | 25 | 26 | 41 | 42 | 42 | 42 |
| **122** | 21 | 21 | 21 | 22 | 30* | 23 | 24 | 25 | 26 | 41 | 42 | 42 | 42 |
| **123** | 21 | 21 | 21 | 22 | 23 | 30* | 24 | 25 | 26 | 41 | 42 | 42 | 42 |
| **131** | 21 | 21 | 21 | 22 | 23 | 23 | 30* | 25 | 26 | 41 | 42 | 42 | 42 |
| **132** | 21 | 21 | 21 | 22 | 23 | 23 | 24 | 30* | 26 | 41 | 42 | 42 | 42 |
| **140** | 21 | 21 | 21 | 22 | 23 | 23 | 24 | 25 | 30* | 41 | 42 | 42 | 42 |
| **200** | 11 | 11 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | | - | - | - |
| **300** | 11 | 11 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | - | | - | - |
| **400** | 11 | 11 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | - | - | | - |
| **500** | 11 | 11 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | - | - | - | |

** 30 Urban renewal if evolution of the physical structures detected by visual interpretation during the period*

Finally, Table 6 shows the LULC change nomenclature used for characterising the changes themselves.

TABLE 6: LULC CHANGE NOMENCLATURE USED FOR CHARACTERISATION OF URBAN CHANGE AREAS

| | *Urban expansion* | RGB Code |
|---|---|---|
| 11 | **Urban expansion – residential**<br>Establishment of new residential urban fabric to replace non-artificial land | 168,0,0 |
| 12 | **Urban expansion - commercial / industrial**<br>Establishment of new commercial & industrial fabric to replace non-artificial land | 153,0,153 |
| 13 | **Urban expansion – transportation**<br>Establishment of new transportation units to replace non-artificial land | 128,128,128 |
| 14 | **Urban expansion - construction sites**<br>Establishment of new construction sites to replace non-artificial land | 255,0,197 |
| 15 | **Urban expansion - vacant land / brownfields**<br>Establishment of new vacant land / brownfields | 168,112,0 |
| 16 | **Urban expansion - urban greenery**<br>Establishment of new urban greenery areas to replace non-artificial land | 152,230,0 |
| | *Internal urban development* | RGB Code |
| 21 | **Internal urban development – residential**<br>Change within urban area between artificial surfaces, establishment of residential urban fabric to replace vacant land / brownfields | 255,0,0 |
| 22 | **Internal urban development - commercial / industrial**<br>Change within urban area between artificial surfaces, establishment of commercial and industrial units to replace vacant land / brownfields | 204,51,153 |
| 23 | **Internal urban development – transportation**<br>Change within urban area between artificial surfaces, establishment of transportation units to replace vacant land / brownfields | 204,204,204 |
| 24 | **Internal urban development - construction sites**<br>Change within urban area between artificial surfaces, establishment of construction sites to replace residential, commercial or industrial areas | 255,190,232 |
| 25 | **Internal urban development - vacant land / brownfields**<br>Change within urban area between artificial surfaces, establishment of vacant land / brownfields | 215,194,158 |
| 26 | **Internal urban development - urban greenery**<br>Change within urban area between artificial surfaces, establishment of urban greenery areas | 209,255,115 |
| | *Urban renewal* | RGB Code |
| 30 | **Urban renewal**<br>Evolution of the physical assets but without impact on LULC classification | 122,142,245 |
| | *Other changes (uptake of artificial area)* | RGB Code |
| 41 | **Agriculture development - uptake of artificial area**<br>Conversion of various types of artificial area into agricultural land | 255,204,102 |
| 42 | **Natural areas development - uptake of artificial area**<br>Conversion of artificial area into various types of natural areas | 84,130,53 |

Considering the main input EO data and the purpose of the service, TABLE 7 shows the product specifications, especially the geometric and thematic accuracies which were applicable for generating the urban area extent and mapping the urban change areas over the AOIs. Accuracy thresholds have been set specifically for intra-urban change detection which was made possible over the period 2010-2020 thanks to the use of optical images with higher spatial resolution (pixel size of 5 m or better).

TABLE 7: MAPPING PRODUCT SPECIFICATIONS

| | |
|---|---|
| **Geometric positional accuracy** | 1 pixel or better considering HR images used<br>5 m for intra-urban changes |
| **Thematic accuracy** | |
| Urban area extent | 85% |
| Urban change areas | 80% |
| **Minimum Mapping Unit (MMU)** | |
| Urban area extent | 1 ha |
| Urban change areas | 0.5 ha |
| Intra-urban change areas | 0.25 ha |
| **Minimum Mapping Width (MMW)** | 10 m |

#### 3.1.2.4 *Spatial indicators*

TABLE 8: LIST AND SPECIFICATIONS OF THE SPATIAL INDICATORS COMPUTED

| Indicator | Definition | Aim | Input data |
|---|---|---|---|
| **Urban area expansion** | Measurement of the evolution of the spatial extent of urban areas over time | Understanding and analysing global trends in terms of urban dynamics (urban sprawl, densification, etc.) | Urban extent maps |
| **Ratio of land consumption rate to population growth rate** | Comparison of the land consumption in terms of built-up areas, agriculture, forestry or other economic activities, and increase of population during a specific period | Assessing the phenomenon of urban sprawl | Urban extent maps<br>Population distribution and density data |
| **Urban fragmentation / Discontinuity** | Degree to which a city is internally (dis)connected or (dis)continuous, measured mainly by the amount, size, shape and location of isolated urban patches (= porosity, discontinuity) | Detecting areas that should be densified to mitigate urban sprawl | Urban extent maps |
| **Compactness / Dispersion** | Degree to which a city is internally connected and continuous, measured by the average distance between urban patches but also geometric attributes (size, shape, density) and accessibility | Understanding the growth patterns of a city and the level of compactness to target investments | Urban extent maps |
| **Land accounting** | Baseline quantitative information about LU/LC assets, consumption and formation flows during observed periods and net changes resulting from these flows (based on UN SEEA and the EEA LEAC analytical framework) | Drawing the profile of a city or districts within the city and highlighting strengths and weaknesses of various areas<br>Assessing the impacts of city master plans | Urban extent maps<br>Urban change area maps |
| **Average distance between services and population** | Measurement of the degree of accessibility of urban facilities (companies, shops and public institutions, education and health facilities, public transport, urban green areas, etc.) from residential areas | Detecting areas with poor accessibility through hotspot maps to target investments | Urban extent maps<br>Transportation network<br>Facilities and building footprints<br>Population distribution and density data |

### 3.1.3 Quality Control and validation

Quality Control (QC) was part of the production phase and consists in the following items:

- Quality check of the input data used
- COTS or in-house tools and procedures supporting production tasks to ensure compliance with the service and product specifications
- Final QC of the products to be delivered

The latter included the following checks, with check-ups of the completeness, logical consistency and geometric accuracy mainly implemented in an automated manner:

- Completeness (omissions/commissions) and thematic accuracy (urban extent and change characterisation including absence of unlikely changes) performed by means of visual check by another image analyst to ensure the product quality and homogeneity
- Geometric and thematic compliance by means of visual check over randomly selected area samples
- Topological consistency (absence of null geometries, duplicates, multipart features, missing connections due to under/overshoots, invalid slivers, overlaps, gaps, …) performed in an automated manner
- Conceptual and domain consistency (attribute table structure and values)

Internal validation of the thematic product accuracy (overall accuracy, classification correctness and completeness) was implemented independently from the production and once the products were generated for ensuring the compliance with the specifications. The validation protocol applied was as follows:

- **Sampling design** – Generation of a number of point samples (200 for Yerevan, 100 for both Gyumri and Vanadzor) using a single stage stratified random sampling approach. Three strata were defined, namely stable artificial surfaces (class 1 at level 1 of the nomenclature on all dates), permanent change areas (evolving over the period of observation) and stable non-artificial surfaces, with a number of points determined by the size of strata (area), with at least 10 samples per strata. In the end, sample points were randomly selected taking care of a minimum distance between them for ensuring homogeneous spatial distribution.
- **Response design** – The reference data were generated independently (double-blind approach) by means of visual interpretation using the EO satellite imagery used for the production as no better resolution and/or ground-truth data were made available.
- **Analysis** – The analysis method consists in the comparison of the classes assigned to features from the product with the reference data. The result of this assessment is presented through confusion matrices.

Confusion matrices were established for the Urban Extent product of each epoch (1995, 2000, 2005, 2010, 2015 and 2020) and weights have been applied to the points considering the stratified sampling approach (3 defined strata: stable artificial areas, non-artificial areas and changes areas) for calculating the accuracy indicators (user accuracy, producer accuracy, overall accuracy). A confusion matrix was also established to assess the accuracy of the Urban Change Areas product over both the whole period 1995-2020 and the last decade which benefitted further look on intra-urban change dynamics.

The resulting overall accuracy is very satisfactory as compliant with the technical specifications (>85%), as shown in TABLE 9 and TABLE 10. Individual confusion matrices can be made available upon request.

TABLE 9: RESULTS OF INTERNAL VALIDATION FOR URBAN EXTENT PRODUCTS

| **Overall Accuracy for Urban Extent products** | | | | | | |
|---|---|---|---|---|---|---|
| | **1995** | **2000** | **2005** | **2010** | **2015** | **2020** |
| **Yerevan** | 98.4% | 97.9% | 97.7% | 98.2% | 98.4% | 98.4% |
| **Gyumri** | 99.5% | 99.5% | 99.5% | 100% | 100% | 100% |
| **Vanadzor** | 99.1% | 99.1% | 99.1% | 99.3% | 99.2% | 99.3% |

TABLE 10: RESULTS OF INTERNAL VALIDATION FOR URBAN CHANGE AREAS PRODUCTS

| **Overall Accuracy for Urban Change Areas products** | | |
|---|---|---|
| | **1995-2020** | **2010-2020** |
| **Yerevan** | 94.4% | 88.2% |
| **Gyumri** | 100% | 100% |
| **Vanadzor** | 100% | 100% |

### 3.1.4 Outputs – content and formats

Service deliverables for each city are of different kinds for ensuring the wider exploitation of the EO-based analysis results. Content and formats are presented in TABLE 11.

TABLE 11: SERVICE OUTPUTS

| | |
|---|---|
| **Vector geospatial datasets** | |
| **Content** | AOI information layer |
| | **Urban Extent** product for each epoch (1995, 2000, 2005, 2010, 2015 and 2020) |
| | **Urban Change Areas** product for each 5-year period, the whole one (1995-2020)* and the last decade (2010-2020) which benefitted from VHR optical images enabling intra-urban change detection |
| | Multidate Urban Extent & Urban Change Areas layer/product which compiles all thematic information derived from image analysis in one single layer and can be extremely useful for GIS users |
| **Formats** | Open source **GeoPackage** format consisting in a single file embedding all layers of information along with symbology settings (compatible especially with free QGIS) |
| | Widely used **ESRI SHP** format consisting in 4 files (.SHP, .SHX, .DBF, .PRJ) for each layer of information provided along with symbology settings as .LYR file and INSPIRE compliant metadata as .XML file |
| | **Google Earth KMZ** format (also readable with any KML format compatible GIS software) for easy handling by non-GIS users especially |
| **Ready-to-use maps** | |
| **Content** | Urban extent and change dynamics over the period 1995-2020 |
| | Detailed urban change dynamics over the period 2010-2020 |
| **Formats** | PDF (300 dpi) and JPG (150 / 300 dpi) |
| **Work Order Report (WOR)** | |
| **Content** | Development context and background |
| | Work logic |
| | EO-based products and services - Indicators of permanent change in the economy: **geospatial datasets** (specifications and outputs) |
| | EO-based products and services - Indicators of permanent change in the economy: **spatial indicators** (specifications and outputs) |
| | **Concept note on a possible platform to support investment prioritisation** |
| **Format** | PDF |

** Urban Change Areas product for the whole period (1995-2020) only includes changes for which LULC characterisation was possible to be made for the reference date 1995 considering the limitation from the satellite images used in terms of spatial resolution. This means that intra-urban changes detected only through the last decade 2010-2020 are logically not included.*

Regarding the geospatial datasets, each layer of information contains area features (polygons) associated with an attribute table whose content is described in TABLE 12.

TABLE 12: ATTRIBUTE FIELDS ASSOCIATED WITH AREA FEATURES

| **Common attributes to all layers** | |
|---|---|
| **AOI_NAME** | Name of the City |
| **PERIMETER** | Perimeter of polygon (in meters) |
| **AREA** | Area of polygon (in square meters) |
| **COMMENT** | Eventual free text, e.g. lower confidence level because of satellite image quality |
| **Attributes specific to Urban Change Area layers** | |
| **C_LU_YYYY** | Class code according to the LULC nomenclature (for each year) |
| **L_LU_YYYY** | Class label according to the LULC nomenclature (for each year) |
| **C_CH_YY_YY** | Class code according to the LULC change nomenclature (for each period) |
| **L_CH_YY_YY** | Class label according to the LULC change nomenclature (for each period) |
| **EXT_EVOL** | Information 'yes/no' depending on whether the change observed is classified as urban extent evolution or not; information about the 5-year period "YYYY-YYYY" in which such a change occurred according to image analysis is provided in the multidate layer. |
| **URBAN_CHG** | Information 'yes/no' depending on whether the change observed is classified as intra-urban mutation or not; information about the 5-year period "YYYY-YYYY" in which such a change occurred according to image analysis is provided in the multidate layer. |
| **URB_RENEW** | Information 'yes/no' depending on whether the change observed is classified as urban renewal or not; information about the 5-year period "YYYY-YYYY" in which such a change occurred according to image analysis is provided in the multidate layer. |
| **RENEW_TYPE** | Type of urban renewal, e.g. new building(s) or infrastructure(s) observed, old building(s) replaced by new one(s), etc. |

**The next sections present for each city the mapping results from the image analysis, as well as the derived spatial indicators which enable to better understand urban dynamics and thus support the identification of permanent change in the economy over the period of interest.**

## 3.1.5 Outputs for Yerevan

### 3.1.5.1 *Mapping results*

The EO-based service aims at providing reliable indicators of permanent change in the economy through the period 1995-2020. Therefore, the following geospatial products were derived from image analysis:

- **Urban Extent** for each reference epoch
- **Urban Change Areas** involving detection in time and space, as well as characterisation

As described in the section 3.1.2.2, urban extent mapping was firstly generated by means of automated classification of HR optical images. The result was intermediate as the algorithm enabled to well detect and extract built-up areas, but not systematically their associated non-sealed and vegetated surfaces. Therefore, the final Urban Extent product for each epoch was obtained by means of visual interpretation using both HR and 2020 VHR images, and manual refinement of the previous mapping result.

The results got for Yerevan city regarding its current extent (2020) are shown in FIGURE 7.

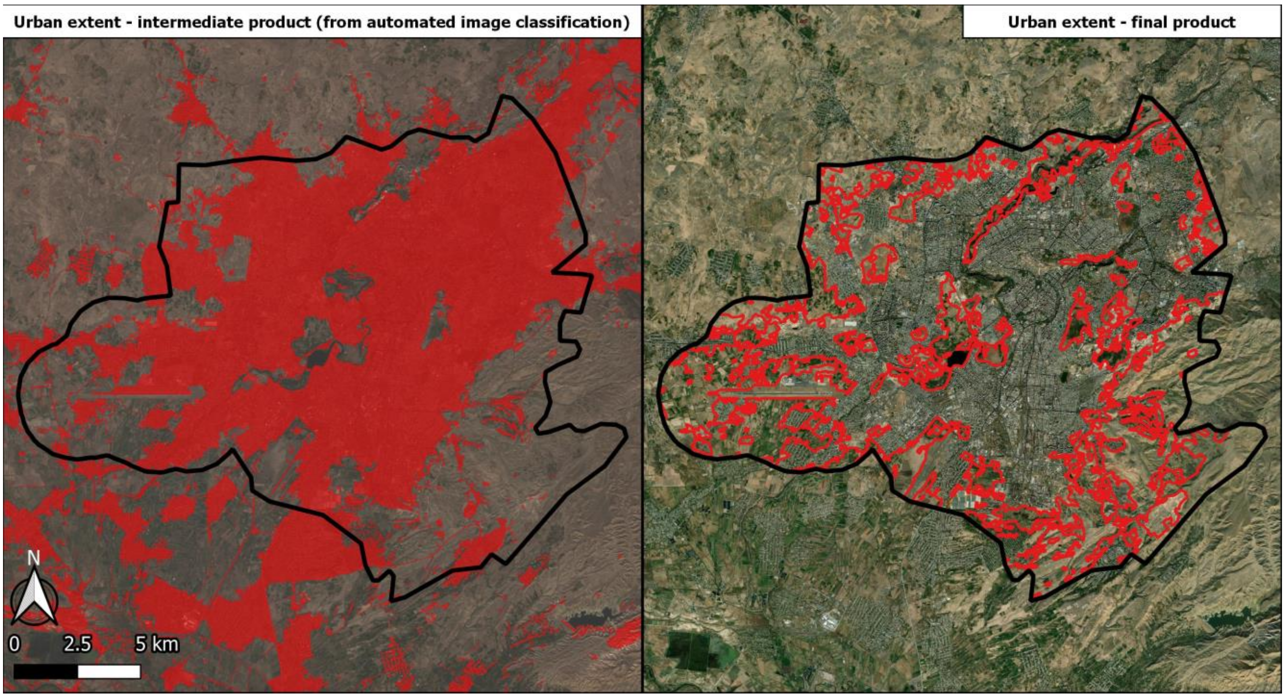



FIGURE 7: URBAN EXTENT MAP OF YEREVAN IN 2020

Once urban extent was mapped for each epoch, it was easy to visually compare and automatically extract change areas occurring throughout each 5-year period by means of basic GIS analysis tool.

FIGURE 8 shows the overall evolution of Yerevan urban extent from 1995 to 2020. The mapping results clearly indicate that urban area has expanded significantly and in a quite homogeneous way.

In addition to detect LULC changes in the urban fringe, most of them impacting urban extent, further analysis was performed by means of visual interpretation of VHR optical images in order to characterise them at best and extract also intra-urban changes in the most recent period 2010-2020. As a result, a consistent map of Urban Change Areas for each 5-year period has been delivered too.

Finally, the mapping results related to urban extent and change dynamics were further analysed and used for the computation of several key spatial indicators. The next sections present the outputs in detail.

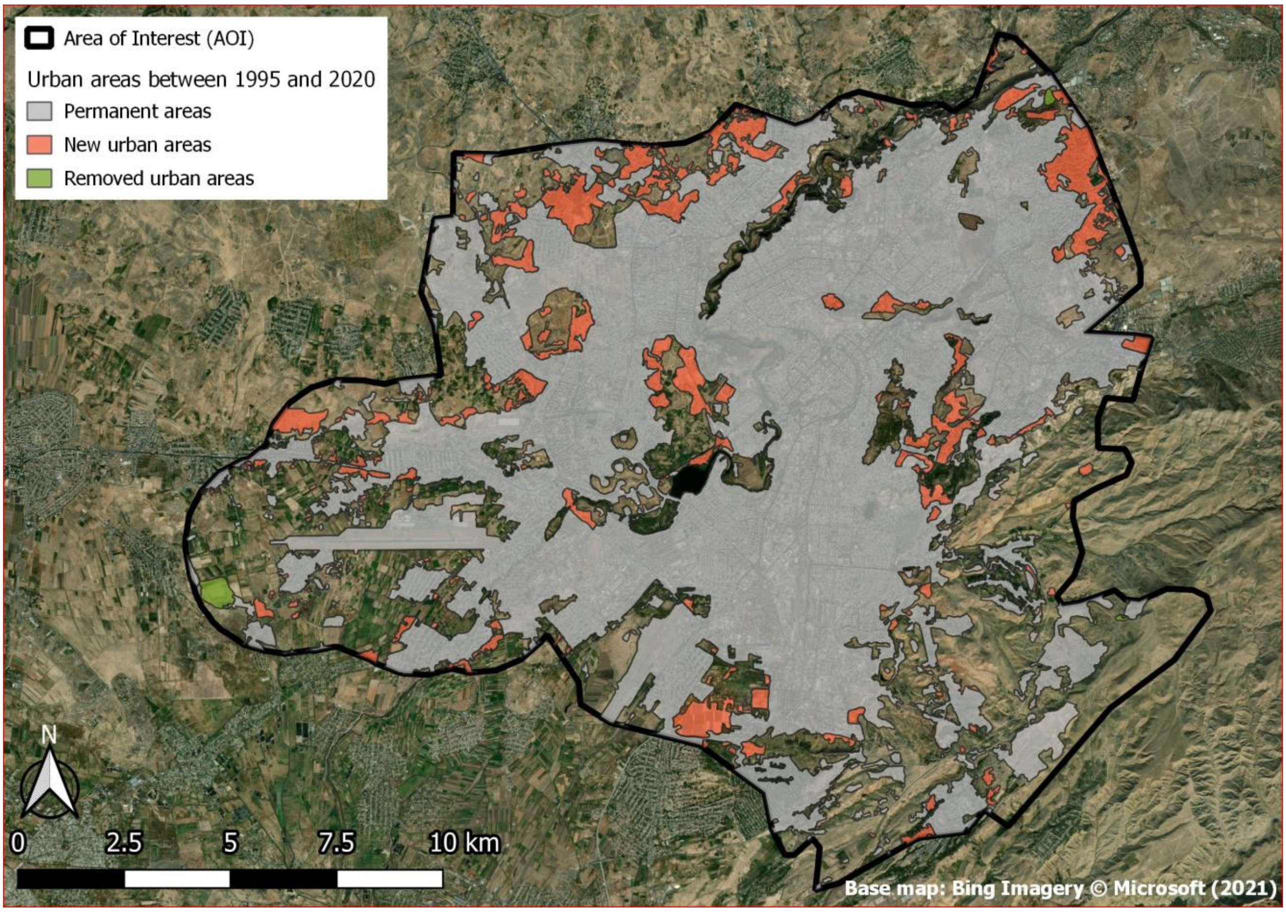



FIGURE 8: MAPPING OF URBAN EXTENT AND CHANGE DYNAMICS IN YEREVAN FROM 1995 TO 2020

#### *3.1.5.2 Urban area expansion*

**Definition of the spatial indicator:** A good understanding of the spatial distribution, but also evolution of human settlements constitutes a key element for sustainable city development strategies. A number of indicators can be derived like the settlement area change for a target region of interest, which allows to characterize the trends of urbanisation over time.

**Aim:** The evolution of the urban area extent / urban footprint over time is interesting to understand the dynamics of a city (densification, sprawl, ...), especially during the diagnosis phase of an urban planning project or for an evaluation of the impacts of development policies and actions.

**Input data used:** Urban Extent product (1995, 2000, 2005, 2010, 2015, 2020)

**Methodology:** Calculation of the evolution rate of the urban extent between 2 epochs.

**Results:** The indicator provides an assessment of spatiotemporal evolution of urban areas.

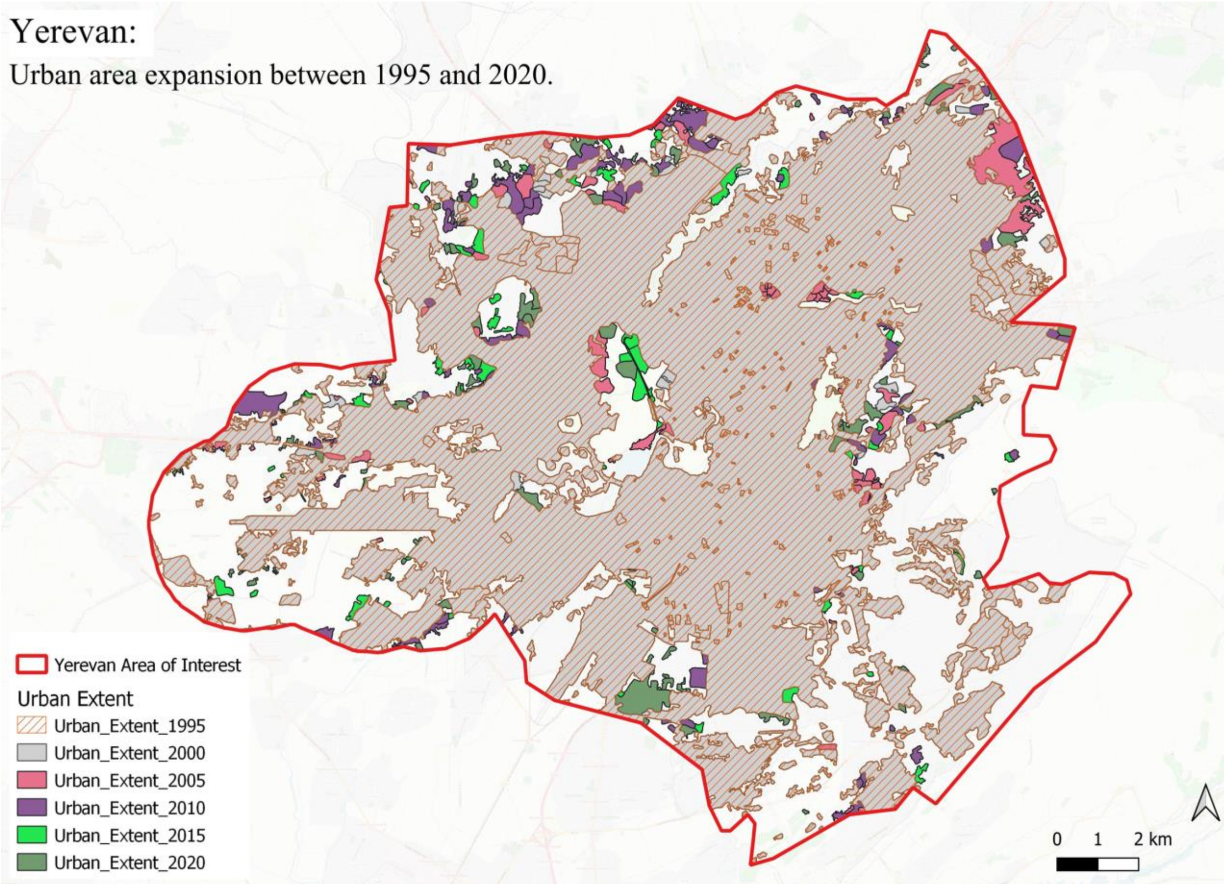



FIGURE 9: URBAN AREA EVOLUTION OF YEREVAN THROUGHOUT THE PERIOD 1995-2020

FIGURE 9 and TABLE 13 show that urban areas occupy a large part (65% in 2020) of the AOI defined for Yerevan (275 km²) and that urban extent grew regularly (2.5% to 3 %) every 5 years from 1995 to 2020. In the end, the total urban area increased from 161 to 179 km² over 25 years, a gain of 18 km² or 11% compared to the 1995 urban area, in a quite homogeneous way spatially speaking too.

Whatever the period, the extensions were of various sizes, isolated or stuck to an existing urban area, located on the periphery or coming to fill in holes in urban fabric. There is no specific trend observed.

TABLE 13: URBAN AREA EVOLUTION OF YEREVAN THROUGHOUT THE PERIOD 1995-2020

| Year | Total urban area | Rate of urban area over AOI | Evolution compared to 1995 | |
|---|---|---|---|---|
| | km² | % | km² | % |
| 1995 | 160.99 | 58.43 | N/A | N/A |
| 2000 | 162.07 | 58.82 | +1.07 | +0.67 |
| 2005 | 166.23 | 60.33 | +5.24 | +3.26 |
| 2010 | 171.79 | 62.34 | +10.80 | +6.71 |
| 2015 | 174.43 | 63.30 | +13.44 | +8.35 |
| 2020 | 178.97 | 64.95 | +17.98 | +11.17 |

### 3.1.5.3 *Ratio of land consumption rate to population growth rate*

**Definition of the spatial indicator:** It consists in comparing two components which are population growth and land consumption. According to the UN-Habitat Methodological Guidance document (UN-Habitat, 2016), population growth rate (PGR) is the evolution (increase generally) of population in a country during a specific period, usually one year. PGR is expressed as a percentage of the population gain or loss of population compared to the population at the beginning of the period.

Similarly, the land consumption rate aims to inform about the gain or loss of areas used for human activities over a period of time. Land consumption includes a) the built-up areas that can be directly measured, b) the absolute extent of land that is subject to exploitation by agriculture, forestry or other economic activities and c) the over-intensive exploitation of land that is used for agriculture and forestry.

The indicator is calculated by using the following formula:

$$\textit{Ratio of land consumption rate to population growth rate (LCRPGR)} = \frac{\textit{Land consumption rate}}{\textit{Annual population growth rate}}$$

| | |
|---|---|
| Population growth rate = $\frac{LN\left(\frac{Pop_{t+n}}{Pop_t}\right)}{y}$ | Land consumption rate = $\frac{LN\left(\frac{Urb_{t+n}}{Urb_t}\right)}{y}$ |
| $Pop_t$ Total population within the city in the past/initial year | $Urb_t$ Total population within the city in the past/initial year |
| $Pop_{t+n}$ Total population within the city in the current/final year | $Urb_{t+n}$ Total population within the city in the current/final year |
| y The number of years between the two measurement periods | y The number of years between the two measurement periods |

**Aim:** This indicator supports the assessment of urban dynamics, i.e. urban sprawl and densification phenomena mostly. With a view to achieving the Sustainable Development Goals (SDGs) set by the United Nations in 2015, in particular SDG 11 – sustainable cities and communities, it is of high importance to limit urban sprawl and densify existing areas as all infrastructures are already in place. This densification will be effective and considered sustainable if a city has a population growth that is higher than the area growth.

**Input data used:**

- Urban Extent product (2000, 2010)
- Population census data made available by the ADB for the reference year 2001 and 2011

**Methodology:** Calculation of the evolution rate of the urban extent as well as the population count in the 10-year period, before applying the formula given in the indicator definition.

**Results:** The indicator provides an assessment of the evolution of urban area in comparison with the one of population counts. If negative values are obtained, this means that one of the phenomenon decreased in the period. Absolute values below 1 means land consumption evolves slower than population in relative proportions which indicates densification more than urban sprawl, and vice versa.

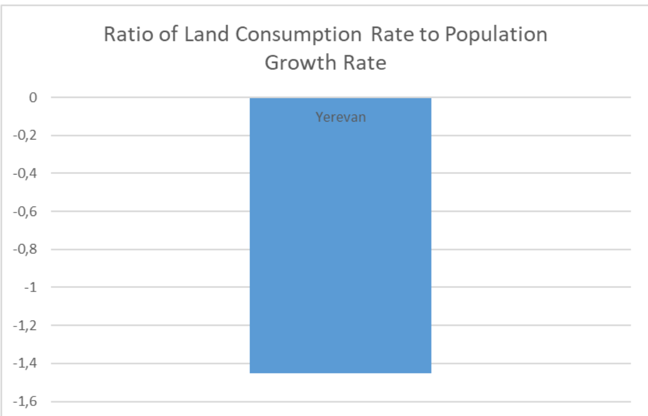



FIGURE 10: RATIO OF LAND CONSUMPTION RATE TO POPULATION GROWTH RATE FOR YEREVAN FROM 2000 TO 2010

The ratio was calculated only in the period 2000-2010 considering the population data availability, while the land consumption rate corresponds to urban area expansion computed previously. FIGURE 10 reveals a decrease in the population (negative index), even almost one and a half times slower than urban expansion in relative proportions. This result tends to consider that urban sprawl is significant.

#### 3.1.5.4 Urban fragmentation

**Definition of the spatial indicator:** Similar to porosity or discontinuity, fragmentation index describes the degree to which a city is internally (dis)connected or (dis)continuous. Often, the amount of isolated urban clusters is decisive for the metric and fragmentation can be seen as one key attribute of urban sprawl. Fragmented urban footprints are characterised by unused open spaces interpenetrating the city resulting in a more scattered and/or leapfrogged form.

The indicator is calculated by using the following formula considering both number and area of urban clusters:

$$Discontiguity = \sum_{n=1}^{N} \left(\frac{\sum_{i=n+1}^{N} A_i}{A_n}\right)\left(\frac{\sum_{i=n}^{N} A_i}{A_{total}}\right)$$

$A_n$ Area of cluster n
$A_{total}$ Joint area of the built-up extent
$N$ Number of urbanised clusters

(City Form Lab, 2012)

**Aim:** Fragmentation index is often used by urban planners as a diagnosis tool. It helps to detect areas that should be densified to ensure a reduction in urban sprawl that implies side effects and costs for cities.

**Input data used:** Urban Extent product (1995, 2000, 2005, 2010, 2015, 2020)

**Methodology:** Calculation of the indicator for each epoch using Urban Extent product and applying the formula given in the definition.

**Results:** The indicator provides an assessment of the morphology of the overall urban extent in terms of discontinuity or porosity. The higher the index value, the more fragmented the urban area.

**Main references:**

Amindarbari, R., Sevtsuk, A. (2013). *Measuring Growth and Change in Metropolitan Form*, presented at the Urban Affairs Association Conference, San Francisco.
Limtanakool, N., Schwanen, T. & Dijst M. (2009). *Developments in the Dutch urban systems on the basis of flows*. Regional Studies, 43(2), 179–196.
Hansen, W. G. (1959). *How accessibility shapes land use*. Journal of the American Planning Association, 25(2), 73–76.

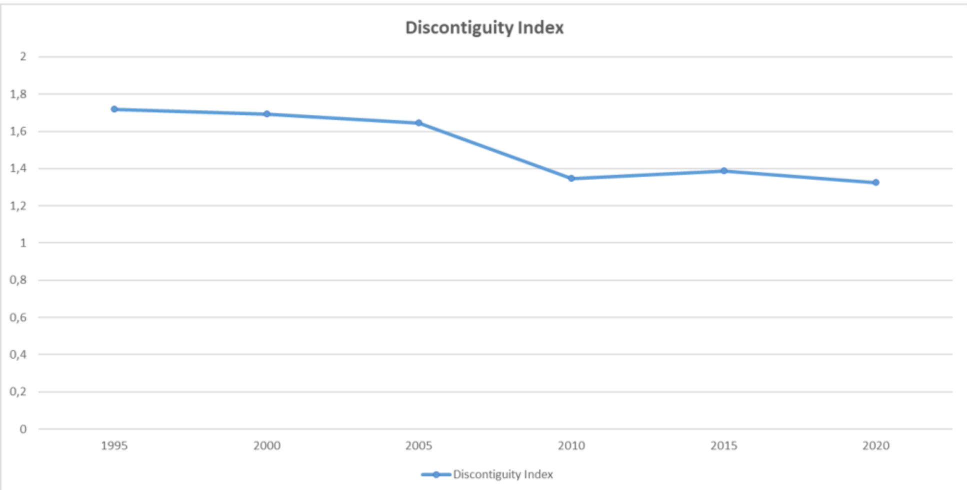



FIGURE 11: URBAN FRAGMENTATION (OR DISCONTINUITY) INDEX OF YEREVAN THROUGHOUT THE PERIOD 1995-2020

FIGURE 11 and FIGURE 12 show that the city is composed of urban clusters that decreased in number and consequently increased in size over the period, a trend which is mostly observed between 2005 and 2010. The index remains stable since then.

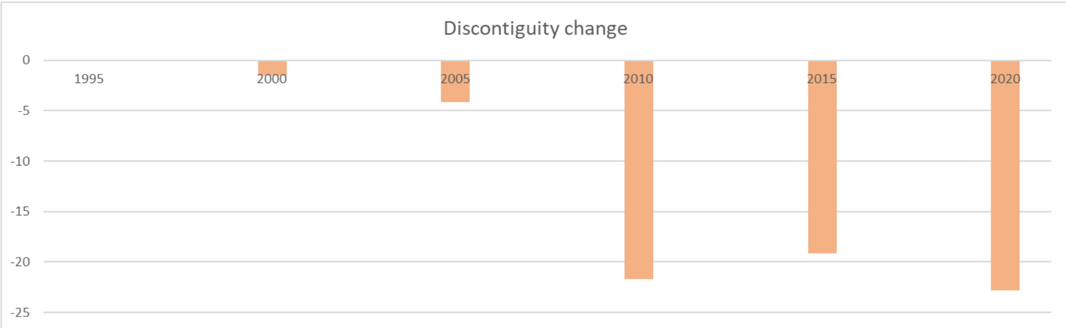
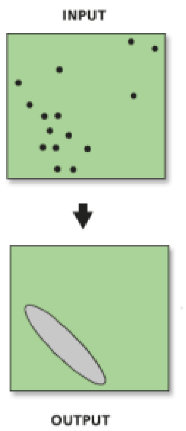



FIGURE 12: FRAGMENTATION INDEX EVOLUTION (%) OF YEREVAN FOR EACH EPOCH COMPARED TO 1995

### 3.1.5.5 *Compactness*

**Definition of the spatial indicator:** While the fragmentation metric targets the number and size of discontinuous patches, the dispersion metric describes the average distances between such separated parts of a city and is thus another important indicator for urban sprawl. Compactness can be described by a combination of different aspects, especially the geometric attributes like size and shape, density measures, as well as internal continuity and accessibility parameters.

The indicator consists in a standard deviational ellipse which takes into account the spatial distribution of urban clusters. This ellipse is derived from the calculation of the standard distances in both directions X and Y, considering the distance measurement between the centre of each cluster and the mean centre of all clusters, by using the following formula:




$$SDE_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{X})^2}{n}}$$

$$SDE_y = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{Y})^2}{n}}$$

$x_i, y_i$ Coordinates of polygon i

$\bar{X}, \bar{Y}$ Mean center of all polygons

$n$ Number of polygons

**Aim:** This information is useful to urban planners as a quick diagnosis tool to understand the growth patterns of a city and how compact the city really is. This method of calculation being standardised is quite useful to Multilateral Development Banks (MDBs) to compare cities. They can propose planning solutions to tackle the trends in the present growth and the growth expected by the local stakeholders. Planning decisions can be taken and investment spatially targeted accordingly. This indicator is relevant but to be considered and combined with other information (e.g. DEMs, hydrography, etc.).

**Input data used:** Urban Extent product (1995, 2000, 2005, 2010, 2015, 2020)

**Methodology:** Calculation of the indicator for each epoch using Urban Extent product and applying the formula given in the definition.

**Results:** The indicator provides an assessment of the morphology of the overall urban extent in terms of compacity or dispersion. The smaller the standard distance values in X and Y directions and the smaller the difference between them, the more compact the city can be considered. Thus, the maximum degree of compactness is observed when the ellipse corresponds to a circle with the smallest possible radius.

**Main reference:** Robert S. Yuill (1971). *Geografiska Annaler.* Series B, Human Geography. Vol. 53, No. 1, pp. 28-39. URL: https://www.jstor.org/stable/490885

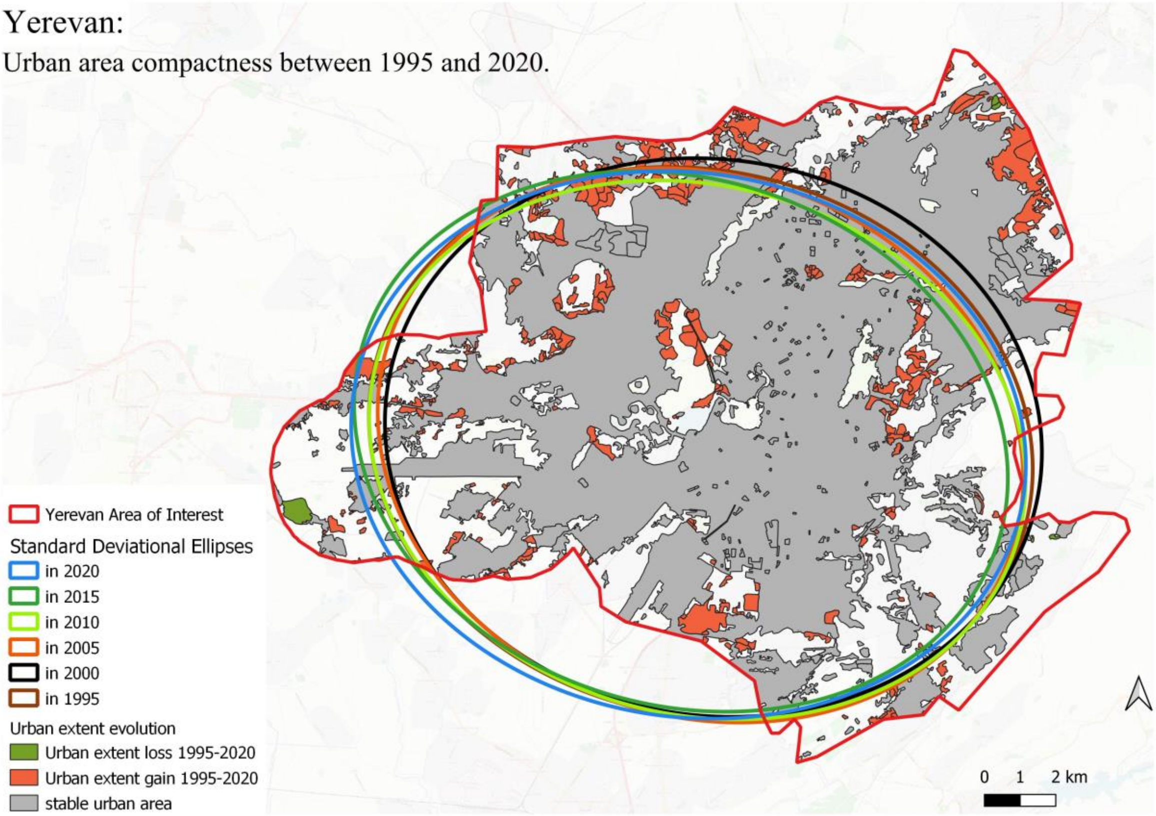



FIGURE 13: STANDARD DEVIATIONAL ELLIPSES FOR THE YEARS 1995 TO 2020 IN YEREVAN.

FIGURE 13 shows the spatial characteristics (central tendency, dispersion and directional trend) of Yerevan and the changes over time.

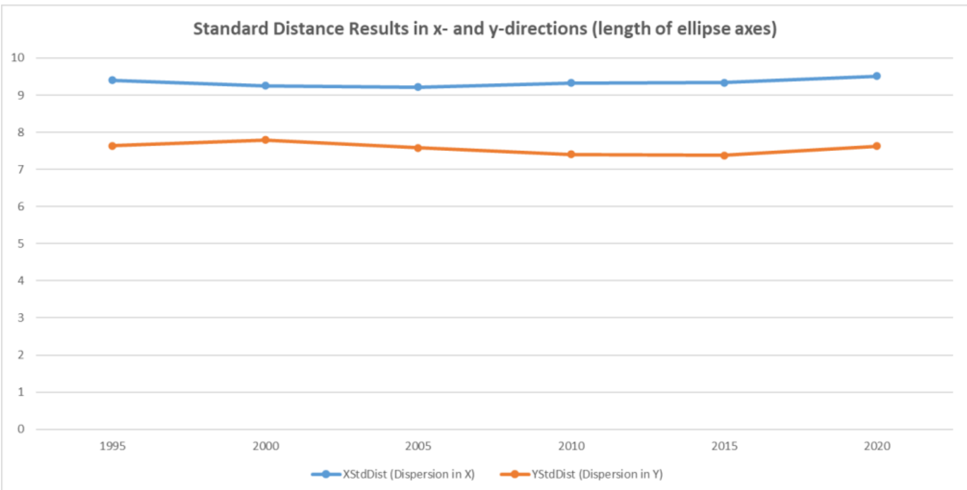



FIGURE 14: STANDARD DISTANCE IN X- AND Y-DIRECTIONS (LENGTH OF ELLIPSE AXES) FOR YEREVAN

Visually, the map shows that the distribution of distances between clusters is uniform and does not allow to detect a distortion in the spatial distribution of clusters. Yerevan is a homogeneous city and remains so since 1995, this is confirmed by the small differences between the X-dispersion and the Y-dispersion, as shown in FIGURE 14 and FIGURE 15.

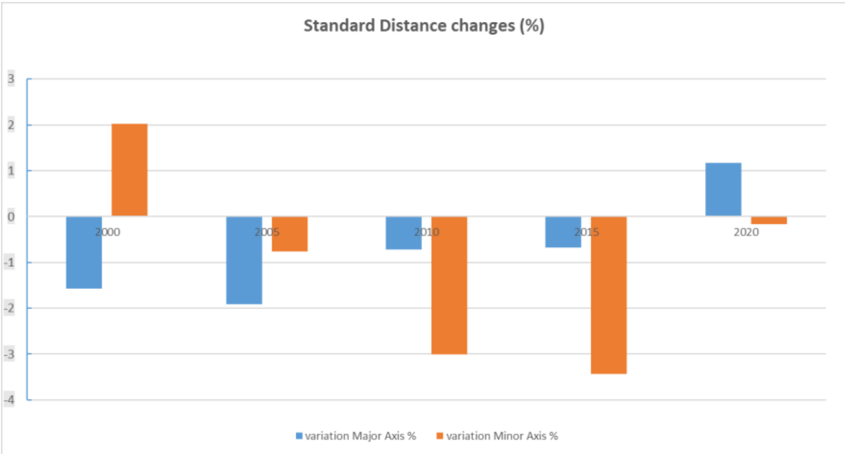



FIGURE 15: STANDARD DISTANCE VARIATIONS IN X- AND Y-DIRECTIONS FOR YEREVAN COMPARED TO 1995

### *3.1.5.6 Land accounting – Urban changes over 1995-2020*

**Definition of the spatial indicator:** Baseline quantitative information about LU/LC assets, consumption and formation flows during observed periods and net changes resulting from these flows (based on UN SEEA and the EEA LEAC analytical framework).

**Aim:** Drawing the profile of a city or districts within the city and highlighting strengths and weaknesses of various areas. Assessing the impacts of city master plans.

**Input data used:** Urban Extent product (1995, 2020) & Urban Change Areas product (1995-2020)

**Methodology:** Summary statistics on urban LULC change areas.

**Results:** Land accounting focusing on urban changes provides the trends in terms of LULC change types, quantity (areas) and relative proportions. Urban Change Areas product for the whole period (1995-2020) only includes changes for which LULC characterisation was possible to be made for the reference date 1995 considering the limitation from the satellite images used in terms of spatial resolution. This means that intra-urban changes detected only through the last decade 2010-2020 are logically not included.

TABLE 14: URBAN CHANGE ACCOUNTING OVER THE PERIOD 1995-2020 IN YEREVAN (AREA TRANSFER, IN HA)

| | | 2020 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **111** | **112** | **113** | **121** | **122** | **131** | **132** | **200** | **300** |
| **1995** | **112** | | | | | | | | | 0.4 |
| | **113** | | | | | | | 16.6 | | 0.4 |
| | **121** | | | | | | 0.1 | 9.8 | 0.1 | |
| | **131** | | | | | | | | 4.4 | 0.3 |
| | **132** | 0.7 | 7.1 | 19.8 | 3.4 | | | | | |
| | **200** | | 21.1 | 56.2 | 25.3 | 1.1 | 8.7 | 16.6 | | |
| | **300** | 0.1 | 2.2 | 20.3 | 13.4 | 0.7 | 13.5 | 5.5 | | |
| | **500** | | | | | | 0.4 | | | |

TABLE 14 provides urban change accounting over the whole period 1995-2020 in Yerevan in the form of a matrix of area transfers (expressed in ha) from one LULC class to another between the two reference dates.

TABLE 15: URBAN CHANGES OBSERVED FROM 1995 TO 2020 IN YEREVAN

| Changes between 1995 and 2020 in Yerevan | Area (km²) | Share (%) |
|---|---|---|
| Urban expansion - residential | 9.99 | 40.2% |
| Urban expansion - commercial / industrial | 3.87 | 15.6% |
| Urban expansion - transportation | 0.18 | 0.7% |
| Urban expansion - construction sites | 2.26 | 9.1% |
| Urban expansion - vacant land / brownfields | 2.21 | 8.9% |
| Internal urban development - residential | 2.76 | 11.1% |
| Internal urban development - commercial / industrial | 0.34 | 1.4% |
| Internal urban development - construction sites | 0.01 | 0.0% |
| Internal urban development - vacant land / brownfields | 2.64 | 10.6% |
| Agriculture development - uptake of artificial area | 0.44 | 1.8% |
| Natural areas development - update of artificial area | 0.12 | 0.5% |
| ***Total of changes*** | **24.81** | - |

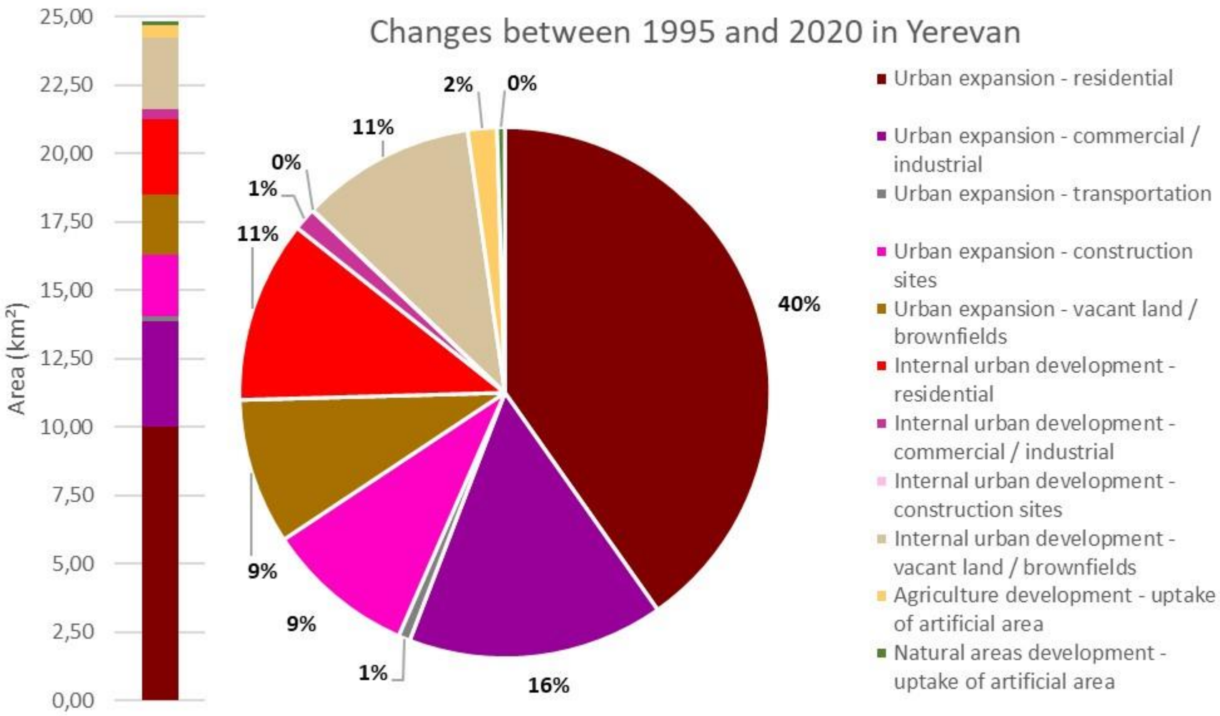
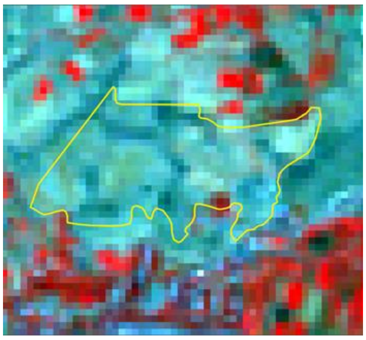
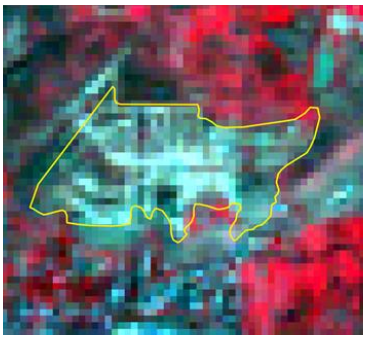



FIGURE 16: URBAN CHANGES OBSERVED FROM 1995 TO 2020 IN YEREVAN

TABLE 15 and FIGURE 16 provide the summary statistics of the urban changes observed from 1995 to 2020 in Yerevan. Change areas represent nearly 25 km² and three quarters are related to urban expansion, which mainly benefits housing (40%) and to a lesser extent commercial and/or industrial areas (16%). Sites under construction (9%) and vacant or brownfield sites (9%) are also still visible in 2020. The other major changes are intra-urban mutations in favour of residential areas (11%) or vacant and brownfield sites (11%). Finally, it should be noted that only one artificial area existing in 1995 and located in the extreme east of the AOI has been reconverted for agricultural use or as natural land. TABLE 16 shows some of the main changes observed over the period in Yerevan.

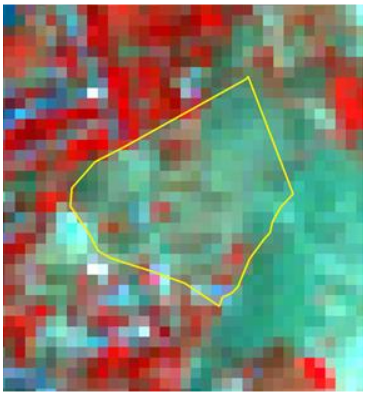
TABLE 16: EXAMPLES OF SOME OF THE MAIN CHANGES OBSERVED OVER THE PERIOD 1995-2020 IN YEREVAN

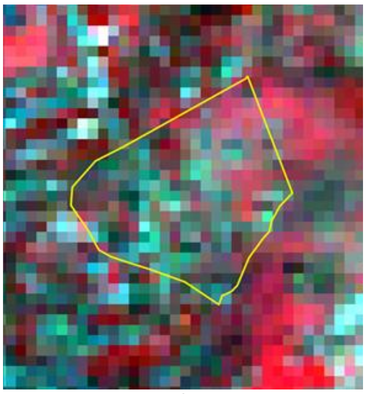

Year: **2000** / class: **200**


Year: **2005** / class: **113**


Year: **2011** (Google Earth)

Change class: **15 Urban expansion – vacant land / brownfields**
*Location: 40°10′19.89″N, 44°22′08.99″E*

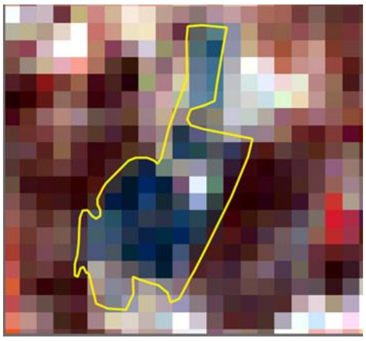

Year: **2000** / class: **300**


Year: **2005** / class: **131**


Year: **2011** (Google Earth)

Change class: **11 Urban expansion – residential**
*Location: 40°13′40.23″N, 44°35′10.18″E*


Year: **2010** / class: **200**


Year: **2015** / class: **131**


Year: **2016** (Google Earth)

Change class: **14 Urban expansion – construction sites**
*Location: 40°11′25.03″N, 44°26′14.87″E*

### 3.1.5.7 Land accounting – Urban changes over 2010-2020

**Definition of the spatial indicator:** Baseline quantitative information about LU/LC assets, consumption and formation flows during observed periods and net changes resulting from these flows (based on UN SEEA and the EEA LEAC analytical framework).

**Aim:** Drawing the profile of a city or districts within the city and highlighting strengths and weaknesses of various areas. Assessing the impacts of city master plans.

**Input data used:**

- Urban Extent product (2010, 2020)
- Urban Change Areas product (2010-2020)

**Methodology:** Summary statistics on urban LULC change areas.

**Results:** Land accounting focusing on urban changes provides the trends in terms of LULC change types, quantity (areas) and relative proportions. Urban Change Areas product for the period 2010-2020 benefitted from the use of satellite images with higher spatial resolution. Full intra-urban change detection and characterisation was implemented thanks to these input data, offering a more detailed analysis of the city dynamics.

TABLE 17 provides urban change accounting over the last decade 2010-2020 in Yerevan in the form of a matrix of area transfers (expressed in ha) from one LULC class to another between the two reference dates.

TABLE 17: URBAN CHANGE ACCOUNTING OVER THE PERIOD 2010-2020 IN YEREVAN (AREA TRANSFER, IN HA)

| | | 2020 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 111 | 112 | 113 | 121 | 122 | 131 | 132 | 140 | 300 |
| 2010 | 111 | | | | 0.1 | | 0.1 | | | |
| | 112 | 0.3 | | | 0.1 | 0.1 | 0.2 | 0.1 | | 0.1 |
| | 113 | | 10.6 | | | | | 11.4 | | |
| | 121 | 0.2 | | | | | 1.1 | 9.3 | | |
| | 122 | | | | 0.1 | | | | | |
| | 131 | 0.7 | 0.1 | 0.2 | 1.0 | 0.1 | | | | 0.3 |
| | 132 | 1.7 | 2.4 | 8.7 | 7.2 | 0.4 | 1.4 | | 0.1 | |
| | 140 | | | | 0.2 | | | 0.1 | | |
| | 200 | | 1.4 | 17.2 | 131.1 | 0.9 | 5.8 | 8.9 | | |
| | 300 | | 0.2 | 9.0 | 5.3 | 0.7 | 6.7 | 3.0 | | |
| | 500 | | | | | | 0.4 | | | |

TABLE 18: URBAN CHANGES OBSERVED FROM 2010 TO 2020 IN YEREVAN

| Changes between 2010 and 2020 in Yerevan | Area (km²) | Share (%) |
|---|---|---|
| Urban expansion - residential | 2.78 | 20.5% |
| Urban expansion - commercial / industrial | 1.84 | 13.6% |
| Urban expansion - transportation | 0.16 | 1.2% |
| Urban expansion - construction sites | 1.30 | 9.6% |
| Urban expansion - vacant land / brownfields | 1.19 | 8.8% |
| Internal urban development - residential | 2.50 | 18.5% |
| Internal urban development - commercial / industrial | 0.86 | 6.3% |
| Internal urban development - transportation | 0.05 | 0.4% |
| Internal urban development - construction sites | 0.28 | 2.1% |
| Internal urban development - vacant land / brownfields | 2.08 | 15.4% |
| Internal urban development - urban greenery | 0.01 | 0.1% |
| Urban renewal | 0.41 | 3.0% |
| Natural areas development - update of artificial area | 0.07 | 0.5% |
| ***Total of changes*** | **13.51** | - |

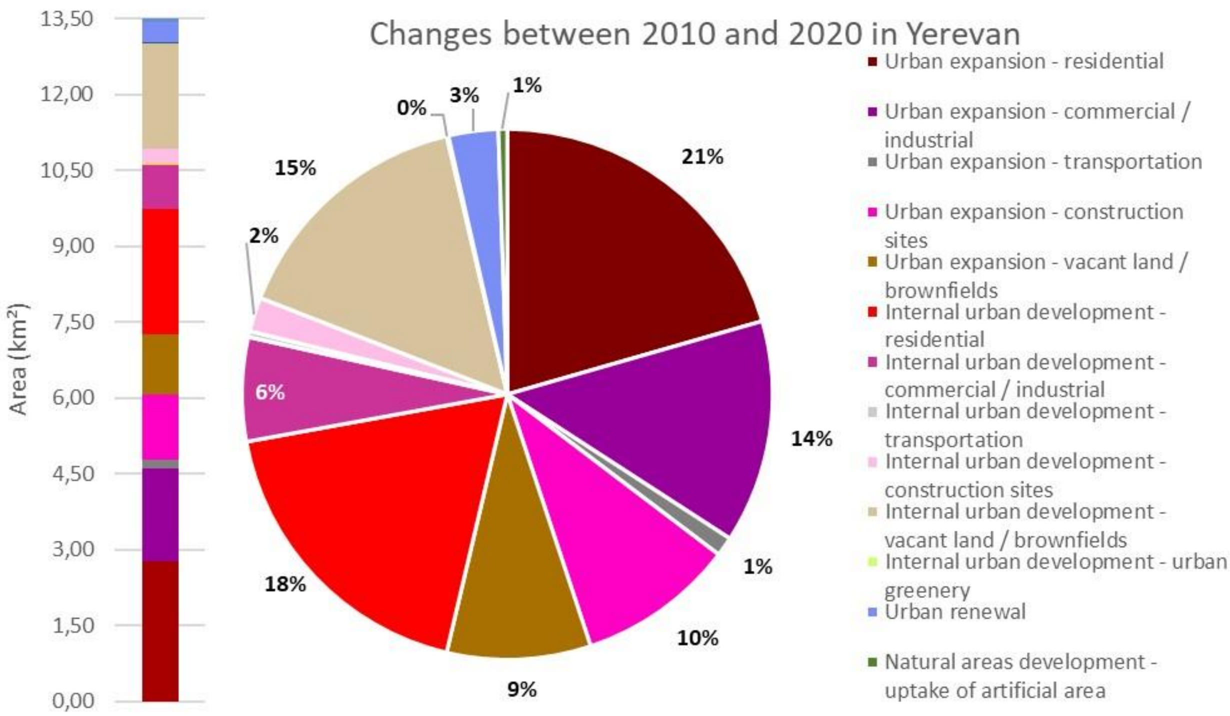



FIGURE 17: URBAN CHANGES OBSERVED FROM 2010 TO 2020 IN YEREVAN

TABLE 18 and FIGURE 17 provide the summary statistics of the urban changes observed from 2010 to 2020 in Yerevan. The results show that overall urban change dynamics in Yerevan seem to be quite high over the last decade, as changes cover 13.51 km² or 7.6% compared to the 2020 urban extent. Otherwise, changes observed from satellite images are quite homogeneously distributed, spread over the whole city including the historic centre, as illustrated in FIGURE 18. More than a half is related to urban expansion which mainly benefits housing (21%) and to a lesser extent commercial and/or industrial areas (14%). Other changes are considered as intra-urban and mostly benefit the same land use classes. It is also interesting to note that more than a third of the change areas are identified as sites under construction or vacant still in 2020. Finally, urban renewal could be considered as a limited phenomenon regarding the cumulative area only (3% or 41 ha). However, it seems surely significant in the historic districts of the city considering the few dozens of sites identified, whose average area is smaller than the one observed for sites related to urban expansion and internal urban development.

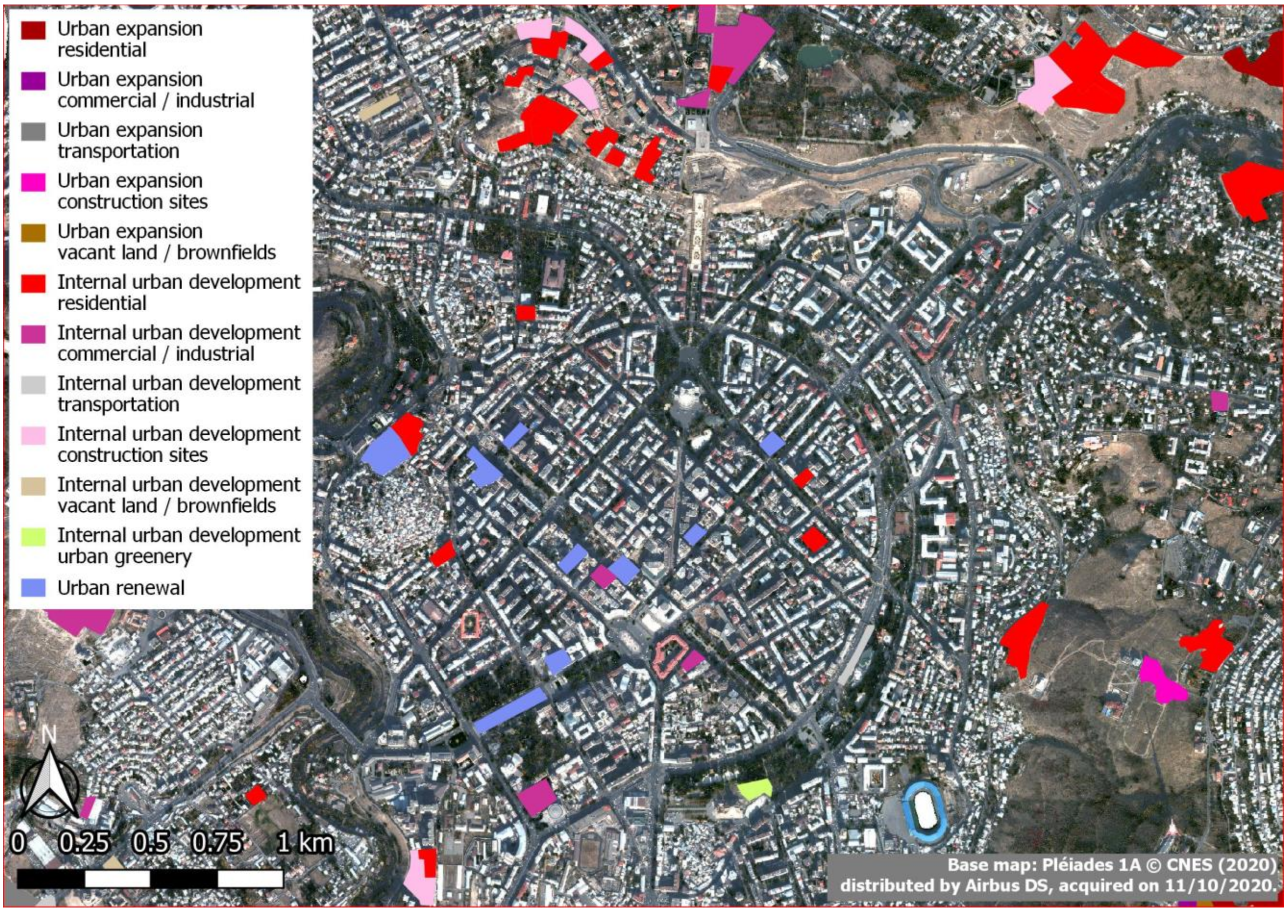



FIGURE 18: MAPPING OF INTRA-URBAN CHANGE DYNAMICS IN YEREVAN FROM 2010 TO 2020

TABLE 19 shows some of the main changes observed over the period in Yerevan.

TABLE 19: EXAMPLES OF SOME OF THE MAIN CHANGES OBSERVED OVER THE PERIOD 2010-2020 IN YEREVAN

Year: **2015** / class: **121**

Year: **2020** / class: **132**

Change class: **25 Internal urban development – vacant land / brownfields**

*Location: 40°11’40.04”N, 44°29’32.07”E*

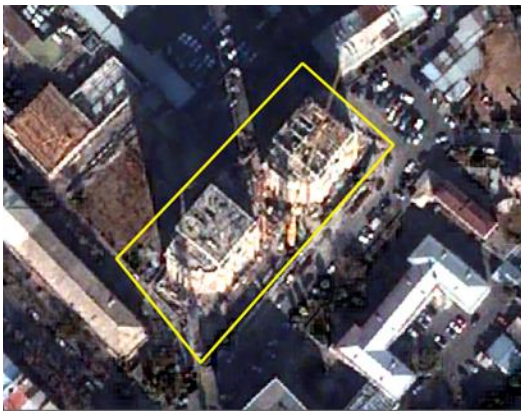
Year: **2015** / class: **131**

Year: **2020** / class: **111**

Change class: **21 Internal urban development – residential**

*Location: 40°10’51.54”N, 44°29’52.81”E*

Year: **2015** / class: **121**



Year: **2020** / class: **131**

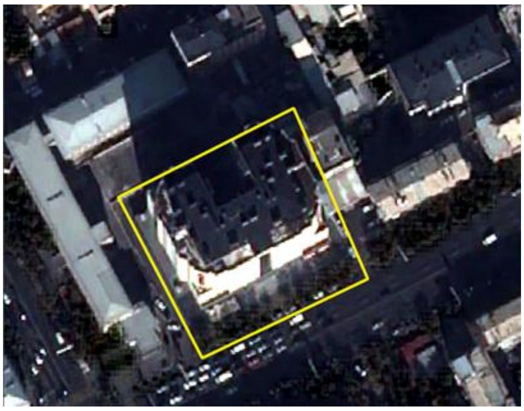
Change class: **24 Internal urban development - construction sites**

*Location: 40°12’21.32”N, 44°31’52.39”E*

Evolution of physical assets but without impact on LULC classification were also detected by visual interpretation of the VHR satellite images. Areas concerned were then extracted and classified as urban renewal (attribute fields “URB_RENEW” and “RENEW_TYPE” filled in accordingly). TABLE 20 gives an example.

TABLE 20: EXAMPLE OF URBAN RENEWAL OBSERVED OVER THE PERIOD 2010-2020 IN YEREVAN

Year: **2015** / class: **111**



Year: **2020** / class: **111**

Change class: **30 Urban renewal - Replacement of building**

*Location: 40°12’12.32”N, 44°29’57.53”E*

### *3.1.5.8 Average distance between services and population*

**Definition of the spatial indicator:** The steady growth of cities very often results in an uncoordinated sprawl with longer distances to urban facilities: jobs, education, health facilities, public transport, urban green areas or other important facilities. The average distance metric can be used as a measure for the reachability of these urban facilities from residential areas. Based on the ESA EO4SD-Urban project, the convenient distance is defined as 500 meters.

**Aim:** Hotspot maps highlighting underserved areas are interesting for urban planners during a diagnosis phase. To avoid transportation over long distances, the ideal is to have a good mix of land use comprising residential, commercial, industrial and other urban facilities. It is to be noted that this data needs to be completed by traditional Origin-Destination studies, in order to understand the real dynamics.

**Input data used:**

- Urban Extent product (2020)
- Road network (source: OSM, downloaded in March 2021)
- Location of urban facilities: economic, health, administrative, education, urban green area (OSM)
- Building footprints (OSM); no(or little) distinction possible on the categories of buildings: houses, offices, commercial, etc. As a result, all buildings were considered.

**Methodology:** Road network analysis and service area computation.

**Results:** Each building is affected to a class of distance (500m, 1000m, 2000m, more than 2000m) from the nearest facilities. Service areas are derived accordingly.

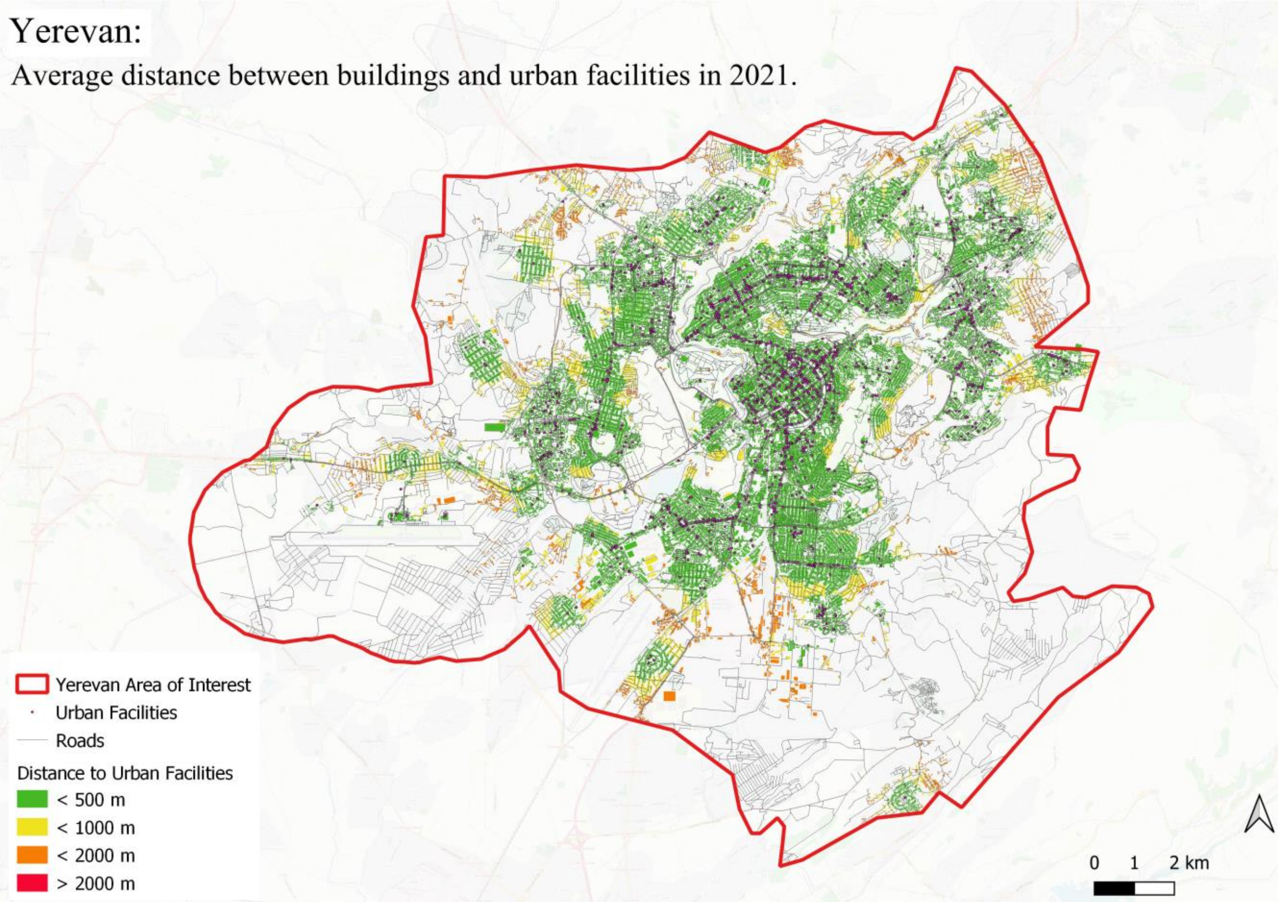



FIGURE 19: ZONAL DISTANCE BETWEEN BUILDING FOOTPRINTS AND URBAN FACILITIES IN 2021 IN YEREVAN

FIGURE 19 shows that most of the buildings in the city are within 500m of an economic, administrative, educational, health or even green space facility. However, we notice that significant areas, in the periphery but also in the heart of the city, are more than 500 m or even 1000 m away from a facility. It is for example the extensions located in the East of Yerevan. On the other hand, it should be noted that no area is more than 2 km away.

### 3.1.6 Outputs for Gyumri

#### *3.1.6.1 Mapping results*

The EO-based service aims at providing reliable indicators of permanent change in the economy through the period 1995-2020. Therefore, the following geospatial products were derived from image analysis:

- **Urban Extent** for each reference epoch
- **Urban Change Areas** involving detection in time and space, as well as characterisation

As described in the section 3.1.2.2, urban extent mapping was firstly generated by means of automated classification of HR optical images. The result was intermediate as the algorithm enabled to well detect and extract built-up areas, but not systematically their associated non-sealed and vegetated surfaces. Therefore, the final Urban Extent product for each epoch was obtained by means of visual interpretation using both HR and 2020 VHR images, and manual refinement of the previous mapping result.

The results got for Gyumri city regarding its current extent (2020) are shown in FIGURE 20.

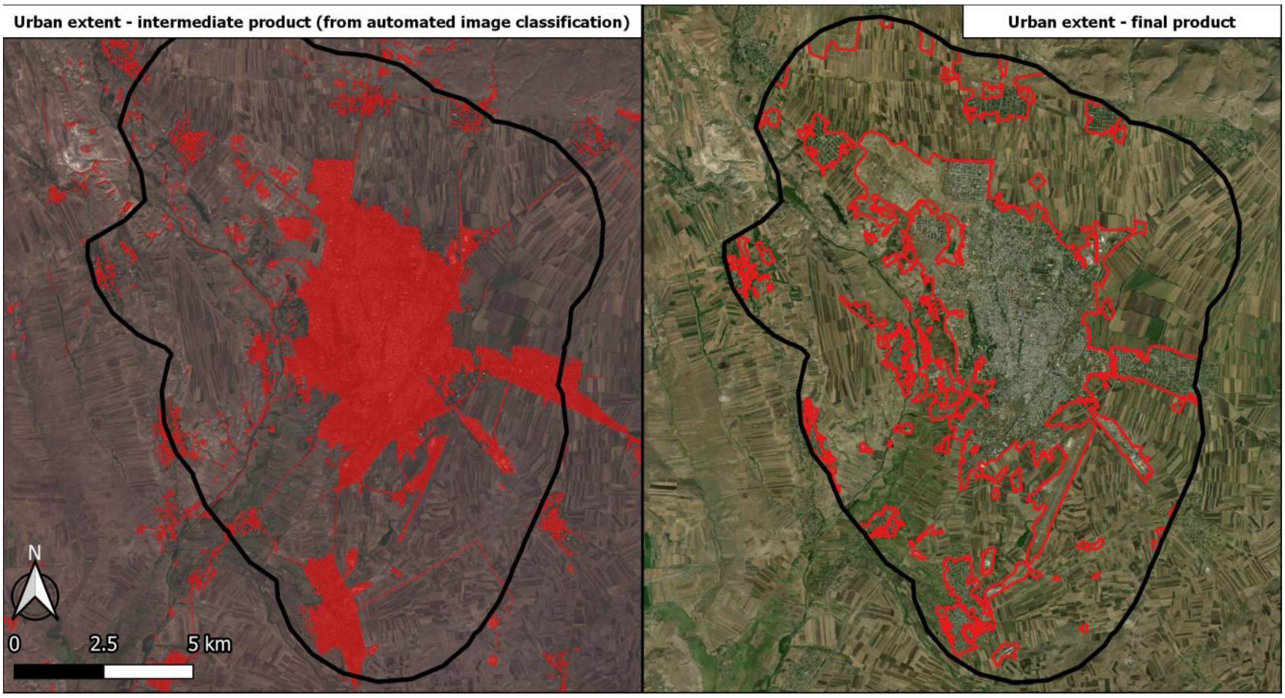



FIGURE 20: URBAN EXTENT MAP OF GYUMRI IN 2020

Once urban extent was mapped for each epoch, it was easy to visually compare and automatically extract change areas occurring throughout each 5-year period by means of basic GIS analysis tool.

FIGURE 8FIGURE 21 shows the overall evolution of Gyumri urban extent from 1995 to 2020. The mapping results clearly indicate that urban area remained globally stable over time with, in the end, a very limited increase.

In addition to detect LULC changes in the urban fringe, most of them impacting urban extent, further analysis was performed by means of visual interpretation of VHR optical images in order to characterise them at best and extract also intra-urban changes in the most recent period 2010-2020. As a result, a consistent map of Urban Change Areas for each 5-year period has been delivered too.

Finally, the mapping results related to urban extent and change dynamics were further analysed and used for the computation of several key spatial indicators. The next sections present the outputs in detail.

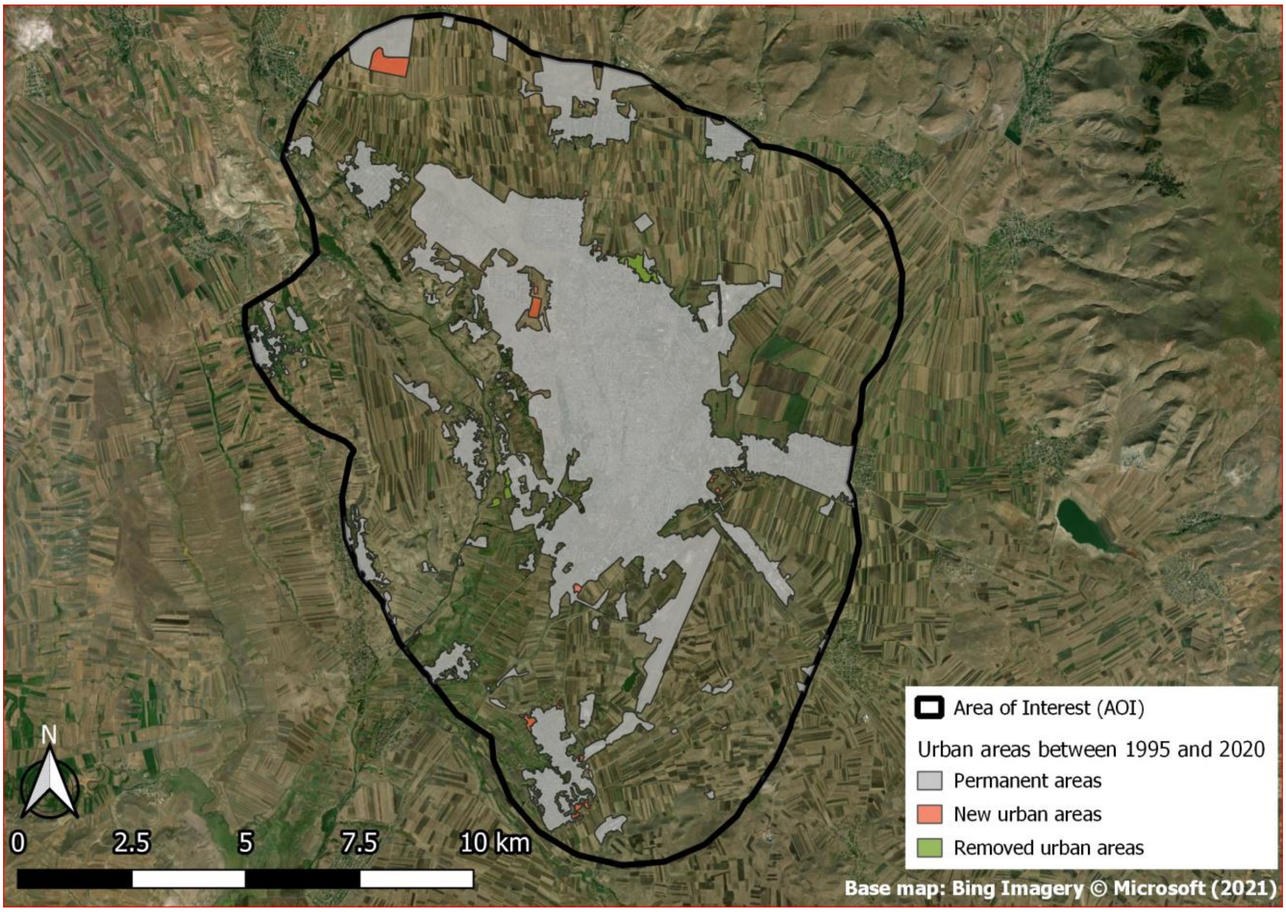



FIGURE 21: MAPPING OF URBAN EXTENT AND CHANGE DYNAMICS IN GYUMRI FROM 1995 TO 2020

### *3.1.6.2 Urban area expansion*

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.2

The indicator provides an assessment of spatiotemporal evolution of urban areas.

TABLE 21: URBAN AREA EVOLUTION OF GYUMRI THROUGHOUT THE PERIOD 1995-2020

| Year | Total urban area | Rate of urban area over AOI | Evolution compared to 1995 | |
|---|---|---|---|---|
| | km² | % | km² | % |
| 1995 | 53.08 | 29.73% | N/A | N/A |
| 2000 | 53.01 | 29.70% | -0.06 | -0.12% |
| 2005 | 53.12 | 29.76% | 0.04 | 0.07% |
| 2010 | 53.33 | 29.88% | 0.26 | 0.48% |
| 2015 | 53.36 | 29.89% | 0.28 | 0.53% |
| 2020 | 53.46 | 29.95% | 0.38 | 0.71% |

FIGURE 22 and TABLE 21 show that urban areas occupy a significant part (30% in 2020) of the AOI defined for Gyumri (208 km²) and that urban extent remained stable from 1995 to 2020. In the end, the total urban area increased from 53.1 to 53.5 km² over 25 years, a gain of 0.4 km² or 0.7% compared to the 1995 urban area. This result contrasts a lot with the long-standing trend of strong growth observed in the urban area of Yerevan.

Whatever the period, the extensions were of various sizes, isolated or stuck to an existing urban area, located on the periphery or coming to fill in holes in urban fabric. There is no specific trend observed, as for Yerevan.

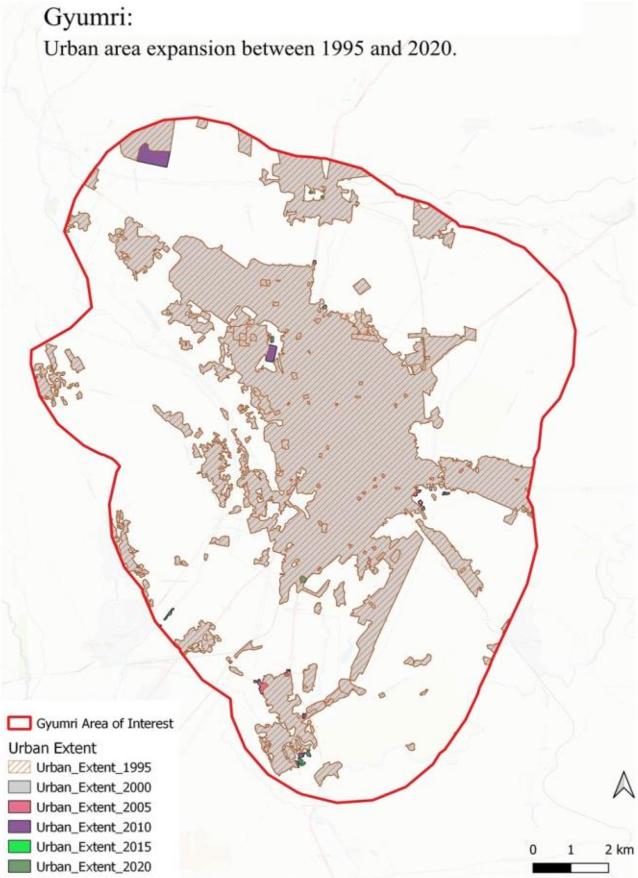



FIGURE 22: URBAN AREA EVOLUTION OF GYUMRI THROUGHOUT THE PERIOD 1995-2020

#### *3.1.6.3 Ratio of land consumption rate to population growth rate*

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.3

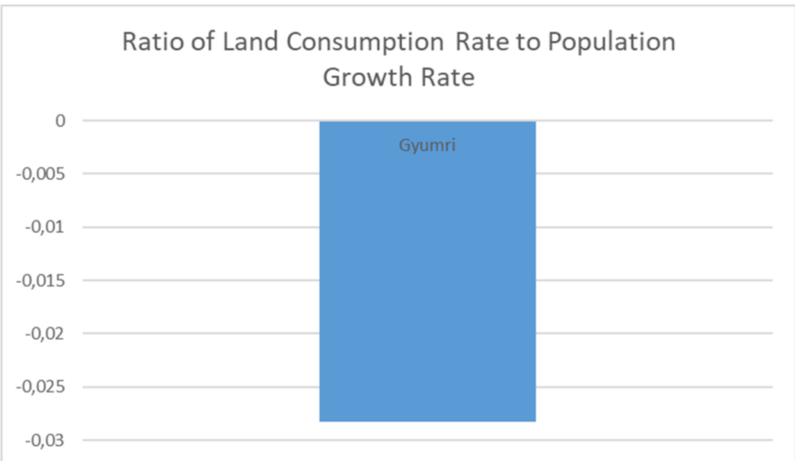



FIGURE 23: RATIO OF LAND CONSUMPTION RATE TO POPULATION GROWTH RATE FOR GYUMRI FROM 2000 TO 2010

The indicator provides an assessment of the evolution of urban area in comparison with the one of population counts. If negative values are obtained, this means that one of the phenomenon decreased in the period. Absolute values below 1 means land consumption evolves slower than population in relative proportions which indicates densification more than urban sprawl, and vice versa.

FIGURE 23 reveals a very low value of the ratio. This result indicates that the changes in population are in line with the ones related to urban areas and are therefore also very minimal.

#### 3.1.6.4 Urban fragmentation

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.4

The indicator provides an assessment of the morphology of the overall urban extent in terms of discontinuity or porosity. The higher the index value, the more fragmented the urban area.

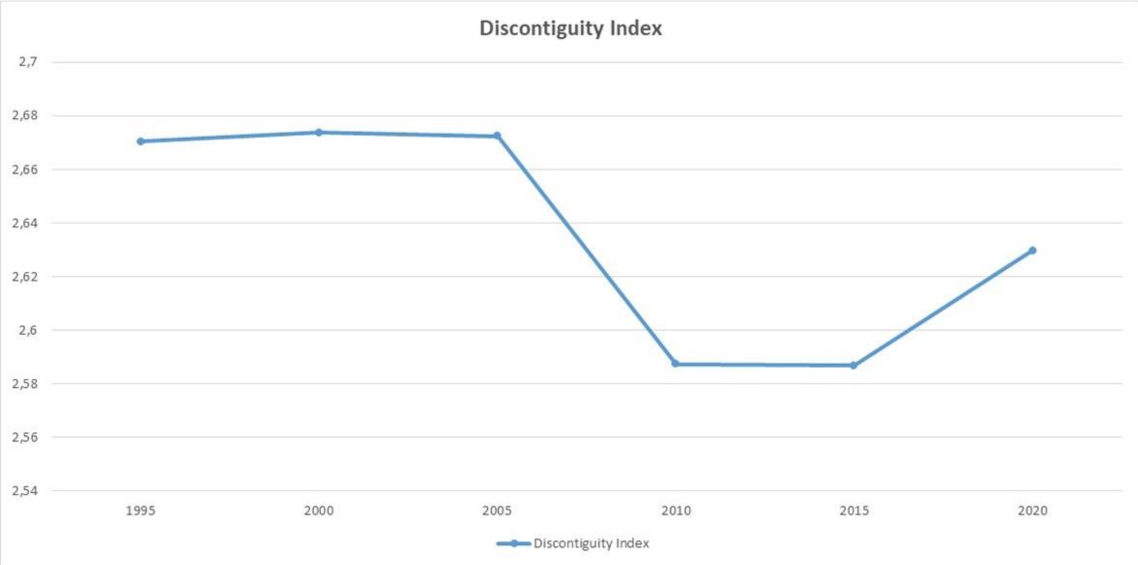



FIGURE 24: URBAN FRAGMENTATION (OR DISCONTINUITY) INDEX OF GYUMRI THROUGHOUT THE PERIOD 1995-2020

FIGURE 24 and FIGURE 25 show that the Gyumri discontinuity index is greater than Yerevan. This index is stable until 2005 and reaches a lower plateau between 2005 and 2015 (2.59 still greater than Yerevan). This shows that the new urban spaces are made in favour of a lower fragmentation.

The interpretation of the results must be considered with caution because the areas involved are minimal. For example, here between 2015 and 2020, the index seems to grow but it is based on an increase of the urban area of only 0.1 km².

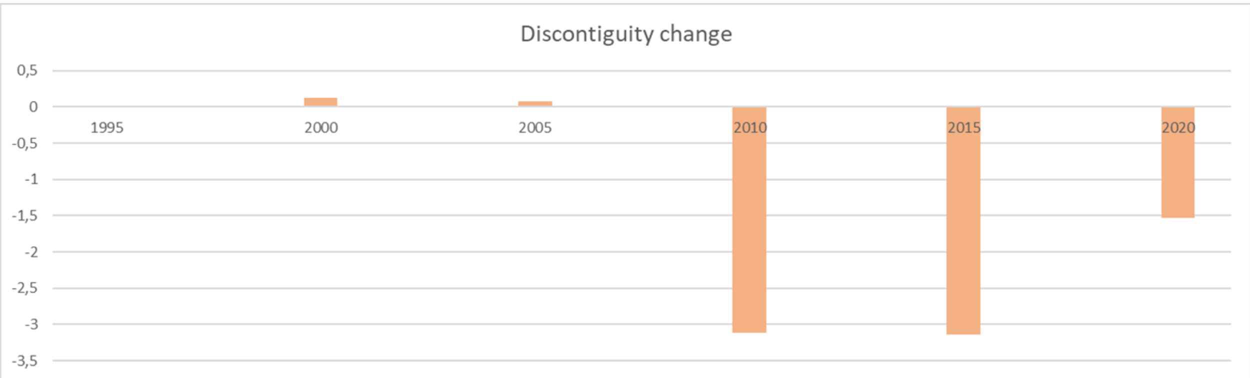



FIGURE 25: FRAGMENTATION INDEX EVOLUTION (%) OF GYUMRI FOR EACH EPOCH COMPARED TO 1995

### 3.1.6.5 Compactness

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.5

The indicator provides an assessment of the morphology of the overall urban extent in terms of compacity or dispersion. The smaller the standard distance values in X and Y directions and the smaller the difference between them, the more compact the city can be considered. Thus, the maximum degree of compactness is achieved when the ellipse corresponds to a circle with the smallest possible radius.

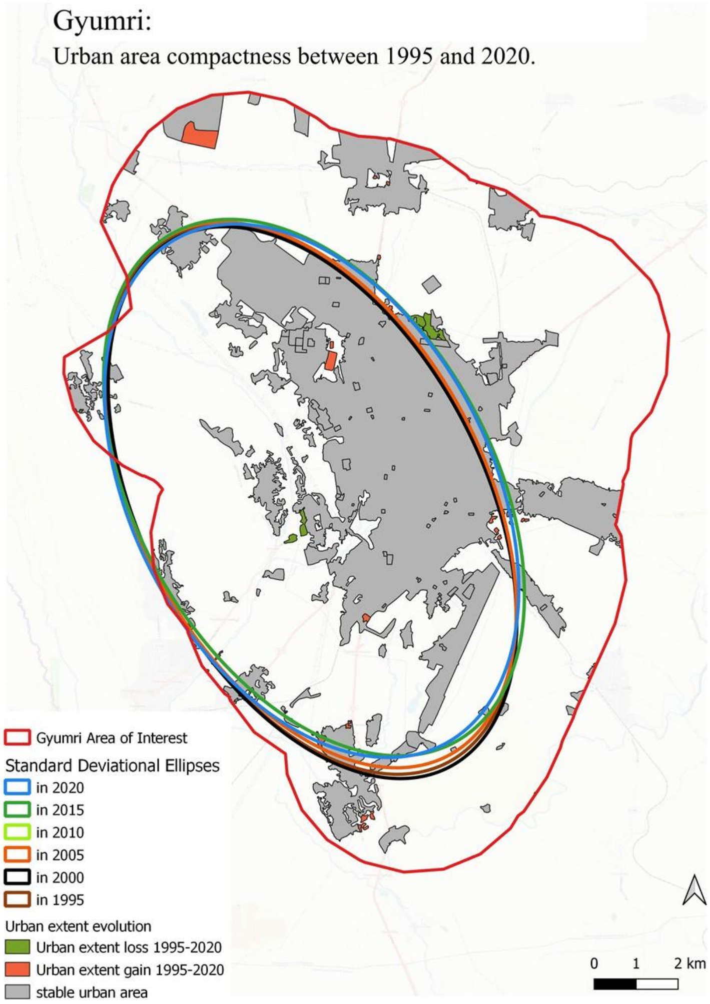



FIGURE 26: STANDARD DEVIATIONAL ELLIPSES FOR THE YEARS 1995 TO 2020 IN GYUMRI.

FIGURE 26 shows that the distribution of clusters unlike Yerevan is oriented north-south. The dispersion according to this orientation tends to decrease very slightly and constantly since 2000. This means that the city is more compact in 2020 than in 2000.

Visually, the map shows that the distribution of distances between clusters is uniform and does not allow to detect a distortion in the spatial distribution of clusters. Gyumri is a homogeneous city and remains so since 1995, this is confirmed by the small differences between the X-dispersion and the Y-dispersion, as shown in FIGURE 27 and FIGURE 28.

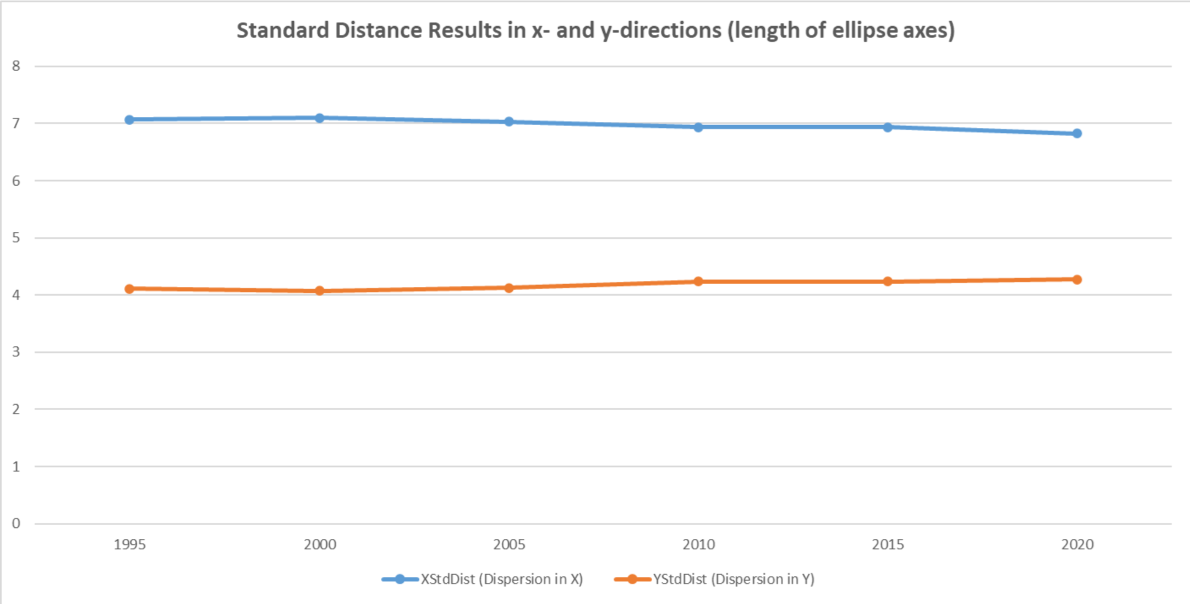



Figure 27: Standard distance in x- and y-directions (length of ellipse axes) for Gyumri

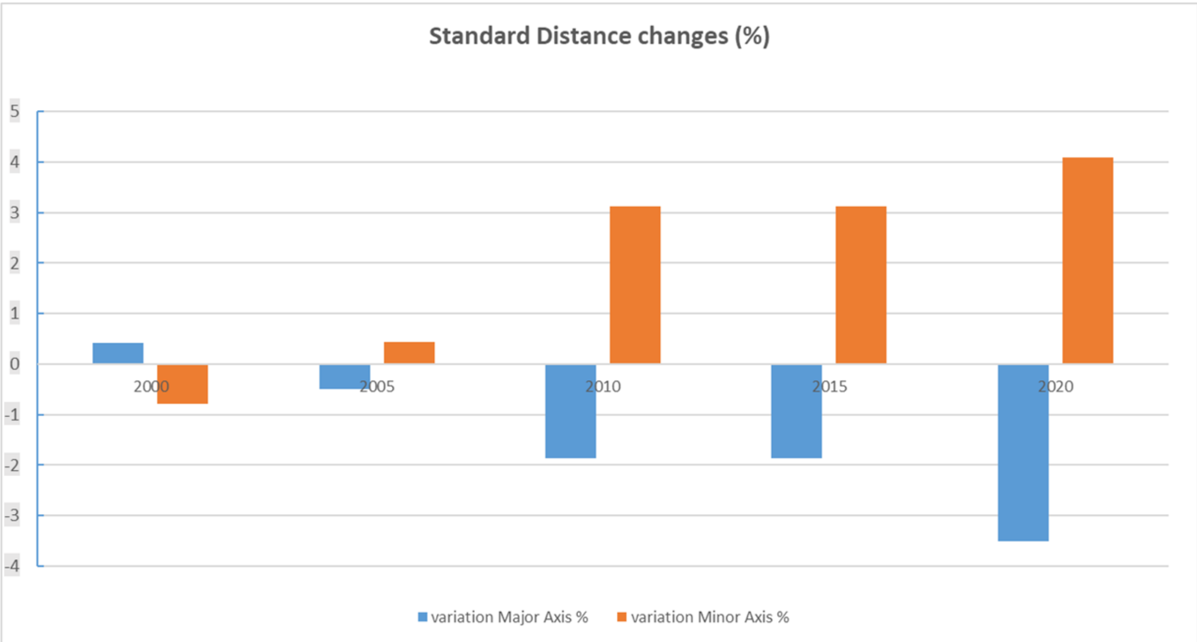



Figure 28: Standard distance variations in x- and y-directions for Gyumri compared to 1995

### *3.1.6.6 Land accounting – Urban changes over 1995-2020*

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.6

Land accounting focusing on urban changes provides the trends in terms of LULC change types, quantity (areas) and relative proportions. Urban Change Areas product for the whole period (1995-2020) only includes changes for which LULC characterisation was possible to be made for the reference date 1995 considering the limitation from the satellite images used in terms of spatial resolution. This means that intra-urban changes detected only through the last decade 2010-2020 are logically not included.

TABLE 22: URBAN CHANGE ACCOUNTING OVER THE PERIOD 1995-2020 IN GYUMRI (AREA TRANSFER, IN HA)

| | | **2020** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **112** | **113** | **121** | **131** | **132** | **140** | **200** | **300** |
| **1995** | **113** | | | | | | | 0.1 | 2.8 |
| | **121** | | | | | 4.1 | | | |
| | **131** | | | | | | | | 0.4 |
| | **200** | 0.5 | 1.2 | 3.6 | | | | | |
| | **300** | | | 0.5 | 0.2 | | 1.0 | | |

TABLE 22 provides urban change accounting over the whole period 1995-2020 in Gyumri in the form of a matrix of area transfers (expressed in ha) from one LULC class to another between the two reference dates.

TABLE 23: URBAN CHANGES OBSERVED FROM 1995 TO 2020 IN GYUMRI

| Changes between 1995 and 2020 in Gyumri | Area ($km^2$) | Share (%) |
|---|---|---|
| Urban expansion - residential | 0.17 | 11.9% |
| Urban expansion - commercial / industrial | 0.41 | 28.3% |
| Urban expansion - construction sites | 0.02 | 1.5% |
| Urban expansion - urban greenery | 0.10 | 7.2% |
| Internal urban development - vacant land / brownfields | 0.41 | 28.5% |
| Agriculture development - uptake of artificial area | 0.01 | 0.4% |
| Natural areas development - update of artificial area | 0.32 | 22.2% |
| ***Total of changes*** | **1.43** | - |

TABLE 23 and FIGURE 29 provide the summary statistics of the urban changes observed from 1995 to 2020 in Gyumri. Change areas observed through the whole period represent less than 1.5 $km^2$ and almost half are related to urban expansion mainly for the benefit of commercial and/or industrial units. Historic artificial areas that have become vacant or brownfields, or have been converted to natural spaces, complete the range of main changes. TABLE 24 shows some of the main changes observed over the period in Gyumri.

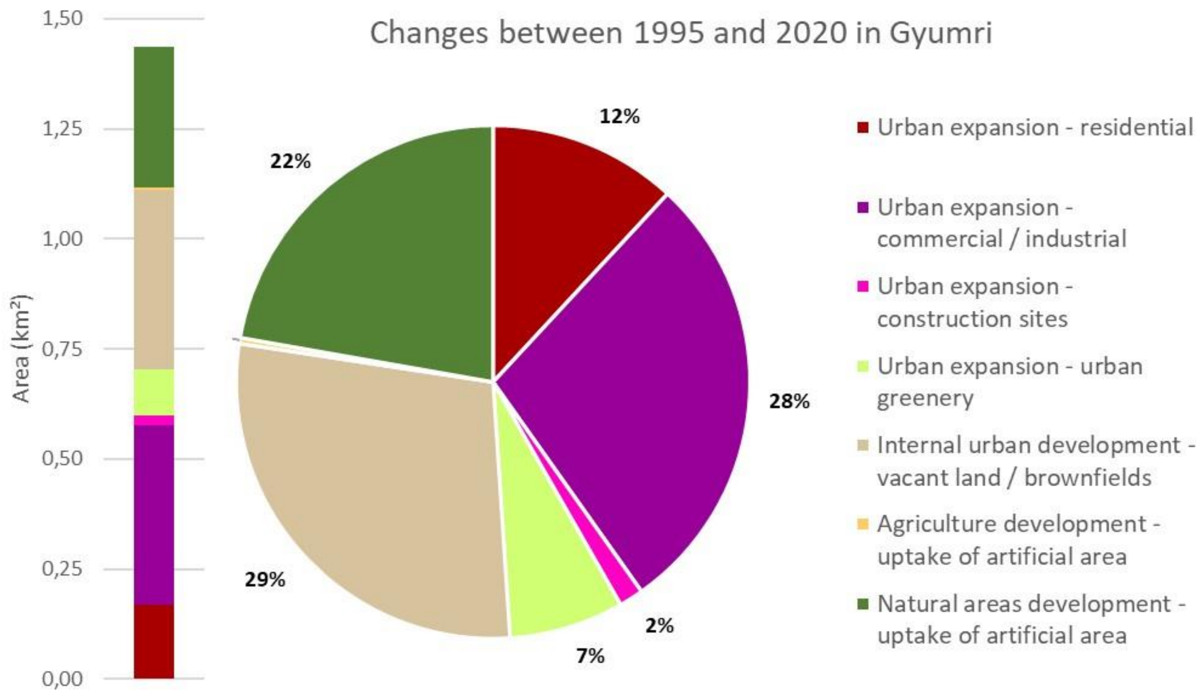
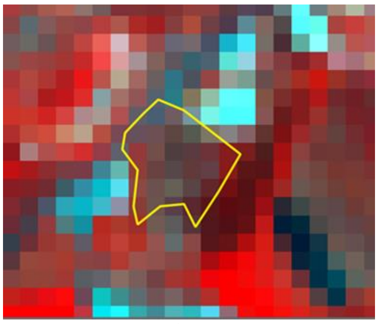
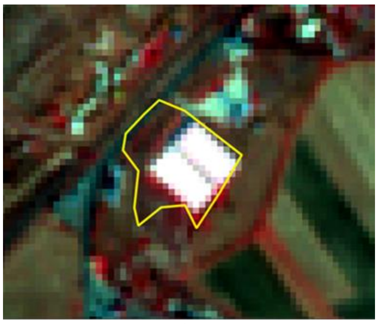



FIGURE 29: URBAN CHANGES OBSERVED FROM 1995 TO 2020 IN GYUMRI

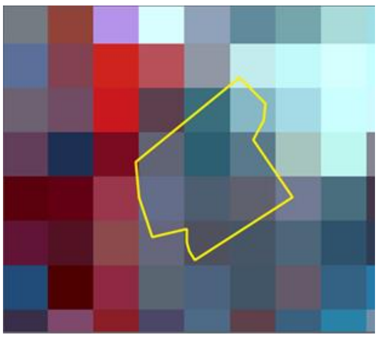
TABLE 24: EXAMPLES OF SOME OF THE MAIN CHANGES OBSERVED OVER THE PERIOD 1995-2020 IN GYUMRI

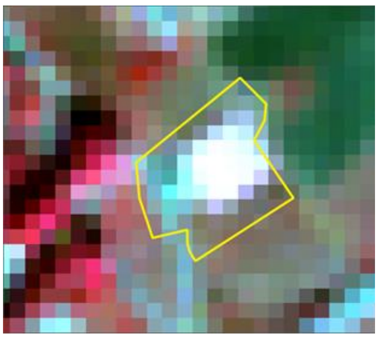

Year: **2015** / class: **300**


Year: **2020** / class: **121**


Year: **2020**

Change class: **12 Urban expansion – commercial / industrial**
*Location: 40°45′21.44″N, 43°50′00.56″E*


Year: **2010** / class: **131**


Year: **2015** / class: **140**


Year: **2015** (Google Earth)

Change class: **12 Urban expansion – commercial / industrial**
*Location: 40°48′39.68″N, 43°49′21.71″E*

### 3.1.6.7 *Land accounting – Urban changes over 2010-2020*

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.7

Land accounting focusing on urban changes provides the trends in terms of LULC change types, quantity (areas) and relative proportions. Urban Change Areas product for the period 2010-2020 benefitted from the use of satellite images with higher spatial resolution. Full intra-urban change detection and characterisation was implemented thanks to these input data, offering a more detailed analysis of the city dynamics.

TABLE 25 provides urban change accounting over the last decade 2010-2020 in Gyumri in the form of a matrix of area transfers (expressed in ha) from one LULC class to another between the two reference dates.

TABLE 25: URBAN CHANGE ACCOUNTING OVER THE PERIOD 2010-2020 IN GYUMRI (AREA TRANSFER, IN HA)

| | | **2020** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **111** | **112** | **113** | **121** | **123** | **131** | **132** | **140** |
| **2010** | **112** | | | 9.9 | 1.4 | | | 0.5 | |
| | **113** | | 2.7 | | | | | | |
| | **121** | | | | | | | 3.7 | |
| | **131** | | 15.8 | | 5.7 | | | 2.3 | 9.1 |
| | **132** | 0.3 | 1.4 | | 23.3 | 2.6 | 15.1 | | 2.5 |
| | **200** | | 0.6 | 3.0 | 1.5 | | | | |
| | **300** | | | | 3.6 | | 2.2 | | 1.2 |

TABLE 26: URBAN CHANGES OBSERVED FROM 2010 TO 2020 IN GYUMRI

| Changes between 2010 and 2020 in Gyumri | Area (km²) | Share (%) |
|---|---|---|
| Urban expansion - residential | 0.04 | 2.7% |
| Urban expansion - commercial / industrial | 0.05 | 3.8% |
| Urban expansion - construction sites | 0.02 | 1.6% |
| Urban expansion - urban greenery | 0.01 | 0.9% |
| Internal urban development - residential | 0.30 | 22.5% |
| Internal urban development - commercial / industrial | 0.30 | 22.7% |
| Internal urban development - transportation | 0.03 | 1.9% |
| Internal urban development - construction sites | 0.15 | 11.3% |
| Internal urban development - vacant land / brownfields | 0.06 | 4.9% |
| Internal urban development - urban greenery | 0.12 | 8.7% |
| Urban renewal | 0.25 | 18.9% |
| ***Total of changes*** | **1.34** | - |

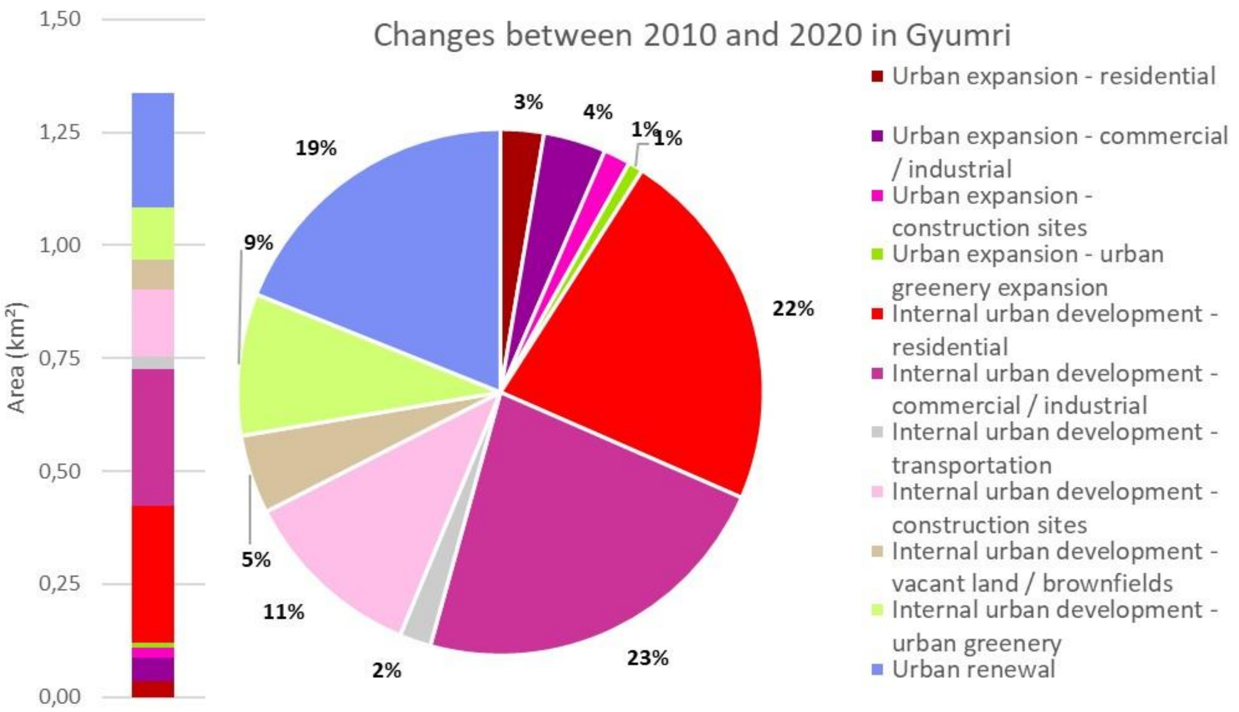



FIGURE 30: URBAN CHANGES OBSERVED FROM 2010 TO 2020 IN GYUMRI

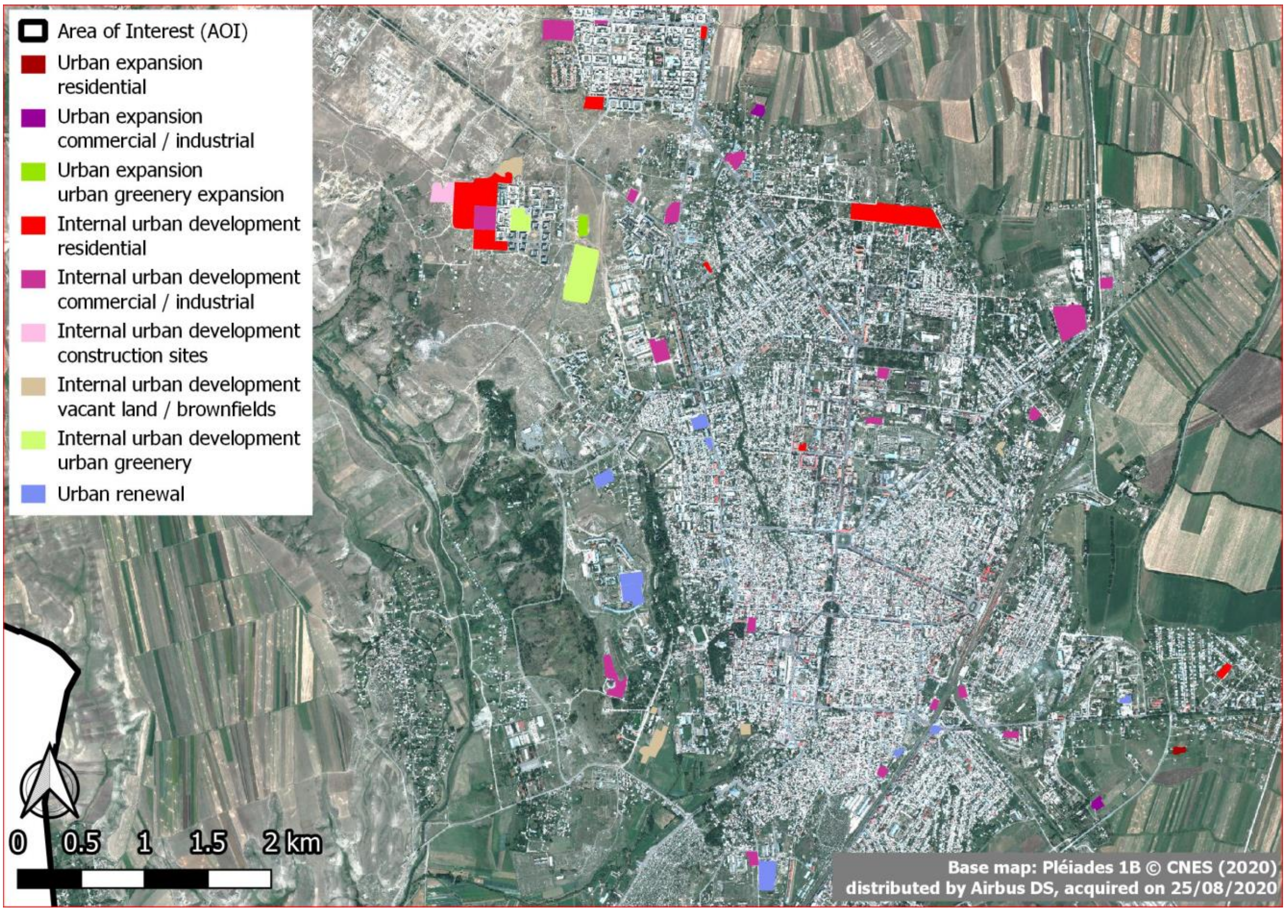



FIGURE 31: MAPPING OF URBAN CHANGE DYNAMICS IN GYUMRI FROM 2010 TO 2020

TABLE 26 and FIGURE 30 provide the summary statistics of the urban changes observed from 2010 to 2020 in Gyumri. The results show that overall urban change dynamics in Gyumri seem to be quite low over the last decade, as changes cover 1.34 km² or 2.5% compared to the 2020 urban extent. Changes observed from satellite images are homogeneously distributed mainly in the urban fringe and none in the heart of the city, as illustrated in FIGURE 31. Internal urban development is the predominant trend representing almost three quarters of all changes. The phenomenon mostly benefits to residential or commercial/industrial use. Urban renewal is also significant with nearly 20% of the change areas, while urban expansion is very limited (less than 10% or 12 ha).

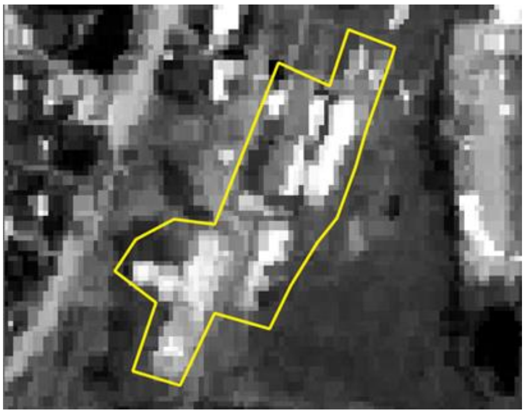
TABLE 27 shows some of the main changes observed over the period in Gyumri.

TABLE 27: EXAMPLES OF SOME OF THE MAIN CHANGES OBSERVED OVER THE PERIOD 2010-2020 IN GYUMRI

Year: **2010** / class: **131**

Year: **2015** / class: **112**

Change class: **21 Internal urban development – residential**
*Location: 40°49′23.79″N, 43°49′24.66″E*



Year: **2010** / class: **121**

Year: **2015** / class: **132**

Change class: **25 Internal urban development – vacant land / brownfields**
*Location: 40°46′40.43″N, 43°49′45.88″E*

Evolution of physical assets but without impact on LULC classification were also detected by visual interpretation of the VHR satellite images. Areas concerned were then extracted and classified as urban renewal (attribute fields “URB_RENEW” and “RENEW_TYPE” filled in accordingly). TABLE 28 gives an example.

TABLE 28: EXAMPLE OF URBAN RENEWAL OBSERVED OVER THE PERIOD 2010-2020 IN GYUMRI

Year: **2015** / class: **122**

Year: **2020** / class: **122**

Change class: **30 Urban renewal - Creation of a roundabout**

*Location: 40°46′44.70″N, 43°51′20.06″E*

### 3.1.6.8 Average distance between services and population

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.8

Each building is affected to a class of distance (500m, 1000m, 2000m, more than 2000m) from the nearest facilities. Service areas are derived accordingly.

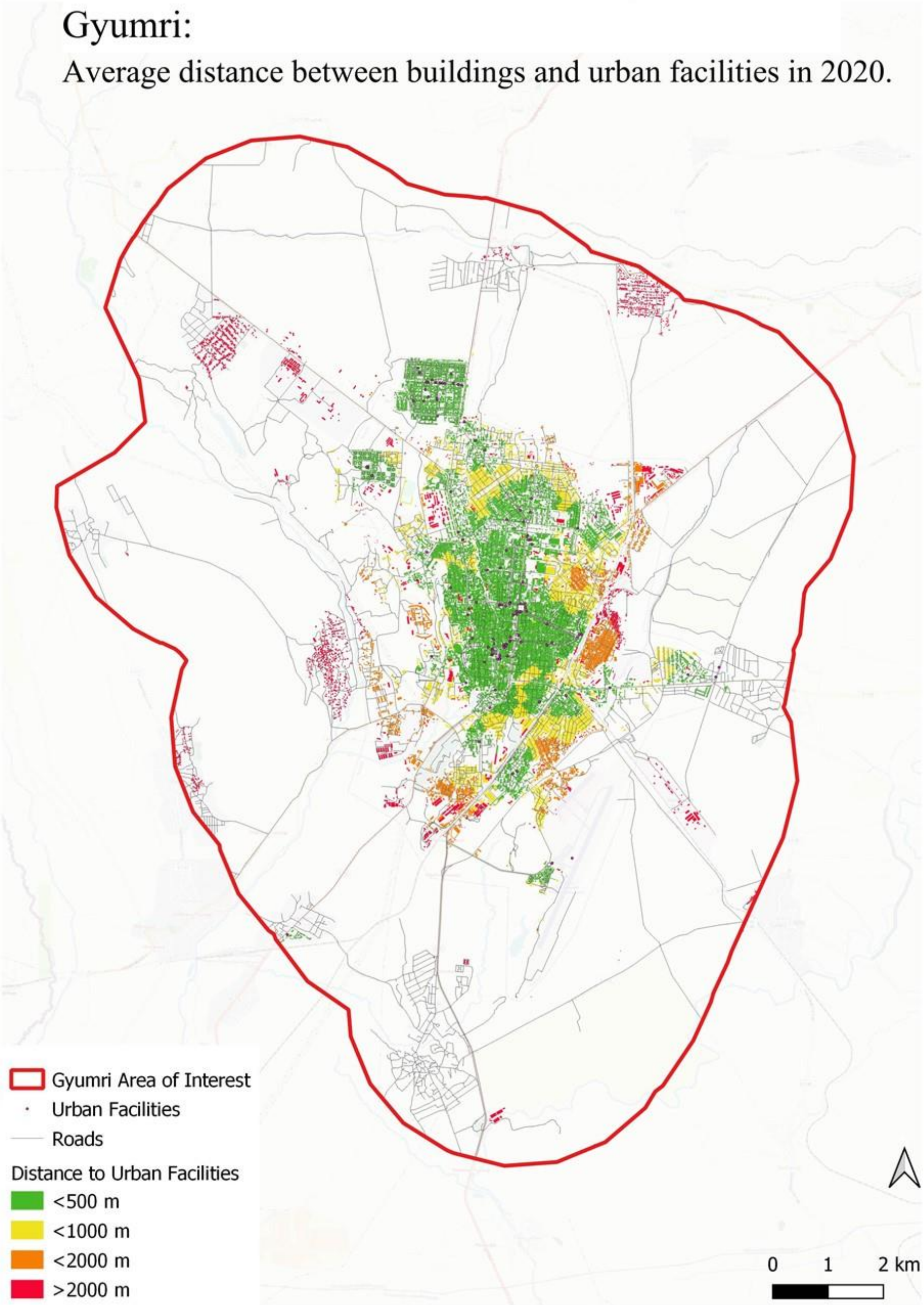



FIGURE 32: ZONAL DISTANCE BETWEEN BUILDING FOOTPRINTS AND URBAN FACILITIES IN 2021 IN GYUMRI

FIGURE 32 shows the analysis of the distances between services and population. It highlights important populated areas located more than 500m, 1000m or even more than 2 km away from any facility. These poorly served places do not have a precise location and can be anywhere in the urban area as in Yerevan.

### 3.1.7 Outputs for Vanadzor

#### *3.1.7.1 Mapping results*

The EO-based service aims at providing reliable indicators of permanent change in the economy through the period 1995-2020. Therefore, the following geospatial products were derived from image analysis:

- **Urban Extent** for each reference epoch
- **Urban Change Areas** involving detection in time and space, as well as characterisation

As described in the section 3.1.2.2, urban extent mapping was firstly generated by means of automated classification of HR optical images. The result was intermediate as the algorithm enabled to well detect and extract built-up areas, but not systematically their associated non-sealed and vegetated surfaces. Therefore, the final Urban Extent product for each epoch was obtained by means of visual interpretation using both HR and 2020 VHR images, and manual refinement of the previous mapping result.

The results got for Vanadzor city regarding its current extent (2020) are shown in FIGURE 7FIGURE 33.

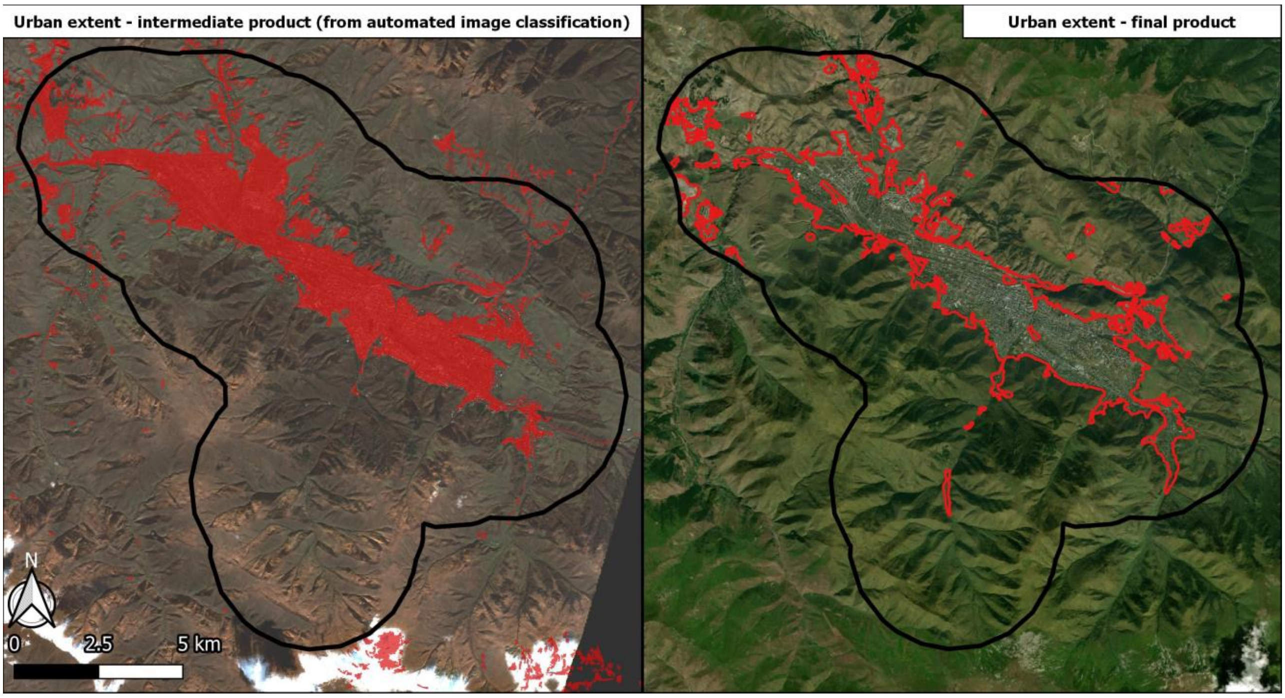



FIGURE 33: URBAN EXTENT MAP OF VANADZOR IN 2020

Once urban extent was mapped for each epoch, it was easy to visually compare and automatically extract change areas occurring throughout each 5-year period by means of basic GIS analysis tool.

FIGURE 34 shows the overall evolution of Vanadzor urban extent from 1995 to 2020. The mapping results show that Vanadzor urban extent remained globally stable over time with, in the end, a very limited decline.

In addition to detect LULC changes in the urban fringe, most of them impacting urban extent, further analysis was performed by means of visual interpretation of VHR optical images in order to characterise them at best and extract also intra-urban changes in the most recent period 2010-2020. As a result, a consistent map of Urban Change Areas for each 5-year period has been delivered too.

Finally, the mapping results related to urban extent and change dynamics were further analysed and used for the computation of several key spatial indicators. The next sections present the outputs in detail.

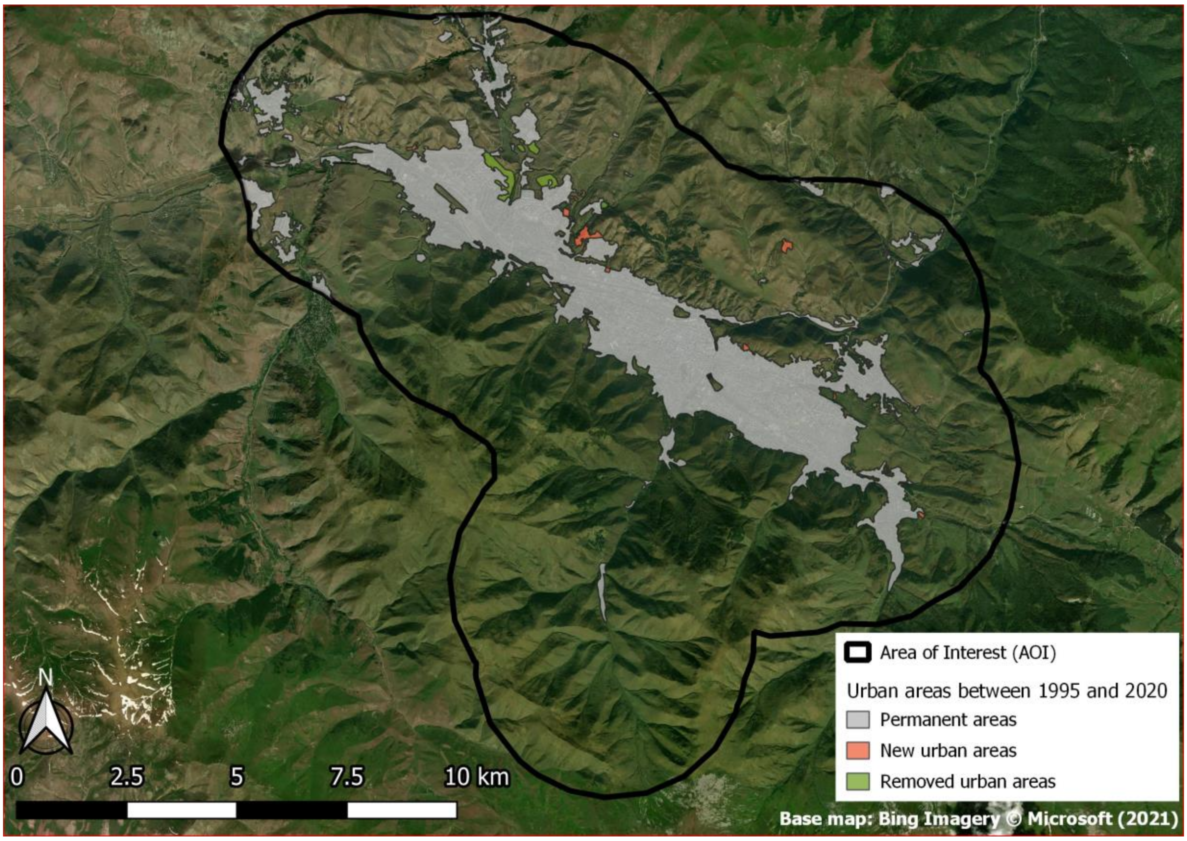



FIGURE 34: MAPPING OF URBAN EXTENT AND CHANGE DYNAMICS IN VANADZOR FROM 1995 TO 2020

#### *3.1.7.2 Urban area expansion*

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.2

The indicator provides an assessment of spatiotemporal evolution of urban areas.

TABLE 29: URBAN AREA EVOLUTION OF VANADZOR THROUGHOUT THE PERIOD 1995-2020

| **Year** | **Total urban area** | **Rate of urban area over AOI** | **Evolution compared to 1995** | |
|---|---|---|---|---|
| | **km²** | **%** | **km²** | **%** |
| 1995 | 30.12 | 15.95% | N/A | N/A |
| 2000 | 30.09 | 15.94% | -0.02 | -0.08% |
| 2005 | 30.09 | 15.94% | -0.03 | -0.09% |
| 2010 | 29.81 | 15.79% | -0.31 | -1.03% |
| 2015 | 29.90 | 15.83% | -0.22 | -0.73% |
| 2020 | 29.90 | 15.84% | -0.22 | -0.72% |

FIGURE 35 and **Erreur ! Source du renvoi introuvable.** show that urban areas occupy a minor part (16% in 2020) of the AOI defined for Vanadzor (188 km²) and that urban extent remained stable from 1995 to 2020. In the end, the total urban area decreased from 30.1 to 29.9 km² over 25 years, a loss of 0.2 km² or 0.7% compared to the 1995 urban area. This contrasts a lot with the long-standing trend of strong growth observed in the urban area of Yerevan. It is however worth to highlight that Vanadzor is in a steep valley, which is a barrier to expansion.

Whatever the period, the extensions were of various sizes, isolated or stuck to an existing urban area, located on the periphery or coming to fill in holes in urban fabric. There is no specific trend observed, as for Yerevan.

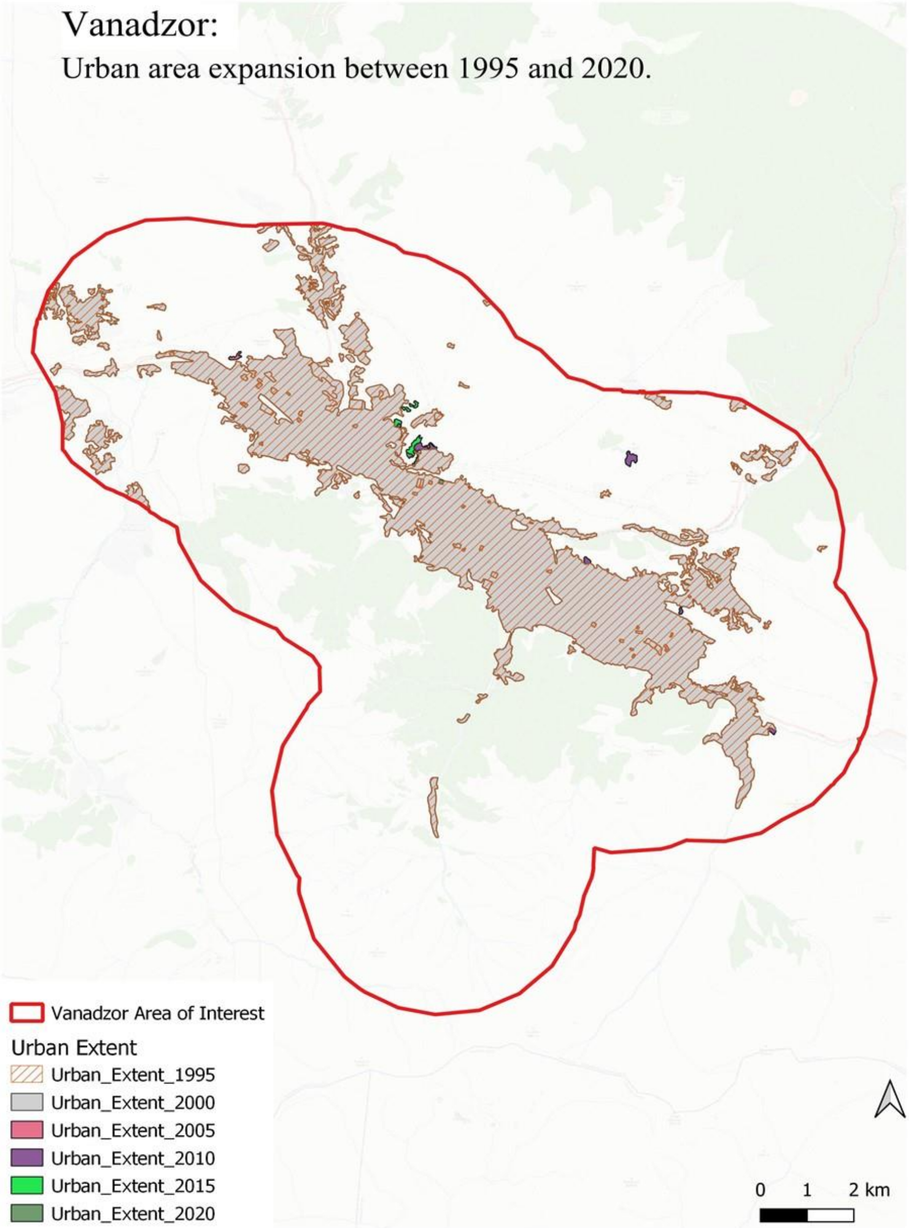



FIGURE 35: URBAN AREA EVOLUTION OF VANADZOR THROUGHOUT THE PERIOD 1995-2020

### *3.1.7.3 Ratio of land consumption rate to population growth rate*

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.3

The indicator provides an assessment of the evolution of urban area in comparison with the one of population counts. If negative values are obtained, this means that one of the phenomenon decreased in the period. Absolute values below 1 means land consumption evolves slower than population in relative proportions which indicates densification more than urban sprawl, and vice versa.

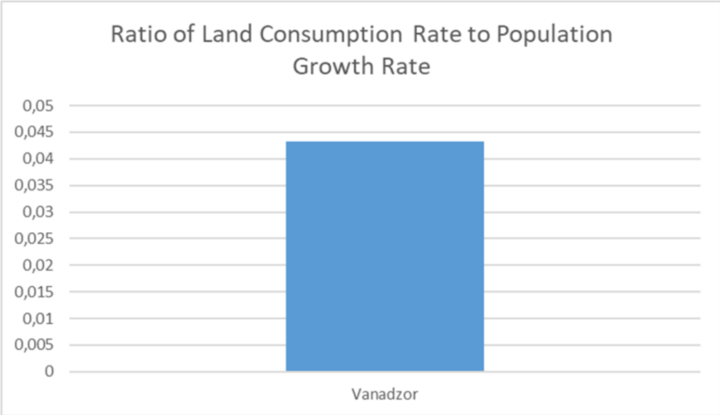



FIGURE 36: RATIO OF LAND CONSUMPTION RATE TO POPULATION GROWTH RATE FOR VANADZOR FROM 2000 TO 2010

As for Gyumri, FIGURE 36. reveals a very low value of the ratio. This result indicates that the changes in population are in line with the ones related to urban areas and are therefore also very minimal.

### *3.1.7.4 Urban fragmentation*

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.4. The indicator provides an assessment of the morphology of the overall urban extent in terms of discontinuity. The higher the index value, the more fragmented the urban area.

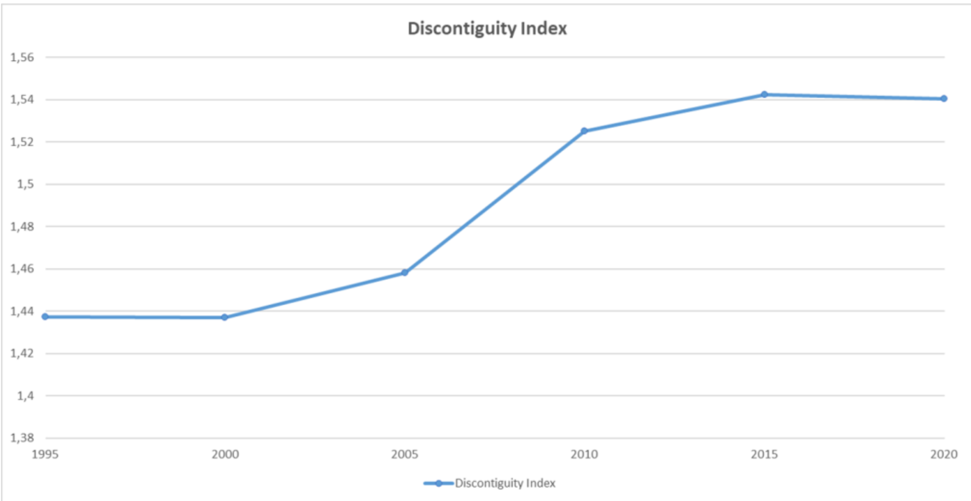



FIGURE 37: URBAN FRAGMENTATION INDEX OF VANADZOR THROUGHOUT THE PERIOD 1995-2020

FIGURE 37 and FIGURE 38 show a clear upward trend from one level to another with values similar to Yerevan. In the opposite of Yerevan and Gyumri, there is a growing fragmentation.

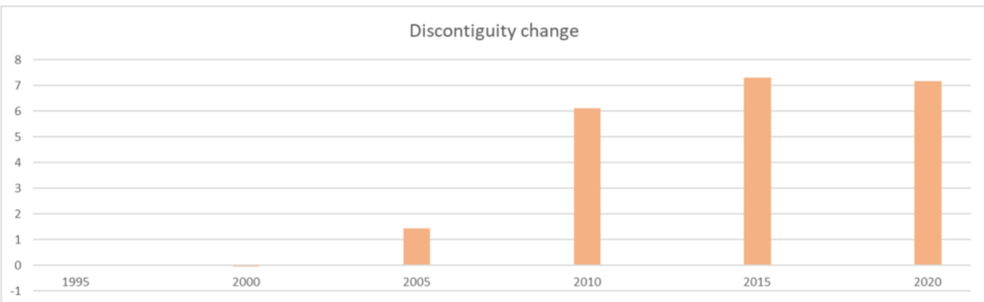



FIGURE 38: FRAGMENTATION INDEX EVOLUTION (%) OF VANADZOR FOR EACH EPOCH COMPARED TO 1995

### 3.1.7.5 Compactness

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.5

The indicator provides an assessment of the morphology of the overall urban extent in terms of compacity or dispersion. The smaller the standard distance values in X and Y directions and the smaller the difference between them, the more compact the city can be considered. Thus, the maximum degree of compactness is achieved when the ellipse corresponds to a circle with the smallest possible radius.

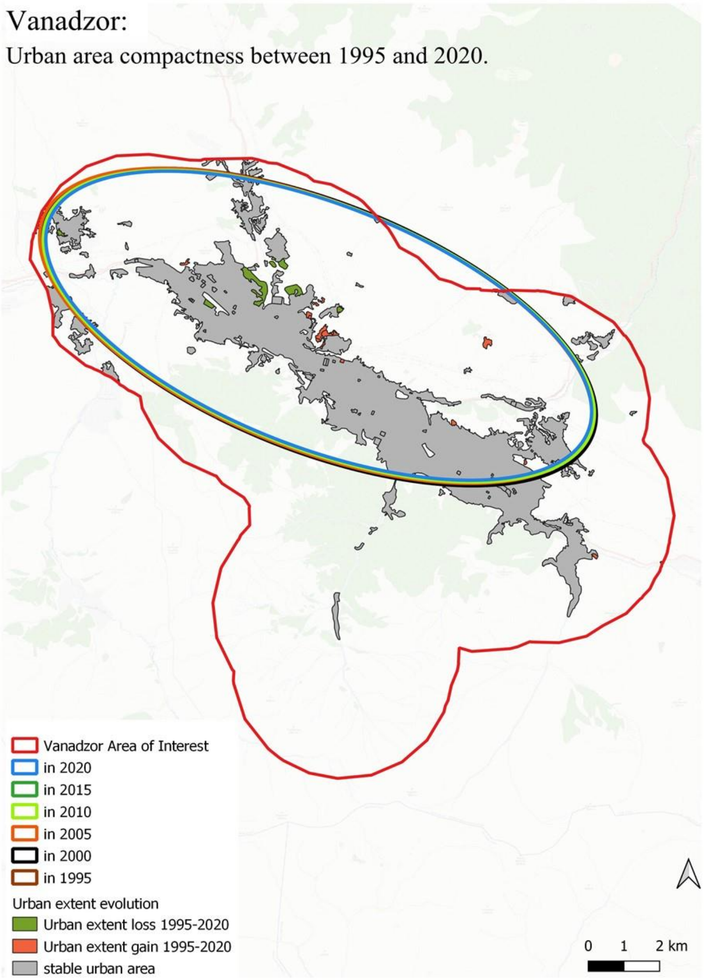



FIGURE 39: STANDARD DEVIATIONAL ELLIPSES FOR THE YEARS 1995 TO 2020 IN VANADZOR.

FIGURE 39 shows that the distribution of clusters like Gyumri is oriented in a specific direction, east-west in the case of Vanadzor. Otherwise, high stability of the compactness is observed over time.

This result is confirmed by the small differences between the X-dispersion and the Y-dispersion, as shown in FIGURE 40 and FIGURE 41.

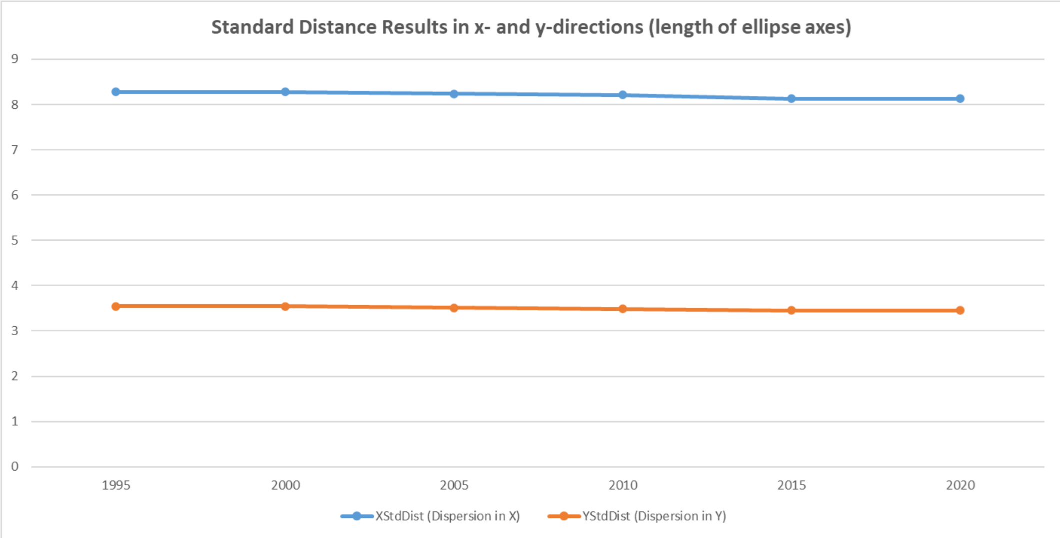



FIGURE 40: STANDARD DISTANCE IN X- AND Y-DIRECTIONS (LENGTH OF ELLIPSE AXES) FOR VANADZOR

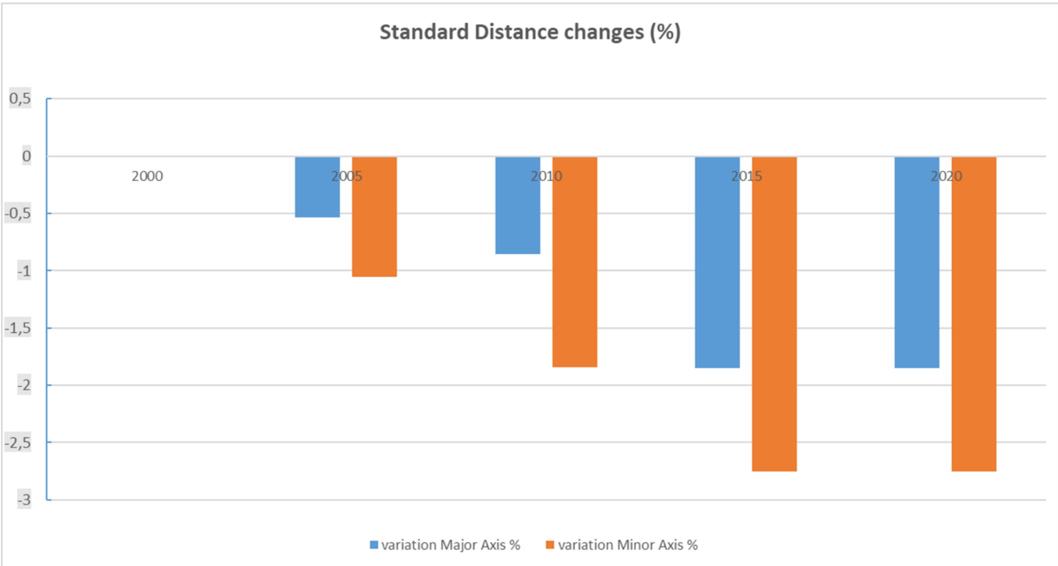



FIGURE 41: STANDARD DISTANCE VARIATIONS IN X- AND Y-DIRECTIONS FOR VANADZOR COMPARED TO 1995

### 3.1.7.6 Land accounting – Urban changes over 1995-2020

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.6

Land accounting focusing on urban changes provides the trends in terms of LULC change types, quantity (areas) and relative proportions. Urban Change Areas product for the whole period (1995-2020) only includes changes for which LULC characterisation was possible to be made for the reference date 1995 considering the limitation from the satellite images used in terms of spatial resolution. This means that intra-urban changes detected only through the last decade 2010-2020 are logically not included.

TABLE 30: URBAN CHANGE ACCOUNTING OVER THE PERIOD 1995-2020 IN VANADZOR (AREA TRANSFER, IN HA)

| | | 2020 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 112 | 113 | 121 | 131 | 132 | 200 | 300 | 500 |
| 1995 | 113 | | | | | 2.0 | | | |
| | 121 | | | | | 6.5 | 0.9 | 2.5 | |
| | 131 | | | | | | | | 2.1 |
| | 132 | 2.3 | | | | | | 41.5 | |
| | 200 | | 5.4 | 3.8 | | | | | |
| | 300 | 0.01 | | 13.3 | 4.8 | 1.7 | | | |

TABLE 30 provides urban change accounting over the whole period 1995-2020 in Vanadzor in the form of a matrix of area transfers (expressed in ha) from one LULC class to another between the two reference dates.

TABLE 31: URBAN CHANGES OBSERVED FROM 1995 TO 2020 IN VANADZOR

| Changes between 1995 and 2020 in Vanadzor | Area ($km^2$) | Share (%) |
|---|---|---|
| Urban expansion - residential | 0.05 | 6.2% |
| Urban expansion - commercial / industrial | 0.17 | 19.7% |
| Urban expansion - construction sites | 0.05 | 5.6% |
| Urban expansion - vacant land / brownfields | 0.02 | 2.0% |
| Internal urban development - residential | 0.02 | 2.0% |
| Internal urban development - vacant land / brownfields | 0.08 | 9.8% |
| Agriculture development - uptake of artificial area | 0.01 | 1.0% |
| Natural areas development - update of artificial area | 0.46 | 53% |
| ***Total of changes*** | **0.87** | - |

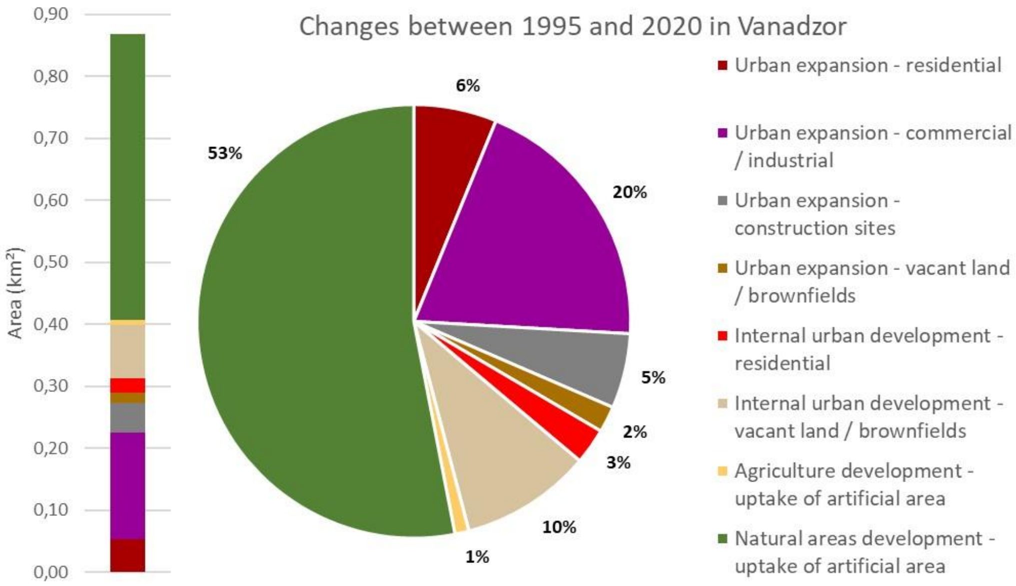
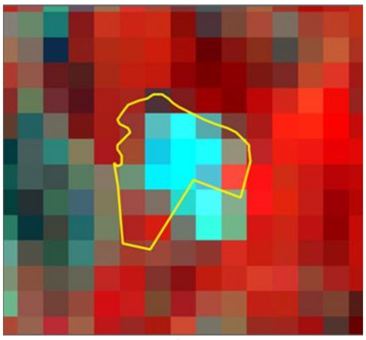



FIGURE 42: URBAN CHANGES OBSERVED FROM 1995 TO 2020 IN VANADZOR

TABLE 31 and FIGURE 42 provide the summary statistics of the urban changes observed from 1995 to 2020 in Vanadzor. Change areas observed through the whole period represent less than 1 km² and more than a half are related to historic artificial areas that have been restored to nature. Urban expansion mainly benefiting commercial and/or industrial areas (20%) as well as old built-up units that have become vacant or brownfields (10%), complete the range of main changes. TABLE 32 shows some of the main changes observed over the period in Vanadzor.

TABLE 32: EXAMPLES OF SOME OF THE MAIN CHANGES OBSERVED OVER THE PERIOD 1995-2020 IN VANADZOR


Year: **2010** / class: **200**

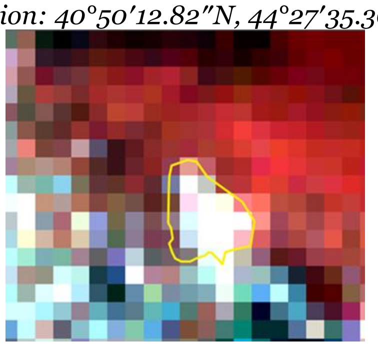

Year: **2015** / class: **121**


Year: **2016** (Google Earth)

Change class: **12 Urban expansion – commercial / industrial**

*Location: 40°50′12.82″N, 44°27′35.36″E*


Year: **2005** / class: **300**


Year: **2010** / class: **131**


Year: **2011** (Google Earth)

Change class: **15 Urban expansion – vacant land / brownfields**

*Location: 40°48′32.81″N, 44°30′29.65″E*

### 3.1.7.7 Land accounting – Urban changes over 2010-2020

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.7

Land accounting focusing on urban changes provides the trends in terms of LULC change types, quantity (areas) and relative proportions. Urban Change Areas product for the period 2010-2020 benefitted from the use of satellite images with higher spatial resolution. Full intra-urban change detection and characterisation was implemented thanks to these input data, offering a more detailed analysis of the city dynamics.

TABLE 33 provides urban change accounting over the last decade 2010-2020 in Vanadzor in the form of a matrix of area transfers (expressed in ha) from one LULC class to another between the two reference dates.

TABLE 33: URBAN CHANGE ACCOUNTING OVER THE PERIOD 2010-2020 IN VANADZOR (AREA TRANSFER, IN HA)

| | | 2020 | | | | | |
|---|---|---|---|---|---|---|---|
| | | 112 | 113 | 121 | 131 | 132 | 140 |
| 2010 | 113 | 0.1 | | 0.3 | | | |
| | 121 | | | | 0.7 | 0.7 | |
| | 131 | | | | | 0.2 | |
| | 132 | 0.2 | | 0.6 | 0.3 | | 0.6 |
| | 200 | | 0.2 | 0.2 | | | |
| | 300 | | | 0.9 | | | |

TABLE 34: URBAN CHANGES OBSERVED FROM 2010 TO 2020 IN VANADZOR

| Changes between 2010 and 2020 in Vanadzor | Area (km²) | Share (%) |
|---|---|---|
| Urban expansion - residential | 0.02 | 4.7% |
| Urban expansion - commercial / industrial | 0.11 | 20.3% |
| Internal urban development - residential | 0.03 | 6.5% |
| Internal urban development - commercial / industrial | 0.06 | 11.8% |
| Internal urban development - construction sites | 0.10 | 19.4% |
| Internal urban development - vacant land / brownfields | 0.09 | 17.1% |
| Internal urban development - urban greenery | 0.06 | 10.8% |
| Urban renewal | 0.05 | 9.3% |
| ***Total of changes*** | **0.52** | - |

TABLE 34 and FIGURE 43 provide the summary statistics of the urban changes observed from 2010 to 2020 in Vanadzor. The results show that overall urban change dynamics in Vanadzor seem to be quite low over the last decade, as changes cover 0.52 km² or 1.7% compared to the 2020 urban extent. Changes observed from satellite images are quite homogeneously distributed, spread over the whole city including some in the centre, as illustrated in FIGURE 44. A quarter of the changes is related to urban expansion mainly benefiting commercial and/or industrial areas (20%), but internal urban development appears as the predominant trend representing two thirds of all changes. In 2020 however, most of those areas are still under construction (19%) or vacant land (17%). Urban renewal remains limited to some sites (9% or 5 ha).

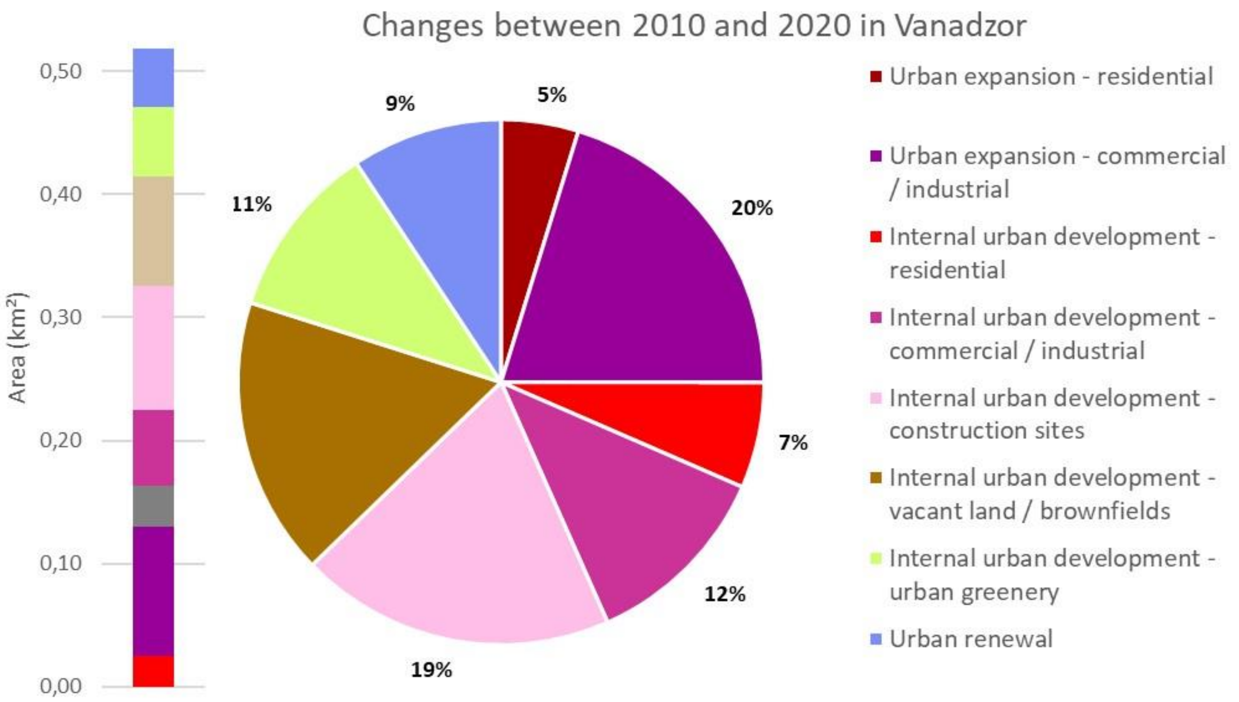



FIGURE 43: URBAN CHANGES OBSERVED FROM 2010 TO 2020 IN VANADZOR

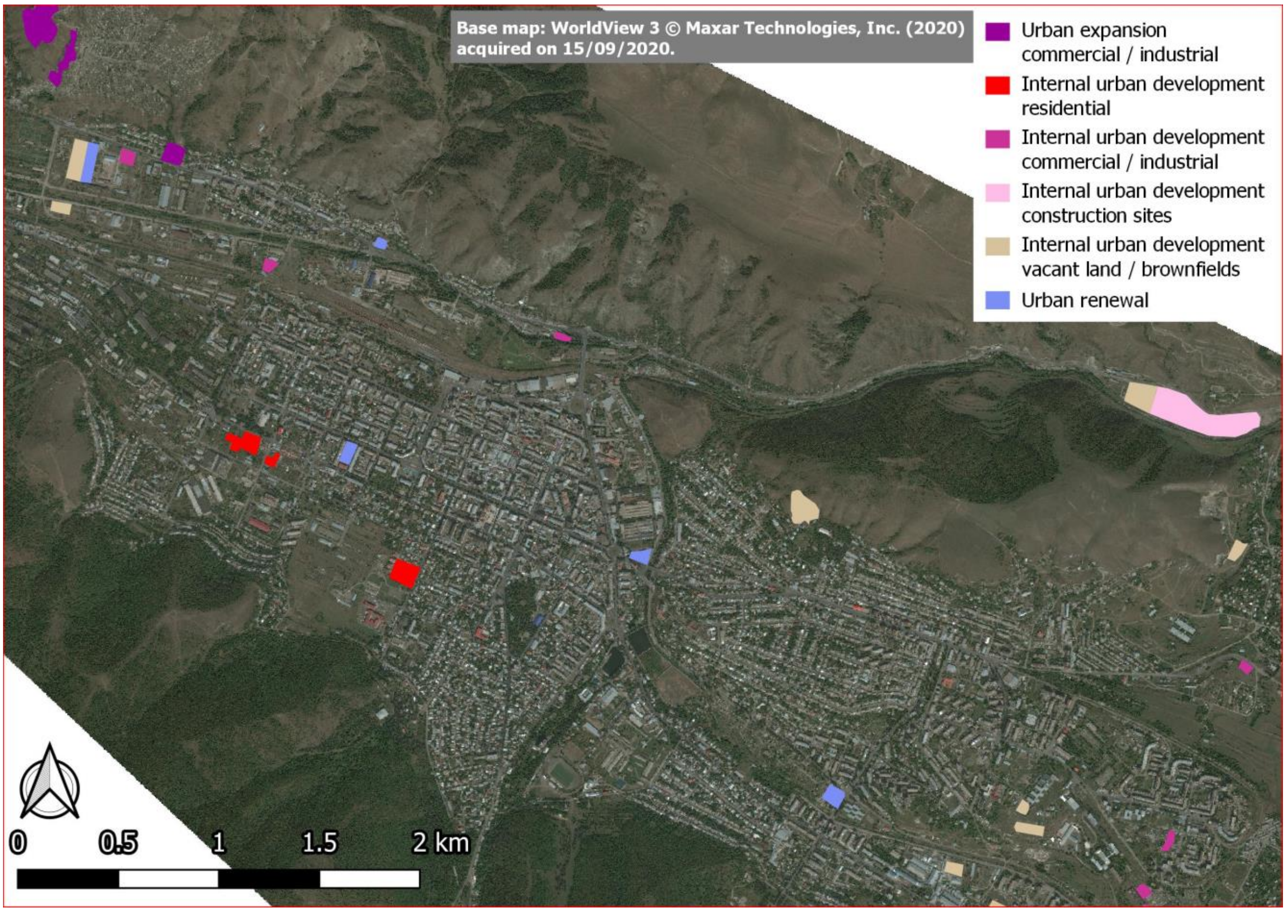
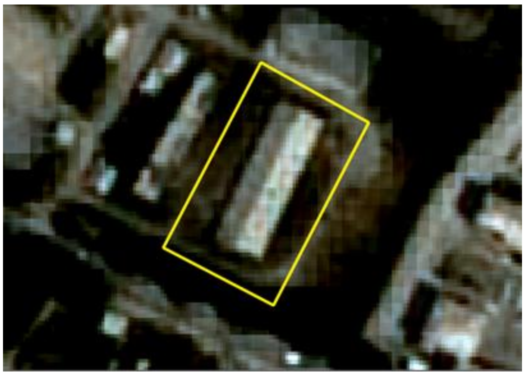



FIGURE 44: MAPPING OF URBAN CHANGE DYNAMICS IN VANADZOR FROM 2010 TO 2020

TABLE 35 shows some of the main changes observed over the period in Vanadzor.

TABLE 35: EXAMPLES OF SOME OF THE MAIN CHANGES OBSERVED OVER THE PERIOD 2010-2020 IN VANADZOR



Year: **2015** / class: **121**

Year: **2020** / class: **132**

Change class: **25 Internal urban development – vacant land / brownfields**
*Location: 40°47′24.59″N, 44°31′12.50″E*

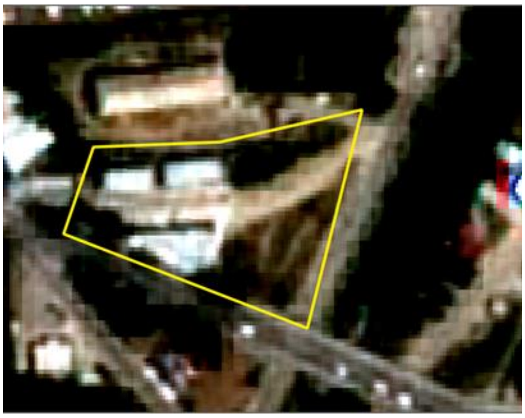
Year: **2015** / class: **131**

Year: **2020** / class: **140**

Change class: **26 Internal urban development – urban greenery**
*Location: 40°50′25.08″N, 44°26′57.74″E*

Evolution of physical assets but without impact on LULC classification were also detected by visual interpretation of the VHR satellite images. Areas concerned were then extracted and classified as urban renewal (attribute fields "URB_RENEW" and "RENEW_TYPE" filled in accordingly). TABLE 36 gives an example.

TABLE 36: EXAMPLE OF URBAN RENEWAL OBSERVED OVER THE PERIOD 2010-2020 IN VANADZOR



Year: **2015** / class: **121**

Year: **2020** / class: **121**

Change class: **30 Urban renewal - Additional buildings**
*Location: 40°48′25.61″N, 44°29′55.41″E*

### 3.1.7.8 Average distance between services and population

Geospatial indicator definition, aim, input data used and methodology are given in the dedicated section to outputs for Yerevan, i.e. section 3.1.5.8

Each building is affected to a class of distance (500m, 1000m, 2000m, more than 2000m) from the nearest facilities. Service areas are derived accordingly.

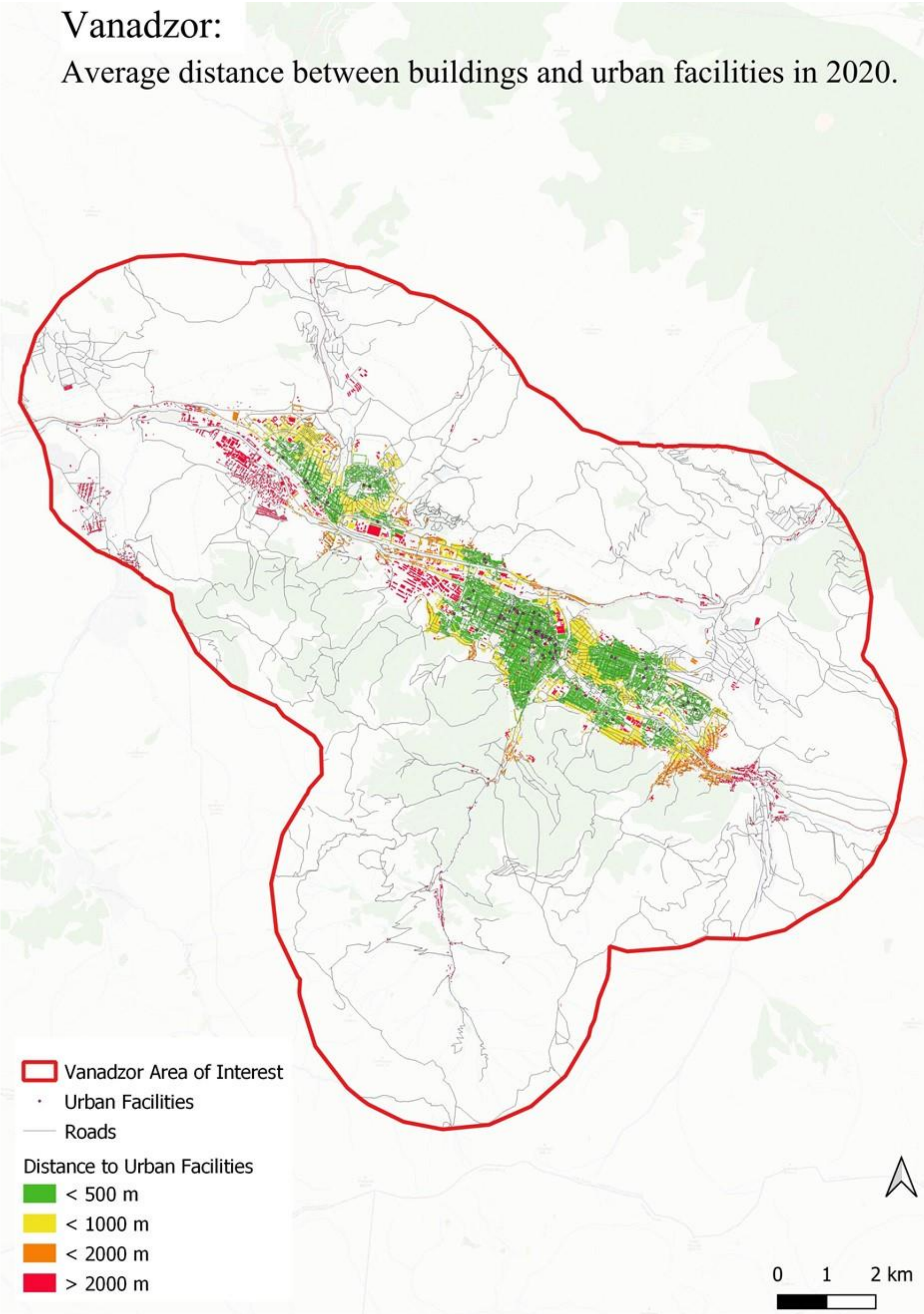



FIGURE 45: ZONAL DISTANCE BETWEEN BUILDING FOOTPRINTS AND URBAN FACILITIES IN 2021 IN VANADZOR

FIGURE 45 shows that the phenomenon highlighted for Gyumri is even more accentuated for Vanadzor where the facilities are concentrated in the heart of the city centre. The other areas are more or less poorly served and quite far from the centre, especially since the urban area has a long linear form.

### 3.1.8 Usage, Limitations and Constraints

#### *3.1.8.1 Geospatial datasets*

Satellite-derived LULC information offers a strong baseline for implementing a wide range of indicators and analyses for addressing many challenges and supporting smart city development and investment. It provides quantitative information for a better understanding of the structural characteristics of a given city area and its change dynamics over time. This kind of data provide relevant support in decision-making for land use planning which generally requires to consider many challenges related to population mobility or urban development in a sustainable way.

The geospatial datasets delivered through the service, namely Urban Extent and Urban Change Areas, characterised by a LULC classification inspired from the European Urban Atlas, allow deeper insight on the urban areas and change dynamics through the years. Analyses related to urban sprawl and detailed change trends occurring within the urban extent can be conducted easily, since LULC products can be used as a basis for developing many spatial indicators relevant for assessing and monitoring the situation such as the ones calculated for this study. Many others are possible in case of full LULC information coverage, such as the proportion of urban green areas or sport and leisure facilities per inhabitant, or the access to public transportation or green areas among other urban challenges. Finally, it is also an efficient tool to compare the city with other neighbouring and similar cities within the area covered by the European Environment Agency (EEA) 39 member and associated countries.

The limitations and constraints are mainly related to the technical specifications of the product. Especially the thematic classification and the exploitation scale (1:10,000) imply to use it for disseminating information and analysis results for building blocks or homogeneous LULC units at city or district level. However, the LULC information combined with other data can be used for conducting further analyses and generating meaningful indicators for supporting the decision-making in land use planning in a sustainable way:

- Population distribution using local census data and even cadastral building footprints for disaggregation at the finest level
- Access to urban green areas and/or sport and leisure facilities using topologically consistent road network for calculating the best routes from residential units (walking distance and time, proportion of inhabitants with easy/fast access) allowing to determine which populated areas/districts would require development investments
- Access to public transport facilities using topologically consistent road network and local data providing the location of the facilities (bus stops, metro/tram/train stations, etc.) for calculating the best routes from residential units (walking distance and time, proportion of inhabitants with easy/fast access) allowing to determine which populated areas/districts would require development investments

#### *3.1.8.2 Spatial indicators*

The spatial indicators calculated thanks to the geospatial datasets offer similar support to urban planners and decision makers with same constraints in terms of use considering the specifications (city or district level). Main limitations to be highlighted are related to indicators for which other input data were required:

- **Ratio of land consumption rate to population growth rate:** Population census data was available only at two dates and covering unknown administrative areas which are different from the AOI.
- **Average distance between services and population:** Calculation of this indicator was performed with some approximations due to the use of OSM data only. Geospatial features like road and street network as well as buildings were used to implement it. However, quality issues are obvious, especially regarding temporal accuracy and completeness, not only at city level but also within a city itself. This is why use and comparisons between the three cities remain hazardous and not recommended without quality certified data (from national or local authorities ideally). Similarly for buildings, thematic information does not allow for a proper differentiation between dwellings and other uses, which prevents populated areas from being located more precisely. Full coverage of LULC information on each of the cities would have made this possible.

## 3.2 Concept note on a possible platform to support investment prioritisation

The service consists in the provision of a brief technical description of such a proposed platform which would offer to users exploring and exploiting EO-based geospatial data and indicators potentially associated with other kinds of data (e.g. socio-economic, environmental, telecommunications, etc.). Technical requirements and a cost estimate for its deployment are also detailed.

### Web platform components

The web platform to be deployed would be based on efficient opensource components that will compose the web mapping infrastructure such as:

- An OGC compliant webserver that would provide spatial data from several data source (vector, raster, grid, database). It will power several webservices such as WMS, WFS, WMTS or WCS that could be displayed into the front-end, an external open data platform or directly to a desktop GIS environment.
- A relational spatial database (RDBMS) to store vector and raster data in the same data warehouse and process on the fly statistics.
- A cache service could be also deployed to improve time answer display performance mainly to avoid some slow display for heavy datasets (VHR imagery, Sentinel time series). If data is already in cache, file will be sent without being regenerated with computing waiting time.
- A responsive front-end able to display on any device maps and data with rich features to be defined in proposal would be deployed.

FIGURE 46 explains how the different components of the web mapping platform would interact between them and users.

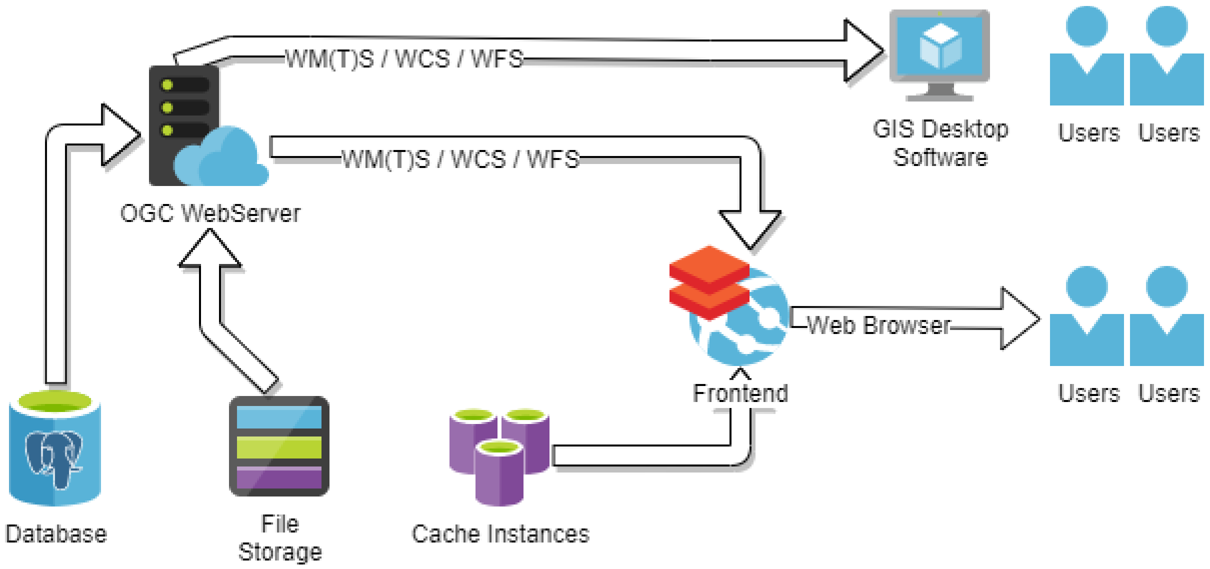



FIGURE 46: CONCEPTUAL SCHEMA SHOWING HOW WEB MAPPING PLATFORM COMPONENTS INTERACT

### User functionalities

The web platform would allow to pan and zoom around the entire country with some base maps (OpenStreetMap) and would display EO data specific to a city at a certain level of zoom (10m Sentinel-2 or VHR images used to process the derived geospatial data and indicators). This a non-exhaustive list of functionalities that would be offered:

- Zoom in and out
- Go to previous or next zoom level
- Display layers (on/off), opacity settings, metadata

- Location (when using mobile device with GPS On)
- Address search engine based on NOMINATIM.org open service (available through Open Street Map) that will help user to easily display a specific part of the country.
- Attribute display (general information and statistics) as spreadsheet or chart (dataviz module) in a dock panel module
- Measurement (length, perimeter, area)
- Permalink to share easily map location with custom layers settings
- User management
- Collaborative online editing
- Responsive display (desktop, tablet, mobile phone devices)

## Technical requirements

From a technical point of view, the requirements to deploy such a service would be the following:

- Processing service (dedicated or cloud) to host web mapping server and database (CPU with number of threads > 20 and 64 to 128 Go RAM)
- Webserver to host front-end
- Storage capacity for tiles cache server or vector tiles (depending on the nature of datasets: from 500 GB to 1 TB)

## Cost estimate for deployment

Estimated prices are as follows:

- 400 € HT per month for hosting and name domain (.com, etc.)
- 50 € HT per month for cloud backup instance
- ~5 days IT admin for deployment (installation on dedicated or cloud instances + secure procedure to avoid DDOS attacks + backup strategy + domain configuration)
- ~15 à 20 days for developer including:
    - dataset pre-processing and optimization
    - dashboard and charts customizing
    - graphic design of the UI
    - users access management
    - cache server

## Deployment details

The deployment would be done based on containers technology to guarantee high availability. A nginx server will serve as reverse proxy and webserver with SSL for HTTPS mode (required to enable GPS location on mobile device), and a PostGreSQL / PostGIS as the relational spatial database (with and adequate postgresql.conf and pg_hba.cong tuning).

Raster data would be converted in Cloud Optimized GeoTIFF (COG) & vector data imported into PostGreSQL.

QGIS Server would act as an OGC webservices engine (with CPU and RAM reserved) ; raw OGC webservices can be accessed through a GIS application (for example with QGIS).

A cache server (Redis) would be configured as a cache server, with adequate memory/disk rules strategy and retention period.

LIZMAP, an efficient PHP front-end, would provide link between QGIS Server and Redis, configure mapping project, publish mapping project and pre-generate cache for large datasets (raster and land use).

Before going into production, several tests would be prepared. The strategy would be to prepare a large number of connections directly with GIS software and with front-end. Then, CLS would ensure that cache is well generated in cache memory and cache disk (Redis), before stating that the web platform is ready.

## Cost estimate for service extension

Finally, a separate cost estimate of extending the EO-based service to the entire country is provided to conclude this report. Extension would concern all the other cities of the country which count more than 20,000 inhabitants to ensure meaningful urban change dynamics over time. It would thus include about ten medium-sized towns: Abovyan, Hrazdan, Vagharshapat, Kapan, Armavir, Masis, Charentsavan, Ararat, Ijevan and Goris. Given the size of the urban areas, their geographical proximity, and the dynamics observed in Gyumri and Vanadzor, a substantial economy of scale would be achieved which is considered in the effort estimate. Also, **service specifications would remain exactly the same**, especially in terms of AOI definition, observation period, thematic classes, minimum mapping units, product accuracies and outputs. The effort estimate detailed in TABLE 37 takes all these input parameters into account accordingly.

TABLE 37: EFFORT ESTIMATE FOR SERVICE EXTENSION TO THE ENTIRE COUNTRY (CITIES >20,000 INHABITANTS)

| Task | Description | Effort estimate |
|---|---|---|
| Input data preparation | Retrieval, quality check and pre-processing of both EO and ancillary data useful for service implementation | ~2 days |
| Built-up area mapping | Mapping of all artificial structures including buildings, roads and parking lots, etc. using automated satellite image classification approach | ~5 days |
| Urban extent mapping & change detection on the urban fringe | Manual refinement of the previous mapping result including associated non-sealed and vegetated surfaces functionally related to human activities except agriculture, and change detection and characterisation on the urban fringe by visual interpretation of satellite images (1995-2020) | ~15 days |
| Intra-urban change detection | Mapping of intra-urban changes with proper characterisation over the last decade by visual interpretation of very high resolution satellite images (2010-2020) | ~10 days |
| Geospatial product generation | Product generation, both vector datasets and ready-to-use maps, including internal validation | ~4 days |
| Spatial indicator computation | Calculation of a series of standard spatial indicators per city considering the best input datasets made available | ~10 days |
| Reporting | Summary of the service operations including especially the mapping results as well as the spatial indicators with first-level analysis | ~2 days |
| Service coordination | Contractual, technical and operational management including interactions and meetings with the clients | ~2 days |
| **TOTAL** | | **~50 days** |

**Extending the service in the very same way as for Yerevan, Gyumri and Vanadzor would thus cost about 50 days of manpower:**

- One half dedicated to urban extent and change mapping performed by image analysts (technicians),
- The other half dedicated to the other tasks performed by EO, GIS and remote sensing experts.

In addition, a couple of days could also be spent in case of availability of other kind of data related to socio-economic activities especially, such as statistics or telecom and electricity consumption data. Spatial and temporal accuracies as well as completeness remain key criteria for exploitation in combination with EO-based data. Beyond the cost of the personnel effort, VHR EO data purchase from archive catalogs should finally be considered as additional cost. As spatial and temporal coverage would be a dozen of medium-sized cities for 3 reference dates (2010, 2015, 2020), a budget between 10,000 and 15,000 € sounds reasonable.