Earth Observation for Sustainable Development

Urban Development Project

EO4SD-Urban Project: Dakar City Report

ESA Ref:	**AO/1-8346/15/I-NB**
Doc. No.:	**City Operations Report**
Issue/Rev.:	**1.1**
Date:	**19.11.2019**

Consortium Partners

No.	Name	Short Name	Country
1	GAF AG	GAF	Germany
2	Système d'Information à Référence Spatiale SAS	SIRS	France
3	GISAT S.R.O.	GISAT	Czech Republic
4	Egis SA	EGIS	France
5	Deutsche Luft- und Raumfahrt e. V	DLR	Germany
6	Netherlands Geomatics & Earth Observation B.V.	NEO	The Netherlands
7	JOANNEUM Research Forschungsgesellschaft mbH	JR	Austria
8	GISBOX SRL	GISBOX	Romania

Summary

This document contains information related to the provision of geo-spatial products from the European Space Agency (ESA) supported project "Earth Observation for Sustainable Development" Urban Applications (EO4SD-Urban) to the benefit of Global Platform for Sustainable Cities (GPSC) programme implemented for the City of Dakar and Senegalese authorities.

	Affiliation/Function	Name	Date
Prepared	SIRS NEO JR	S. Delbour, D. Fretin, V. Gastal F. Fang M. Hirschmugl, H. Proske	26/09/2019
Reviewed	SIRS	C. Sannier	27/09/2019
Approved	GAF AG, Project Coordinator	T. Haeusler	02/10/2019

The document is accepted under the assumption that all verification activities were carried out correctly and any discrepancies are documented properly.

Distribution

Affiliation	Name	Copies
ESA	Z. Bartalis	electronic copy
Government agencies	M. Ndaw F. Cheikh M. Diara	electronic copy
UNIDO	M. Draeck K. Barunica	electronic copy

Document Status Sheet

Issue	Date	Details
1.0	02/10/2019	First Document Issue
1.1	19/11/2019	Addition of section 4.4 Sustainable Development Goal 11 Indicators

Document Change Record

#	Date	Request	Location	Details
1	02/10/2019			Initial version

This page is intentionally left blank.

Executive Summary

The European Space Agency (ESA) has been working closely together with the International Finance Institutes (IFIs) and their client countries to demonstrate the benefits of Earth Observation (EO) in the IFI development programmes. Earth Observation for Sustainable Development (EO4SD) is a new ESA initiative, which aims to achieve an increase in the uptake of satellite-based information in the regional and global IFI programmes. The overall aim of the EO4SD Urban project is to integrate the application of satellite data for urban development programmes being implemented by the IFIs or Multi-Lateral Development Banks (MDBs) with the developing countries. The overall goal will be achieved via implementation of the following main objectives:

- To provide a service portfolio of Baseline and Derived urban-related geo-spatial products
- To provide the geo-spatial products and services on a geographical regional basis
- To ensure that the products and services are user-driven

This Report describes the generation and the provision of EO-based information products to the GEF supported programme "Global Platform for Sustainable Cities**"** for Senegal and the counterpart City authorities in Dakar. The Report provides a Service Description by referring to the user-driven service requirements and the associated product list with the detailed product specifications. The following products were requested:

- Urban and Peri-Urban Land Use/ Land Cover and Changes
- Settlement Extent and Imperviousness and Changes
- Urban Green Areas and Changes
- Flood Hazard and Risk Assessment

The current Version of this Report contains the description of the generation and delivery of each requested product, especially the Land Use/Land Cover (LU/LC) and the LU/LC Changes between 2006 and 2018. The Urban Green Areas and Flood Hazard and Risk Assessment study conducted, and the resulting products are also described in detail in this Report.

This City Operations Report for Dakar systematically reviews the main production steps involved and importantly highlights the Quality Control (QC) mechanisms involved; the steps of QC and the assessment of quality is provided in related QC forms in the Annexe of this Report. Standard analytical work undertaken with the products can be further included as inputs into further urban development assessments, modelling and reports.

This page is intentionally left blank.

Table of Contents

Annexes

List of Figures

List of Tables

List of Abbreviations

AOI	Area of Interest
CDS	City Development Strategy
CS	Client States
DEM	Digital Elevation Model
DLR	German Space Agency
EDF	European Development Fund
EEA	European Environmental Agency
EGIS	Consulting Company for Environmental Impact Assessment and Urban Planning, France
EO	Earth Observation
ESA	European Space Agency
EU	European Union
GAF	GAF AG, Geospatial Service Provider, Germany
GCC	General Clauses and Conditions for ESA Contracts
GCT	General Conditions of Tender
GEO	Group on Earth Observations
Geo-SDI	Geo Sustainable Development Indicators
GIS	Geographic Information System
GISAT	Geospatial Service Provider, Czech Republic
GISBOX	Romanian company with activities of Photogrammetry and GIS
GPSC	Global Platform for Sustainable Cities
GUF	Global Urban Footprint
HR	High Resolution
HRL	High Resolution Layer
IFI	International Financing Institute
INSPIRE	Infrastructure for Spatial Information in the European Community
ISO/TC 211	Standardization of Digital Geographic Information
JR	JOANNEUM Research, Austria
LU / LC	Land Use / Land Cover
LULCC	Land Use and Land Cover Change
MMU	Minimum Mapping Unit
NDVI	Normalized Difference Vegetation Index
NEO	Geospatial Service Provider, The Netherlands
QA	Quality Assurance
QC	Quality Control
QM	Quality Management
R&D	Research and Development
SAR	Synthetic Aperture Radar
SC	Service Cluster
SIRS	Geospatial Service Provider, France
SME	Small and Medium-sized Enterprise
SO	Service Operations

SP	Service Provider
ToC	Table of Contents
UN	United Nations
UNDP	United Nations Development Programme
UN-ESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
UNITAR	United Nations Institute for Training and Research
US	United States of America
UUA	User Utility Assessment
VHR	Very High Resolution
WB	World Bank
WBG	World Bank Group
WP	Work Package

This page is intentionally left blank.

1 General Background of EO4SD-Urban

Since 2008 the European Space Agency (ESA) has worked closely together with the International Finance Institutes (IFIs) and their client countries to harness the benefits of Earth Observation (EO) in their operations and resources management. Earth Observation for Sustainable Development (EO4SD) is a new ESA initiative, which aims to achieve an increase in the uptake of satellite-based information in the regional and global IFI programmes. The EO4SD-Urban project initiated in May 2016 (with a duration of 3 years) has the overall aim to integrate the application of satellite data for urban development programmes being implemented by the IFIs with the developing countries. The overall goal will be achieved via implementation of the following main objectives:

- To provide the services on a regional basis (i.e. large geographical areas); in the context of the current proposal with a focus on S. Asia, SE Asia and Africa, for at least 35-40 cities.
- To ensure that the products and services are user-driven; i.e. priority products and services to be agreed on with the MDBs in relation to their regional programs and furthermore to implement the project with a strong stakeholder engagement especially in context with the validation of the products/services on their utility.
- To provide a service portfolio of Baseline and Derived urban-related geo-spatial products that have clear technical specifications and are produced on an operational manner that are stringently quality controlled and validated by the user community.
- To provide a technology transfer component in the project via capacity building exercises in the different regions in close co-operation with the MDB programmes.

This Report supports the fulfilment of the third objective, which requires the provision of geo-spatial Baseline and Derived geo-spatial products to various stakeholders in the IFIs and counterpart City authorities. The Report provides a Service Description, and then in Chapter 3 systematically reviews the main production steps involved and importantly highlights whenever there are Quality Control (QC) mechanisms involved with the related QC forms in the Annexe of this Report. The description of the processes is kept intentionally at a top leave and avoiding technical details as the Report is considered mainly for non-technical IFI staff and experts and City authorities. Finally, Chapter 4 presents the standard analytical work undertaken with the products which can be inputs into further urban development assessments, modelling and reports.

2 Service Description

The following Section summarises the service as it has been realised for the city of Dakar, Senegal, within the EO4SD-Urban Project and as it was delivered to the UNIDO (United Nations Industrial Development Organisation), the GPSC Implementing Agency for the Senegalese city of Dakar, and the Senegalese Governmental agencies.

2.1 Stakeholders and Requirements

The EO4SD-Urban products described in this Report were provided for the benefit of the Global Platform for Sustainable Cities (GPSC) programme. GPSC is funded by the Global Environment Facility (GEF) and currently includes 28 cities in 11 countries. The GPSC initiative is supported by different Multi-Lateral Development Banks (MDBs) and UN organisations. The two Senegalese cities of St. Louis and Dakar are part of the GPSC programme and were identified for collaboration with the EO4SD-Urban project via interactions with UNIDO, the Implementing Agency.

The GPSC has an overarching aim to provide a knowledge platform for partner cities, as well as relevant networks and institutions to support the cities via:

- “Knowledge transfer activities that support urban investments and sustainability initiatives,
- A global network for collaborative engagement, tapping into and complementing existing efforts,
- Long-term, systematic engagement with cities, financial institutions, and organizations for transformational impact” (GPSC Programme Booklet, 2016).

Dakar is a GPSC Partner City and the capital city of Senegal. Located along the Atlantic coast in the east of the country, this geographical position necessarily exposes the city to major environmental hazards (flood, coastal erosion, rise of the sea level).
In the context of the GPSC programme the city has the objective to “integrate climate risks in urban planning and management and will focus on urban planning and management, capacity building through the development of integrated climate resilience solutions and strengthening the urban national policy framework to promote cities’ sustainability at the national level” (GPSC website, 2018). The project also aims at developing a sustainable cities master plan.

The main local stakeholder for the city of Dakar is the Directorate of Urbanism and Architecture of the Senegalese Ministry of Urban Renewal, Habitat and Living Environment. Other stakeholders include mostly other Senegalese governmental agencies.
The Directorate of Urbanism and architecture, that works in close collaboration with the Ministry of Territorial Planning, will use the EO4SD products to develop more accurate policy mechanisms. Furthermore, the project will provide a regional view of the environmental dynamics, that will be used by the Directorate of Urbanism and Architecture’s team.

2.2 Service Area Specification

So far, no internationally accepted definition for the term “Urban Area” and the related Core and Peri-Urban areas exists. Different initiatives are currently trying to address a standardised approach for defining the terms “Urban Area”. During discussions with the GPSC Co-ordinator it was considered important to use a uniform definition for the GPSC cities in order for the cities to exchange information and share products/experiences and conduct potential comparative studies.

In this context, it was decided to use an international approach for the demarcation of the Area of Interest (AOI) for mapping the GPSC cities in terms of Core Urban area and Peri-Urban area. Thus, the approach is based on the European Union’s Directorate-General for Regional and Urban Policy (DG REGIO) method and the definitions are described in the Regional Working Paper 2014 from the European Commission on “A harmonised definition of cities and rural areas: the new degree of urbanisation” (European Commission, 2014). Following the naming of the DG Regio approach, the Urban Core is named as “High Density Core” and the Peri-Urban area is termed as “Urban Cluster”. Within the DG REGIO approach, the High Density Core area is defined as contiguous grid cells of 1 km^2 with a density of at least 1 500 inhabitants per km^2 and a minimum population of 50 000. The Urban Cluster is defined as clusters of contiguous grid cells of 1 km^2 with a density of at least 300 inhabitants per km^2 and a minimum population of 5 000.

The DG REGIO methodology used in the EO4SD-Urban project was slightly adjusted to Non-European countries. For the first three GPSC cities (namely Bhopal, Vijayawada and Saint-Louis) produced within the project the Global Human Settlement Population (GHSP) grid with a spatial resolution of 1 km were used for the classification into “High Density Core” and ”Urban Cluster”. The raster dataset is available for the years 1975, 1990, 2000, 2015. This dataset depicts the distribution and density of population, expressed as the number of people per cell. The data can be downloaded under following link http://data.jrc.ec.europa.eu/dataset/jrc-ghsl-ghs_pop_gpw4_globe_r2015a.

In 2019, a higher resolution population layer (spatial resolution of 10 m) produced by the German Aerospace Centre (DLR) became available. The AOIs for the remaining GPSC cities (namely Melaka, Abidjan, Dakar and Campeche) were produced based on the DLR population layer.

The High Density Core AOI for a city is created by merging the contiguous grid cells of 1 km^2 with a density of at least 1500 inhabitants per km^2 and a minimum population of 50 000. In the definition of the High Density Core the contiguity is only allowed via a vertical or horizontal connection. In a next step, gaps are filled. Due to the coarse resolution of the population grid cells additional grid cells were in a last step added for under estimated settlement areas. The same was done for over estimations, here grid cells were removed. The GHSP layer can be directly used for the calculation, while the DLR population has to be aggregated to a resolution of 1 km^2 before being used for the AOI definition. In this aggregation step, each output cell contains the sum of the input cells that are encompassed by the extent of that new cell.

The Urban Cluster is created very similar to the High Density Core. Continuous grid cells of 1 km^2 with a density of at least 300 inhabitants per km^2 and a minimum population of 5 000 are merged together to form the Urban Cluster. The contiguity within the Urban Cluster can also be diagonal. After gaps are filled, areas, which were over or under estimated by the population grid were removed or added to the AOI. The GHSP layer was directly used, the DLR population layer had to undergo an aggregation step in order to reduce the spatial resolution to 1 km^2.

For Bhopal and Vijayawada a buffer of 1 km was calculated around the High Density Core AOI and the Urban Cluster AOI to smoothen the border of the AOIs.

In all remaining GPSC cities, the border was not smoothed, but when the population grid was under or over estimating the real settlement extent, grid cells were added or removed.

In some cases, the city counterparts requested that the AOIs for the High Density Core and the Urban Cluster follow the municipal or administrative boundary of the city. In this case, the municipal/administrative boundary was used, but enlarged in areas where the AOI created according to the adjusted DG Regio approach was bigger. This adjustment of the DG Regio AOI was done for Melaka, Abidjan, Dakar and Campeche. These further adjusted DG Regio AOIs are in the following report named as Core City Area (see Figure 1a) and Larger Urban Area (see Figure 1b).

A more detailed description on how the AOIs are calculated is provided in Annex 1.

The AOIs were presented in a power point and sent to the Users for verification. Figure 1 shows the resulting AOIs after combining the DG Regio AOIs with the municipal/administrative boundaries of the cities.

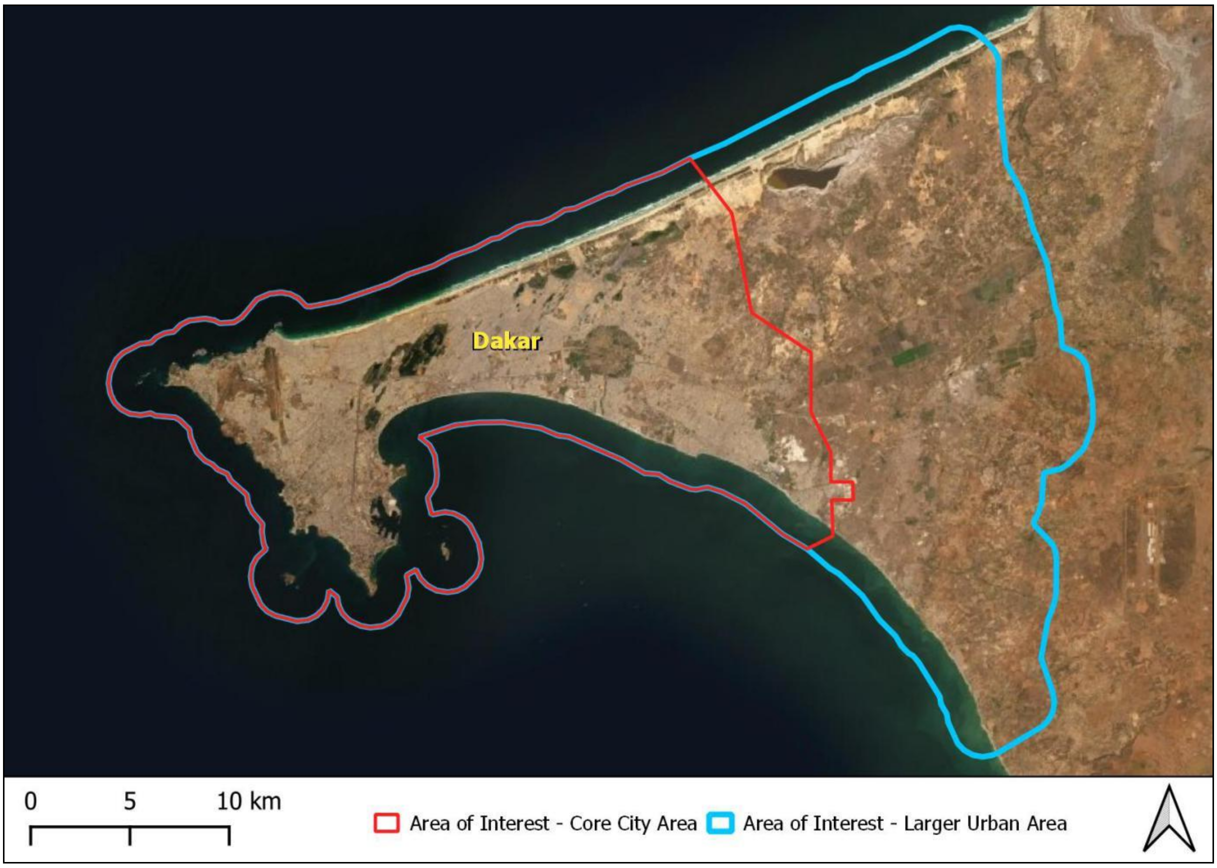

Figure 1: Illustration of Core City and Larger Urban Areas of Dakar.

The Core City has an area of 422 km^2 and the Larger Urban has an area of 823 km^2.

2.3 Product List and Product Specifications

During the discussions related to the AOIs the potential geo-spatial products that could be provided for the Cities were also reviewed with the WB Team and Users. It was noted that the Baseline Land Use/Land Cover (LU/LC) products (for the Core and Peri-Urban areas) were a standard product that would be provided for all Cities as it is required for the derived products. In the case of Dakar, the full list of products for both the Core and Peri-Urban areas is as follows:

- Settlement Extent & Change (producer: DLR)
- Percentage Impervious Surface & Change (producer: DLR)
- Core City and Larger Urban Land Use / Land Cover (LU/LC) & Change (producer: SIRS)
- Urban Green Areas & Change (producer: NEO)
- Flood Hazard & Risk Assessment (producer: JR)

The first two products have been generated by the German Aerospace Agency (DLR) over the full metropolitan area for four reference years: 2000 - 2005 - 2010 - 2015.

Two time slots were used to provide historic and recent information regarding LU/LC for Dakar, 2006 and 2018 over the Core City and Larger Urban Areas. The last section of the Report is fully dedicated to the Flood Hazard & Risk Assessment study.

2.4 Land Use/Land Cover Nomenclature

A pre-cursor to starting production was the establishment with the stakeholders on the relevant Land Use/Land Cover (LU/LC) nomenclature as well as class definitions. The approach taken was to use a standard remote sensing based LU/LC nomenclature i.e. the European Urban Atlas Nomenclature (European Union, 2011) and adapt it to the User’s LU requirements. Thus, the remote-sensing based LU/LC classes in the urban context can be grouped into five Level 1 classes, which are Artificial Surfaces, Natural/ Semi Natural Areas, Agricultural Areas, Wetlands, and Water. These classes can then be sub-divided into several different more detailed classes such that the dis-aggregation can be down to Level 2-4. This hierarchical classification system is often used in operational Urban mapping programmes and is the basis for example of the European Commission’s Urban Atlas programme which provides pan-European comparable LU/LC data with regular updates. A depiction of the way the levels and classes in the Urban Atlas programme are structured is presented as follows:

<u>Level I Artificial surfaces</u>

- Level II: Urban Fabric

Level III

- *Continuous Urban Fabric (Sealing Layer-S.L. > 80%)*
- *Discontinuous Urban Fabric (S.L. 10% - 80%)*

Level IV

1) *Discontinuous Dense Urban Fabric (S.L. 50% - 80%)*
2) *Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)*
3) *Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)*
4) *Discontinuous Very Low Density Urban Fabric (S.L. < 10%)*

- Level II: Industrial, Commercial, Public, Military, Private Units and Transport

Level III

- *Industrial, Commercial, Public, Military and Private Units*
- *Transport Infrastructure*

Level IV

5) *Fast Transit Roads*
6) *Other Roads*
7) *Railway*

- *Port and associated land*
- *Airport and associated land*

- Level II: Mine, Dump and Construction Sites

Level III

- *Mineral Extraction and Dump Sites*
- *Construction Sites*
- *Land Without Current Use*

- Level II: Artificial Non-Agricultural Vegetated Areas

Level III

- *Green Urban Areas*
- *Sports and Leisure Facilities*

(Reference: European Union, 2011)

It should be noted that in the current project, the Level 1 classes were used as the basis for classification of the Urban Cluster areas using the High Resolution (HR) data such as Landsat or Sentinel. However, for the High Density Core areas using the Very High Resolution (VHR) data it was possible to go down to Level III and IV.

The different levels, classes and sub-classes from the remote sensing based urban classification, were harmonised within the GPSC cities. The following tables give the nomenclature for the High Density Core and the Urban Cluster region (see Table 1 and Table 2).

Table 1: LU/LC Nomenclature for GPSC Cities (Core City AOI).

Actual and Historic Nomenclature Core City Area			
Level I	**Level II**	**Level III**	**Level IV**
1000 Artificial Surfaces	1100 Residential	1110 Continuous Urban Fabric (80 - 100 % Sealed)	
		1120 Discontinuous Urban Fabric	1121 Discontinuous dense urban fabric (50 - 80 % Sealed)
			1122 Discontinuous medium density urban fabric (30 - 50 % Sealed)
			1123 Discontinuous low density urban fabric (10 - 30 % Sealed)
			1124 Discontinuous very low density urban fabric (0 - 10 % Sealed)
	1200 Industrial, Commercial, Public, Military, Private Units and Transport	1210 Industrial, Commercial, Public, Military and Private Units	
		1220 Transport Infrastructure	1221 Arterial Roads
			1222 Collector Roads
			1223 Railway
		1230 Port Area	
		1240 Airport	
	1300 Mine, Dump and Construction Sites	1310 Mineral Extraction and Dump Sites	
		1330 Construction Sites	
		1340 Land Without Current Use	
	1400 Artificial Non-Agricultural Vegetated Areas	1410 Green Urban Areas	
		1420 Sports and Leisure Facilities	
2000 Agricultural Area			
3000 Natural and Semi-natural Areas	3100 Forest and Shrublands		
	3200 Natural Areas (Grassland)		
	3300 Bare Soil		
4000 Wetlands			
5000 Water	5100 Inland Water		
	5200 Marine Water		

Table 2: LU/LC Nomenclature for GPSC Cities (Larger Urban AOI).

Actual and Historic Nomenclature Larger Urban Area			
Level I	**Level II**	**Level III**	**Level IV**
1000 Artificial Surfaces			
2000 Agricultural Area			
3000 Natural and Semi-natural Areas	3100 Forest and Shrublands		
	3200 Natural Areas (Grassland)		
	3300 Bare Soil		
4000 Wetlands			
5000 Water	5100 Inland Water		
	5200 Marine Water		

It is important to note that the possibility to classify at Level IV is highly dependent on the availability of reliable reference datasets from the City or sources such as Google Earth. This aspect is further discussed in Chapter 3.

Especially regarding the road hierarchy used in the classification at Level IV, the international road classification standards have been followed; this is for example defined by the European Commission (https://ec.europa.eu/transport/road_safety/specialist/-knowledge/road/designing_for_road_function/road_classification_en).

Roads are divided into three groups: arterial or through traffic flow routes (in our case **Arterial Roads**), distributor roads (in our case **Collector Roads**), and access roads (or **Local Roads**). The three road types are defined as follows:

Arterial Roads:

Roads with a flow function allow efficient throughput of (long distance) motorized traffic. All motorways and express roads as well as some urban ring roads have a flow function. The number of access and exit points is limited. (https://ec.europa.eu/transport/road_safety/specialist/knowledge/-road/designing_for_road_function/road_classification_en)

Collector Roads:

Roads with an area distributor function allow entering and leaving residential areas, recreational areas, industrial zones, and rural settlements with scattered destinations. Junctions are for traffic exchange (allowing changes in direction etc.); road sections between junctions should facilitate traffic in flowing.
(https://ec.europa.eu/transport/road_safety/specialist/knowledge/road/designing_for_road_function/road_classification_en)

Local Roads:

Roads with an access function allow actual access to properties alongside a road or street. Both junctions and the road sections between them are for traffic exchange. (https://ec.europa.eu/transport/-road_safety/specialist/knowledge/road/designing_for_road_function/road_classification_en).

2.5 World Settlement Extent

Reliably outlining settlements is of high importance since an accurate characterization of their extent is fundamental for accurately estimating, among others, the population distribution, the use of resources (e.g. soil, energy, water, and materials), infrastructure and transport needs, socioeconomic development, human health and food security. Moreover, monitoring the change in the extent of settlements over time is of great support for properly modelling the temporal evolution of urbanization and thus, better estimating future trends and implementing suitable planning strategies.

At present, no standard exists for defining settlements and worldwide almost each country applies its own definition either based on population, administrative or geometrical criteria. The German Space Agency (DLR) was responsible for the provision of the "Settlement Extent" product; when generating the settlement extent maps from HR imagery, pixels are labelled as **settlement** if they *intersect any building, lot or – just within urbanized areas – roads and paved surface* where we define:

- **building** as any structure having a roof supported by columns or walls and intended for the shelter, housing, or enclosure of any individual, animal, process, equipment, goods, or materials of any kind;
- **lot** as the area contained within an enclosure (wall, fence, hedge) surrounding a building or a group of buildings. In cases where there are many concentric enclosures around a building, the lot is considered to stop at the inner most enclosure;
- **road** as any long, narrow stretch with a smoothed or paved surface, made for traveling by motor vehicle, carriage, etc., between two or more points;
- **paved surface** as any level horizontal surface covered with paving material (i.e., asphalt, concrete, concrete pavers, or bricks but excluding gravel, crushed rock, and similar materials).

Instead, pixels not satisfying this condition are marked as **non-settlement**.

The settlement extent product is a binary mask outlining - in the given Area of Interest (AOI) – settlements in contrast to all other land-cover classes merged together into a single information class. The settlement class and the non-settlement class are associated with values "255" and "0", respectively.

2.6 Percentage Impervious Surface

Settlement growth is associated not only to the construction of new buildings, but – more in general – to a consistent increase of all the impervious surfaces (hence also including roads, parking lots, squares, pavement, etc.), which do not allow water to penetrate, forcing it to run off. To effectively map the percentage impervious surface (PIS) is then of high importance being it related to the risk of urban floods, the urban heat island phenomenon as well as the reduction of ecological productivity. Moreover, monitoring the change in the PIS over time is of great support for understanding, together with information about the spatiotemporal settlement extent evolution, also more details about the type of urbanization occurred (e.g. if areas with sparse buildings have been replaced by highly impervious densely built-up areas or vice-versa).

In the framework of the EO4SD-Urban project, one pixel in the generated PIS maps is associated with the estimated percentage of the corresponding surface at the ground covered by buildings or paved surfaces, are defined as:

- **building** as any structure having a roof supported by columns or walls and intended for the shelter, housing, or enclosure of any individual, animal, process, equipment, goods, or materials of any kind;
- **paved surface** as any level horizontal surface covered with paving material (i.e. asphalt, concrete, concrete pavers, or bricks but excluding gravel, crushed rock, and similar materials).

The product provides for each pixel in the considered AOI the estimated PIS. Specifically, values are integer and range from 0 (no impervious surface in the given pixel) to 100 (completely impervious surface in the given pixel) with step 5.

2.7 Urban Green Areas Nomenclature

Developing cities in a sustainable way implies to preserve and promote green areas also and especially within the urban extent. Green areas refer to any surfaces covered by vegetation (grass, bushes, trees).

Table 1: Nomenclature used for the mapping and identification of Urban Green Areas.

Single date		
Code 0	Non-urban green area	
Code 1	Urban green area	
Code 255	Non-urban areas. All areas that do not fall in "Artificial Surfaces" Level 1 class of the Land Use Land Cover product (See Table 1).	
Change product		
Code 0	Non-urban green area. No vegetated surfaces occurring on "Artificial Surfaces", Level I, at both points in time.	
Code 1	Permanent urban green area. Vegetated surfaces in historic and recent year.	
Code 2	Loss of urban green area. Vegetated areas in historic year, which changed to non-vegetated areas in recent year.	
Code 3	New urban green area. Non-vegetated surfaces in historic year with vegetation cover in recent year.	
Code 255	Non-Urban Areas. All areas that do not fall in "Artificial Surfaces" Level 1 class of the Land Use Land Cover product.	

2.8 Terms of Access

The Dissemination of the digital data and the Report was undertaken via FTP.

3 Service Operations

The following Sections present all steps of the service operations including the necessary input data, the processing methods, the accuracy assessment and the Quality Control procedures. Methods are presented in a top-level and standardised manner for all the EO4SD-Urban City Reports.

3.1 Source Data

This Section presents a summary of the remote sensing and ancillary datasets that were used. Different types of data from several data providers have been acquired. A complete list of source data as well as a quality assessment is provided in Annex 3.

High Resolution Optical EO Data

The major data sources for the current and historic mapping of LULC for Larger Urban Area, Settlement Extent and PIS products were Landsat and Sentinel-2 data which were accessible and downloadable free of charge.

- **Landsat 7:** As a source of historical data four scenes of Landsat TM 7 from the 14th of January 2006 to 28th of March have been acquired which covers the whole area of interest.
- **Sentinel-2:** The most recent data coverage comprises one Sentinel-2 data set from the 27th of February 2018. The data was downloaded and processed at Level 1C.

Very High Resolution Optical EO Data

The VHR data for the Core Urban Area mapping had to be acquired and purchased through commercial EO Data Providers such as Airbus Defence and European Space Imaging.

It has to be noted that under the current collaboration project the VHR EO data had to be purchased under **mono-license agreemen**ts between GAF AG and the EO Data Providers. If EO data would have to be distributed to other stakeholders, then further licences for multiple users would have to be purchased.

The following VHR sensor data have been acquired to cover the AOI:

- **Quickbird-2:**
  - 4 scenes from the 07 November 2005 to the 21th of December 2005 covering 99.3% of the Core Urban AOI
- **Pléiades 1-A & Pléiades 1-B:**
  - 3 scenes from the 1st of March 2018 to the 3rd of March 2018 covering 99.9% of the Core Urban AOI

Detailed lists of the used EO data as well as their quality is documented in the attached Quality Control Sheets in Annex 3.

Ancillary Data

Open Street Map (OSM) data: OSM data is freely available and generated by volunteers across the globe. The so-called crowd sourced data is not always complete but has for the most parts of the world valuable spatial information. Data was downloaded to complement the Transport Network layer and further enhanced. The spatial location of the OSM based streets was used a geospatial reference.

Detailed lists of the used EA and ancillary data as well as their quality is documented in the attached Quality Control Sheets in Annex 3.

3.2 Processing Methods

Data processing starts at an initial stage with quality checks and verification of all incoming data. This assessment is performed in order to guarantee the correctness of data before geometric or radiometric pre-processing is continued. These checks follow defined procedures in order to detect anomalies, artefacts and inconsistencies. Furthermore, all image and statistical data were visualized and interpreted by operators.

The main techniques and standards used for data analysis, processing and modelling for each product are described in Annex 2.

3.3 Accuracy Assessment of Map Products

Data and maps derived from remote sensing contain - like any other map - uncertainties which can be caused by many factors. The components, which might have an influence on the quality of the maps derived from EO include quality and suitability of satellite data, interoperability of different sensors, radiometric and geometric processing, cartographic and thematic standards, and image interpretation procedures, post-processing of the map products and finally the availability and quality of reference data. However, the accuracy of map products has a major impact on secondary products and its utility and therefore an accuracy assessment was considered as a critical component of the entire production and products delivery process. The main goal of the thematic accuracy assessment was to guarantee the quality of the mapping products with reference to the accuracy thresholds set by the user requirements.

The applied accuracy assessments were based on the use of reference data and applying statistical sampling to deduce estimates of error in the classifications. In order to provide an efficient, reliable and robust method to implement an accuracy assessment, there are three major components that had to be defined: the **sampling design**, which determines the spatial location of the reference data, the **response design** that describes how the reference data is obtained and an **analysis design** that defines the accuracy estimates. These steps were undertaken in a harmonized manner for the validation of all the geo-spatial products.

3.3.1 Accuracy Assessment of the LU/LC Products

Sampling Design

The sampling design specifies the sample size, sample allocation and the reference assessment units (i.e. pixels or image blocks). Generally, different sampling schemes can be used in collecting accuracy assessment data including: simple random sampling, systematic sampling, stratified random sampling, cluster sampling, and stratified systematic unaligned sampling. In the current project a **single stage stratified random sampling** based on the method described by Olofson et al (2013[1]) was applied which used the map product as the basis for stratification. This ensured that all classes, even very minor ones were included in the sample.

The sampling design is applied separately for the Core City Area and for the Larger Urban Area classification.

[1] Olofsson, P., Foody, G. M., Stehman, S. V., & Woodcock, C. E. (2013). Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sensing of Environment, 129, 122–131. doi:10.1016/j.rse.2012.10.031

In the complex LU/LC product with many classes, this usually results in a large number of strata (one stratum per LU/LC classes), of which some classes cover only very small areas (e.g. sport fields, cemeteries) and not being adequately represented in the sampling. In order to achieve a representative sampling for the statistical analyses of the mapping accuracy it was decided to extend the single stage stratified random sampling. Slightly different approaches were used for the Core City and the Larger Urban Area classification.
The first step is the same for both classifications: the number of required samples is allocated within each of the Level I strata (1000 Artificial Surfaces, 2000 Agricultural Area, 3000 Natural and Semi-natural Areas, 4000 Wetlands, 5000 Water).
In the second step, all Level III classes that were not covered by the first sampling were grouped into one new stratum for the Core City Area classification. For the Larger Urban Area classification all Level II classes that were not covered by the first sampling were grouped into one new stratum.

Within that stratum the same number of samples was randomly allocated as the Level I strata received. To avoid a clustering of point samples within classes and to minimise the effect of spatial autocorrelation a minimum distance in between the sample points was set to be 150 m. The final sample size for each class can be considered to be as close as possible to the proportion of the area covered by each stratum considering that the target was to determine the overall accuracy of the entire map.

The total sample size per stratum was determined by the expected standard error and the estimated error rate based on the following formula, which assumes a simple random sampling (i.e. the stratification is not considered):

$$n = \frac{P * q}{(\frac{E}{Z})^2}$$

n = number of samples per strata / map class
p = expected accuracy
$q = 1 - p$
E = Level of acceptable (allowable) sample error
Z = z-value (the given level of significance)

Hence, with an expected accuracy of $p = 0.85$, a 95% confidence level and an acceptable sampling error of 5%, the minimum sample size is 196. A 10% oversampling was applied to compensate for stratification inefficiencies and potentially inadequate samples (e.g. in case of cloudy or shady reference data). For each Level I strata 215 samples have been randomly allocated. Afterwards, for all classes of Level III of the Core City Area classification that did not received samples in the first run, additionally 215 samples were randomly drawn across all these classes. A summary of the number of sample point for each Core City Area class is given in Table 3.

The same applies for the Larger Urban Area classification: All Level II classes that did not receive samples in the first run, additionally 215 samples were randomly drawn across all these classes. A summary of the number of sample point for each Larger Urban Area class is given in

Table 4.

The main difference of the sampling design for the two areas is that the resampling is done at Level III for the Core City Area and at Level II for the Larger Urban Area.

Table 3: Number of sampling points for the Core City Area classes after applied sampling design with information on overall land cover by class.

Class Name	Class ID	No. Of Sampling Points	Km^2 Coverage
Continuous Urban Fabric	1110	196	108.2
Discontinuous Urban Fabric	1120	19	7.1
Industrial, Commercial, Public, Military and Private Units	1210	148	31.4
Transport Infrastructure	1220	31	7.9
Port Area	1230	12	1.9
Airport	1240	24	5.5
Mineral Extraction and Dump Sites	1310	28	3.5
Construction Sites	1330	32	4.1
Land Without Current Use	1340	141	17.3
Green Urban Areas	1410	20	2.3
Sports and Leisure Facilities	1420	20	2.6
Agricultural Area	2000	180	22.3
Forest and Shrublands	3100	40	5.0
Natural Areas (Grassland)	3200	151	18.7
Bare Soil	3300	107	13.2
Wetlands	4000	59	7.3
Inland Water	5100	27	3.3
Marine Water	5200	215	160.7
Total	**-**	**1450**	**422.4**

Table 4: Number of sampling points for the Larger Urban Area classes after applied sampling design with information on overall land cover by class.

Class Name	Class ID	No. Of Sampling Points	Km^2 Coverage
Artificial Surfaces	1000	215	259.9
Agriculture	2000	215	243.6
Forest and Shrublands	3100	61	15.5
Natural Areas	3200	215	54.8
Bare Soil	3300	75	29.1
Wetlands	4000	31	10.3
Inland Water	5100	27	5.8
Marine Water	5200	215	204.4
Total	**-**	**1054**	**823.4**

Response Design

The response design determines the reference information for comparing the map labels to the reference labels. Collecting reference data on the ground by means of intensive fieldwork is both costly and time-consuming and is in most projects not feasible. The most cost-effective reference data sources are VHR satellite data with 0.5 m to 1 m spatial resolution. Czaplewski (2003)[2] indicated that visual interpretation of EO data is acceptable if the spatial resolution of EO data is sufficiently better compared to the thematic classification system. However, if there are no EO data with better spatial resolution available, the assessment results need to be checked against the imagery used in the production process.

The calculated number of necessary sampling points for each mapping category was randomly distributed among the strata and overlaid onto the two LULC mapping products. The following two Figures (see Figure 2 and Figure 3) are showing the mapping result with the overlaid sample points.

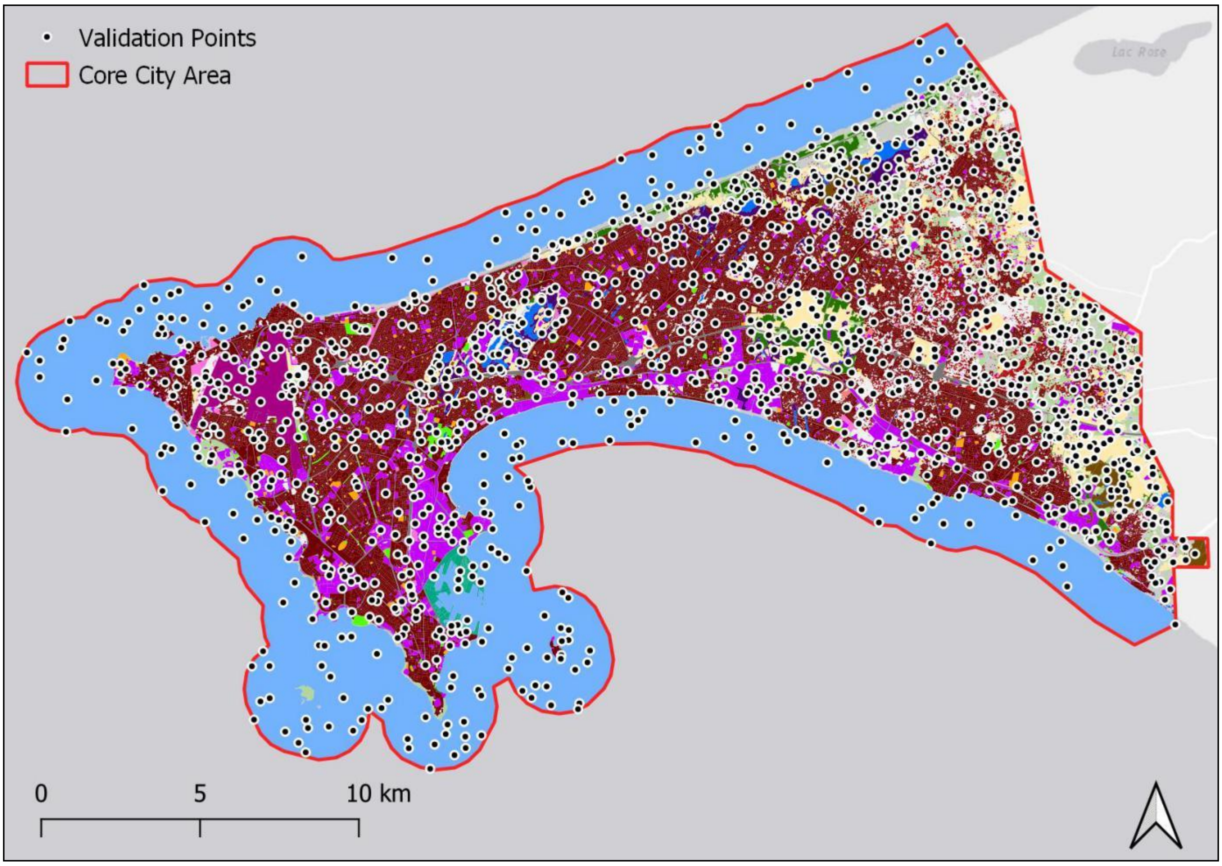

Figure 2: Mapping result of the Core City Area of Dakar of the year 2018 overlaid with randomly distributed sample points used for accuracy assessment.

[2] Czaplewski, R. L. (2003). Chapter 5: accuracy assessment of maps of forest condition: statistical design and methodological considerations, pp. 115–140. In Michael A.Wulder, & Steven E. Franklin (Eds.), Remote sensing of forest environments: concepts and case studies. Boston: Kluwer Academic Publishers (515 pp.).

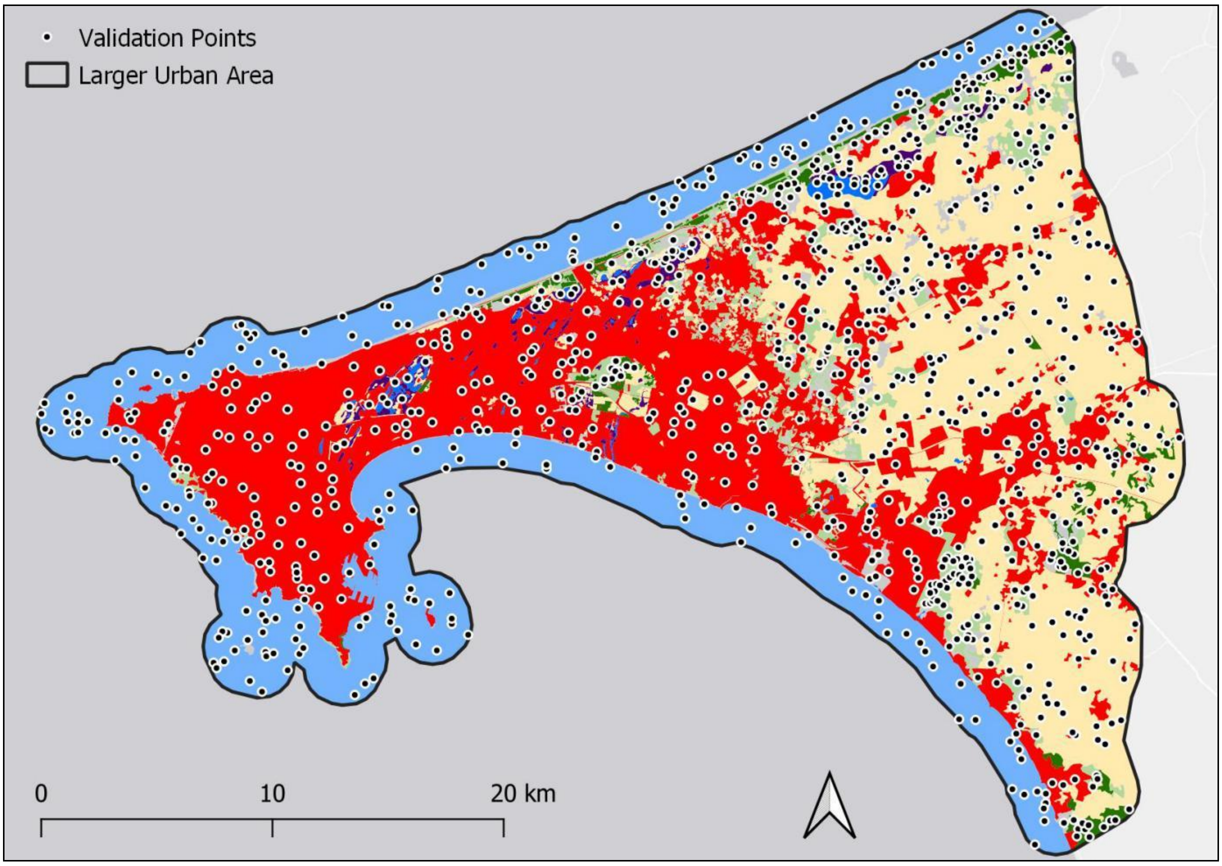

Figure 3: Mapping result of the Larger Urban Area of Dakar of the year 2018 overlaid with randomly distributed sample points used for accuracy assessment.

In this way a reference information could be extracted for each sample point by visual interpretation of the VHR data for all mapped classes. The size of the area to be observed had to be related to the Minimum Mapping Unit (MMU) of the map product to be assessed. The reference information of each sampling point was compared with the mapping results and the numbers of correctly and not-correctly classified observations were recorded for each class. From this information the specific error matrices and statistics were computed (see next Section).

Analysis

Each class usually has errors of both omission and commission, and in most situations, these errors for a class are not equal. In order to calculate these errors as well as the uncertainties (confidence intervals) for the area of each class a statistically sound accuracy assessment was implemented.

The confusion matrix is a common and effective way to represent quantitative errors in a categorical map, especially for maps derived from remote sensing data. The matrices for each assessment epoch were generated by comparing the "reference" information of the samples with their corresponding classes on the map. The *Reference* represented the "truth", while the *Map* provided the data obtained from the map result. Thematic accuracy for each class and overall accuracy is then presented in error matrices. Unequal sampling intensity resulting from the random sampling approach was accounted for by applying a weight factor (p) to each sample unit based on the ratio between the number of samples and the size of the stratum considered[3]:

[3] Selkowitz, D. J., & Stehman, S. V. (2011). Thematic accuracy of the National Land Cover Database (NLCD) 2001 land cover for Alaska. Remote Sensing of Environment, 115(6), 1401–1407. doi:10.1016/j.rse.2011.01.020.

$$\hat{p}_{ij} = \left(\frac{1}{M}\right) \sum_{x \in (i,j)} \frac{1}{\pi^*_{uh}}$$

Where i and j are the columns and rows in the matrix, M is the total number of possible units (population) and π is the sampling intensity for a given sample unit u in stratum h.

Overall accuracy and User and producer accuracy were computed for all thematic classes and 95% confidence intervals were calculated for each accuracy metric.

The standard error of the error rate was calculated as follows: $\sigma_h = \sqrt{\frac{p_h(1-p_h)}{n_h}}$ where n_h is the sample size for stratum h and p_h is the expected error rate. The standard error was calculated for each stratum and an overall standard error was calculated based on the following formula:

$$\sigma = \sqrt{\sum w_h^2 . \sigma_h^2}$$

In which w_h is the proportion of the total area covered by each stratum. The 95% Confidence Interval (CI) is +/- 1.96*σ.

Results

The confusion matrices are provided within the Annex 3 and show the mapping error for each relevant class. For each class the number of samples which are correctly and not correctly classified are listed, this allows the calculation of the user and producer accuracies for each class as well as the confidence interval at 95% confidence levels based on the formulae above.

The Land Use/Land Cover product for Dakar in 2018 in Core City Area has an overall mapping accuracy of 98.94% with a CI ranging from 98.41% to 99.47% at a 95% CI. For the Larger Urban Area, the overall accuracy is 89.23% with a CI ranging from 87.36% to 91.1% at a 95% CI. The specific class accuracies are given in Annex 3.

3.3.2 Accuracy Assessment of the World Settlement Extent Product

In the following, the strategy designed for validating the World Settlement Extent (WSE) or World Settlement Footprint (WSF) 2015, i.e. a global settlement extent layer obtained as a mosaic of ~18.000 tiles of 1x1 degree size where the same technique employed in the EO4SD-Urban project is presented. In particular, specific details are given for all protocols adopted for each of the accuracy assessment components, namely response design, sampling design, and analysis; final results are discussed afterwards. In the light of the quality and amount of validation points considered, it can be reasonably assumed that the corresponding quality assessment figures are also representative for any settlement extent map generated in the framework of EO4SD-Urban.

Response Design

The response design encompasses all steps of the protocol that lead to a decision regarding agreement of the reference and map classifications. The four major features of the response design are the source of information used to determine the source of reference data, the spatial unit, the labelling protocol for the reference classification, and a definition of agreement.

- **Source of Reference Data:** Google Earth (GE) satellite/aerial VHR imagery has been used given its free access and the availability for all the project test sites in the period 2014-2015. In particular, GE automatically displays the latest available data, but it allows to browse in time over all past historical images. The spatial resolution varies depending on the specific data source; in the case of SPOT imagery it is ~1.5m, for Digital Globe's WorldView-1/2 series, GeoEye-1, and Airbus' Pleiades it is in the order of ~0.5m resolution, whereas for airborne data (mostly available for North America, Europe and Japan) it is about 0.15m.
- **Spatial Assessment Unit:** A 3x3 block spatial assessment unit composed of 9 cells of 10x10m size has been used. Specifically, this choice is justified one the one hand by the fact that input data with different spatial resolutions have been used to generate the WSF2015 (i.e. 30m Landsat-8 and 10m S1). On the other hand, GE imagery exhibited in some cases a mis-registration error of the order of 10-15m, hence using a 3x3 block allows defining an agreement e.g. based on statistics computed over 9 pixels, thus reducing the impact of such shift.
- **Reference Labelling Protocol:** For each spatial assessment block any cell is finally labelled as **settlement** if *it intersects any building, lot or – just within settlements – roads and paved surface*. Instead, pixels not satisfying this condition are marked as **non-settlement**.
- **Definition of Agreement:** Given the classification and the reference labels derived as described above, three different agreement criteria have been defined:
  8) for each pixel, positive agreement occurs only for matching labels between the classification and the reference;
  9) for each block, a majority rule is applied over the corresponding 9 pixels of both the classification and the reference; if the final labels match, then the agreement is positive;
  10) for the classification a majority rule is applied over each assessment block, while for the reference each block is labelled as “settlement” only in the case it contains at least one pixel marked as “settlement”; if the final labels match, then the agreement is positive.

Crowd-sourcing was performed internally at Google. In particular, by means of an ad-hoc tool, operators have been iteratively prompted a given cell on top of the available Google Earth reference VHR scene closest in time to the year 2015 and given the possibility of assigning to each cell a label among: “building”, “lot”, “road/paved surface” and “other”. For training the operators, a representative set of 100 reference grids was prepared in collaboration between Google and DLR.

Sampling Design

The stratified random sampling design has been applied since it satisfies the basic accuracy assessment objectives and most of the desirable design criteria. In particular, stratified random sampling is a probability sampling design and it is one of the easier to implement; indeed, it involves first the division of the population into strata within which random sampling is performed afterwards. To include a representative population of settlement patterns, 50 out of the ~18.000 tiles of 1x1 degree size considered in the generation of the WSF2015 have been selected based on the ratio between the number of estimated settlements (i.e. disjoint clusters of pixels categorized as settlement in the WSF2015) and their area. In particular, the i-th selected tile has been chosen randomly among those whose ratio belongs to the interval $]P_{2(i-1)}; P_{2i}], i \in [1; 50] \subset \mathbb{N}$ (where P_x denotes the x-th percentile of the ratio).

Table 5: Accuracies exhibited by the WSF2015 according to the three considered agreement criteria for different definitions of settlement.

Settlement =	Accuracy Measure	Agreement Criterion 1		Agreement Criterion 2		Agreement Criterion 3	
buildings	*OA%*	86.96		87.86		91.15	
	AA%	88.57		90.35		88.91	
	Kappa	0.6071		0.6369		0.7658	
	$UA_{NS}\%$ - $UA_S\%$	98.11	54.69	98.73	56.76	94.84	80.58
	$PA_{NS}\%$ - $PA_S\%$	86.24	90.90	86.72	93.98	93.32	84.51
buildings + lots	*OA*	88.08		88.94		91.26	
	AA%	88.64		90.19		88.71	
	Kappa	0.6510		0.6784		**0.7716**	
	$UA_{NS}\%$ - $UA_S\%$	97.54	60.71	98.13	62.66	94.29	82.62
	$PA_{NS}\%$ - $PA_S\%$	87.79	89.49	88.26	92.12	93.95	83.48
buildings + lots + roads / paved surface	*OA*	88.77		90.09		88.51	
	AA%	86.34		88.28		84.27	
	Kappa	**0.6938**		**0.7317**		0.7219	
	$UA_{NS}\%$ - $UA_S\%$	94.49	72.20	95.35	75.06	88.13	89.60
	$PA_{NS}\%$ - $PA_S\%$	90.78	81.91	91.62	84.94	96.04	72.51

As the settlement class covers a sensibly small proportion of area compared to the merger of all other non-settlement classes (~1% of Earth's emerged surface), an equal allocation reduces the standard error of its class-specific accuracy. Moreover, such an approach allows to best address user's accuracy estimation, which corresponds to the map "reliability" and is indicative of the probability that a pixel classified on the map actually represents the corresponding category on the ground. Accordingly, in this framework for each of the 50 selected tiles we randomly extracted 1000 settlement and 1000 non-settlement samples from the WSF2015 and used these as centre cells of the 3x3 reference block assessment units to label by photointerpretation. Such a strategy resulted in an overall amount of $(1000 + 1000) \times 9 \times 50 = 900.000$ cells labelled by the crowd.

Analysis

As measures for assessing the accuracy of the settlement extent maps, we considered:

- the percentage overall accuracy *OA%*;
- the Kappa coefficient;
- the percentage producer's ($PA_S\%$, $PA_{NS}\%$) and user's ($UA_S\%$, $UA_{NS}\%$) accuracies for both the settlement and non-settlement class;
- the percentage average accuracy *AA%* (i.e., the average between $PA_S\%$ and $PA_{NS}\%$).

Results

Table 5 reports the accuracies exhibited by the WSF2015 according to the three considered agreement criteria for different definitions of settlement; specifically, we considered as "settlement" all areas covered by: i) buildings; ii) buildings or building lots; or iii) buildings, building lots or roads / paved surfaces. As one can notice, accuracies are always particularly high, thus confirming the effectiveness of the employed approach and the reliability of the final settlement extent maps. The best performances in terms of kappa are obtained when considering settlements as composed by buildings, building lots and roads / paved surfaces for criteria 1 and 2 (i.e., 0.6938 and 0.7317, respectively) and by buildings and building lots for criteria 3 (0.7716); the OA% follows a similar trend. This is in line with the adopted settlement definition. Moreover, agreement criteria 3 results in accuracies particularly high with respect to criteria 1 and 2 when considering as settlement just buildings or the combination of buildings and lots. This can be explained by the fact that when the detection is mainly driven by Landsat data then the whole 3x3 assessment unit tends to be labelled as settlement if a building or a lot intersect the corresponding 30m resolution pixel.

3.3.3 Accuracy Assessment of the Percentage Impervious Surface Product

In the following section, the strategy designed for validating the PIS product is presented; specifically, details are given for all protocols adopted for each of the accuracy assessment components, namely response design, sampling design, and analysis. Results are discussed afterwards.

Response Design

The response design encompasses all steps of the protocol that lead to a decision regarding agreement of the reference and map classifications. The four major features of the response design are the source of information used to determine the source of reference data, the spatial unit, the labelling protocol for the reference classification, and a definition of agreement.

- **Source of Reference Data:** Cloud-free VHR multi-spectral imagery (Visible + Near Infrared) acquired at 2m spatial resolution (or higher) covering a portion of the AOI for which the Landsat-based PIS product has been generated;
- **Spatial Assessment Unit:** A 30x30m size unit has been chosen according to the spatial resolution of the Landsat imagery employed to generate the PIS product;
- **Reference Labelling Protocol:** As a first step, the NDVI is computed for each VHR scene followed by a manual identification of the most suitable threshold that allows to exclude all the vegetated areas (i.e. non-impervious). Then, the resulting mask is refined by extensive photointerpretation.
- **Definition of Agreement:** The above-mentioned masks are aggregated at 30m spatial resolution and compared per-pixel with the resulting VHR-based reference PIS to the corresponding portion of the Landsat-based PIS product.

Sampling Design

The entirety of pixels covered by the available VHR imagery over the given AOI is employed for assessing the quality of the Landsat-based PIS product.

Analysis

As measures for assessing the accuracy of the PIS maps, following indices are computed:

- the *Pearson's Correlation coefficient*: it measures the strength of the linear relationship between two variables and it is defined as the covariance of the two variables divided by the product of their standard deviations; in particular, it is largely employed in the literature for validating the output of regression models;
- The *Mean Error (ME)*: it is calculated as the difference between the estimated value (i.e., the Landsat-based PIS) and the reference value (i.e., the VHR-based reference PIS) averaged over all the pixels of the image;
- The *Mean Absolute Error (MAE)*: it is calculated as the absolute difference between the estimated value (i.e., the Landsat-based PIS) and the reference value (i.e., the VHR-based reference) averaged over all the pixels of the image.

Results

To assess the effectiveness of the method developed to generate the PIS maps, its performances over 5 test sites is analysed (i.e. Antwerp, Helsinki, London, Madrid and Milan) by means of WorldView-2 (WV2) scenes acquired in 2013-2014 at 2m spatial resolution. In particular, given the spatial detail offered by WV2 imagery, it was possible to delineate with a very high degree of confidence all the buildings and other impervious surfaces included in the different investigated areas. Details about acquisition date and size are reported in Table 6, along with the overall number of final 30x30m validation samples derived for the validation exercise. Such a task demanded a lot of manual interactions and transferring it to other AOIs would require extensive efforts; however, it can be reasonably assumed that the final quality assessment figures (computed on the basis of more than 1.9 million validation samples) shall be considered representative also for PIS maps generated in the framework of EO4SD-Urban. Table 6 reports the quantitative results of the comparison between the PIS maps generated using Landsat-7/8 data acquired in 2013-2014 and the WV2-based reference PIS maps. In particular, the considered approach allowed to obtain a mean correlation of 0.8271 and average ME and MAE equal to -0.09 and 13.33, respectively, hence assessing the great effectiveness of the Landsat-based PIS products. However, it is worth also pointing out that due to the different acquisition geometries, WV2 and LS8 images generally exhibit a very small shift. Nevertheless, despite limited, such displacement often results in a one-pixel shift between the Landsat-based PIS and the WV2-based reference PIS aggregated at 30m resolution. This somehow affects the computation of the MAE and of the correlation coefficient (which however yet resulted in highly satisfactory values). Instead, the bias does not alter the ME, which always exhibited values close to 0, thus confirming the capabilities of the technique and the reliability of the final products.

Table 6: Acquisition dates and size of the WV2 images available for the 5 test sites analysed in the validation exercise along with the number of corresponding 30x30m validation samples.

	Acquisition Date [DD.MM.YYYY]	Original Size [2x2m pixel]	Validation Samples [30x30m unit]
Antwerp	31.07.2014	5404 x 7844	188.280
Helsinki	21.04.2014	12468 x 9323	516.882
London	28.08.2013	7992 x 8832	313.937
Madrid	20.12.2013	10094 x 13105	588.202
Milan	14.05.2014	8418 x 7957	297.330

3.3.4 Accuracy Assessment of Urban Green Areas Product

The validation of the Green Area mapping results is done in a similar way as the validation for the Land Use Land Cover product. The necessary amount of sampling points is calculated according to the formula of Goodchild et al. (1994), which is given in Table 2.

Table 2: Calculation of the minimum number of samples according Goodchild et al. (1994).

Variables	Values
p	0.85
q	0.15
E	0.05
z	1.96
$n = \frac{p * q}{(E / z)^2}$	**196**
n with 10% oversampling	**215**
with:	
p = required accuracy of the data	
q = 1-p	
E = Level of acceptable (allowable) sample error	
Z = value from table (for the given level of significance)	

The calculated number of 215 sample points was randomly distributed among the entire map and overlaid on the VHR data of each epoch. The following Figure (see Figure 4) shows the mapping result with the overlaid sample points.

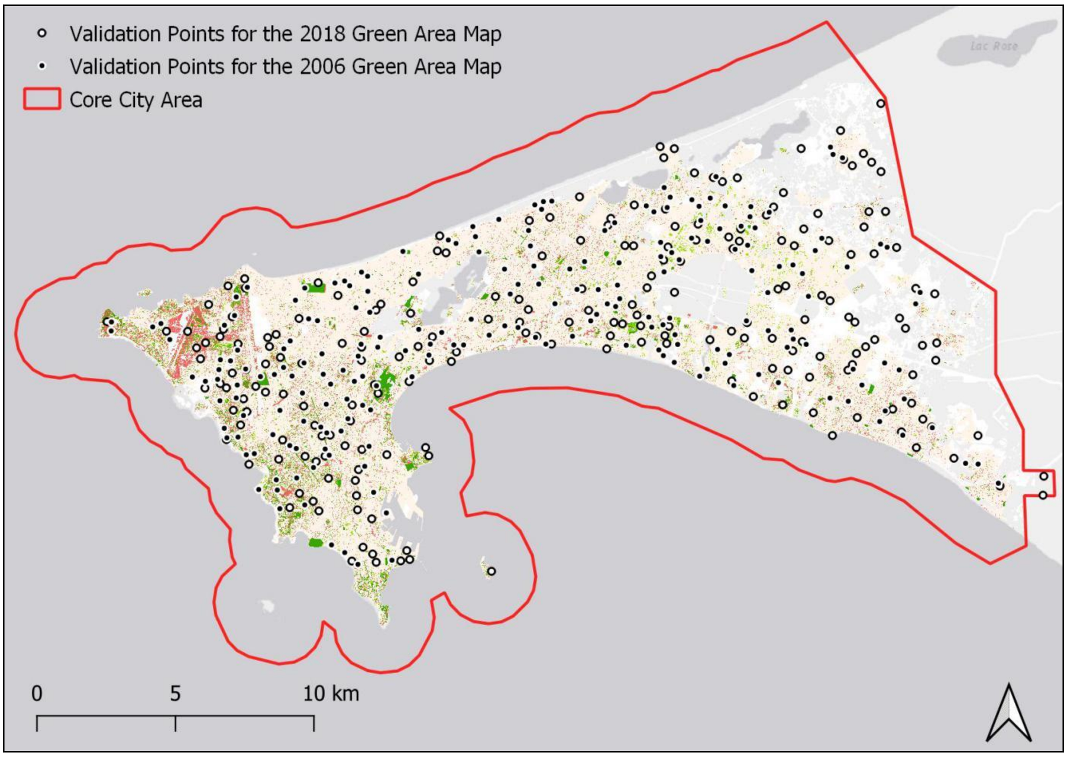

Figure 4: Result of the Urban Green Area mapping in Dakar (change product) with sampling points used for product validation.

At each sample point location, the reference data was collected by visual interpretation of the VHR data. The size of the area to be observed had to be related to the Minimum Mapping Unit (MMU) of the map product to be assessed. Finally, visual interpreted land cover type was compared with the mapping results and the numbers of correctly and not-correctly classified observations were recorded. From this information the specific error matrices and statistics were computed.

The confusion matrices show the mapping error for each relevant class. For each class the number of samples which are correctly and not correctly classified are listed in the Tables below. They allow the calculation of the user and producer accuracies for each class as well as the confidence interval at 95% confidence levels based on the formulae above. The results of the Accuracy Assessment are listed in Table 3 and Table 4 below, for 2006 and 2018 respectively.

Table 3: Results of the Accuracy Assessment of Urban Green Areas in Dakar, 2006.

Overall Accuracy: 99.07 %.

Urban Green 2006	Reference Data		Totals
	0 - Non-Urban Green Area	1 - Urban Green Area	
0 - Non-Urban Green Area	175	2	177
1 - Urban Green Area	0	38	38
Totals	175	40	**215**

Table 4: Results of the Accuracy Assessment of Urban Green Areas in Dakar, 2018.

Overall Accuracy: 98.6 %.

Urban Green 2018	Reference Data		Totals
	0 - Non-Urban Green Area	1 - Urban Green Area	
0 - Non-Urban Green Area	190	3	193
1 - Urban Green Area	0	22	22
Totals	190	25	**215**

The confusion matrices are additionally provided within the Quality Control documentation in Annex 3 and showing the mapping error for each relevant class. For each class the number of samples, which are correctly and not correctly classified, are listed, which allows the calculation of the user and producer accuracies for each class as well as the confidence interval at 95% confidence levels.

3.3.5 Accuracy Assessment of Flood Extent Product

The Accuracy Assessment of the Flood Extent product was performed only for the flood events for which Google Earth VHR images are available for performing the extraction of the reference dataset by independent visual interpretation. Sampling points are selected for each event to ensure a representative sampling for evaluating the product accuracy. Flood event years are going from 2009 to 2018.

Single-stage stratified random sampling approach was implemented. For each event, 20 sampling points were randomly selected within the flood extent extracted by the producer (stratum 1), and additional 10 points within a buffer area of 200 meters (stratum 2). The samples selected for each event and combined in a single layer are illustrated in Figure 5.

In this way, the reference information was extracted for each sample point by visual interpretation of the VHR data made available to image analysis expert. Then, the results were compiled through confusion matrices allowing to calculate the overall thematic accuracy for each event. The results of the accuracy assessment for the whole series of flood events are presented in Table 7.Table 7: Results of the accuracy assessment of flood extents in Dakar - Overall Accuracy 90.33 %.

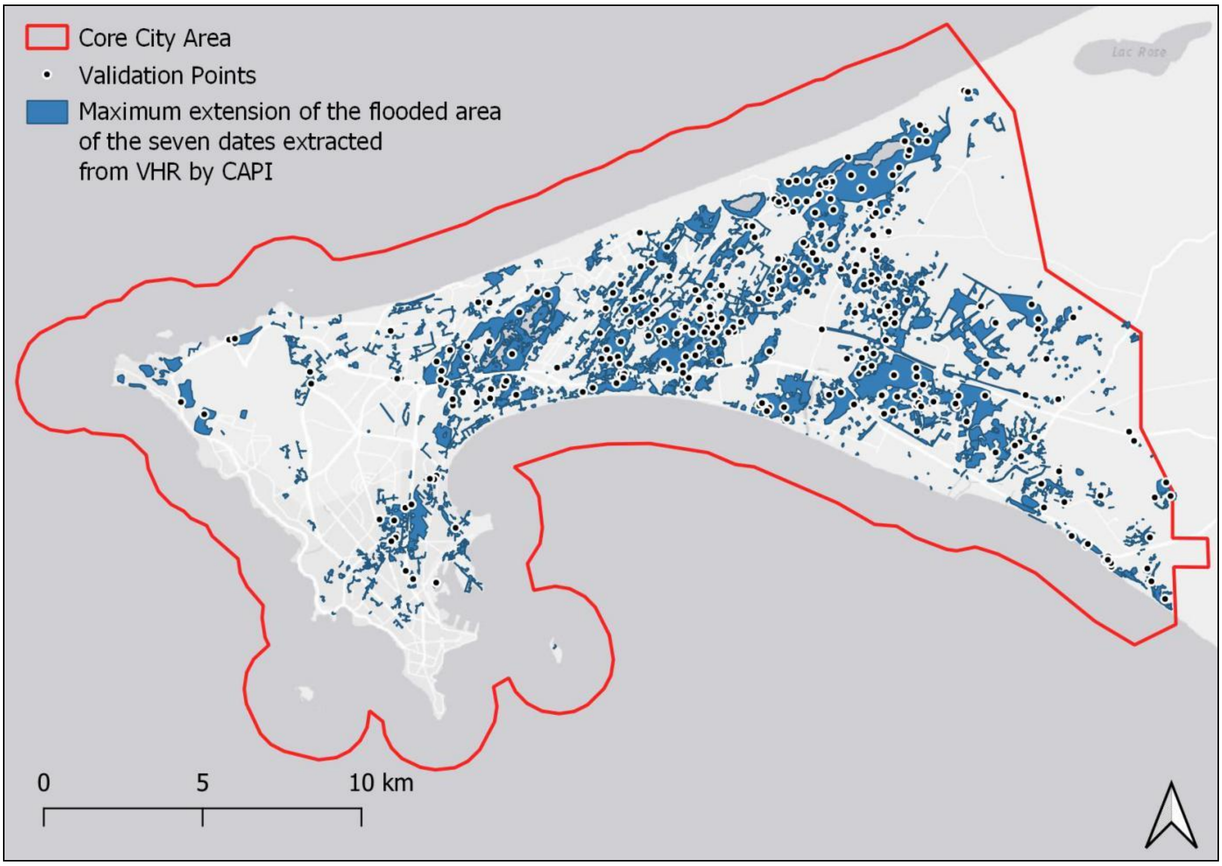

Figure 5: Result of the Flood extent mapping in Dakar with sampling points used for product validation.

Table 7: Results of the accuracy assessment of flood extents in Dakar - Overall Accuracy 90.33 %.

Flood Extent Dates extracted by CAPI	Reference Data		Totals
	Non flooded area	Flooded area	
Non flooded area	78	22	**100**
Flooded area	7	193	**200**
Totals	**85**	**215**	**300**

The number of samples which were correctly and not correctly classified is made clearly visible, allowing the calculation of the overall accuracy, the user and producer accuracies for each class, as well as the confidence interval at 95% confidence level. The matrices and analysis results for the whole series of events and for each of them are made available in Annex 3.

3.4 Quality Control/Assurance

A detailed Quality Control and Quality Assurance (QC/QA) system has been developed which records and documents all quality relevant processes ranging from the agreed product requirements, the different types of input data and their quality as well as the subsequent processing and accuracy assessment steps. The main goal of the QC/QA procedures was the verification of the completeness, logical consistency, geometric and thematic accuracy and that metadata are following ISO standards on geographic data quality and INSPIRE data specifications. These assessments were recorded in Data Quality Sheets which are provided in Annex 3. The QC/QA procedures were based on an assessment of a series of relevant data elements and processing steps which are part of the categories listed below:

- Product requirements;
- Specifications of input data: EO data, in-situ data, ancillary data;
- Data quality checks: EO data quality, in-situ data quality, ancillary data quality;
- Geometric correction, geometric accuracy, data fusion (if applicable), data processing;
- Thematic processing: classification, plausibility checks;
- Accuracy: thematic accuracy, error matrices
- Delivery checks: completeness, compliancy with requirements

After each intermediate processing step a QC/QA was performed to evaluate products appropriateness for the subsequent processing (see Figure 6).

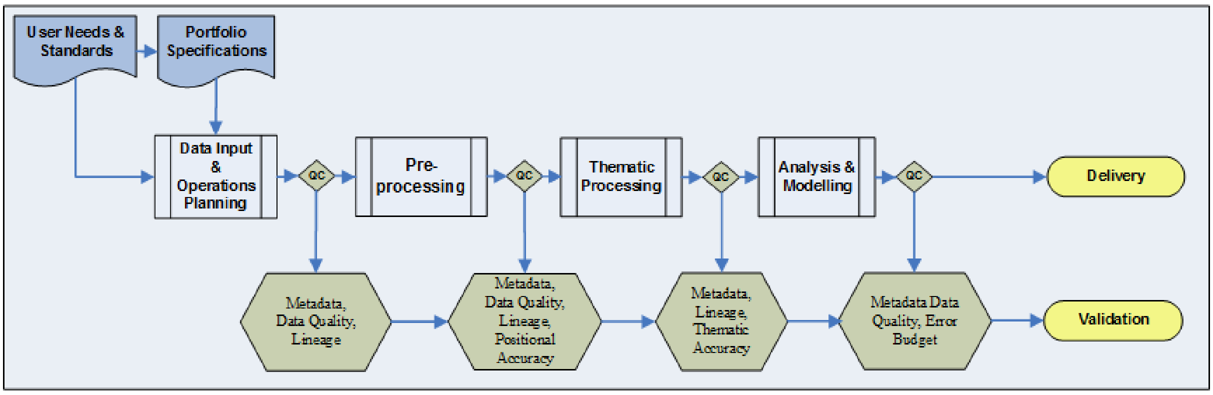

Figure 6: Quality Control process for EO4SD-Urban product generation. At each intermediate processing step output properties are compared against pre-defined requirements.

After the initial definition of the product specifications (output) necessary input data were defined and acquired. Input data include all satellite data and reference data e.g. in-situ data, reference maps, topographic data, relevant studies, existing standards and specifications, statistics. These input data were the baseline for the subsequent processing and therefore all input data had to be checked for **completeness**, **accuracy** and **consistency**. The evaluation of the quality of input data provides confidence of their suitability for further use (e.g. comparison with actual data) in the subsequent processing line. Data processing towards the end-product required multiple intermediate processing steps. To guarantee a traceable and quality assured map production the QC/QA assessment was performed and documented by personnel responsible for the Quality Control/Assurance. The results of all relevant steps provided information of the acceptance status of a dataset/product.

The documentation is furthermore important to provide a comprehensive and transparent summary of each production step and the changes made to the input data. With this information the user will be able to evaluate the provided services and products. Especially the accuracy assessment of map products and the related error matrices are highly important to rate the quality and compare map products from different service providers.

The finalised QC/QA forms are attached in Annex 3.

3.5 Metadata

Metadata provides additional information about the delivered products to enable it to be better understood. In the current project a harmonised approach to provide metadata in a standardised format applicable to all products and end-users was adopted. Metadata are provided as XML files, compliant to the ISO standard 19115 "Metadata" and ISO 19139 "XML Scheme Implementation". The metadata files have been created and validated by the GIS/IP-operator for each map product with the Infrastructure for Spatial Information in Europe (INSPIRE) Metadata Editor available at: http://inspire-geoportal.ec.europa.eu/editor/.

The European Community enacted a Directive in 2007 for the creation of a common geo-data infrastructure to provide a consistent metadata scheme for geospatial services and products that could be used not only in Europe but globally. The geospatial infrastructure called INSPIRE was built in a close relation to existing International Organization for Standardization (ISO) standards. These are ISO 191115, ISO 19119 and ISO 15836. The primary incentive of INSPIRE is to facilitate the use and sharing of spatial information by providing key elements and guidelines for the creation of metadata for geospatial products and services.

The INSPIRE Metadata provides a core set of metadata elements which are part of all the delivered geo-spatial products to the users. Furthermore, the metadata elements provide elements that are necessary to perform queries, store and relocate data in an efficient manner. The minimum required information is specified in the Commission Regulation (EC) No 1205/2008 of 3 December 2008 and contains 10 elements:

- Information on overall Product in terms of: Point of contact for product generation, date of creation
- Identification of Product: Resource title, Abstract (a short description of product) and Locator
- Classification of Spatial Data
- Keywords (that define the product)
- Geographic information: Area Coverage of the Product
- Temporal Reference: Temporal extent; date of publication; date of last revision; date of creation
- Quality and Validity: Lineage, spatial resolution
- Conformity: degree of conformance to specifications
- Data access constraints or Limitations
- Responsible party: contact details and role of contact group/person

These elements (not exhaustive) constitute the core information that has to be provided to meet the minimum requirements for Metadata compliancy. Each element and its sub-categories or elements have specific definitions; for example, in the element “Quality” there is a component called “Lineage” which has a specific definition as follows: “a statement on process history and/or overall quality of the spatial data set. Where appropriate it may include a statement whether the data set has been validated or quality assured, whether it is the official version (if multiple versions exist), and whether it has legal validity. The value domain of this element is free text,” (INSPIRE Metadata Technical Guidelines, 2013). The detailed information on the Metadata elements and their definitions can be found in the “INSPIRE Metadata Implementing Rules: Technical Guidelines,” (2013). Each of the EO4SD-Urban products will be accompanied by such a descriptive metadata file. It should be noted that the internal use of metadata in these institutions might not be established at an operational level, but the file format (*.xml) and the web accessibility of data viewers enable for the full utility of the metadata.

4 Analysis of Mapping Results

This Chapter presents and assesses all results that have been produced within the framework of the current project. Especially, it provides the results of some standard analytics undertaken with these products including the following:

- Settlement Extent – Developments from 2000, 2005, 2010 to 2015
- Land Use / Land Cover - Status and Trends between 2006 and 2018
- Urban Green Areas - Status and Change between 2006 and 2018

It is envisaged that these analytics provide information on general trends and developments in the Core City and Larger Urban areas, which can then be further interpreted and used by Urban planners and the City Authorities for city planning.

It should be noted that all digital data sets for these products are provided in concurrence with this City Report with all the related metadata and Quality Control documentation.

4.1 Settlement Extent – Developments 2000, 2005, 2010 and 2015

The Urban or World Settlement Extent (WSE) product in the EO4SD-Urban project is provided by the German Aerospace Centre (DLR) and is provided for 4 points in time; this product and its accuracy was described in Section 2.5 and 3.3.2. In the current project, the Urban Extent product for Dakar was first used to assess historical developments from 2000-2015 (see Figure 7 and Figure 8). Further analysis by overlaying administrative boundaries can be performed to assess urbanisation extent patterns based on administrative units.

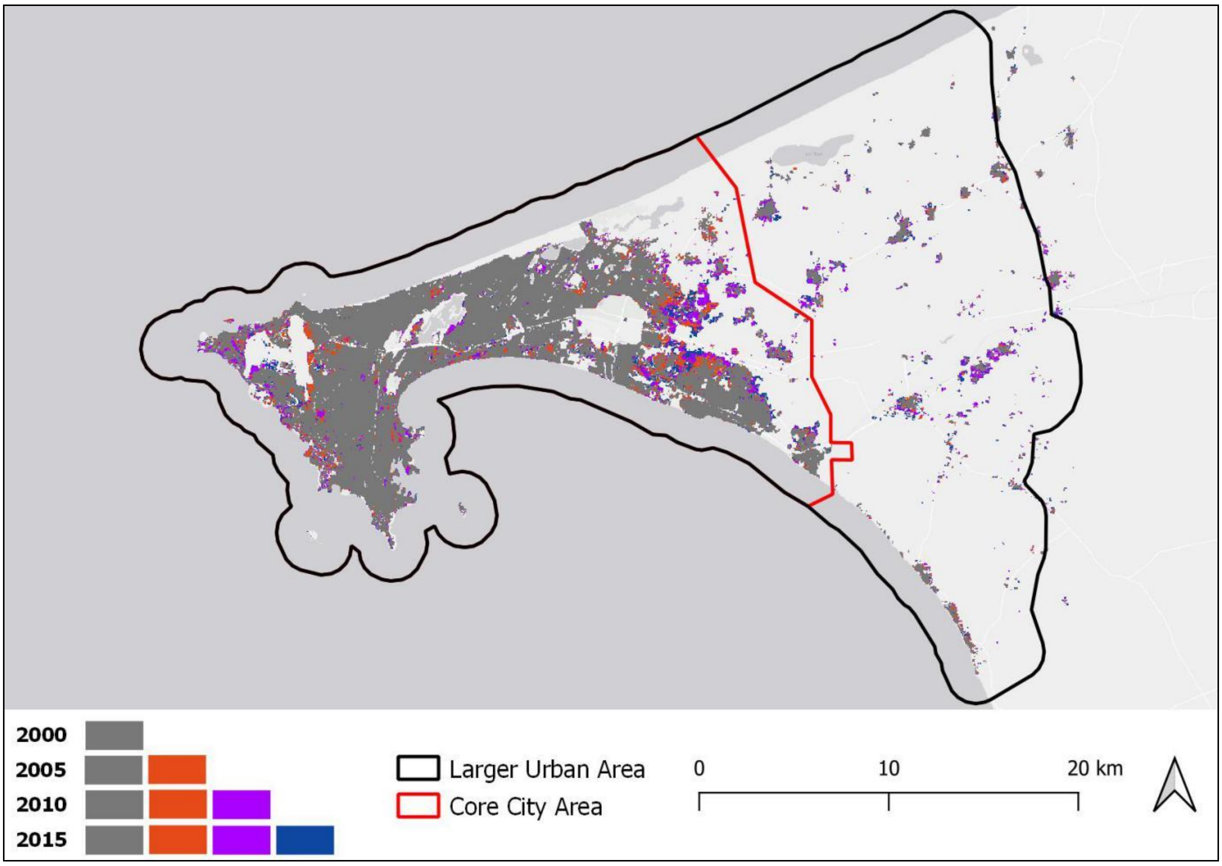

Figure 7: Settlement Extent developments in the epochs 2000 to 2005, 2005 to 2010 and 2010 to 2015 in Dakar and surrounding region.

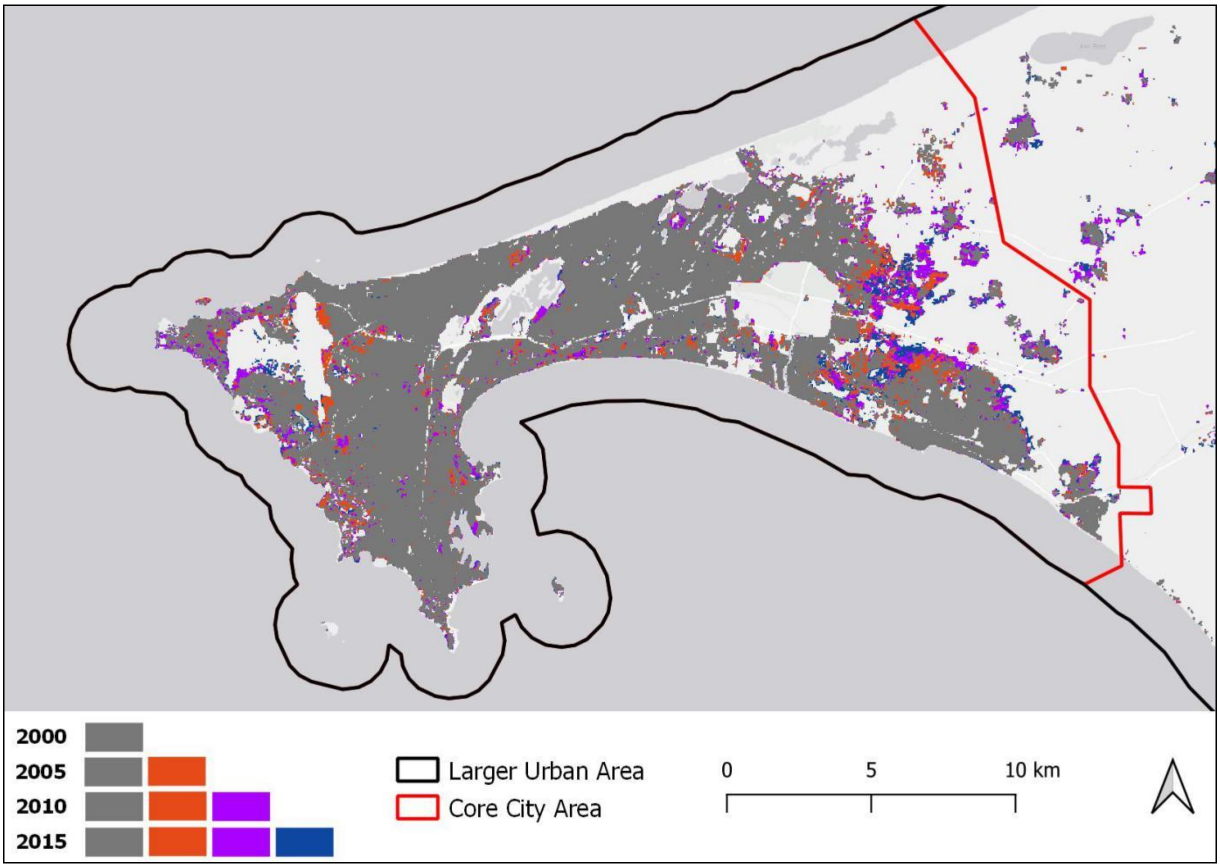

Figure 8: Settlement Extent developments in the epochs 2000 to 2005, 2005 to 2010 and 2010 to 2015 in Dakar within the High Density Area.

4.2 Land Use / Land Cover 2003/2006 and 2018

This Section presents the results of the LU/LC mapping for the Historic and Current status as well the statistical information on the changes between these two epochs, first for the Core City Area, and then for the Larger Urban Area.

4.2.1 LU/LC Mapping for Core City Area

The LU/LC map generated for 2018 reference year is depicted in Figure 9 for the Core City area. A cartographic version of the map layout is provided as a pdf file in addition to the geo-spatial product.

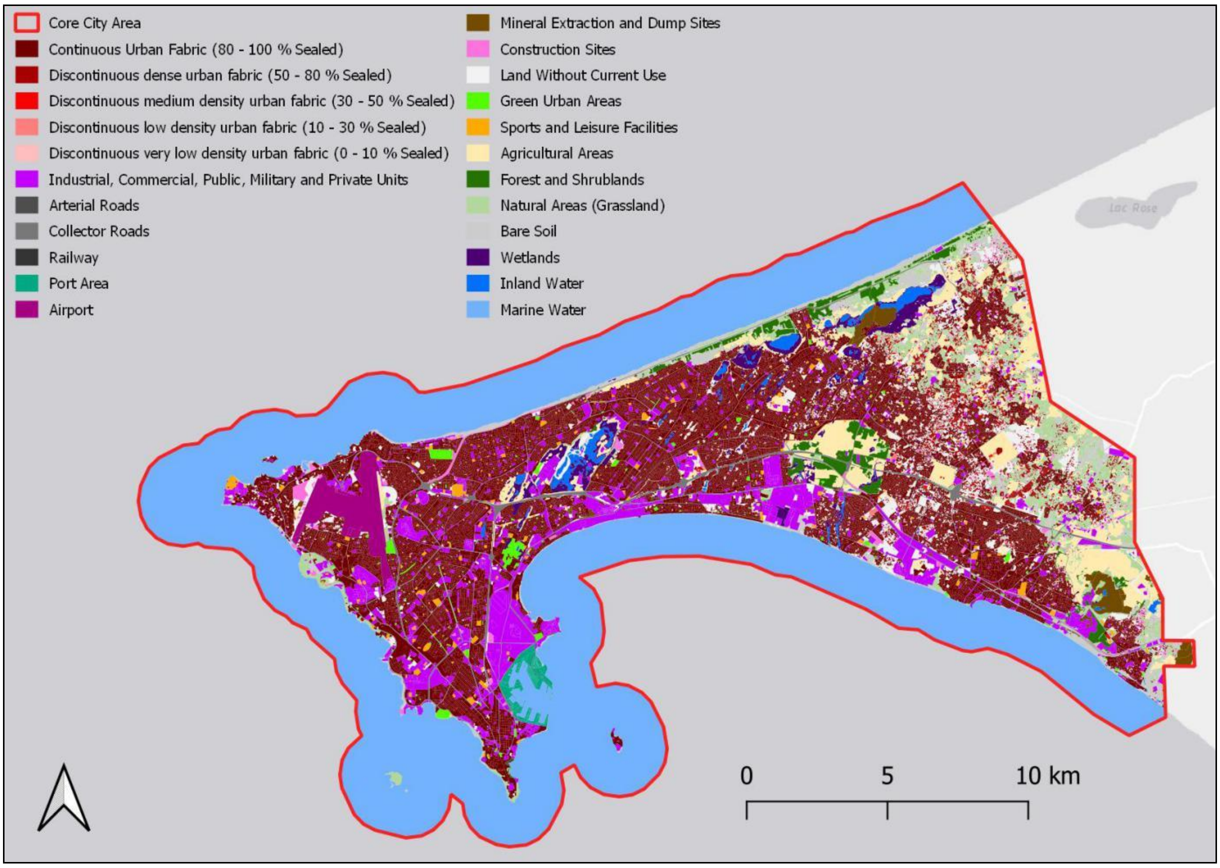

Figure 9: Core City Area - Detailed LU/LC 2018 in Dakar

Logically, most of the area is covered by artificial surfaces, such as the ones shown in Figure 10. Located along the Atlantic coast, the city has developed from west to east over time. The international airport is very close to the sea on the western district while the port and large industrial zones are located on the south coast.

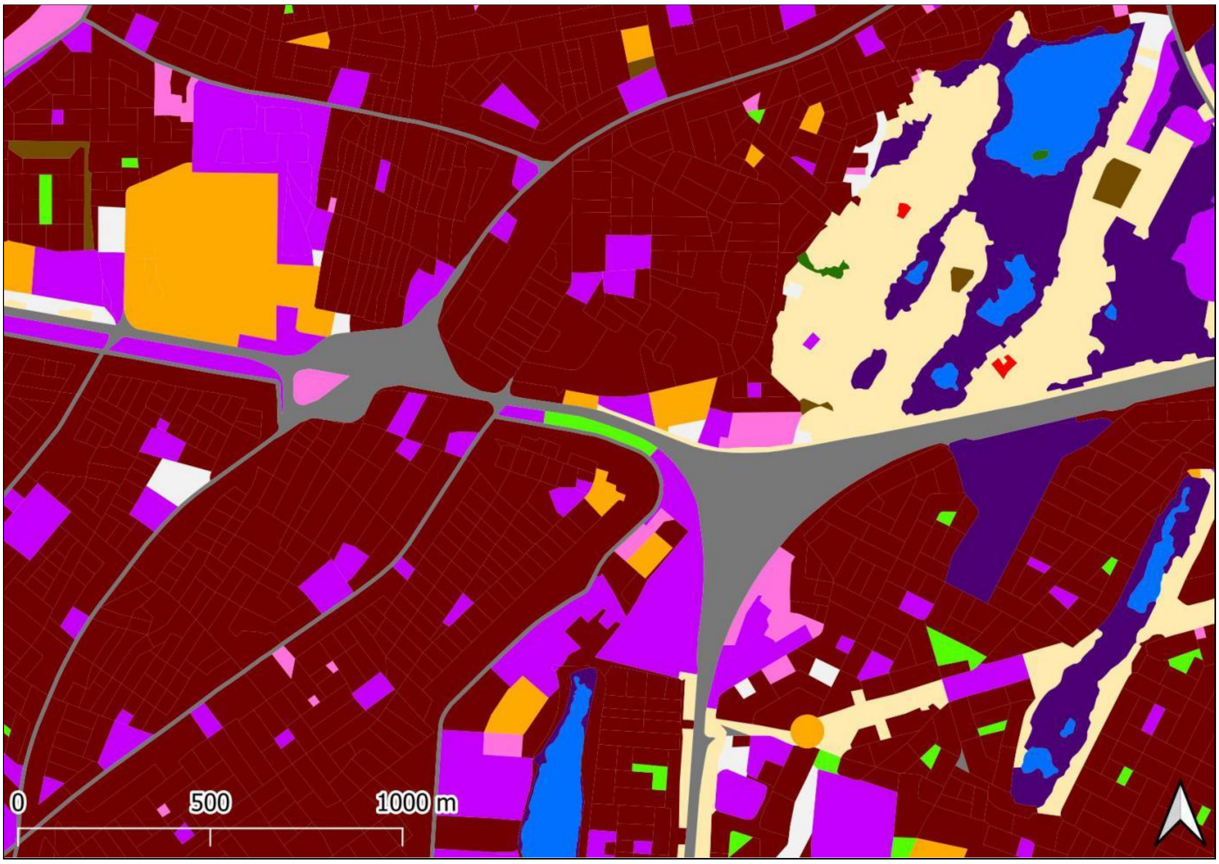

Figure 10: Core City Area - Insight on the detailed Land Use Land Cover 2018 inside the city.

Figure 11 and Figure 12 provide more detailed information on the class disaggregation and area coverage for the epochs 2006 and 2018.

Considering that 38% of the defined area of interest is covered by the Atlantic Ocean, it is confirmed that the land is mainly covered by artificial surfaces. Continuous residential areas, industrial and commercial zones as well as land without current use especially in the eastern part are the main LULC classes with transport infrastructure (including one airport and one port area). The remaining areas in the eastern part are used for agriculture purposes or generally covered by natural areas (grassland) or bare soil.

Urban sprawl is clearly the main trend when comparing the figures from 2006 and 2018: continuous residential areas as well as industrial and commercial zones expanded a lot respectively from 20 to 25.6% and from 6.1 to 7.5% over the period, while agricultural areas and natural ones decreased respectively from 11.2 to 5.1% and from 5.6 to 4.4%.

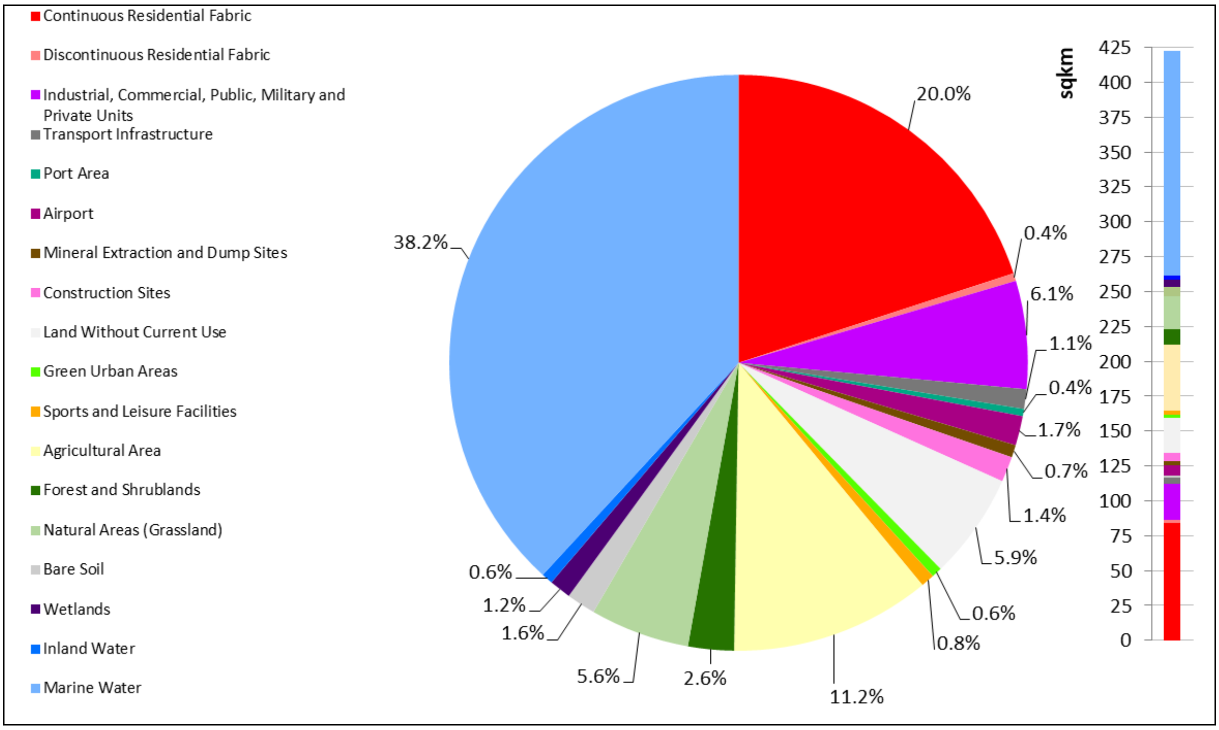

Figure 11: Core City Area - Detailed LU/LC 2006 structure, in % (left) and km^2 (right).

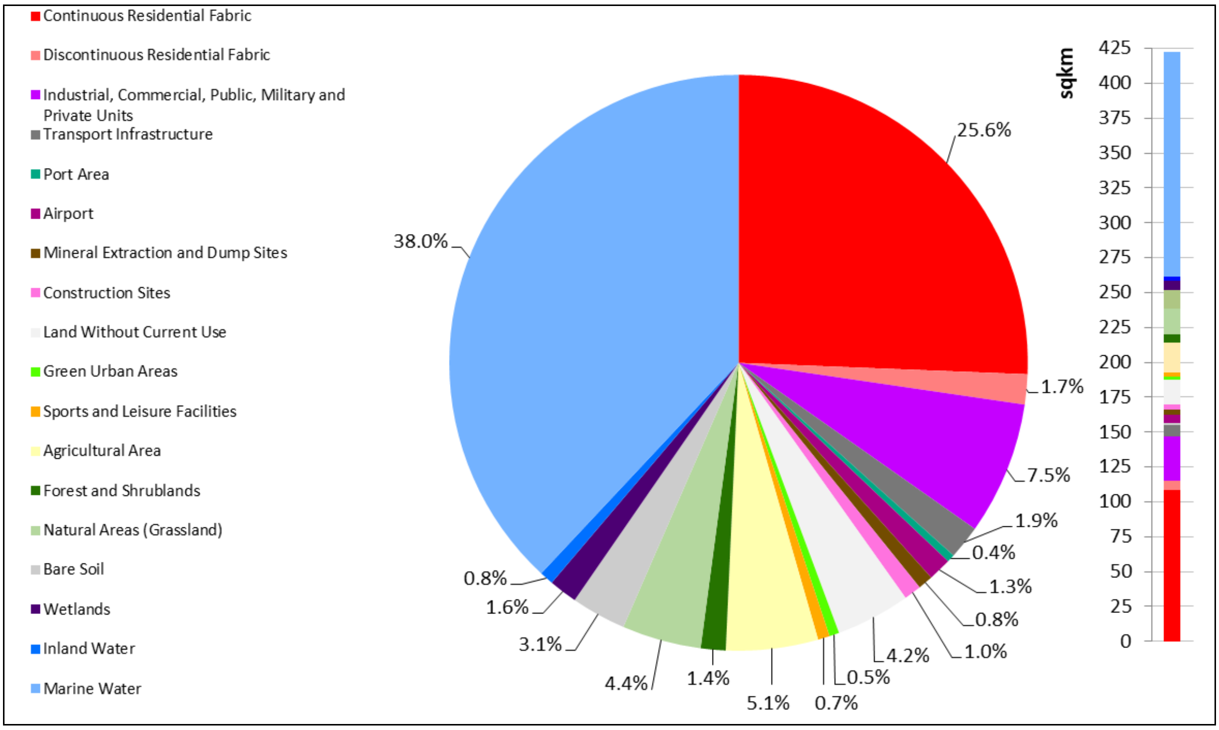

Figure 12: Core City Area - Detailed LU/LC 2018 structure, in % (left) and km^2 (right).

Description of LULC Changes:

In addition to the overall LU/LC classification for the two epochs it is interesting to assess the different trends between classes over the 12 year time period. The quantitative figures for each class are first provided in Table 8 for the Core City area to get an overview. The next Section will highlight the LU/LC change information between the two epochs in more detail.

Table 8: Detailed information on area and percentage of total area for each class for 2006 and 2018 as well as the changes for the Core City area

LU/LC Classes	2018		2006		Change		Change per Year	
	sqkm	% of total	sqkm	% of total	sqkm	%	sqkm	%
1110 - Continuous Urban Fabric (80 - 100 % Sealed)	108.3	25.63%	84.4	19.97%	23.9	28%	2.0	2.4%
1121 - Discontinuous dense urban fabric (50 - 80 % Sealed)	6.6	1.57%	1.5	0.36%	5.1	342%	0.4	28.5%
1122 - Discontinuous medium density urban fabric (30 - 50 % Sealed)	0.3	0.07%	0.2	0.05%	0.1	48%	0.0	4.0%
1123 - Discontinuous low density urban fabric (10 - 30 % Sealed)	0.2	0.04%	0.1	0.02%	0.1	62%	0.0	5.2%
1124 - Discontinuous very low density urban fabric (0 - 10 % Sealed)	0.0	0.00%	0.0	0.00%	0.0	-80%	0.0	-6.7%
1210 - Industrial, Commercial, Public, Military and Private Units	31.5	7.46%	25.6	6.06%	5.9	23%	0.5	1.9%
1222 - Collector Roads	7.5	1.78%	4.2	1.00%	3.3	78%	0.3	6.5%
1223 - Railway	0.4	0.10%	0.4	0.10%	0.0	0%	0.0	0.0%
1230 - Port Area	1.9	0.44%	1.7	0.40%	0.1	8%	0.0	0.7%
1240 - Airport	5.5	1.30%	7.0	1.65%	-1.5	-22%	-0.1	-1.8%
1310 - Mineral Extraction and Dump Sites	3.5	0.83%	3.0	0.70%	0.6	19%	0.0	1.6%
1330 - Construction Sites	4.1	0.97%	6.0	1.42%	-1.9	-32%	-0.2	-2.7%
1340 - Land Without Current Use	17.5	4.15%	25.1	5.95%	-7.6	-30%	-0.6	-2.5%
1410 - Green Urban Areas	2.3	0.55%	2.5	0.58%	-0.1	-6%	0.0	-0.5%
1420 - Sports and Leisure Facilities	2.8	0.66%	3.2	0.76%	-0.4	-13%	0.0	-1.1%
2000 - Agricultural Areas	21.7	5.14%	47.4	11.21%	-25.6	-54%	-2.1	-4.5%
3100 - Forest and Shrublands	5.9	1.39%	10.8	2.56%	-5.0	-46%	-0.4	-3.8%
3200 - Natural Areas (Grassland)	18.7	4.42%	23.5	5.55%	-4.8	-20%	-0.4	-1.7%
3300 - Bare Soil	13.0	3.07%	6.9	1.62%	6.1	89%	0.5	7.4%
4000 - Wetlands	6.7	1.59%	5.1	1.22%	1.6	31%	0.1	2.5%
5100 - Inland Water	3.3	0.78%	2.7	0.63%	0.6	23%	0.1	1.9%
5200 - Marine Water	160.7	38.05%	161.2	38.17%	-0.5	0%	0.0	0.0%
Total	**422.4**	**100%**	**422.4**	**100%**	-	-	-	-

The previous analysis is confirmed. Indeed, the main changes between the two epochs come from agriculture whose area has been reduced by more than half (from 47.4 to 21.7 sqkm), forests and shrublands whose extent has also been halved, while natural areas have been reduced by 20% (from 23.5 to 18.7 sqkm). This decrease of agriculture and main natural LULC classes is due to urban expansion, especially related to high-density residential areas (+28%) and industrial and commercial activities (+23%). This partially explains also the reduction of 30% of land without current use in the city. Finally, it is worth to highlight the slight decrease of urban green areas (-6%) and sports and leisure facilities (-13%).

4.2.2 Spatial Distribution of Main LU/LC Change Categories for Core City Area

In order to better analyze the growth trends and the spatial distribution of changes, meaningful aggregations of the Core city area LU/LC classes in both epochs were used. The following categories were developed for the City Core Area:

- Urban Densification: Changes from lower Residential Density Class into a higher Residential Density class;
- Urban Residential Expansion: all changes from Non-Urban Residential classes to a Residential class;
- Other Urban Land Use Expansion: all changes from Non-Residential Urban classes to Other Urban and Non-Urban classes.
- Urban to Agricultural or Natural/Semi-Natural Areas
- Natural or Semi-Natural to Agricultural Areas
- Agricultural to Natural or Semi-Natural Areas
- Changes within Natural and Semi-Natural Areas

The overlay analysis of these aggregated categories of the epochs 2006 and 2018 is depicted in Figure 13 and Figure 14 for the Core City area.

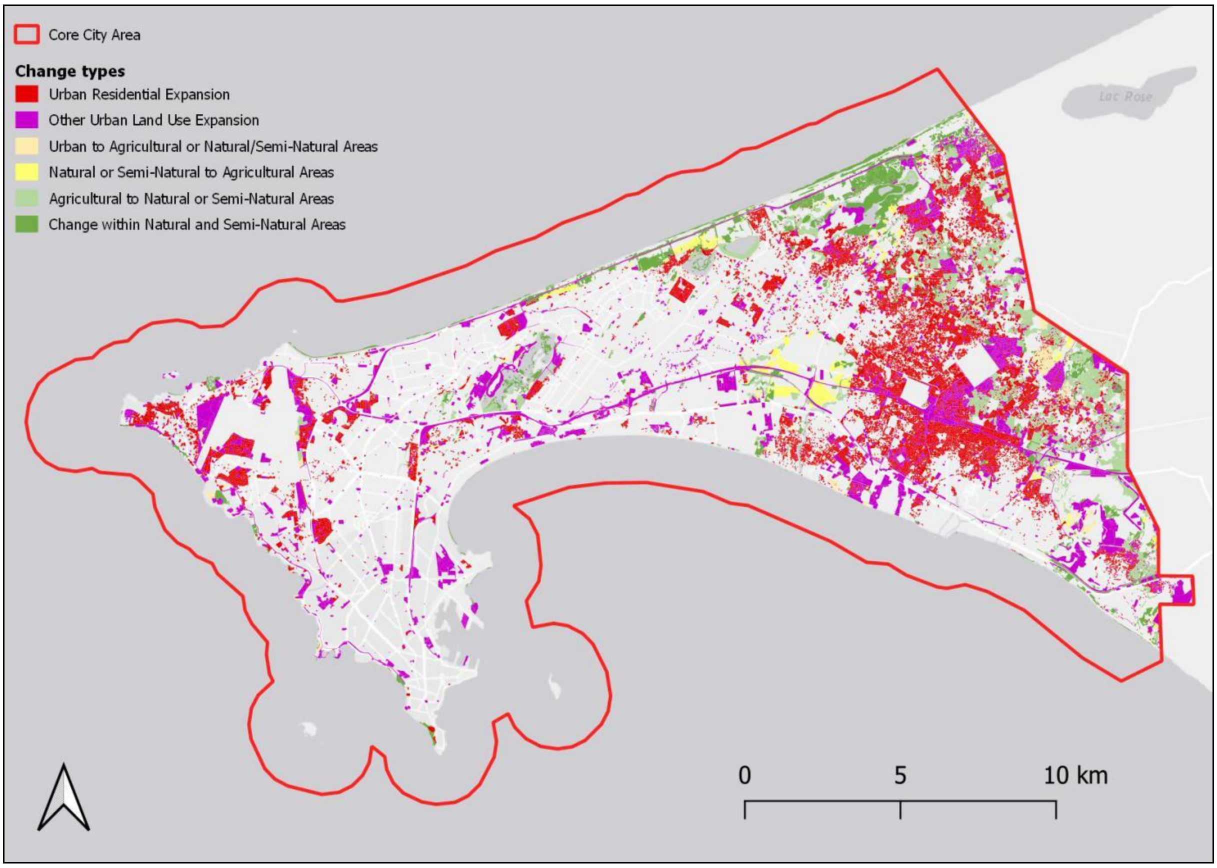

Figure 13: Core City Area – LU/LC change types and spatial distribution

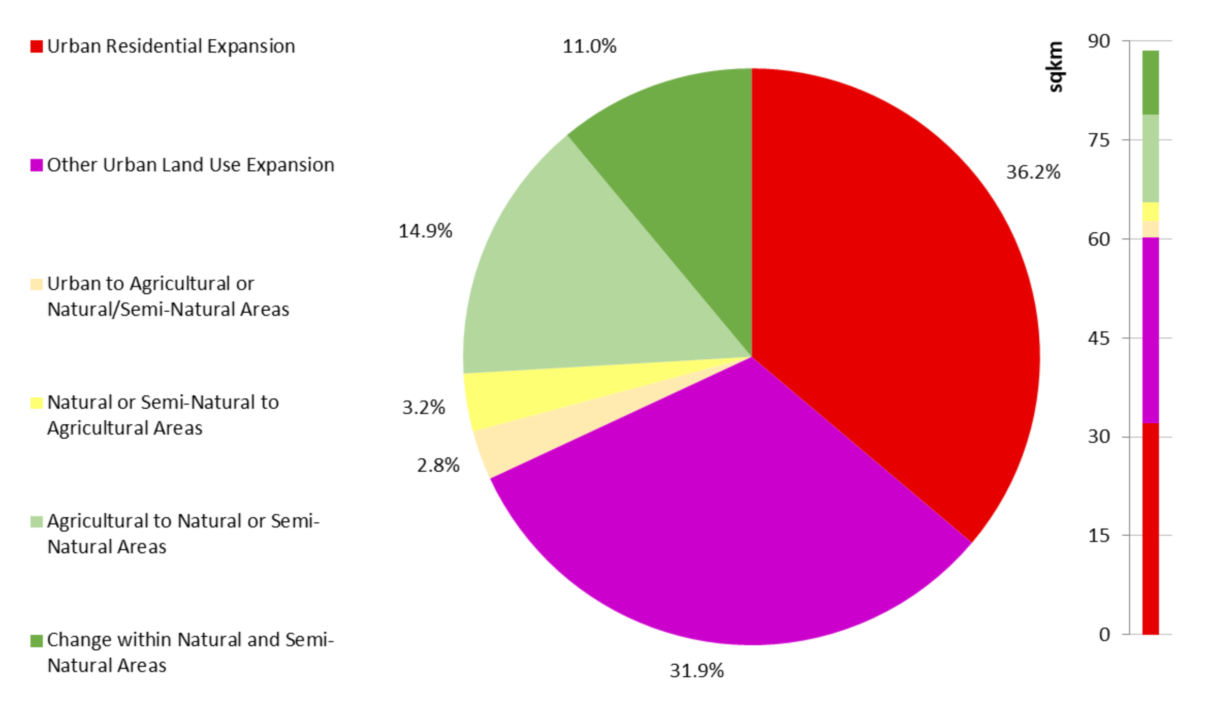

Figure 14: Core City Area – LU/LC Change types between 2006 and 2018 presented in % (left) and sqkm (right).

If there is no urban densification, the city expansion is quite huge on the original urban fringe since the phenomenon concerns two thirds of the changes that occurred between 2006 and 2018 in Dakar, representing around 60 sqkm of new built-up areas for residential, industrial and commercial purposes mainly. It is also worth to mention that some new urban areas in the nearest surroundings of the airport and a new major road from west to east were built during the period. The remaining changes mostly concern the loss of agricultural areas to natural or semi-natural ones and change dynamics within the latter, representing respectively 15 and 11% of the total area in evolution. Table 9 summarizes these analysis results.

Table 9: Overall Main LU/LC Changes Statistics for the Core City Area.

Change Classes	Change Core City area	
	sqkm	%
Urban Residential Expansion	32.0	36.2%
Other Urban Land Use Expansion	28.2	31.9%
Urban to Agricultural or Natural/Semi-Natural Areas	2.4	2.8%
Natural or Semi-Natural to Agricultural Areas	2.9	3.2%
Agricultural to Natural or Semi-Natural Areas	13.2	14.9%
Change within Natural and Semi-Natural Areas	9.8	11.0%
Total	**88.5**	**100%**

4.2.3 LU/LC Mapping for Larger Urban Area

The LU/LC for 2018 is depicted in Figure 15 for the Larger Urban area. A cartographic version of the map layout is provided as a PDF file in addition to the geo-spatial product.

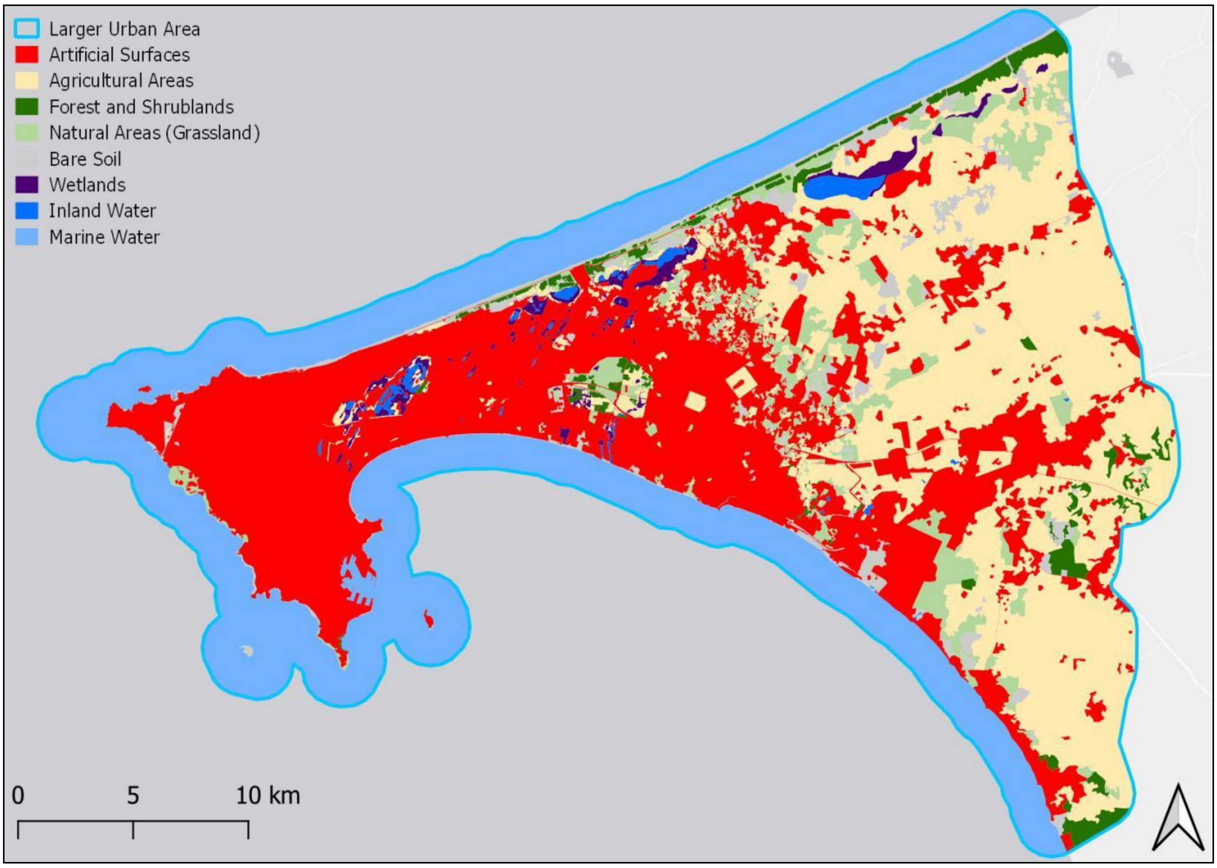

Figure 15: Larger Urban area – LU/LC 2018 in Dakar.

Figure 16 gives an insight on the LU/LC on the urban fringe.

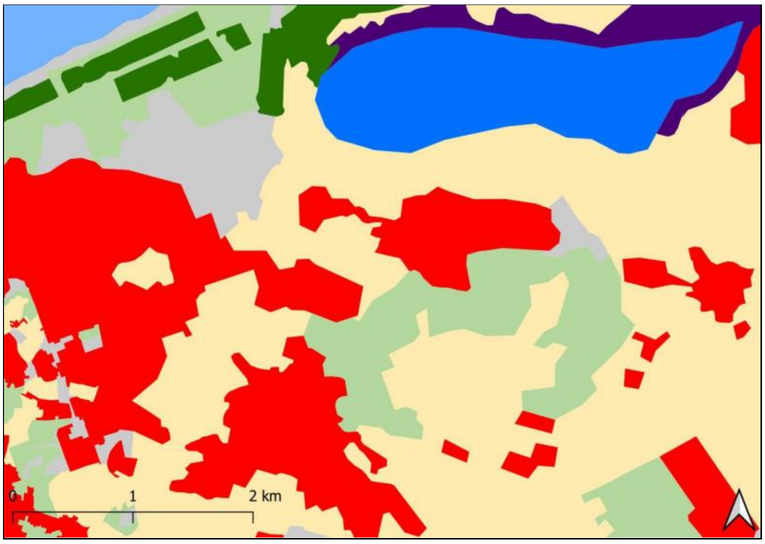

Figure 16: Larger Urban Area - Insight on the Land Use Land Cover 2018 on the urban fringe.

Artificial areas are predominant covering the full western part of the land as well as along the south coast. The remaining land is covered especially by agriculture and natural or semi-natural areas, while forests, shrublands, wetlands and inland water have a very limited presence.

Figure 17 and Figure 18 provide more detailed information on the class disaggregation and area coverage for the epochs 2006 and 2018.

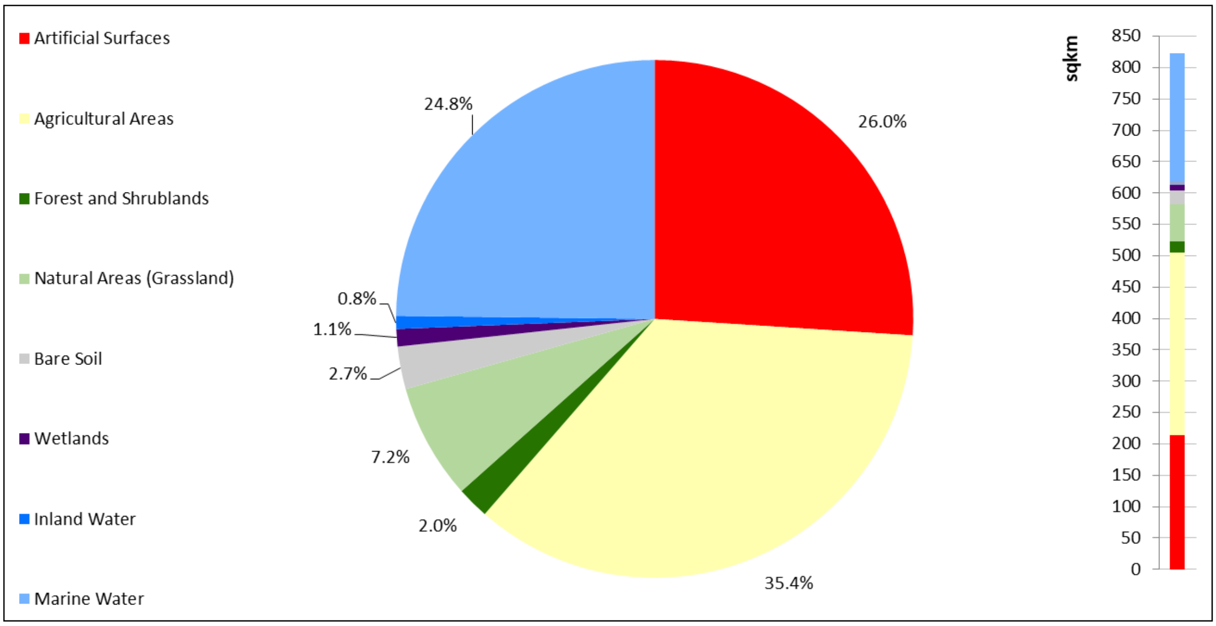

Figure 17: Larger Urban Area - Detailed LU/LC 2006 structure presented in % (left) and km² (right).

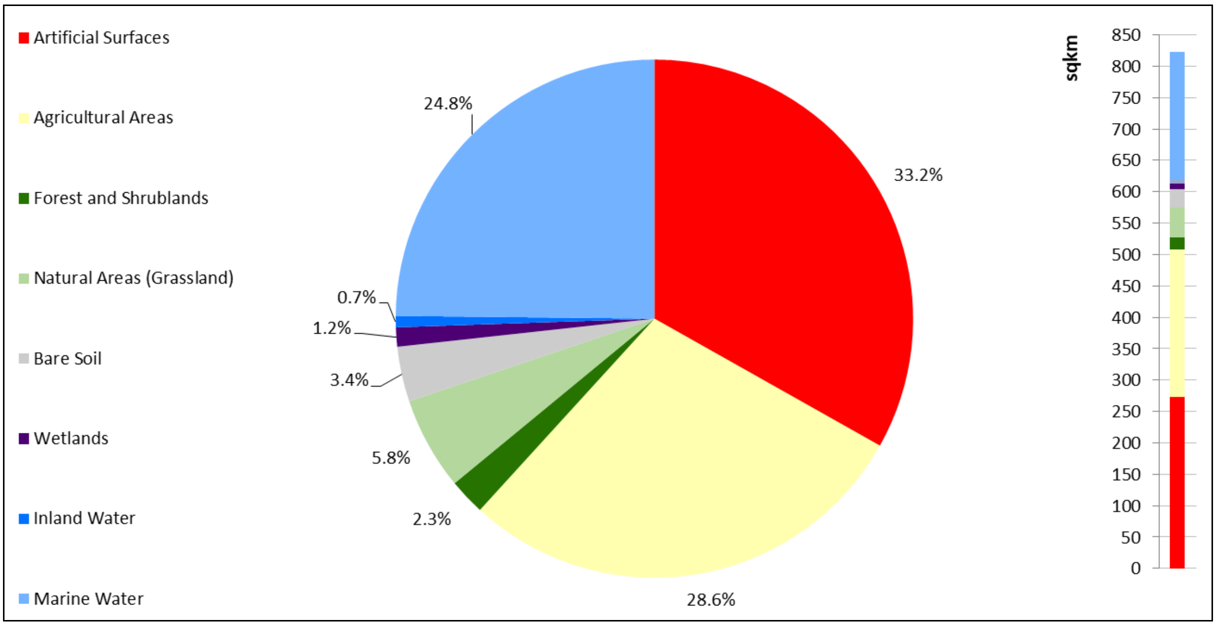

Figure 18: Larger Urban Area - Detailed LU/LC 2018 structure presented in % (left) and km² (right).

Artificial surfaces expanded a lot during the period as they represented only 26% in 2006 but 33% in 2018. Meanwhile, the shares of agricultural land and natural areas (grassland) decreased respectively from 35.4% to 28.6% and from 7.2% to 5.8%. The other LU/LC classes remain quite stable in terms of both share and area.

Description of LULC Changes:

In addition to the overall LU/LC classification for the two epochs it is interesting to assess the different trends between classes over the 12-year time period. The quantitative figures for each class are first provided in Table 10 for the Larger Urban area to get an overview.

Table 10: Larger Urban Area - Detailed information on area and percentage of total area for each class for 2006 and 2018 as well as the changes.

LU/LC Classes	2018		2006		Change		Change per Year	
	sqkm	% of total	sqkm	% of total	sqkm	%	sqkm	%
Artificial Surfaces	272.98	33.2%	214.21	26.02%	58.78	27.4%	4.90	2.3%
Agricultural Area	235.72	28.6%	291.44	35.40%	-55.72	-19.1%	-4.64	-1.6%
Forest and Shrublands	18.66	2.3%	16.56	2.01%	2.10	12.7%	0.18	1.1%
Natural Areas (Grassland)	47.69	5.8%	59.37	7.21%	-11.68	-19.7%	-0.97	-1.6%
Bare Soil	28.23	3.4%	21.91	2.66%	6.32	28.8%	0.53	2.4%
Wetlands	9.88	1.2%	8.95	1.09%	0.93	10.4%	0.08	0.9%
Inland Water	5.80	0.7%	6.69	0.81%	-0.89	-13.3%	-0.07	-1.1%
Marine Water	204.42	24.8%	204.25	24.81%	0.17	0.1%	0.01	0.0%
Total	**823.38**	**100%**	**823.38**	**100%**	-	-	-	-

The result of the analysis is confirmed: Urban expansion is the main trend with nearly 60 sqkm of new built-up areas (+27.4%), mainly to the detriment of agricultural land in the same area proportions (-19.1%) and to a lesser extent natural and semi-natural areas (-19.7%). It is finally worth to mention that bare soil is expanding too over the period (+28.8%).

4.2.4 Spatial Distribution of Main LU/LC Change Categories for Larger Urban Area

In order to better analyze the trends and the spatial distribution of changes, meaningful aggregations of the Larger Urban Area LU/LC classes in both epochs were used. The following categories were developed:

- Artificial Surface Expansion: all changes from non-artificial to artificial surface
- Agriculture Development: all changes from non-agricultural to agricultural land
- Changes within Natural and Semi-Natural Areas: all changes in between the natural and semi-natural classes (e.g. Forest to Natural Grassland).

The overlay analysis of these aggregated categories of the epochs 2006 and 2018 is depicted in Figure 19 and Figure 20 for the Larger Urban Area. Table 11 summarizes the analysis results.

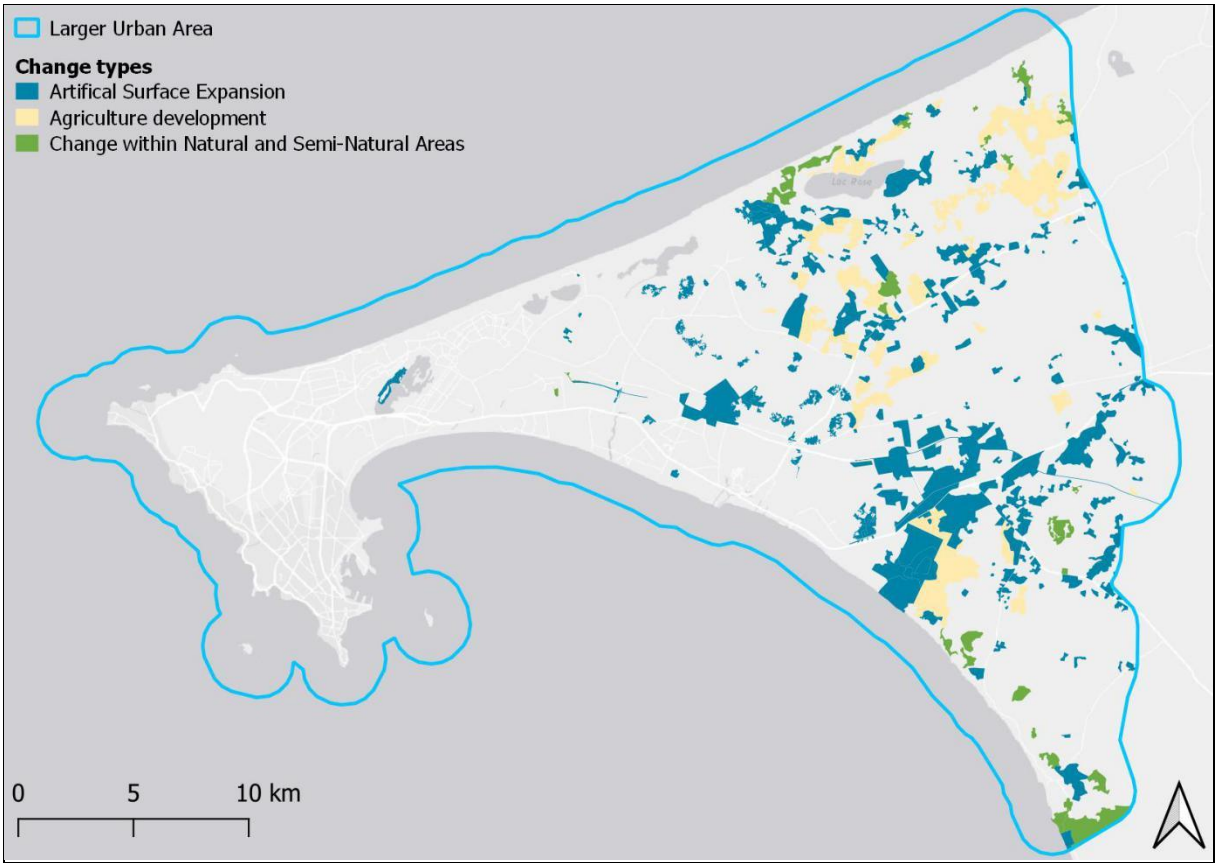

Figure 19: Larger Urban Area – LU/LC Change types and spatial distribution.

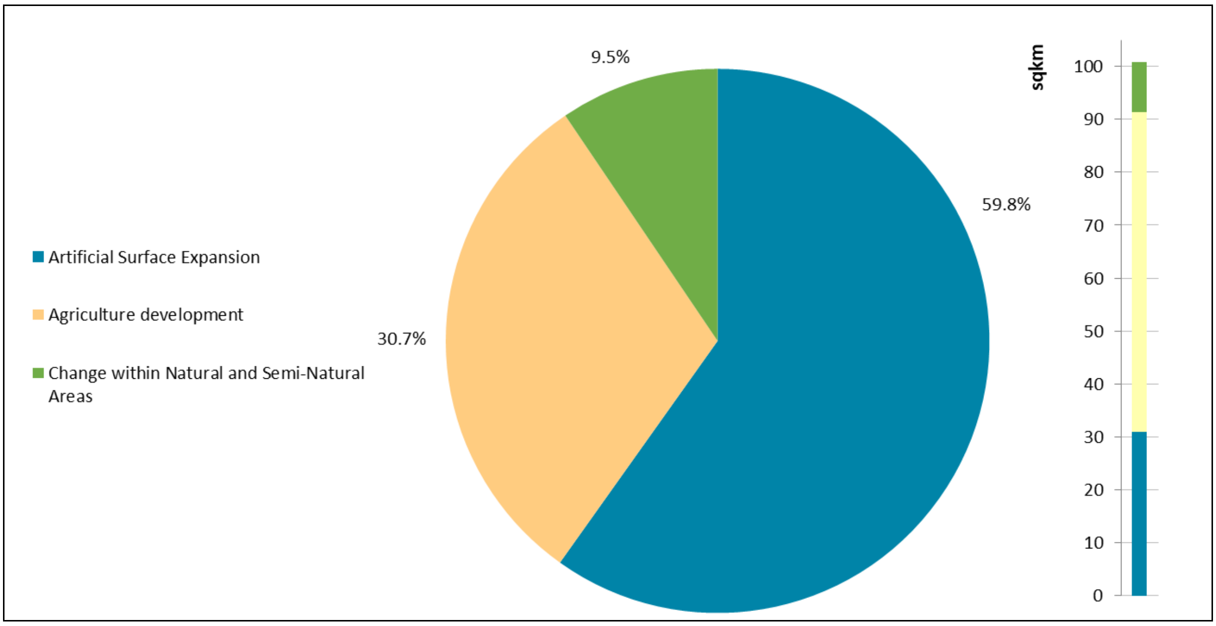

Figure 20: Larger Urban Area – LU/LC Change types 2006 -2018 area in % (left) and sqkm (right)

Not surprisingly, LU/LC changes spread over the eastern part of the area of interest, at the urban fringe, and artificial surface expansion is the main trend over the period, representing 60% of the total area in evolution and nearly 60 sqkm. However, it is interesting to point out that more than 30% of the change areas concern land newly used for agriculture purposes. This trend seems clearly not to be sufficient to compensate for the loss of agricultural land due to urban expansion, since Table 10 revealed a net decline in agriculture of nearly 20%, or 56 sqkm. Finally, changes within natural and semi-natural areas represent 9.5% of the total area in evolution, or less than 10 sqkm, but those LU/LC classes have a much lower coverage of the Larger Urban Area.

Table 11: Overall LU/LC statistics of the Larger Urban Area.

Change Classes	**Change Larger Urban area**	
	sqkm	**%**
Artificial Surface Expansion	30.95	30.7%
Agriculture development	60.37	59.8%
Change within Natural and Semi-Natural Areas	9.55	9.5%
Total	**100.87**	**100%**

4.3 Urban Green Areas

Urban green areas refer to land within and on the edges of a city that is partly or completely covered with grass, trees, shrubs, or other vegetation. The product delivered provides accurate information (1 m resolution) on the spatial location and extent of green areas located within the urban extent (Level I class: 1000 – Artificial Surfaces) derived from the baseline LU/LC information product. This section will present the results of the urban green areas mapping for 2006 and 2018 focusing on the spatial and statistical information related to the changes between these two epochs.

The Urban Green Areas change map generated over the AOI is depicted in Figure 21. A cartographic version of the map layout is provided as a pdf file in addition to the geo-spatial product.

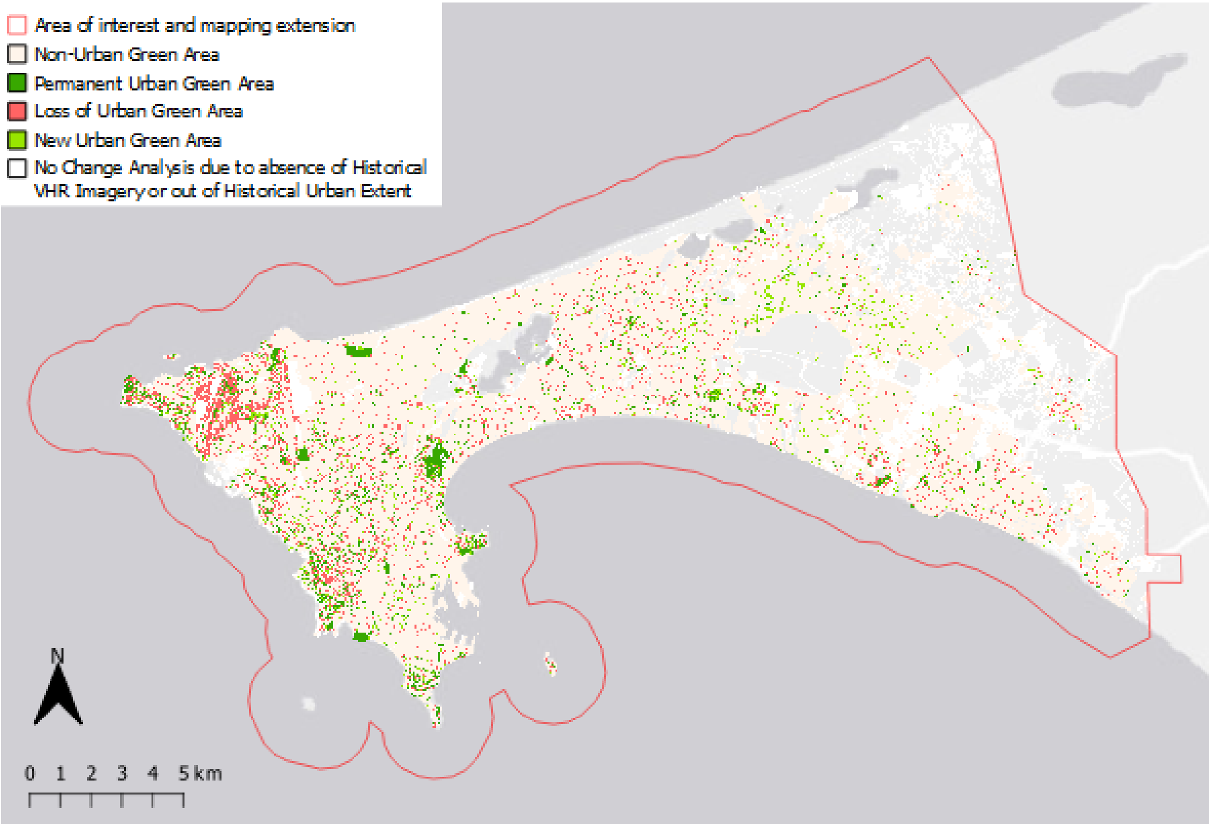

Figure 21: Urban Green Areas changes and spatial distribution.

The urban extent over the AOI is limited to the areas along the coastline. Clearly, the predominant class is non-urban green area, since it represents the 69.84% of the total area, it means 136.07 sqkm. Even so, most of green areas are located in the west of the urban extent. It also seems that there are more variations of green areas than permanent ones over the time.

The quantitative results are shown in Figure 22 and Figure 23. The permanent green spaces over the period represent only 3.52% of the entire area, or 6.87 sqkm. The loss of green areas represents 5.77% while new ones only 2.48%. This difference between loss and gain is not so abrupt nevertheless, as there is a loss of 6.40 sqkm over the time.

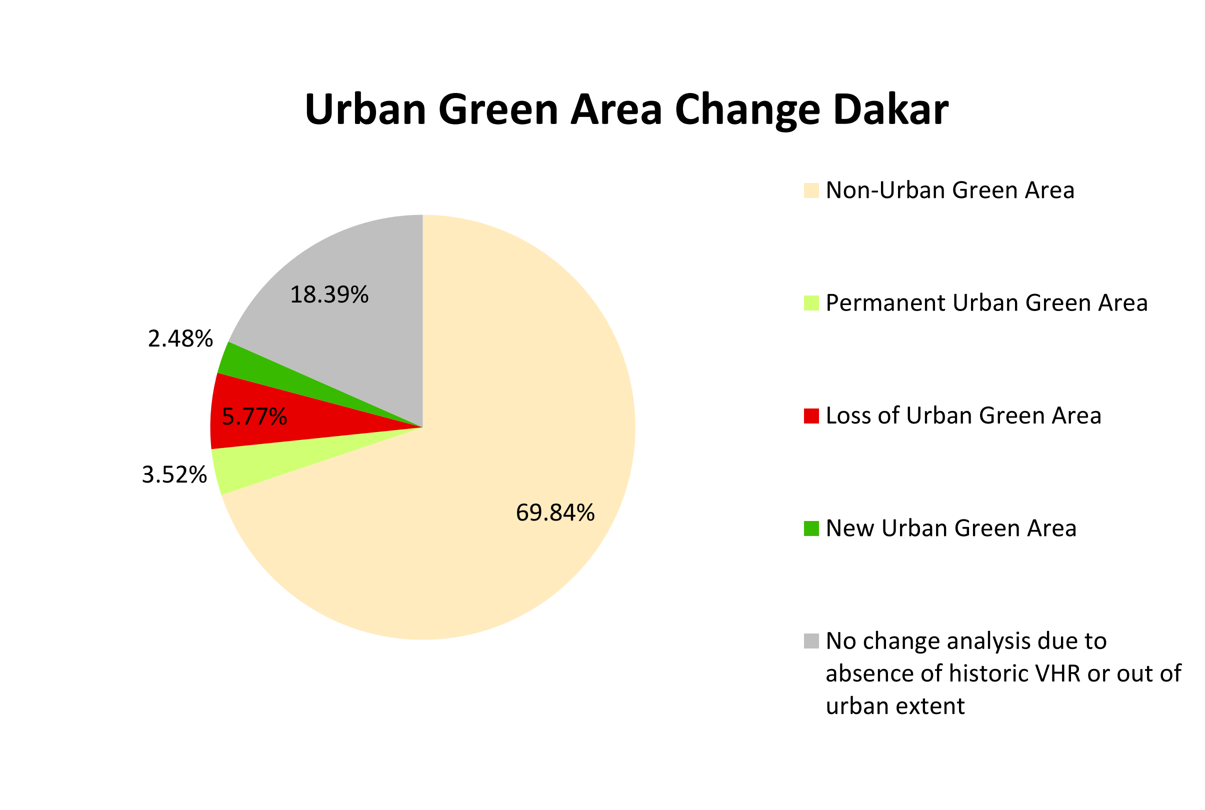

Figure 22: Status and change of urban green areas in-between 2004/2006 and 2018 expressed in %.

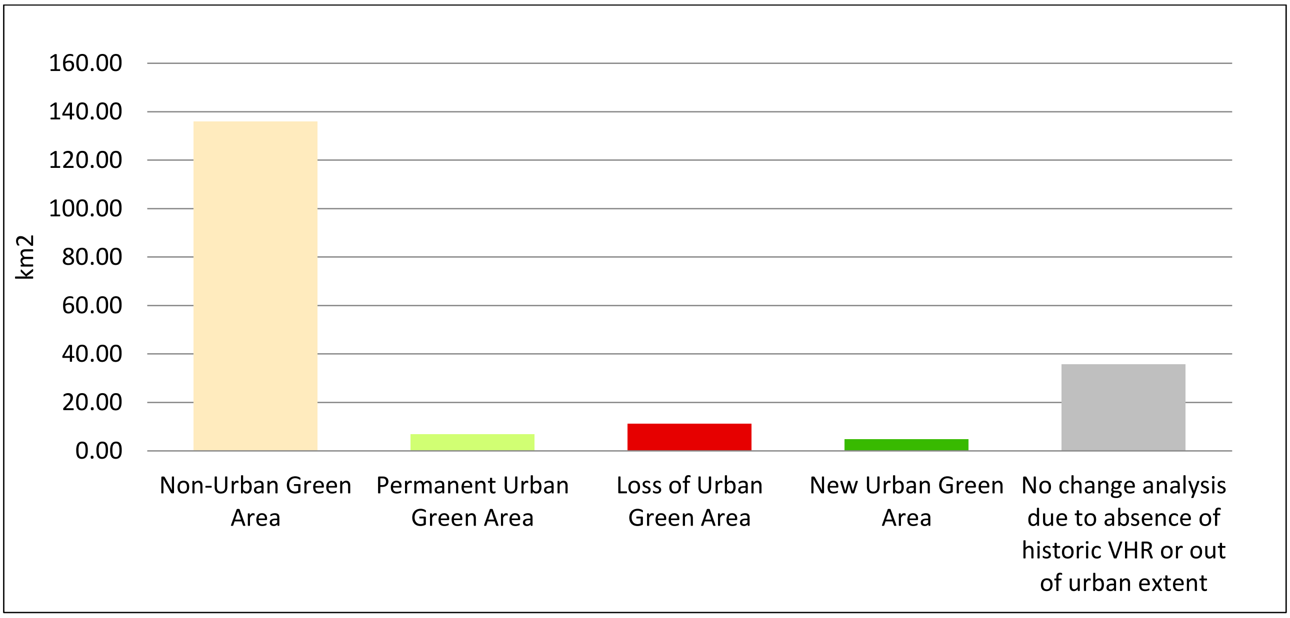

Figure 23: Status and change of urban green areas in-between 2004/2006 and 2018 expressed in area.

4.4 Sustainable Development Goal 11 Indicators

A main objective of the EO4SD-Urban Product Portfolio is to support the reporting requirements of Urban Development Policies and Strategies. One of the most important policy frameworks that countries are trying to implement are the UN Sustainable Development Goals (SDGs). Seventeen SDGs were developed with a focus on "ending extreme poverty; fighting inequality & injustice; and addressing climate change," by 2030. To achieve the 17 goals there are 169 targets and for each target, indicators will be used to assess the level of achievement of the countries.

The SDG Goal 11 "Make cities and human settlements inclusive, safe, resilient and sustainable" is specifically dedicated to Sustainable Urban Development. A list of Urban Sustainability Indicators specific to the SDG Goal 11, have been defined in March 2016 by the UN and are described in the UN-Habitat "SDG Goal 11 Monitoring Framework Report (UN, 2016a)".

The EO4SD-Urban project supports seven GPSC cities, namely Bhopal and Vijayawada in India, Campeche in Mexico, Saint-Louis and Dakar in Senegal, Abidjan in Ivory Coast and Lima in Peru. For these seven cities, the indicators for which the needed input data is available were calculated and are described in the following subsections. The EO4SD-Urban products can be fully or partly used for the calculation of four SDG 11 indicators (see Table 12).

Table 12: SDG 11 indicators measurable with the support of EO4SD-Urban products.

TARGETS	INDICATORS
Target 11.1: By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	11.1.1: Proportion of urban population living in slums, informal settlements or inadequate housing
Target 11.2: By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	11.2.1: Proportion of the population that has convenient access to public transport by sex, age and persons with disabilities
Target 11.3: By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	11.3.1: Ratio of land consumption rate to population growth rate
Target 11.7: By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities	11.7.1: Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities

A short description of the calculation as well as the needed input data and the achieved outputs are described in the next sections for the indicators 11.2.1, 11.3.1 and 11.7.1. For Dakar, it is not possible to calculate the Indicator 11.1.1, as the needed input data is not available.

More information including the exact calculation steps of each indicator are described in the UN-Habitat Methodological Guidance document to monitor and report on the SDG Goal 11 indicators (UN-Habitat, 2016).

4.4.1 SDG 11 Indicator 11.2.1

The 11.2.1 Indicator calculates the ***Proportion of the population that has convenient access to public transport by sex, age and persons with disabilities*** and describes the Target 11.2: “By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, and children, persons with disabilities and older persons.”

The indicator aims to monitor the use and access of public transportation system and move towards reaching a convenient access for all. According to UN-Habitat and described in the Methodological Guidance document (UN-Habitat, 2016) the access to public transport is considered convenient when an officially recognised stop is accessible within a distance of 0.5 km from a reference point such as home, school, workplace, market, etc.

The indicator is calculated by using the following formula:

$$\text{\% with access to public transport} = \frac{100\text{x (population with convenient access to public transport)}}{\text{city population}}$$

At a diagnosis phase, this indicator helps urban planners in identifying areas that are underserved and to be put as a priority in the Master Plans for the localisation of transport stations and addition of new transport lines (bus, metro, tramway, train).

Calculating this indicator considering parameters such as sex, age and persons with disabilities would require additional census data, as not available through EO data. However, the indicator can be calculated over the Larger Urban Area using the Global Human Settlement Population Layer and the OpenStreetMap (OSM) transportation features (bus and subway stations and stops, railway stations, ferry terminals), both available for the reference year 2015. It provides a first good estimate of the proportion of the population that has convenient access to public transport.

The results are presented in Figure 24 below. For comparative reasons the graphic shows the indicator results for all GPSC cities, but Bhopal and Vijayawada. The proportion of the population that has convenient access to public transport is estimated more than 50% of the total population of Dakar which is a slightly higher value than for Lima, while this indicator is lower for Abidjan and Saint-Louis with a value close to 30% and for Campeche with 20%.

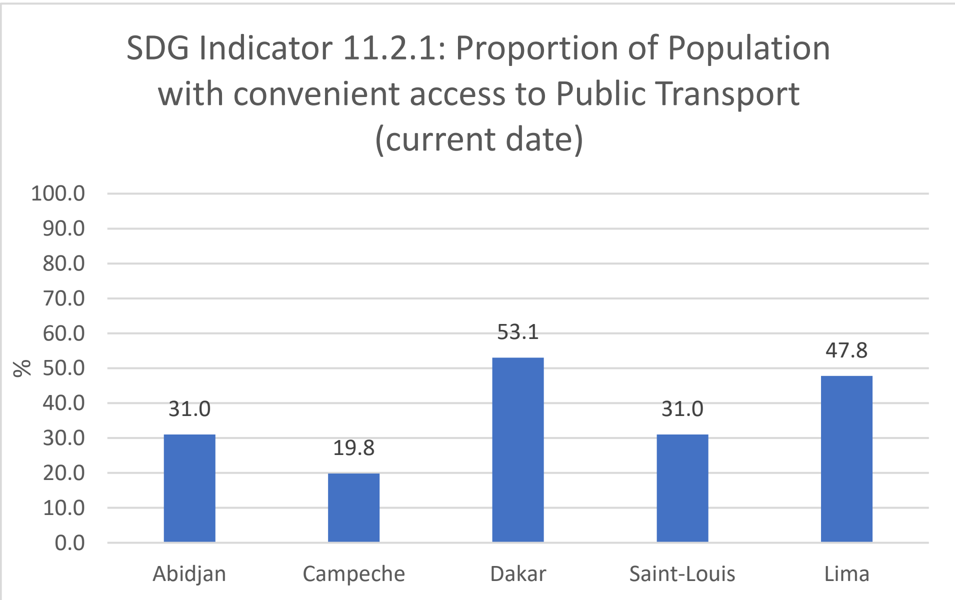

Figure 24: Proportion of population with convenient access to public transport.

4.4.2 SDG 11 Indicator 11.3.1

The 11.3.1 Indicator calculates the ***Ratio of land consumption rate to population growth rate*** and describes the Target 11.3: “By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.”

The indicator needs the definition of the two components population growth and land consumption rate. According to the UN-Habitat Methodological Guidance document (UN-Habitat, 2016) the population growth rate (PGR) is the increase of population in a country during a specific period, usually one year. The PGR is expressed as a percentage of the population at the start of that period.

Further, the land consumption rate includes a) the expansion of build-up area that can be directly measured and 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 following formula:

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

The ratio of land consumption rate to population growth rate is an indicator for measuring land use efficiently and is intended to answer the questions of whether the remaining undeveloped urban land is being developed at a rate that is less than or greater than the prevailing rate of population growth. As the ratio of land consumption rate to population growth rate is dimensionless and not straightforward in its interpretation, several countries report the urban expansion and the population growth rate in terms of percentage change instead of using the ratio values (Nicolau et. al., 2018).
In the following, the ratio (see Figure 25) and the percentage change values (see Figure 26) for all GPSC cities were calculated. For the calculation of the population growth rate the Global Human Settlement Population Layer available for the years 2000 and 2015 were used. For the calculation of the land consumption rate the built-up area extracted from the Larger Urban Area LU/LC classification is taken by dissolving all artificial classes.

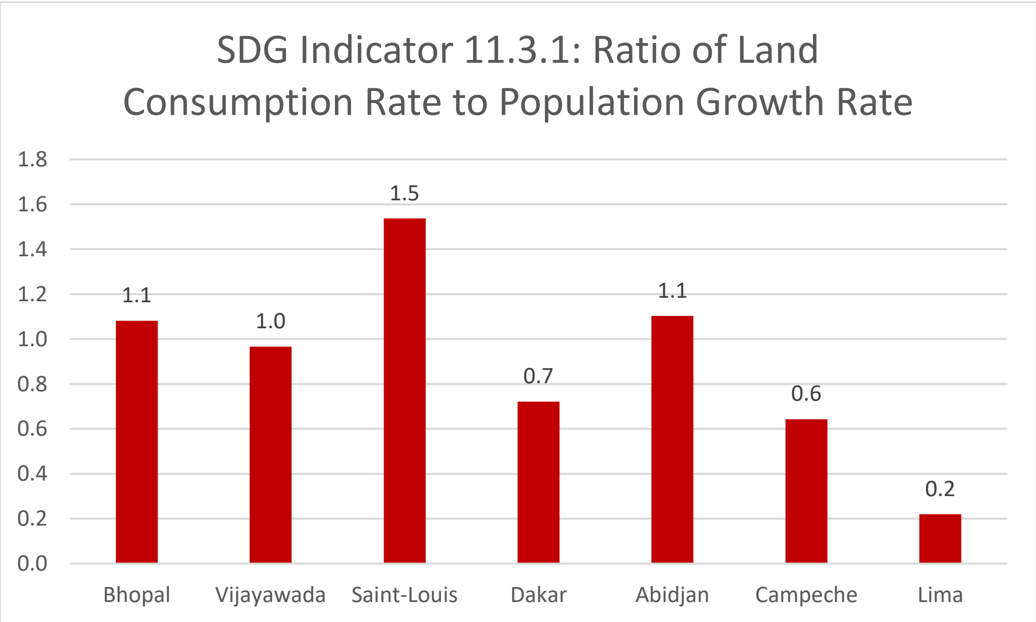

Figure 25: Ratio of land consumption rate to population growth rate between 2005 and 2015.

Figure 25 shows the ratio of land consumption rate to population growth rate for all GPSC cities. All GPSC cities are visualised in the bar chart for comparative reasons. Dakar, as well as Campeche and Lima, has a value significantly below one, which means that the population growth rate is higher than the land consumption rate and let assume that the land is efficiently used.
Cities with values close to one have a population growth rate similar to the land consumption rate. This indicates that the land is efficiently used too.
On the contrary, cities with values significantly above one have a higher land consumption rate than a population growth rate. This indicates that the land is not as efficiently used as for example in Dakar.
European countries, for comparison very often have values below zero. This means that either the population or the land consumption shows a decrease.

Looking at the percentage change values of population and land consumption between 2000/2006 and 2015/2018 all cities have a growing population and a growing urban extent, which is typical for cities in developing countries. Dakar's population grew by 53.2% between 2000 and 2015. Its land consumption grew by 27.9% between 2006 and 2018. This means that the population grew faster than the built-up area of the city and indicates also that the city seems to grow in a compact way.

In Saint-Louis for example, it is the other way around. Here the land consumption grew by 21% while the population grew by only 17%, indicating that the city had a less compact growth in the last years.

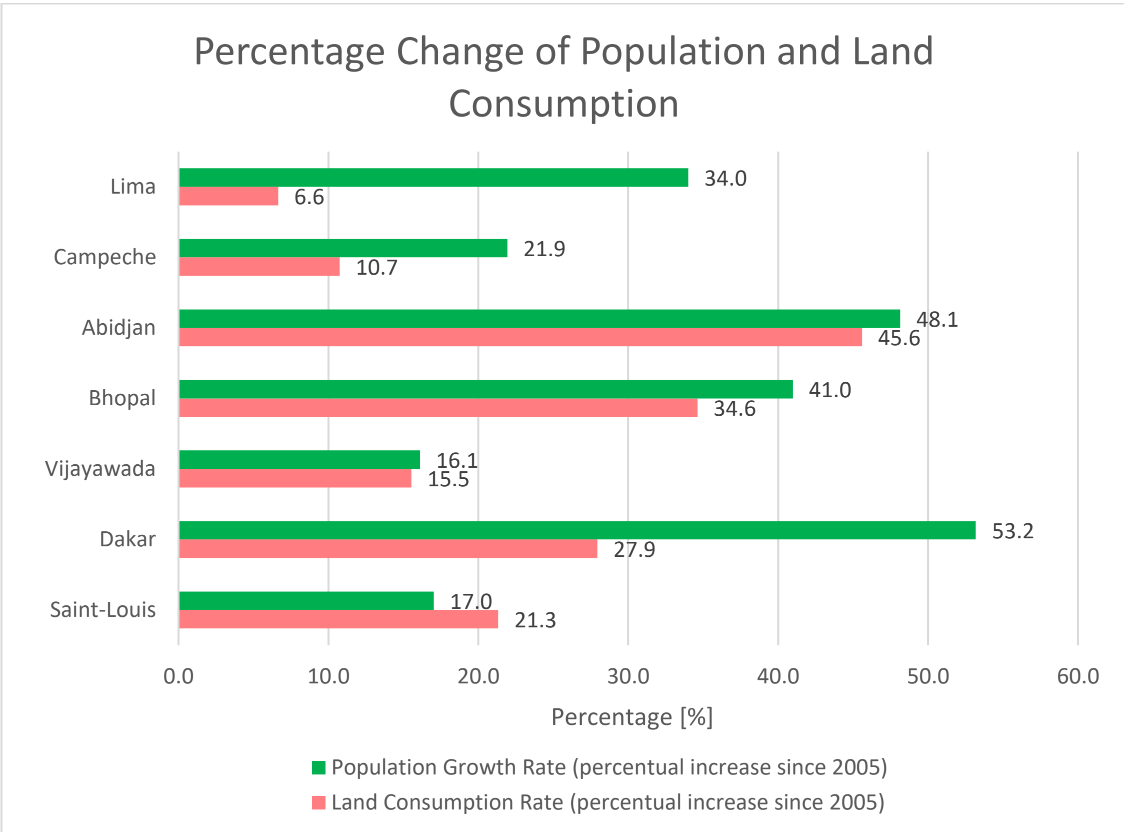

Figure 26: Percentage change of population and land consumption between 2005 and 2015.

A significant limitation of this indicator is that the approach captures only the urban extent change, not the internal city dynamics.

4.4.3 SDG 11 Indicator 11.7.1

The SDG 11 Indicator 11.7.1 ***"Average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities"*** refers to the Target 11.7.: By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.

The indicator aims to monitor the amount of land that is dedicated by cities for public space. According to the UN-Habitat Methodological Guidance document (UN-Habitat, 2016) public space includes open spaces and streets and should be accessible by all.

The indicator is calculated by using following formula:

$$\text{\% of land that is dedicated by cities for public space (open spaces and streets)} = \frac{(\text{Total surface of open public space} + \text{Total surface of land allocated to streets})}{\text{Total surface of built up area of the urban agglomeration}}$$

The share of land in public open spaces cannot be obtained directly from the use of high-resolution satellite imagery, because it is not possible to determine the ownership or use of open spaces by remote sensing. Additional metadata that helps to describe the land use patterns in the locale is additionally required to map out land that is for public and non-public use.

As this information is not available, the LU/LC classes *Urban Green Areas* and *Sports and Leisure Facilities*, which are available in the Core City Area LU/LC classification, were taken with the assumption that these places are public places and accessible by all.

To calculate the total surface of land allocated to streets, the road network was used. Different buffers were applied for three different road types (6m for Arterial Roads, 5m for Collector Roads and 3m for Local Roads) to assess the total surface of streets. The total surface of built-up area of the urban agglomeration is extracted from the LU/LC classification by summarising all artificial classes of the Core City Area.

The results are presented in Figure 27 below. For comparative reasons the graphic shows the indicator results for all GPSC cities, but Lima.

The indicator was calculated for two points in time i.e. around 2005 and 2015. In Dakar, the average share of built-up area that is open space for public use slightly increases from 17% in 2006 to 18.4% in 2018. Abidjan also shows an increase, while all the other cities show a decrease in open spaces.

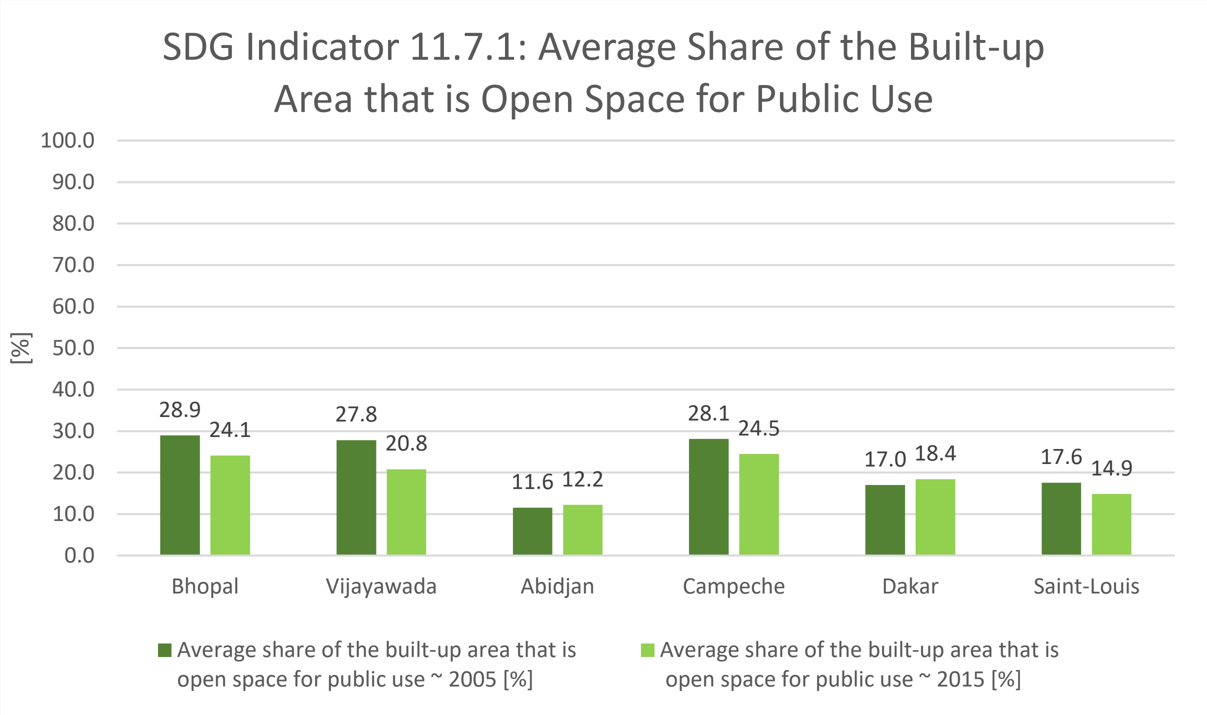

Figure 27: Average share of the built-up area that is open space for public use.

4.5 Concluding Points

This Chapter 4 presented a summary and an overview of what is possible in term of analytics with the geo-spatial datasets provided for Dakar in the current project. This Report is a living document and will be complemented with further analysis during the project.

5 Flood Hazard and Risk Assessment

Flood Hazard and Risk Mapping is a vital component for appropriate land use planning in flood-prone areas. First of all, Flood Hazard and Risk Maps are designed to increase awareness of the likelihood of flooding among the public, local authorities and other organisations.

Specific flood regimes and underlying causes for the flooding events in the area of interest have to be analysed carefully, as these can be very varied in different regions.

For the urban and peri-urban area of Dakar, basically two main flood scenarios have to be considered:

a. fluvial floods (seasonal floods from small rivers) after heavy tropical rains

b. floods triggered by rainfall stagnation after heavy local cloudbursts

For Dakar, the potential flood season covers the period between August and November (Diouf et al. 2013, JICA 2016); Scenario a.) and b.) normally occur at the same time.

Flooding is one of the most severe hazards threatening Dakar, and in the last years it has become a frequent and enduring reality. The underlying causes are complex and involve not only the recent increase of rainfalls, but in particular the whole socio-economic process of an out-of-control urban sprawl. Almost each year between 100,000 and 300,000 people are affected by floods (Wang et al 2009, Hungerford et al. 2019).

According to (among others) Mbow et al. (2008), these floods are often connected with problems with the drainage system. The ground water table in many regions is very shallow and Dakars drainage system is not yet adequate to cope with heavy rain. Furthermore, rubbish is often blocking the drains, and debris and trash clog the outlets (cf. Figure 28).

Figure 28: Four days after a storm in August 2015, flood waters are still visible in N'Gor Village, Dakar, Senegal (Photo: Jürgen Fauth, BRACED)

5.1 General Characteristics of the Study Area

Dakar is the capital and outstanding urban pole in Senegal. It serves as the political and administrative centre of Senegal, as well as the international gateway for global trade and business activities.

Administratively, the region of Dakar is divided into four departments (Dakar, Guédiawaye, Pikine, and Rufisque, cf. Figure 29) and 10 districts (Ndiaye et al. 2016). The entire urban area covers around 550 sqkm while the population in 2013 reached about 3.137,000.

Figure 29: Position of main parts of Dakar (taken from Wikipedia)

The area of interest (Service Area) as defined by the user includes substantial additional areas covered by the sea and therefore covers a total of 823,38 sqkm (422,40 sqkm defined as Core City and 400,98 sqkm defined as Larger Urban Area, cf. Figure 30).

The former traditional villages of Rufisque, Yoff, Ngor, Ouakam, Thiaroye, Yeumbeul, Mbao, Kounoune, etc. nowadays have become part of the urban area (Mbow et al 2008).

Historically, Dakar has been continuously expanding eastwards, receiving population influxes from the rural areas. The rate of growth was especially rapid after Senegal became an independent state in 1960. Several very dry decades between 1968–1997 with extreme droughts resulted in massive migration of rural people into Dakar, especially into its lowland areas, which originally were not inhabitable. Uncontrolled urban sprawl has created an unbalanced urban structure with a concentration of business and commercial functions in downtown Dakar. The development of infrastructures and public facilities has not been fast enough to catch up with the rapid urbanization. The natural condition of Dakar surrounded by the sea on three sides has limited the effects of the government's efforts to solve this problem. As a result, the lag has led to the deterioration of people's living environments and has caused huge disparities in the social services and urban services (JICA 2016).

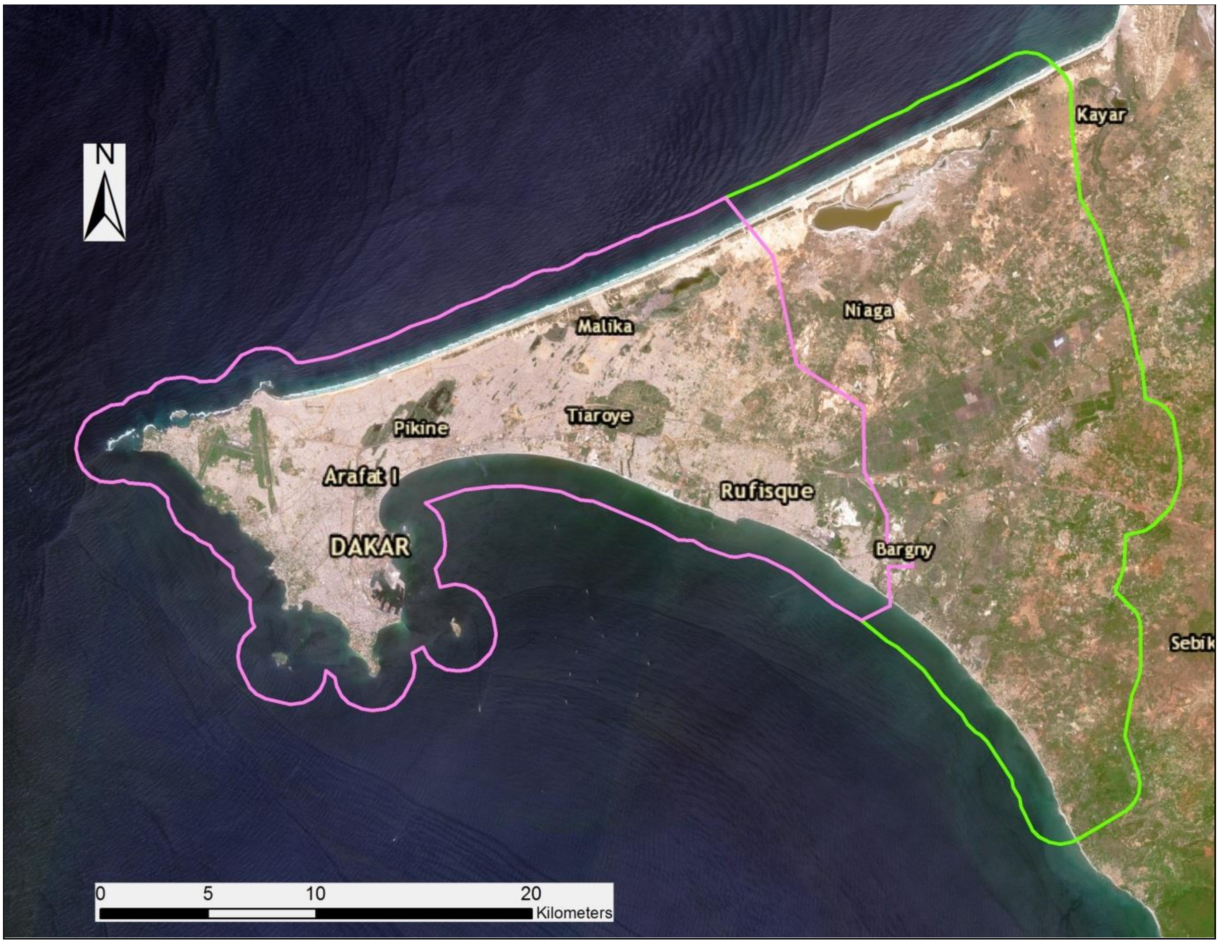

Figure 30: Dakar, Senegal – Service Area: pink: Core City Area of Interest; green: Larger Urban Area of Interest (Background Image: Sentinel 2, recorded on 10/10/2016, European Space Agency)

Dakar is located on a peninsula ("Cap Vert") that can be divided into four geomorphological zones (JICA 2016, cf. Figure 31):

- The rocky tip at the western part of the city is formed almost entirely of Early Quaternary dolerites and basanites (Roger et al. 2009). The volcanic rocks build hills (the "Mamelles") which reach a maximum height of about 100 m. The west coast between Cap Vert and Cap Manuel, the "Corniche Ouest", is often a rugged steep coast of volcanic rock.
- To the east, the central dune system follows that is generally aligned parallel to the coast and running NE-SW. The dunes closer to the shore are more pronounced. Inland they become gently undulating with the inter-dune areas infilled with colluvium. The inter-dune depressions are known as the Niayes. They are often marshy during the rainy season and contain relatively lush vegetation when compared with the adjacent plain. The dune systems of Pikine, Keur Massar, Bambilor and Sangalkam stretch to the north and form a zone of semi-fixed coastal sand dunes alternating with marine sands and brackish deposits (organic clay and sand, gravels, Roger et al. 2009). Soils are characterized by sandy dune soils on hills and hydromorphic or even partially halomorphic clay soils where the static groundwater table is shallow (Mbow et al. 2008).
- The Bargny Plateau lies to the southeast of the dunes. This marly-limestone plateau extends along the "Petite-Côte" between Rufisque, Bargny and Sendou.
- The sandstone hills are located in the far southeast of the Service Area and are a series of Maastrichtian sandstone hills with gentle slopes up to 50 m in elevation.

No major rivers cross the Service Area. Some smaller watercourses can be found near the southern coast (e.g. Rivière Nougouna in Rufisque) and in the southern part of the peri-urban area (e.g. near Siendou). Unplanned urban growth and soil sealing has provoked the disappearance of most of the natural hydrographic network in the area of the Niayes (JICA 2016).

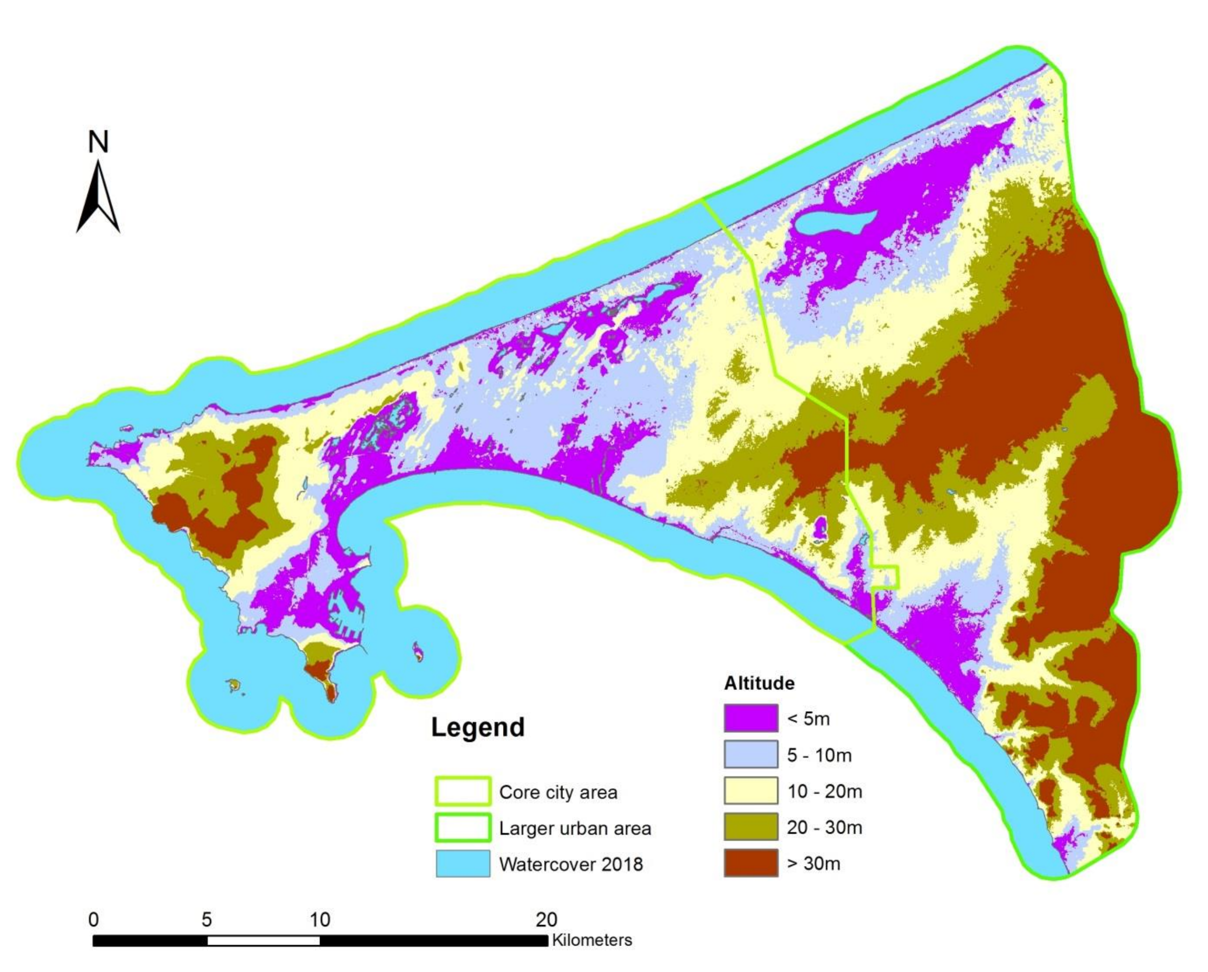

Figure 31: Altitudes in Dakar Service Area as derived from available Digital Terrain and Surface Models (western part: 5m Digital Terrain Model of Dakar (BaseGéo Sénégal, (http://www.basegeo.gouv.sn/) based on Urban Database (UDB) product; eastern part: ALOS Global Digital Surface Model "ALOS World 3D - 30m (AW3D30)", version 2.1 (©JAXA): Amthyst areas indicate most flood prone zones (altitudes below 5 m).

Senegal’s climate is generally characterized as tropical with heat throughout the year, and possessing well-defined dry and rainy seasons. The dry season (November to May) is dominated by the “Harmattan” wind that brings hot and dry weather from the northeast. The rainy season is caused by the southwest wind from the Gulf of Guinea (JICA 2016).

Dakar Region has a fairly mild climate compared to the rest of the country, due to the oceanic influences of winds for most of the year. This climate is marked by a rainy season from June to October which is characterized by heat, humidity and storms with heavy cloudbursts. Precipitation peaks can be observed in August with up to 250 mm. The dry season is characterized by maritime winds from the Azores high. These winds give rise to an unusually cool climate. During the dry season there is almost no rain at all.

Annual rainfall has varied between 150 mm (1983) and 664 mm (2005) over recent decades. The current average annual rainfall amounts to 484 mm and has become slightly above the mean of 410 mm between 1961-1990 (Diouf et al. 2013).

According to ANACIM (Agence Nationale de l'Aviation Civile et de la Météorologie), most heavy rainfall events in the rainy season are caused by moving cumulonimbus system from east to west. The rainfall’s intensity is strong, but the duration is usually short (JICA 2016).

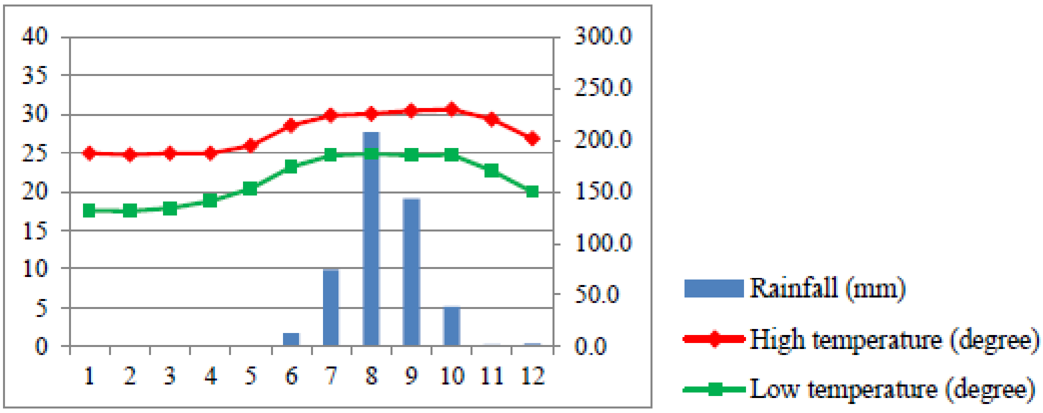

Figure 32: Climate average from 2000 to 2012 in Dakar, Source: World Weather Online

Beginning with the new upsurge in rainfall in 2005, and in particular in 2009 and 2012, Dakar suffered heavy flooding, sometimes in areas that had never been flooded before. Flooding has appeared as a major threat especially for poor population leaving in the suburbs of Dakar. The flooding process is not a mere climate variability related issue, it is tightly bound with poor urban management and occupation of irregular, unsuited land (Ndiaye et al. 2016).

According to Ndiaye et al. (2016), approximately 50% of the Dakar region are vulnerable to flooding and particularly the suburban area concerning the departments of Pikine and Guédiawaye.

The vulnerability of Dakar and its inhabitants is characterized by the significant land use change triggered by extreme droughts in the 1970s, 80s and 90s which forced rural populations into urban areas. Today, almost half of Senegal’s population lives in urban areas (GFDRR 2014). The urban growth of Dakar is estimated to 7 - 8% per annum since the seventies with most of the settlements unplanned. Poor people were forced to settle in cheap yet risky lands. The most accessible land for housing was the depressions (the “Niayes”), mostly situated in the departments of Guédiawaye and Pikine, which were dried during the drought period (Mbow et al. 2008).

When migrants came to Pikine, they often settled in areas that were formerly wetlands but had turned into dry patches suitable for settlement. The 1970s and 1980s were dry climatic periods in Senegal, so the low-lying areas that constitute much of Pikine were dry, and water tables were below average depths. As ground cover has changed from wetland or vegetation to densely populated, largely unplanned settlements, soil compaction and drainage have become major issues in the region.

This lack of natural drainage and infiltration is exacerbated by the lack of infrastructure to facilitate the evacuation of surface water. So far, although some networked infrastructure is under construction, the largest infrastructure project is the construction of catchment basins across Pikine city. These basins were placed in low-lying areas of the commune as a collection point for surface waters. Before the construction of the basins, these areas were some of the worst flooded neighborhoods, and thus the houses were razed, and basins created in their place. These basins have alleviated some, but certainly not all, of the localized flooding. According to Hungerford et al. (2019), Pikine still experiences regular and devastating floods, and residents cope with heavy economic and health burdens. One-third of Pikine’s 1.2 million residents regularly experience flooding, with a significant portion of these people living in areas that were not flooded previously.

The main particularity of the Service Area with regard to flood risk thus is the occupation of the Niayes (interdunal depressions) which before were occupied by marshes, open water and natural vegetation (Ndiaye et al. 2016).

The Niayes constitute catchment and storage areas for runoff. By building new houses in these areas, the buildings also reduced the drainage area of the watershed. Floods result from the reduction of infiltration of rain water in urban areas following the increase of more or less sealed surfaces (Diop et al. 2017).

Furthermore, there is a drastic lack of sanitation system with waste water directly released in the rest of depressions (sludge traps) or individual pits. The aquifer in the Quaternary sands (Thiaroye aquifer) plays a major role in supplying drinking and irrigation water. The use of this resource began in the 1950s. During the last two decades, the pumping was considerably reduced because of the nitrate pollution derived from improper sanitation system in the urbanized area (JICA 2016). This reduction obviously influences the flooding phenomenon as the water table has risen very close to the surface (Mbow et al 2008, Diouf et al. 2013).

Mbow et al. (2008) differ between natural and human causes for flooding:

The **natural factors** are twofold: the topography and the rainfall variability. Large parts in the departments of Pikine and Guédiawaye are characterized by depressions (Figure DTM). Floods preferably can be observed in sites below 5 m. The groundwater table generally is near surface in these depressions (< 1 - 2 m). The high altitudes are about 10 - 15 m on sand dunes where the original villages were built. The fact of setting houses in normally flooded depression is one aspects of the vulnerability of these settlements.

Another natural factor is the extreme climate variability. One aspect of climate variability is extreme droughts during which the depressions in Dakar get dry and become a possible settlement site for most of the poor migrants from rural yet unproductive lands. The strong rainfall years are associated with rapid water saturation of occupied depressions.

According to Sakho (2006), the floods are not due to total rainfall alone; the most relevant rainfall parameter is the amount of rain during the peak season in august. These heavy rains within a short time are the main cause of flooding. The total rainfall contributes to the underground saturation whilst heavy rains within a short time are the trigger of water accumulation in occupied depressions.

Examples for heavy rain events in the flood season of 2005 are:

- 16th-17th August : 87.4 mm
- 19th-22nd August : 184.5 mm
- 28th-31st August : 55.2 mm

However, daily maximums appear stable, although there is a trend towards increasing intensity of rainfall for durations of up to 15 minutes (Cissé & Sèye 2015).

The most important factor for floods is the **human factors** with the poor management of land and the occupation of depressions where no space was left for rainwater infiltration leading to a strong runoff which favors rapid flooding situations. A network of roads was built inside former watercourses without any drainage system (cf. Figure 33).

Figure 33: Tally Neitty Mbar (main street of Djeddah Thiaroye Kao in the Department of Pikine), flooded in 2009. Source: Requalification des zones inondés de Djeddah Thiaroye Kao.urbaDTK.org

Additionally, people release their wastes in depressions with a serious clogging process. In many places, the duration of inundation was more than three days, which is much longer than the usual storm events. Once the depressions are filled with floodwater, its existence is prolonged because there is no drainage to remove the water (JICA 2016). These lasting water bodies are polluted by pathogenic bacteria of fecal origin, even in case of low-intensity precipitation (Green Climate Fund).

According to Ndiaye et al. (2016), very low vulnerability to flooding is recorded exclusively in the department of Grand Dakar (western part of the peninsula, downtown area).

Within the frame of the "Project for Urban Master Plan of Dakar and the Neighboring Area for 2035" the Japan International Cooperation Agency (JICA) estimated possible flooding areas in the new development areas (peri-urban area), by employing the Flo2D model. The grid size of the simulation is 50 m. The result is shown in Figure 34.

Based on this simulation, it is expected that excess runoff will increase in the new urban expansion area (e.g. area of Diamniadio). This effect should be taken into account during planning for the territory in the 2035 Master Plan. Special attention should be paid to changes in the hydrological situation around existing small-scale reservoirs in the new urban expansion area, because of the potential risk of spilled floodwater, as well as dam breakage.

Flood Hazard in the new development area could not be confirmed neither based on RS data nor based on existing reports. Therefore, no hazard and risk zones were indicated on the Flood Hazard and Risk Maps.

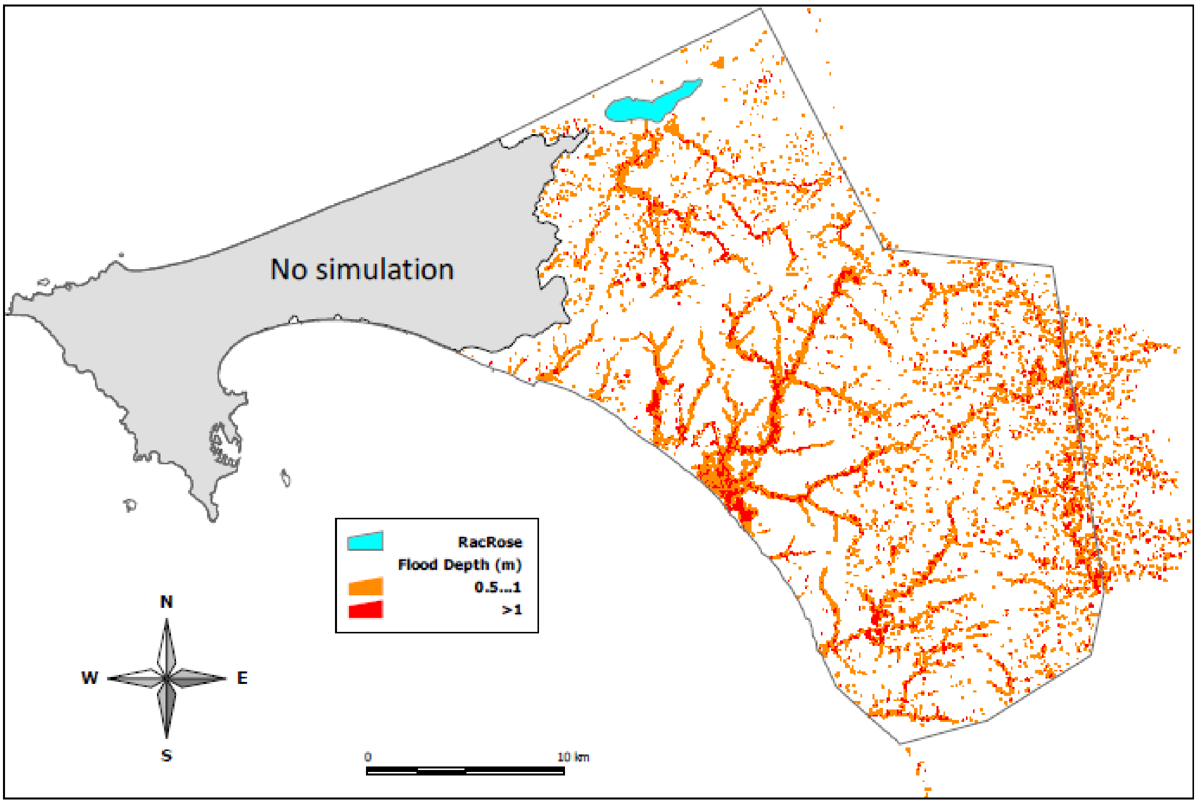

Figure 34: Possible Flooding Area in the New Urban Expansion Area based on Flo2D modelling results (taken from JICA 2016)

Regarding the situation of coastal erosion in the Service Area, according to JICA 2016, there seems to be relatively low risk of coastal erosion at the moment in general. Coastal erosion is particularly felt in the area of Rufisque- Bargny with the narrowing of the beach of Rufisque, particularly along the center of the city. Damages have been observed at places where buildings were constructed along the shoreline. Some countermeasures have been applied in Rufisque. In the Dakar Corniche area, significant cracking of the cliffs and the degradation of coastal rocky cliffs can be observed.

On the basis of the tidal data from the UHSLC from 1996 to 2013 (with some gaps), the average spring high tide is about 0.81 m above MSL. The World Bank (2013) estimated the premium values of the extreme high tide event with a 100-year return period at 1.0 m for Grande Côte and 0.7 m for Petite Côte. Considering the premium values, the extreme high tide with a 100-year return period could be 1.81 m above MSL for Grande Côte and 1.51 m above MSL for Petite Côte. The land where the elevation is lower than for these extreme high-tide levels could be flooded during extreme storm events with a 100-year return period.

The future possible sea level rise due to climate change may increase the potential coastal flooding area. The estimated increase of the mean sea level according to the World Bank (2013) is 0.2 m in 2030 and 0.8 m in 2080. There is a possibility of coastal flooding at lowland areas along the shoreline during extreme storm events.

The magnitude of these coastal hazards could increase in the future due to climate change. There is also a pressure resulting from development along the shoreline due to urban expansion, which raises the risk of disaster. The proper management and conservation of the coastal area is required (Wang et al. 2009, JICA 2016).

Flood Hazard caused by coastal erosion could not be confirmed neither based on RS data nor based on existing reports. Therefore, no hazard and risk zones were indicated on the Flood Hazard and Risk Maps.

In the last years there have been multiple interventions in the suburbs of Dakar to respond to flooding. They can be divided into two categories:

1. Structural approaches that favor physical intervention through reconstruction and engineering works.
2. Non-structural approaches that support capacity building at the local level and social reform.

Flood management nowadays is a major part of the Senegalese government's Disaster Risk Reduction framework and building resistance to flooding is a top priority within the country's INDC submission. The Directorate of Civil Protection (DPC) under the Ministry of Interior is the agency responsible for the coordination of DRM activities in Senegal. DPC acts as the secretariat of the national platform for the prevention and reduction of major disaster risks which was established in 2008. It is responsible for promoting the integration of DRM into national development policies, plans and strategies.

The 2009 floods (affecting Dakar and surrounding areas primarily) appear to mark a new start for the Senegal Government, with three steps to commit permanently to a sustainable recovery and flood management policy. These three steps were:

1. Assessing damage, losses and post disaster needs (PDNA) for 2009;
2. The storm water management and climate change adaptation project;
3. The Ten-Year Flood Management program (PDGI, 2012-2022).

Among other projects, the most important ones are the Plan Jaxaay, that aims at resettling people living in low-lying, flood-prone areas, launched in 2006 and the emergency phase of the PDGI that also included 100 million USD worth of investment in infrastructure.

- In recognition of the impacts of regular flooding, Dakar city government has attempted an innovative flood control program that involved the construction of water basins. The water basins were part of the urban planning project called Plan Jaxaay, which relocated people from flood-prone areas alongside efforts to channel storm water into these catchment basins. The first basin in Pikine was built in 2007. The design included pumps that were to move water from the basins into lake systems and eventually to the Atlantic Ocean, but these plans were not fully realized, and the basins were never fully connected to each other or to the coast (Hungerford et al. 2019).
- The Ten-Year Flood Management Program for 2012 to 2022, known as PDGI, is managed by the Ministry for Restructuring and Managing Flood Zones (MRAZI), with an estimated cost of 18 million USD, and includes a 2012-2013 emergency phase, a short-term phase in 2014-2016 and a medium and long-term phase 2017-2022. This program has four main components:
    1. resettlement of flood victims in furnished and equipped areas, providing an improved living environment;
    2. installation of storm water drainage;
    3. restructuring of urban areas and flood-prone districts;
    4. improvement of land-use planning policy and development of new urban centers.

Among the further on-going and recently completed projects and studies on flood management are the following:

- CLUVA - CLimate change and Urban Vulnerability in Africa: FP7 Environment, 2010 – 2013: CLUVA's analysis of extreme rainfall events, based on climate projection data until 2050, suggests that intensity and frequency of extreme events will significantly increase and enhance flood risks in the future (Coly et al. 2011; Coly et al. 2012).

- In 2010, the Storm Water Management and Climate Change Project ("Projet de Gestion des Eaux Pluviales – PROGEP") was launched which was financed mainly by the World Bank. PROGEP is an implementation plan of the PDD (Plan Directeur de Drainage de la région de Dakar) for Pikine and Guédiawaye Departments. The Government designated the Municipal Development Agency (ADM) with the preparation and implementation of the five-year project (2013-2017, later extended to 2019). The objective of PROGEP was to improve storm water drainage and flood prevention in peri-urban Dakar for the benefit of local residents.

PROGEP aims at reducing floods through an integrated and sustainable approach. It is being implemented together with priority measures such as:

1. the preparation of a master plan for storm water drainage and the construction of drainage structures;
2. construction of storm water drainage on the outskirts of Dakar;
3. mapping of flood risks and within detailed urban plans (PUD);
4. developing a flood prevention Geographic Information System (GIS);
5. involving communities in flood reduction and climate change adaptation through information campaigns to raise public awareness and support micro-projects for reducing local flood risks.

Figure 35: A pump to clear out flooded streets of the Pikine neighbourhood of the Senegal capital Dakar PROGEP measures (Photo Mamadou Lamine Camara, Agence de développement municipal (ADM) Dakar)

- The Government of Senegal has been making substantial efforts to control urban growth by preparing Urban Development Master Plans. Those successive plans, however, have failed to control urban growth fully due to non-compliance with the land use guidelines set forth, especially in the suburbs where the development of large irregular settlements took place on flood areas, mainly in the Niayes area. The Dakar Urban Development Master Plan by the Horizon 2025 was prepared in 2001 and approved in 2009. It had the ambition of rebalancing the regional structure by creating new urban poles outside the existing Dakar agglomeration. The 2025 Master Plan has not been effective because it was not based on an accurate understanding of local conditions, lacking the sharing of information with all stakeholders (JICA 2016). Therefore, supported by the Japan International Cooperation Agency (JICA), the “Project for Urban Master Plan of Dakar and the Neighboring Area for 2035” was realized from August 2014 to January 2016 with the following objectives:

  (a) to prepare an urban development master plan for Dakar Region and the neighboring area for the target year of 2035;
  (b) to prepare a detailed plan for at least one selected area as a tool to realize the 2035 Master Plan;
  (c) to conduct pre-feasibility studies on the priority projects to be selected as a tool to realize the 2035 Master Plan;

(d) to undertake the capacity development of the Department of Urbanization and Architecture (DUA) and related ministries, organizations and local governments, strengthening their staff capabilities so that they will be able to properly manage urban development.

- Senegal Integrated Urban Flood Management Project coordinated by the Agence Française de Développement (AFD) and funded by the UNFCCC Green Climate Fund (GCF) aims at supporting Senegalese policy on flood risk management through a disaster risk reduction perspective. GCF financing will focus on soft measures. Flood risk mapping will also be undertaken, and assessments carried out on how to increase the resilience of urban areas. Future risk will be reduced through hazard monitoring, and protocols developed for managing extreme rain events. These actions will be complemented by AFD financing towards hard investments in drainage and sanitation infrastructure in one of the most vulnerable areas of the capital city (Pikine Irrégulier Sud). The project will also contribute to establishing a national-scale integrated policy for disaster risk management in order to optimize investment at national scale and most importantly deal with the risk that will never be cost-efficiently covered by infrastructure. This approach of strengthening infrastructure and governance will put Senegal at the cutting edge of flood-management policy in West Africa. Approved in October 2016, the project has an estimated lifespan of 5 years.
- The "Living with Water" (“Vivre avec l'eau”) project aims to improve resilience to urban flooding of 860 000 vulnerable persons living in ten communes in the suburbs of Dakar through a multidisciplinary, integrated and inclusive approach, involving stakeholders at the local and national levels. This project, implemented since May 2015 by a consortium of nine organizations, of which the Consortium for Economic and Social Research (CRES) is lead partner, combines infrastructure activities (with the construction of rainwater evacuation system) to capacity building activities, and supports the development and implementation of a better flood management strategy in the departments of Dakar, Pikine, Guédiawaye and Rufisque. The project also helps the beneficiaries to improve their waste collection system, supports the creation of waste related small companies and improve the environment of the beneficiaries by building public furniture and embellishments. “Living With Water” supports the beneficiaries in doing income generating activities, waste collection, urban gardening, production and selling of compost etc. In each commune a flood emergency plan was elaborated and the population trained to be able to prevent the flooding and know how to react quickly in case of flooding.

5.2 Flood History

No major floods occurred during the 1960s, 1970s and 1980s, which were marked by a drought that affected the whole of West Africa. Conditions returned to more humid climate in the 1990s. Flooding did not immediately accompany the return to normal rainfall and water table levels in the 1990s but instead began significantly in 2005.

Recent flood events as taken from global databases (Dartmouth Flood Observatory, GLIDE Disaster Data Base, Emergency Events Database (EM-DAT), UNDRR DesInventar Sendai, ReliefWeb, GFDRR) local sources and press releases include:

2005

In 2005, the Dakar metropolitan region received its highest rainfall in nearly 20 years. Examples for heavy rain events in the flood season of 2005 are:

- 16th-17th August : 87.4 mm
- 19th-22nd August : 184.5 mm
- 28th-31st August : 55.2 mm

Widespread flooding occurred across much of the region with Rufisque, Pikine and Guédiawaye being most concerned. In Pikine, the floods displaced thousands of people and cost billions of francs (Hungerford et al. 2019).

2007

The town of Thies (to the east of Dakar) reportedly received 127 millimetres of rain on the night of 13th August. Heavy Rains and floods were reported as well in the capital, Dakar (GLIDE).

2008

From September 1st to 4th, Dakar received 133mm of rain, twice as much as would normally be expected (GLIDE). Thousands were affected by flooding in more than 40 neighborhoods across Senegal, including 21 Dakar suburbs. Dakar neighborhoods affected include Pikine, Guédiawaye, Thiaroye and Diamaguène (Gambia News 2008).

2009

In August and September 2009, it was about 360 000 people who were directly affected by floods in Pikine and 22 000 people in Guédiawaye; respectively 44% and 7.2% of the population in both departments (Ndiaye et al. 2016).

Figure 36: In the "streets" of Dakar, 17/09/2009 - Photo: SOS Archives

The Post- Disaster Needs Assessment (PDNA), funded through the Global Facility for Disaster Reduction and Recovery (GFDRR), estimated damage and losses to total of approx. 103 million USD nationwide, of which 82 million USD was for damage and loss in the Dakar region alone. An estimated 30,000 houses were affected in the Dakar region, most of which were uninhabitable permanently and often abandoned (Cissé 2018).

2010

Due to heavy rainfall since September 2, 2010, large areas in Senegal were affected by floods. One of the most affected areas was the capital Dakar with its suburban areas, affecting more than 30,000 households. According to information received from UN-OCHA some roads as well as critical infrastructure were blocked by water (SAFER Rapid Mapping Activity by DLR, funded by European Community's 7th Framework Programme (FP7/2007-2013) under grant agreement No. 218802).

2012

Since the beginning of the rainy season in July 2012, torrential rains have caused local flooding in several areas of Senegal, including St. Louis (North), Bambey (center) and Dakar (GLIDE).

The emergency relief plan (ORSEC) was activated after the heavy rains of August 26th. Due to heavy flooding, 26 deaths, 264,000 affected people and 7,737 damaged houses were reported in Senegal. Floods displaced over 5,000 families (over half from the regions of Dakar and Matam) and contaminated 7,700 drinking water sources.

Figure 37: Flooded settlement in the Department of Pikine, August/September 2012 (Photo: Steve Cockburn)

Figure 38: Flooding in Pikine, Sptember 2012 (Senegal7.com)

2013

In September, an estimated 163,000 people have once again been affected by severe flooding across Senegal. Above average rains triggered damaging floods that affecting an estimated 100,000 people. Nearly the entire south-western part of the country was inundated: from the capital of Dakar to the regions of Mbour, Fatick, Djilor, Passy, Kaffrine, and Kaolack. (OCHA 2013).

2015

In August and September, torrential rains in Senegal triggered severe floods. According to radio reports, more water fell within two hours than over a 45-day average. Dakar suburbs (e.g. Pikine, Guédiawaye, N'gor) were most concerned once again. However, in Pikine measures taken within the frame of the *Vivre avec l'eau / Live with water* project with the installation of a pilot drainage system proved to be successful as the runoff was redirected and captured in low-lying natural basins.

2016

July to August: extreme rainfall causing floods (GLIDE)

2018

September: flooding due to heavy rainfall (GLIDE)

5.3 EO Data Used

In general, there are two types of data available for this purpose: optical and Radar data. Available HR optical data from the sensors Landsat 5, Landsat 8, and Sentinel-2 covering the period from 2009 to 2018 was downloaded and analysed with regard to regional and/or local flooding.

The following datasets were used for flood extent mapping:

- Landsat 5, recorded on 22/10/2009
- Landsat 5, recorded on 25/10/2010
- Landsat 5, recorded on 12/10/2011
- Landsat 8 recorded on 01/10/2013
- Landsat 8 recorded on 21/11/2014
- Landsat 8 recorded on 08/11/2015
- Sentinel 2 recorded on 30/10/2016
- Sentinel 2 recorded on 10/10/2017
- Sentinel 2 recorded on 15/10/2018

VHR Imagery covering the core city area was provided by the Project Coordinators:

- Mosaic: QuickBird-2 recorded on 07/11/2005, 06/05/2006, 21/12/2006,
- Mosaic: Pleiades recorded on 01/03/2018 and 02/03/2018

This data gives a good impression of the rapid development and expansion of Dakar but no information about flooding could be obtained as VHR data was acquired in dry periods.

After experiences from other urban areas (e.g. Saint Louis, Senegal), no Radar data was downloaded and processed. The data tend to give unreliable results in urban environment due to the high number of low backscattering objects.

The flood risk product is a combination of hazard with Land Use / Land Cover (LULC) information. The latter is derived from the Very High Resolution (VHR) satellite data based LULC classification produced by NEO covering the Core City Area.

The Larger Urban Area LULC classification is based on Landsat 7 Mosaic (14/01/2006, 03/03/2006, 12/03/2006, 28/03/2006) and Sentinel 2 data (27/02/2018) respectively. Thus, these datasets are also indirectly used for the flood risk product.

For the following events VHR imagery is available in Google Earth and was used for visual interpretation of flood extents (cf. Figure 40 and Figure 41):

- October 2009 (recorded on 14/10/2009)
- December 2010 (recorded on 27/12/2010)
- October 2011 (recorded on 14/10/2011)
- October 2012 (recorded on 16/10/2012)
- October 2013 (recorded on 20/10/2013)
- September 2014 (recorded on 02/09/2014)
- August 2015 (recorded on 27/08/2015)
- October 2016 (recorded on 07/10/2016)
- August, September 2017 (recorded on 13/08/2017, 05/09/2017)
- October 2018 (recorded on 15/10/2018)

For physiographic analyses two different Digital Terrain Models were available:

- the 5m Digital Terrain Model of Dakar (BaseGéo Sénégal, (http://www.basegeo.gouv.sn/) based on Urban Database (UDB) product (covering part of Core City Area only, cf. Figure 39);

- the ALOS Global Digital Surface Model "ALOS World 3D - 30m (AW3D30)", version 2.1 (©JAXA) was used for physiographic analyses.

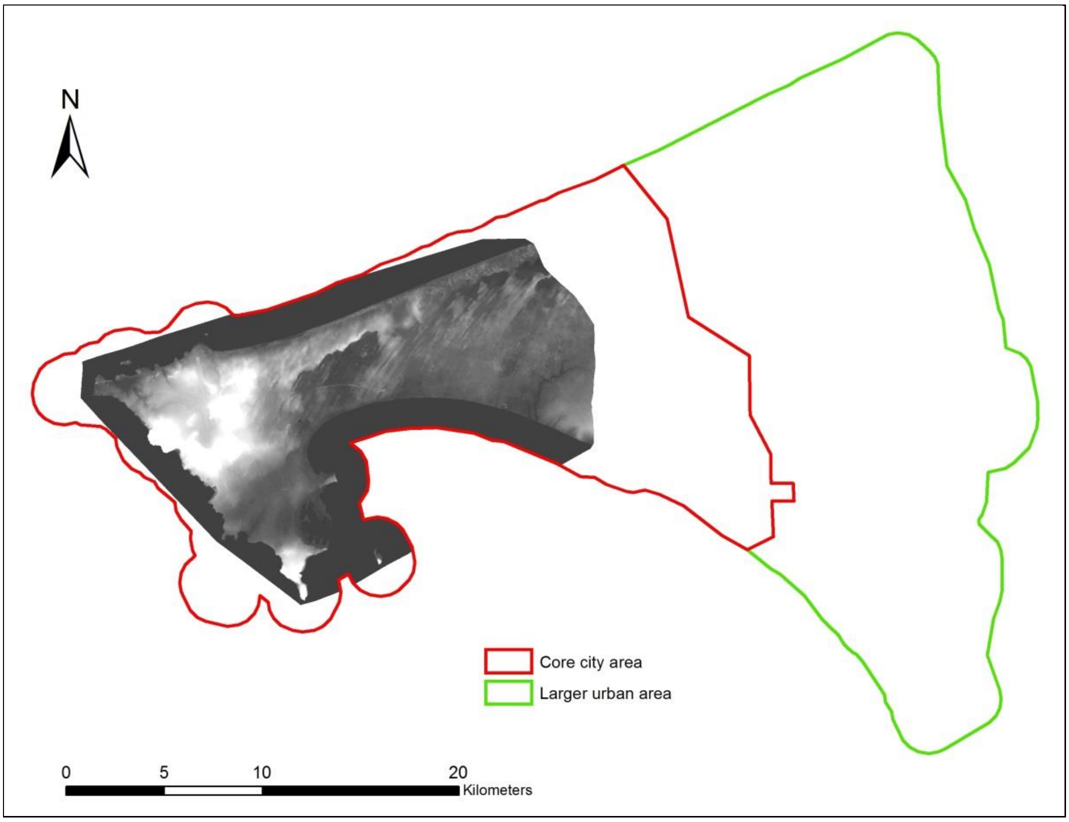

Figure 39: Coverage of the 5m Digital Terrain Model of Dakar (© BaseGéo Sénégal)

5.4 Short description of methodological approach

Historic flood extent mapping

Flood extent mapping based on EO data heavily depends on available datasets as well as on types of floods in focus. Whereas there is a good chance to identify river floods and long-term water stagnation, normally no information regarding short-term local floods (flash-floods) can be obtained from EO data due to short duration and/or cloud cover. In some cases, short-term local floods can be recorded and localized based on reports (e.g. in social media) and press releases but such inventory never will meet the claim of being complete.

The flood extent is derived from historical optical satellite imagery of 30-meter resolution (Landsat 5 and Landsat 8) and 10-meter resolution (Sentinel 2).

The relevant datasets were corrected atmospherically applying the Dark Object Subtraction (DOS) approach.

For defining the water extent, the water cover was classified by applying the Automated Water Extraction Index AWEIsh (Feyisa et al. 2014) which makes use of the reflectance values of Blue, Green, Near Infrared and Shortwave Infrared spectral bands of the Landsat 5, Landsat 8, and Sentinel-2 sensors. The AWEIsh is an index formulated to effectively eliminate non-water pixels, including dark built surfaces in areas with urban background. The equation is intended to effectively eliminate shadow pixels and improve water extraction accuracy in areas with shadow and/or other dark surfaces.

The delimitation of permanent water cover (representing a high water-level during the rainy season) is based on the EO4SD LULC classification (performed by SIRS).

Finally, mapping of flood extents by visual interpretation of VHR imagery when available in Google Earth was done (cf. Figure 40 and Figure 41). For Dakar, a large archive of VHR imagery is available.

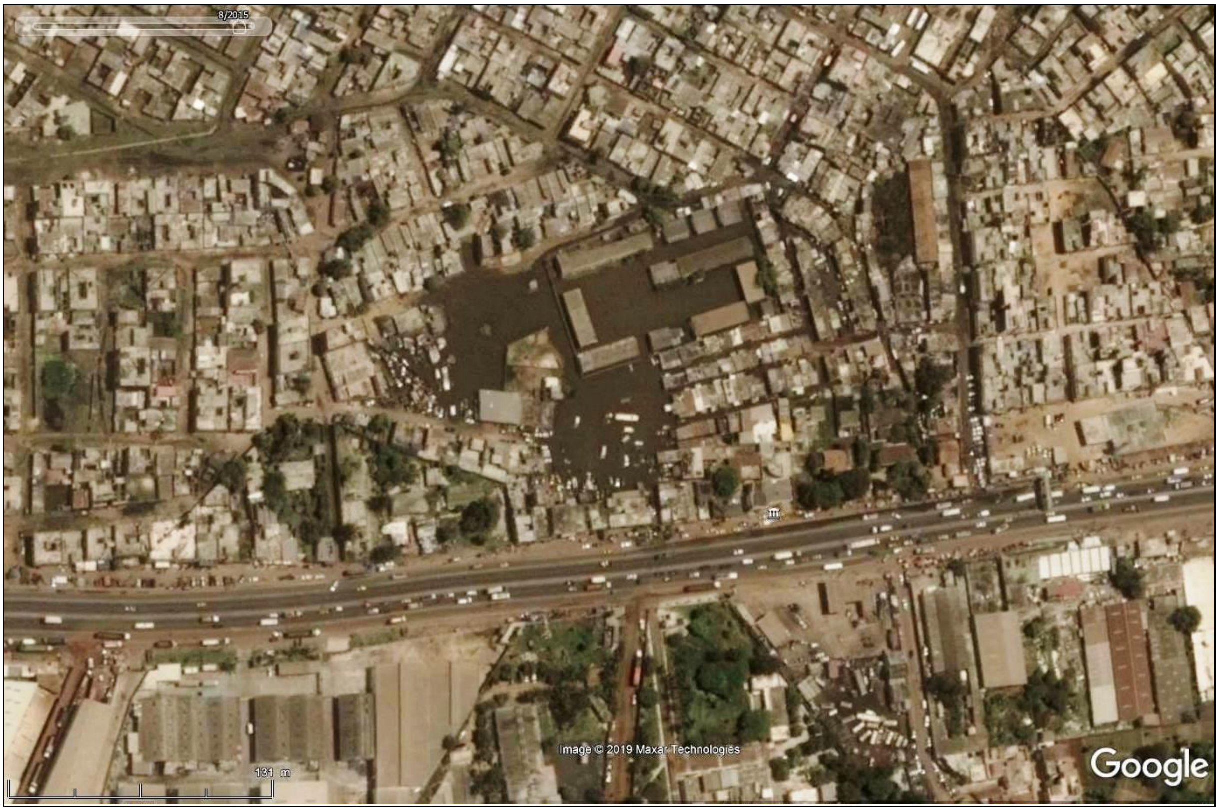

Figure 40: Flooded areas in southern part of Pikine (neighbourhood of Diammaguen) in August 2015 (image recorded on 27/08/2015, © Maxar Technologies)

Figure 41: Flooded areas in southern part of Pikine (neighbourhood of Dalifort) in August 2017 (image recorded on 13/08/2017, © Maxar Technologies)

Flood hazard mapping

The flood hazard map was generated based on the occurrence of flood events during the past 10 years (2009 – 2018). The map aims to give an idea about the flood presence in terms of both frequency and extent in the city, and illustrates which part is generally flooded more often than other areas.

Water extents representing floods of small rivers as well as rainwater stagnation after heavy rains (9 events) are based on:

- data from Landsat 5 (acquired on 22/10/2009, 25/10/2010, 12/10/2011), Landsat 8 (acquired on 01/10/2013, 21/11/2014, 08/11/2015, both provided by the US Geological Survey), and Sentinel-2 (acquired on 30/10/2016, 10/10/2017, 15/10/2018, provided by the European Space Agency)
- and on visual interpretation of VHR data as available in Google Earth (10 events, see Chapter 5.1.3).

The flood hazard classification was done according to the approach selected by NEO on Cambodia cities during EO4SD Phase 1: a "number of occurrences" was calculated by combining flood extents as derived from HR imagery and from visual interpretation of VHR imagery. This data was classified according to the following specifications for the hazard definition:

- area flooded once between 2009 and 2018: low hazard
- area flooded twice or three times: medium hazard
- area flooded more than three times: high hazard

However, it has to be underlined that both approaches for the flood extent identification differ significantly and that the analysis of VHR data does not cover the peri-urban area. Furthermore, in some cases, the areas identified as flooded in HR and VHR data respectively refer to the same event.

Therefore the "number of occurrences" may not be used for any further sub-classifications or interpretations.

Flood risk mapping

Risk is defined as a combination of probability and consequences. A detailed and uniform land-use map is an important prerequisite to perform flood risk calculations, since it determines what is damaged in case of flooding.

Two different datasets regarding the urban Land Use / Land Cover were made available for this analysis:

- LULC product generated by SIRS through EO4SD-Urban based on VHR data covering the Core City Area (approx. 422,4 sqkm)
- LULC product generated by SIRS through EO4SD-Urban based on HR data covering the Larger Urban Area (approx. 823,4 sqkm)

The exposition is classified following an approach developed by NEO (based on: Dasgupta et al. 2015) integrating economic costs, social damage, physical damage and flood duration. Four land use damage levels (A, B, C, D) are defined based on this estimation.

Both land-use classification results were recoded to pre-defined categories (as given in Table 13 and Table 14) and merged after categorization.

The flood risk product is a combination of hazard with Land Use / Land Cover (LULC) information. The latter is derived from the Very High Resolution (VHR) satellite data based LULC classification produced by SIRS covering the Core City Area. The Larger Urban Area LULC classification is based on Landsat 7 and Sentinel 2. Thus, these datasets are also indirectly used for the flood risk product.

Table 13: Land use classes and reclassification to pre-defined damage levels in Core City Area

Classes	Damage				Total	Level
	Economic Costs 0-2	Social Damage 0-2	Physical Damage 0-2	Flood Duration 0-2		
Very high density continuous urban fabric	1.5	1.5	2	1.5	6.5	D
High and medium density discontinuous urban fabric	1.5	1	2	1	5.5	C
Low and very low density discontinuous urban fabric	0.5	1.5	1.5	1	4.5	C
Industrial, commercial, public, military and private units	2	0.5	1	0.5	4	B
Arterial and Collector roads	1.5	1	2	1.5	6	C
Railway	1.5	1	2	1.5	6	C
Port area	2	1	0.5	1.5	5	C
Airport	2	0.5	1.5	1.5	5.5	C
Mineral Extraction and Dump Sites	1	0	0.5	0.5	2	A
Construction sites	1	0.5	0	0	1.5	A
Land without current use	0	0	0	0	0	A
Green urban area	0.5	0.5	0.5	1	2.5	B
Sports and leisure facilties	0.5	0.5	0	0.5	1.5	A
Agricultural area	1.5	0.5	0	1	3	B
Forests and shrublands	0.5	0	0	0	0.5	A
Natural areas (grassland)	0	0	0	0	0	A
Bare soil	0	0	0	0	0	A
Wetlands	0	0	0	0	0	A
Inland and marine water	0	0	0	0	0	A

Table 14: Land use classes and reclassification to pre-defined damage levels in Larger Urban Area

Classes	Damage				Total	Level
	Economic Costs 0-2	Social Damage 0-2	Physical Damage 0-2	Flood Duration 0-2		
Artificial Surfaces	1.5	1.5	2	1.5	6.5	D
Agricultural area	1.5	0.5	0	1	3	B
Forests ans shrublands	0.5	0	0	0	0.5	A
Natural areas (grassland)	0	0	0	0	0	A
Bare soil	0	0	0	0	0	A
Wetlands	0	0	0	0	0	A
Inland and marine water	0	0	0	0	0	A

The Flood Risk matrix is generated based on above code and flood hazard classified into three hazard levels. The flood risk level is classified in four qualitative classes based on the combination of flood hazard and land use damage as shown in Table 15.

Table 15: Flood Hazard and Risk classification

		Damage cost on land use			
		A	B	C	D
Flood Hazard	1 (low)	1A	1B	1C	1D
	2 (medium)	2A	2B	2C	2D
	3 (high)	3A	3B	3C	3D
Flood Risk classification					
Low Risk	1A 1B 2A				
Medium Risk	1C 1D 2B 2C 3A 3B				
High Risk	2D 3C				
Very high Risk	3D				

5.5 Product Description and Accuracy Assessment

There are three final layers in this product: (1) the raw data on past flood extents as derived from EO data and ancillary data (flood history), (2) the Flood Hazard map which summarizes past flood events and thus gives information about the likelihood of future events, and (3) the Flood Risk map combining this data with information on urban and peri-urban land use and its damage potential in case of flooding.

The Flood Hazard map (subset on Figure 42) displays flood hazard information (delivered in vector format). This data is based on the occurrence of floods of the past 10 years (2009 – 2018). It takes into account both the hazard from seasonal floods and rainwater stagnation in the rainy season as well as from tidal waves and coast erosion. The classification in three qualitative hazard levels is expert-based under consideration of mapped frequencies of floods.

The map aims to give an idea about the flood presence in terms of both frequency and extent in Dakar and illustrates which part is in general flooded more often than other areas.

Since no independent reference data are available no accuracy assessment is possible. The plausibility of the results nevertheless was evaluated on basis of local reports and press releases.

The Flood Risk Map (subset see Figure 43) displays flood risk information (delivered in vector format). This data is based on the occurrence of floods of the past 10 years (2009 – 2018) combined with information of the land use map provided by SIRS of this project area. It takes into account both the hazard level and potential damages, based on different land uses. The damages are assessed on 4 aspects: economic, social, physical and flood duration.

Since this product is a direct derivation and combination of the Hazard Classification and the Land Use Classification, its plausibility can be rated high when the mentioned input datasets are rated as being plausible and reliable.

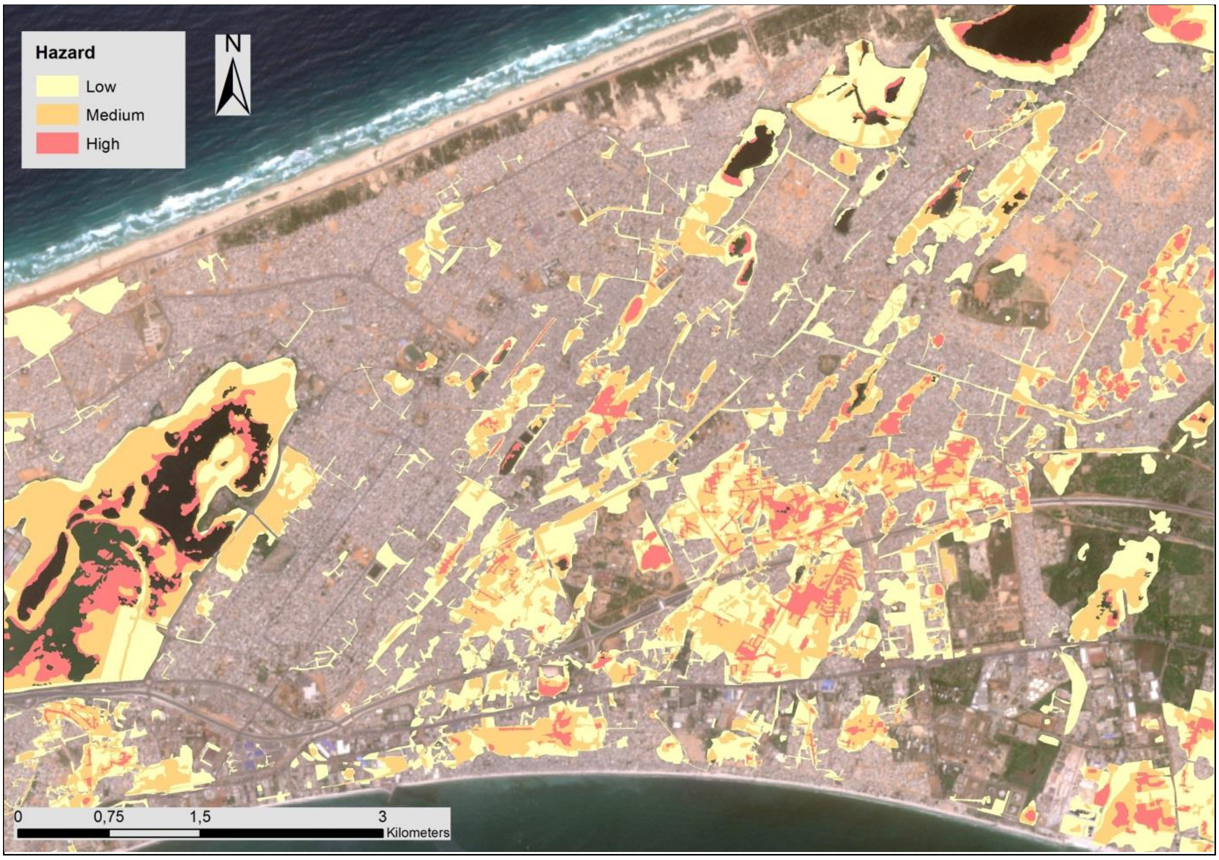

Figure 42: Subset of Flood Hazard Map of Dakar (Department of Pikine) (Background Image: Sentinel 2, recorded on 10/10/2016, European Space Agency)

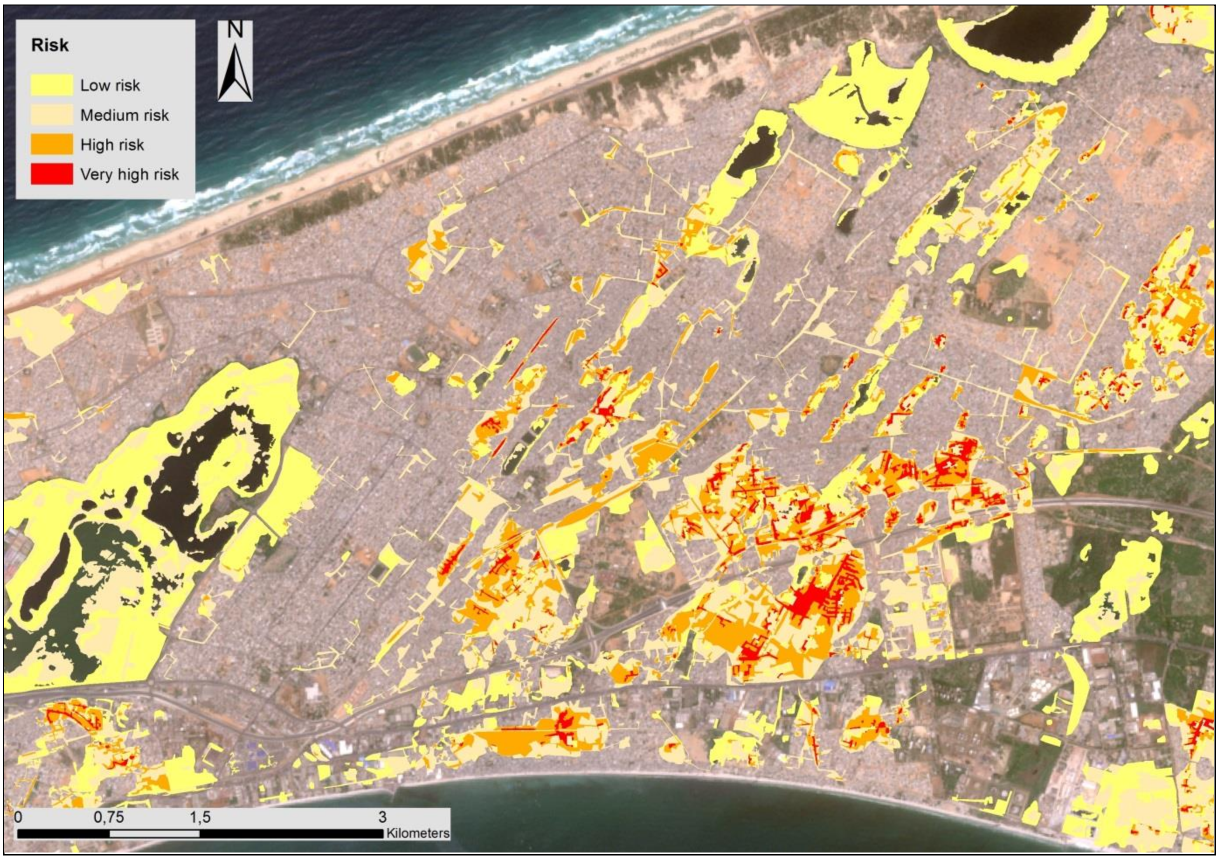

Figure 43: Subset of Flood Risk Map of Dakar (Department of Pikine) (Background Image: Sentinel 2, recorded on 10/10/2016, European Space Agency)

5.6 Results

Flood Hazard

For the Department of Grand Dakar (administrative centre, airport and port area) some parts are indicated with low hazard (which means they were flooded once within the last 10 years): this was the case in September 2014 in the area west of the airport (Ngor) and in September 2017 in the area north of the port (Colobane). The floods were caused by rainwater stagnation after heavy local rainstorms. However, most parts of Grand Dakar are not endangered by floods.

Most flood prone zones are indicated in the departments of Pikine and Guédiawaye (cf. Figure 42). Some zones in the Niayes are flooded almost every year in the rainy season. This is not only true for areas which are covered by different vegetation but also for densely built-up areas.

In the department of Rufisque there is also a high percentage of the area indicated as flood prone but most of the concerned area is classified with low or medium hazard (flooded up to three times within the last 10 years).

Only a low proportion of the larger urban area is classified as flood prone. This is also due to the fact that the analysis of VHR data was restricted to the core urban area and analysis of flood events in the larger urban area is based on automatic classification of HR data only.

For the following calculations the permanent water bodies as defined by the EO4SD LULC classification by SIRS are not considered. While the share of permanent water cover in the core city area is about 38,8%, this share is only approx. 11,6% in the peri-urban area. For the total area of interest, a percentage of 25,6% was calculated.

With regard to the flood hazard zones it can be observed that the expansion of such zones differs significantly in Dakar Core City Area and in the Larger Urban region: approx. 24,8% in the Core City area, but only about 1,2% in the Larger Urban region, are classified as flood prone (cf. Figure 44 and Figure 45): 12,25% of the Core City Area are defined as medium and high hazard zones whereas this percentage is only 0,93% in the peri-urban region.

This is mainly because the extensive marshes to the north of Saint Louis are flooded regularly during the rainy season and thus are classified as high- and medium-hazard areas with the selected approach.

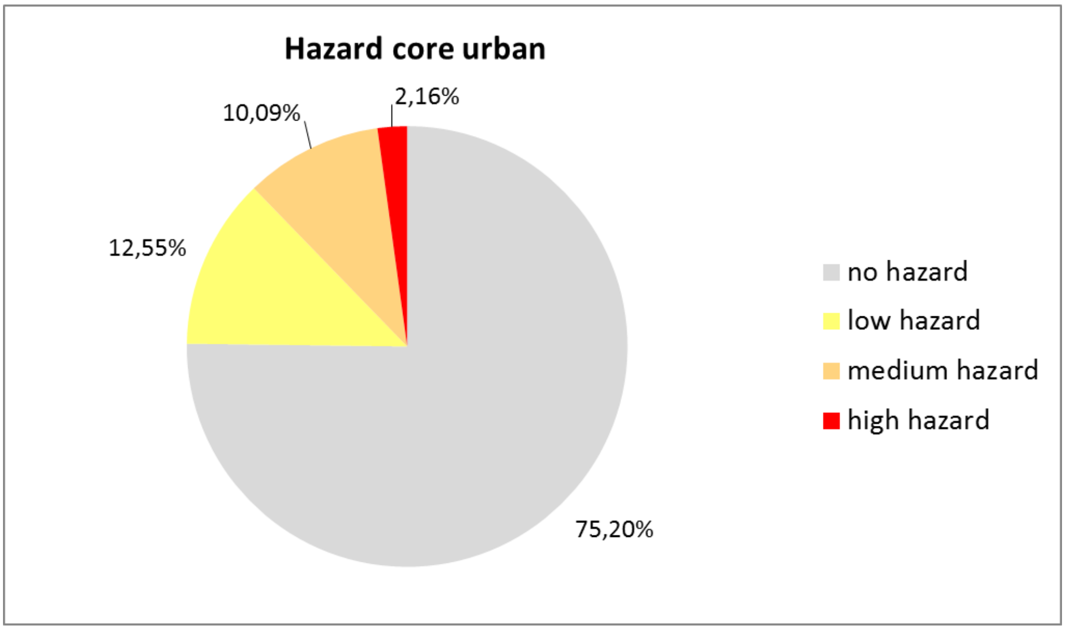

Figure 44: Percentages of flood hazard zones in Dakar core city area

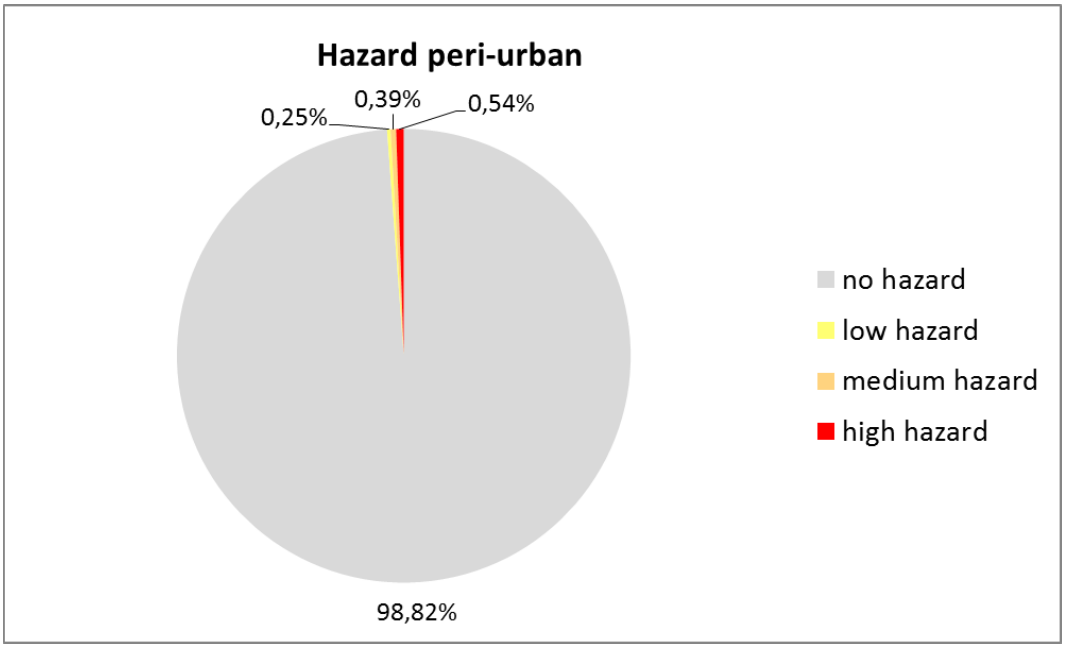

Figure 45: Percentages of flood hazard zones in Dakar peri-urban region

Residential Urban Fabric with high damage potential (LU classes: Residential – continuous urban fabric, Residential – discontinuous dense urban fabric, Residential – discontinuous medium density urban fabric, Residential – discontinuous low density urban fabric, Residential – discontinuous very low density urban fabric, Industrial, Commercial, Public) was analyzed more detailed and combined with the Flood Hazard Map in the core city area of interest.

For the peri-urban area the LU class "Artificial Surfaces" was analyzed in detail.

The statistics for Residential Urban Fabric in the core city area is shown in Figure 46; based on these statistics, approx. 4,7% of Dakar's Residential Urban Fabric is situated in Medium and High Flood Hazard Zones. Additional 11,28% of these landuse classes is situated in Low Flood Hazard Zones.

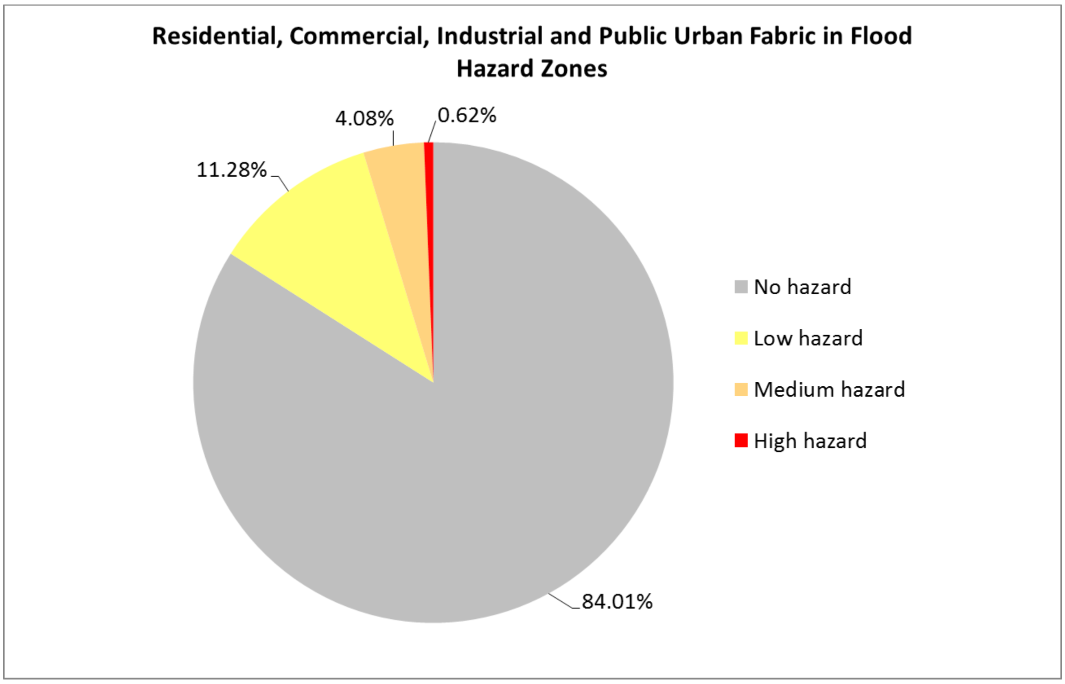

Figure 46: Proportion of Residential Urban Fabric in flood hazard zones in Dakar core city area

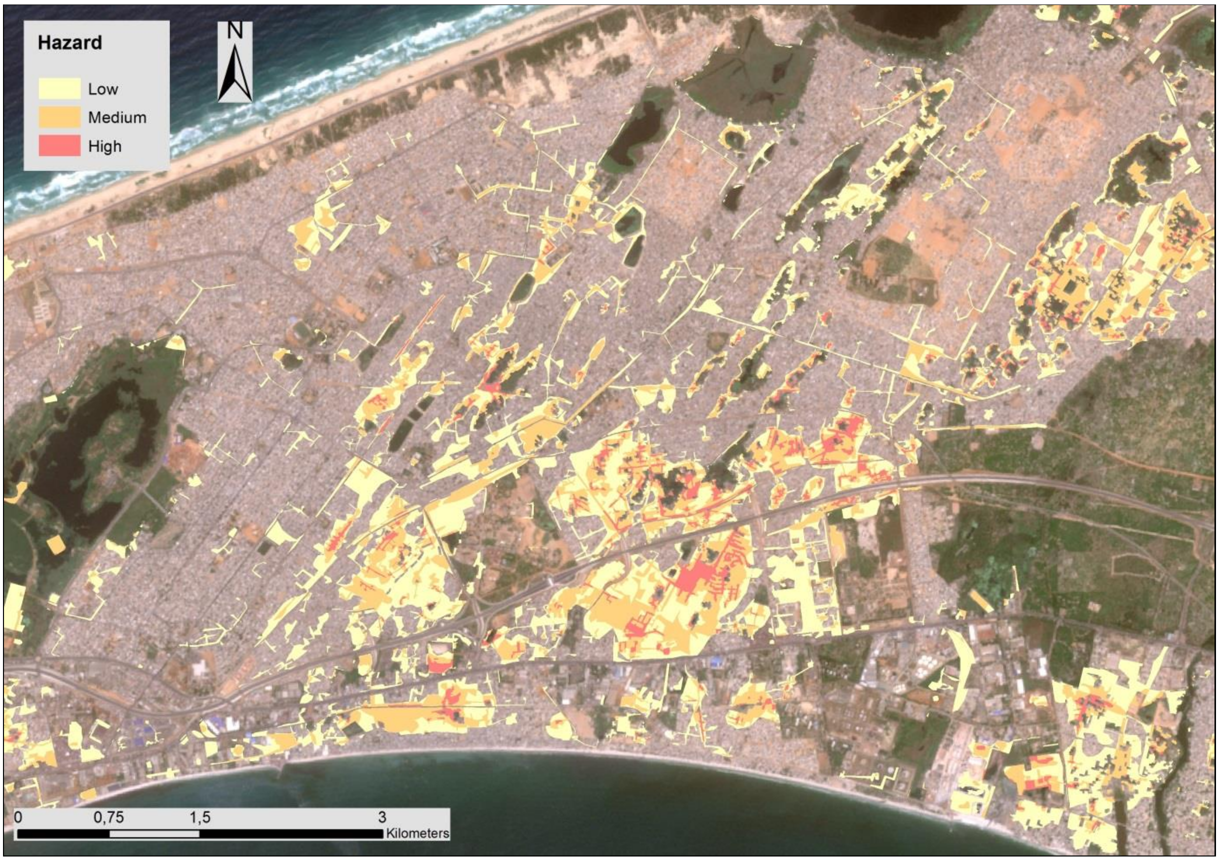

Figure 47: Subset of map of Residential, Industrial, Commercial and Public Urban Fabric combined with Flood Hazard Zoning in Dakar's department of Pikine (Background Image: Sentinel 2, recorded on 10/10/2016, European Space Agency)

For the larger urban area only 0,17% of the landuse class "Artificial Surface" is situated in Medium and High Flood Hazard Zones. Additional 0,15% of this landuse class is situated in Low Flood Hazard Zones.

Flood Risk

Generally, flood risk zones are well known - but to limited degree respected and enforced. In Dakar, following many years of drought, the population moving in from rural parts occupied parts of the interdunal depressions (Niayes) normally under water; consequently, many districts may be flooded in the event of a major rise in water level. Long-term rainwater stagnation in the rainy season and high flooding risk can be observed especially in the departments of Pikine and Guédiawaye (cf. Figure 29).

Flood risk is exacerbated by rapid urbanization, insufficient drainage, and poor sewage infrastructure, which has resulted in the settling of low-lying areas and a reduction in soil infiltration potential. Rising sea levels and increasingly intense storms may be causes of future coastal erosion and flood risks (JICA 2016).

It is important to be aware that the applied methodology of flood risk classification involves some degree of human interpretation. Therefore, flood risk levels must be considered as relative metrics rather than absolute ones.

For the following calculations the permanent water bodies as defined by the EO4SD LULC classification by SIRS again are not considered.

As the expansion of flood risk zones is equal to that of hazard zones this results in a similar picture with regard to the total extent of the risk zones. Because of the higher exposition of urban land use the high and very high risk categories (accumulated) occur disproportionately high in the Core City area (approx. 2,33% vs. 0,04% in the Larger Urban region, cf. Figure 48 and Figure 49). Also areas classified as medium- and low-risk zones can be observed more frequently in the core urban region (15,57% vs. 1,15%, cf. Fig. 25 and 26). This is mainly a result of the absence of land use classes with high damage potential in the larger urban area and in the low distribution of flood hazard zones because of the restriction of the analysis of VHR data to the core urban area.

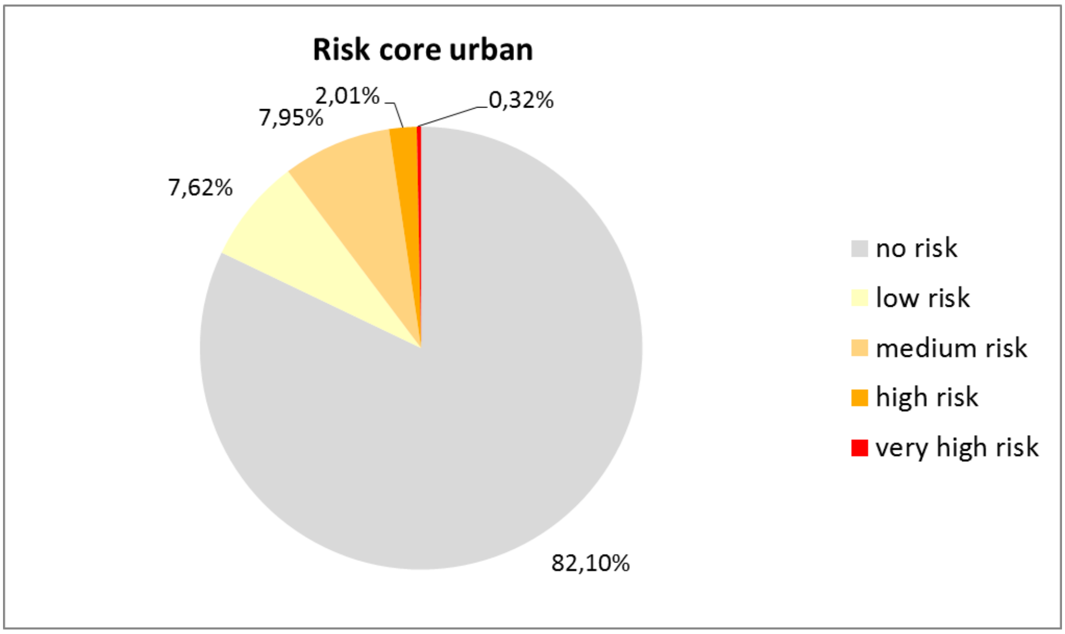

Figure 48: Percentages of flood risk zones in Dakar Core city Area

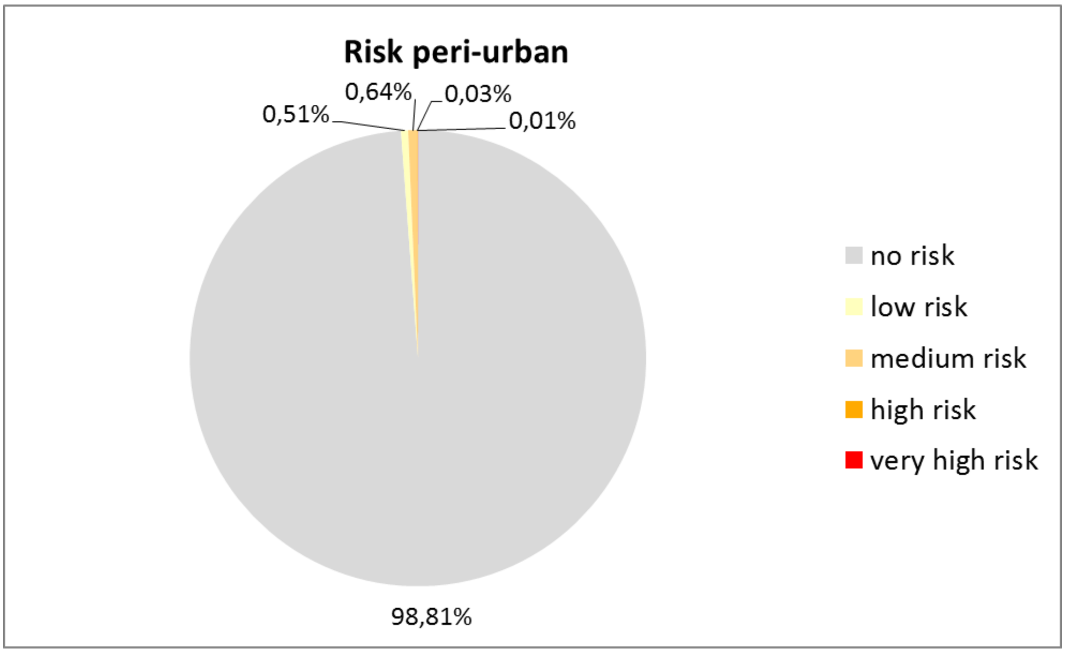

Figure 49: Percentages of flood risk zones in Dakar Larger Urban Area

Residential Urban Fabric with high damage potential was analyzed more detailed and combined with the Flood Risk Map both in the Core City Area as well as in the Larger Urban Area. A subset of the Flood Risk map combined with Residential, Industrial, Commercial and Public Urban Fabric in Dakar's department of Pikine is given in Figure 50. The focus of high-risk zones in landuse classes with high damage potential can well be observed to the South of the department of Pikine.

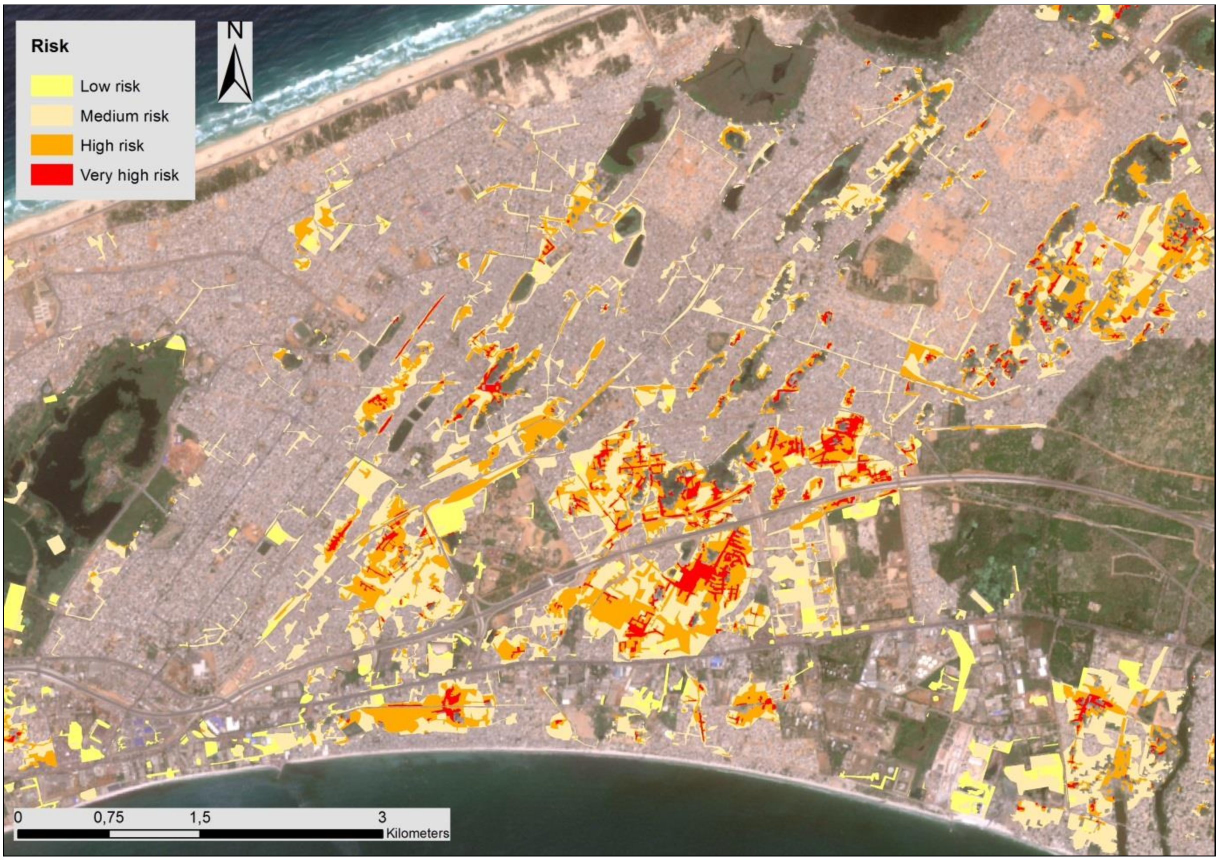

Figure 50: Subset of map of Residential, Industrial, Commercial and Public Urban Fabric combined with Flood Risk Zoning in Dakar's department of Pikine (Background Image: Sentinel 2, recorded on 10/10/2016, European Space Agency)

The statistics for Residential Urban Fabric only in Dakar Core City Area is shown in Figure 51: Based on these statistics, about 4,08 % of Dakar's Residential Urban Fabric is situated in high to very high risk zones, another 10,16% in medium risk zones.

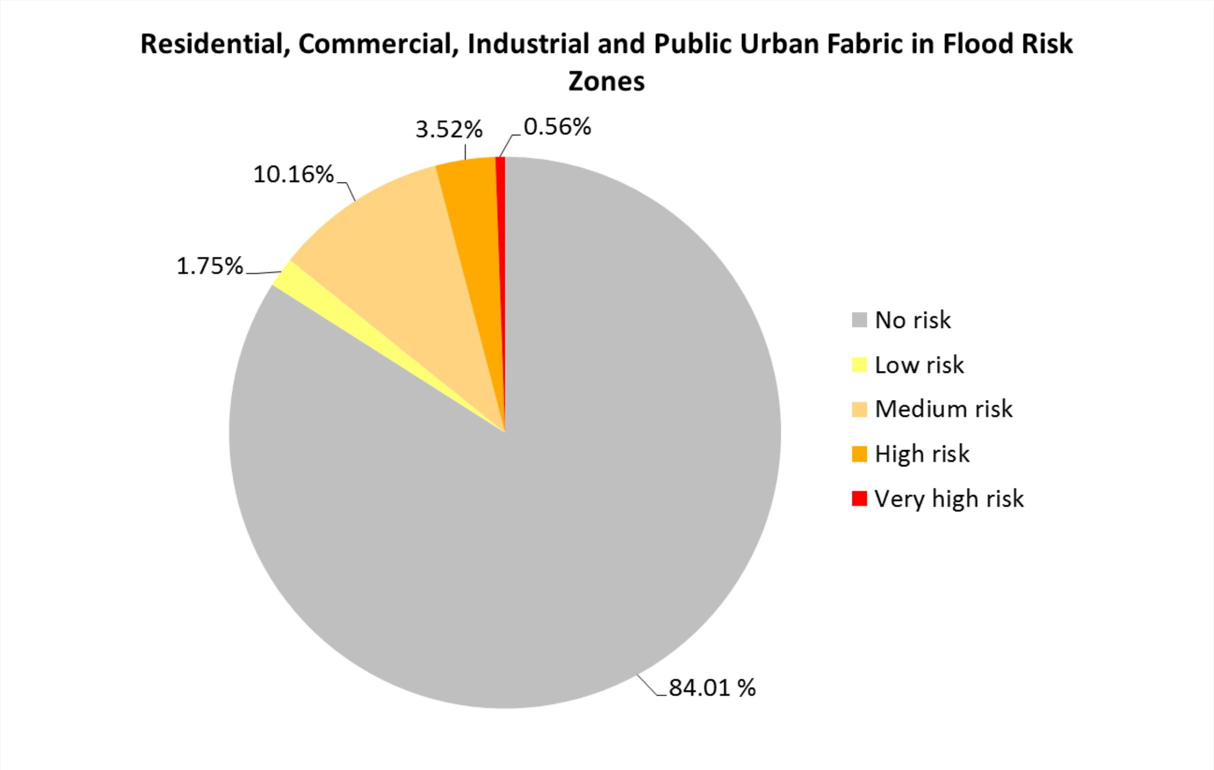

Figure 51: Proportion of Residential Urban Fabric in flood hazard zones in Dakar Core City Area

For the peri-urban area, only 0,17% of the landuse class "Artificial Surface" is situated in high and very high flood risk zones. Additional 0,15% of this landuse class is situated in medium flood risk zones.

6 References

Czaplewski, R. L. (2003). Chapter 5: Accuracy assessment of maps of forest condition: statistical design and methodological considerations, pp. 115–140. In Michael A. Wulder, & Steven E. Franklin (Eds.), Remote sensing of forest environments: concepts and case studies. Boston: Kluwer Academic Publishers (515 pp.).

European Union (2011). Mapping Guide for a European Urban Atlas, Version 11.0

Goodchild, M., Chih-Chang, L. and Leung, Y. (1994): Visualizing fuzzy maps, pp. 158-67. In Heamshaw, H.H. and Unwin, D.J. (Eds.), Visualization in geographical information systems. Chichester: Wiley.

Olofsson, P., Foody, G. M., Stehman, S. V., & Woodcock, C. E. (2013). Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sensing of Environment, 129, 122–131. doi:10.1016/j.rse.2012.10.031

Selkowitz, D. J., & Stehman, S. V. (2011). Thematic accuracy of the National Land Cover Database (NLCD) 2001 land cover for Alaska. Remote Sensing of Environment, 115(6), 1401–1407. doi:10.1016/j.rse.2011.01.020.

Internet

Road classification, European Commission, 2017, https://ec.europa.eu/transport/road_safety/specialist-/knowledge/road/designing_for_road_function/road_classification_en, last accessed 2017.08.17

Flood-related products

Cissé, O. (2018): Les inondations à Dakar.: Gestion des risques et adaptations locales.- Hommes et sociétés. KARTHALA Editions.

Cissé, O., & Sèye, M. (2015): Flooding in the suburbs of Dakar: impacts on the assets and adaptation strategies of households or communities.- Environment & Urbanization, International Institute for Environment and Development (IIED), Vol 28(1): 183–204. DOI: 10.1177/0956247815613693.

Coly, A., D'Almeida, A., Diakhaté M.M., Lo, M., Sy, B.A., Ndour, N.M., Gueye, S., Sall, F., & Sy, A.A. (2011): Report on climate related hazard in the city of Saint-Louis. Internal CLUVA report (D5.2), University of Gaston Berger.

Coly A, Sall F, & Weets G (2012): Changements climatiques et vulnérabilité des villes africaines – Saint Louis du Sénégal. Rapport de Synthese, CLUVA (D5.8), UGB.

Dasgupta, S., Asif, Z., Subhendu, R., Mainul, H., Sarwar, J. & Ainun, N. (2015): Urban Flooding of Greater Dhaka in a Changing Climate: Building Local Resilience to Disaster Risk. Directions in Development. Washington, DC: World Bank. doi:10.1596/978-1-4648-0710-7. License: Creative Commons Attribution CC BY 3.0 IGO

Diop, A., Ndiaye, M.L., Sambou, H., Dacosta, H., & Sambou, B. (2017): Integrated a GIS and Multicriteria Evaluation approach for Mapping Flood Vulnerability of Buildings in the Grande Niaye Watershed of Dakar, Senegal.- American Journal of Geographic Information System 2017, 6(2): 41-53, DOI: 10.5923/j.ajgis.20170602.01.

Diouf, O.C., Faye, S.C., Dieng, N.M., Faye, S., & Faye, A. (2013): Hydrological risk analysis with optical remote sensing and hydrogeological modelling: Case study of Dakar flooding area (Senegal). Geoinfor. Geostat. An Overview. 2013, 8.

Feyisa, G. L., Meilby, H., Fensholt, R. et Proud, S. R. (2014): Automated Water Extraction Index : A new technique for surface water mapping using Landsat imagery. Remote Sensing of Environment, 140, 23–35. https://doi.org/10.1016/j.rse.2013.08.029.

Gambia News: http://wow.gm/africa/senegal/dakar/article/2008/9/10/senegal-flooding-spreads-as-rains-continue *Retrieved 2019-09-16.*

GFDRR (2014): Senegal: Urban Floods Recovery and Reconstruction since 2009.- Country Case Study Series. Guide for Disaster Recovery Frameworks.

GLIDE Disaster Data Base: http://www.glidenumber.net/glide/public/search/search.jsp *Retrieved 2019-09-16.*

Hay, M. The Planet: A Flood of Good Intentions in Senegal; GOOD Worldwide Inc.: New York, NY, USA; Available online: https://www.good.is/articles/pikine-senegal-flood-basins-living-with-water (*Retrieved 2019-09-23*).

Hungerford, H., Smiley, L.S., Blair, T., Beutler, S., Bowers, N., & Cadte, E. (2019): Coping with Floods in Pikine, Senegal: An Exploration of Household Impacts and Prevention Efforts.- Urban Sci. 2019, 3(2), 54; https://doi.org/10.3390/urbansci3020054.

JICA Study Team: Project for Urban Master Plan of Dakar and Neighboring Area for 2035. Final Report: Volume. I (2016): Ministry of Urban Renewal, Housing and Living Environment, Republic of Senegal, Japan International Cooperation Agency.

Le Cozannet, G., Raucoules, D., Wöppelmann, G., Garcin, M., Da Sylva, S., Meyssignac, B., Gravelle, M., & Lavigne, F. (2015): Vertical ground motion and historical sea-level records in Dakar (Senegal).- Environ. Res. Lett. 10 084016, doi:10.1088/1748-9326/10/8/084016.

Mbow C., Diop A., Diaw A. T., & Niang C. I. (2008): Urban sprawl development and Flooding at Yeumbeul Suburb (Dakar, Senegal).- African Journal of Environmental Science and Technology, Vol. 4, pp. 75-88.

Ndiaye, M., Traore, V., Toure, M., Sambou, A., Diaw, A., & Beye, A. (2016): Detection and ranking of vulnerable areas to urban flooding using GIS and ASMC (spatial analysis multicriteria): A case study in Dakar, Senegal. Int. J.Adv. Eng. Manag. Sci. 2016, 2, 1270–1277.

Roca, T., Schwarz, B., Tellman, B., Sullivan, J., Kuhn, C., Mahtta, R., Pandey, N., Hammett, L., & Pestre, G. (2017): Vulnérabilité sociophysique aux inondations au Sénégal. Une analyse exploratoire sur la base de nouvelles données et de Google Earth Engine.- Notes Techniques No. 25, Agence Française de Développement: http://librairie.afd.fr.

Roger, J., Banton, O., Barusseau, J.P., Castaigne, P., Comte, J.-C., Duvail, C., Nehlig, P., Noël, B.J., Serrano, O., & Travi, Y. (2009): Notice explicative de la cartographie multi-couches à 1/50 000 et 1/20 000 de la zone d'activité du Cap-Vert Ministère des Mines, de l'Industrie et des PME, Direction des Mines et de la Géologie, Dakar 245.

Thiam, M. D. (2011): Le syndrome des inondations au Sénégal.- Dakar: Presses universitaires du Sahel, 2011.

Wang, H.G., Montoliu-Munoz, M., & Gueye, N. (2009): Preparing to Manage Natural Hazards and Climate Change Risks in Dakar, Senegal.- Pilot Study Report, World Bank Group, Finance, Economics and Urban Development Department, Sustainable Development Network.

This page is intentionally left blank.

Annex 1 – AOI Calculation based on the DG Regio approach

This page is intentionally left blank.

AOI Calculation Methodology based on the DG Regio Approach

So far, no internationally accepted definition for the term "Urban Area" and the related Peri-Urban area exists. Different initiatives are currently trying to address a standardised approach for defining the term "Urban Area". During discussions with the GPSC Co-ordinator it was considered important to use an uniform definition for the GPSC cities in order for the cities to exchange information and share products/experiences and conduct potential comparative studies.

In this context, it was decided to use an international approach for the demarcation of the Areas of Interest (AOI) for mapping the GPSC cities in terms of Core Urban area and Peri-Urban area. Thus, the approach is based on the European Union's Directorate-General for Regional and Urban Policy (DG REGIO) method and the definitions are described in the Regional Working Paper 2014 from the European Commission on "A harmonised definition of cities and rural areas: the new degree of urbanisation" (European Commission, 2014). Following the naming of the DG Regio approach, the Urban Core is named as "High Density Core" and the Peri-Urban area is termed "Urban Cluster". Within the DG REGIO approach, the High Density Core is defined as contiguous grid cells of 1 km^2 with a density of at least 1 500 inhabitants per km^2 and a minimum population of 50 000. The Urban Cluster is defined as clusters of contiguous grid cells of 1 km^2 with a density of at least 300 inhabitants per km^2 and a minimum population of 5 000.

The DG REGIO methodology used in the EO4SD-Urban project was slightly adjusted to Non-European countries. For the first two GPSC cities (namely Bhopal and Vijayawada) produced within the project the Global Human Settlement Population (GHSP) grid with a spatial resolution of 1 km were used for the classification into "High Density Core" and "Urban Cluster". The raster dataset is available for the years 1975, 1990, 2000, 2015. This dataset depicts the distribution and density of population, expressed as the number of people per cell. The data can be downloaded under following link http://data.jrc.ec.europa.eu/dataset/jrc-ghsl-ghs_pop_gpw4_globe_r2015a.

In 2019, a higher resolution population layer (spatial resolution of 10 m) produced by the German Aerospace Centre (DLR) became available. The AOIs for the remaining GPSC cities (namely Melaka, Abidjan, Dakar and Campeche) were produced based on the DLR population layer.

In the following, a more detailed description of the calculation methodology for the High-Density Core and the Urban Cluster follows. The calculation is exemplary described on the AOI generation for the city of Melaka.

To start with, Figure 52 shows the city of Melaka and the surrounding area. Figure 53 shows the population distribution grid over Melaka produced by the European Commission. Figure 54 shows the DLR population grid with 10 meter spatial resolution for Melaka while Figure 55 illustrates the aggregated DLR population grid with 1 km spatial resolution.

Figure 52: Satellite image showing Melaka and the surrounding area.

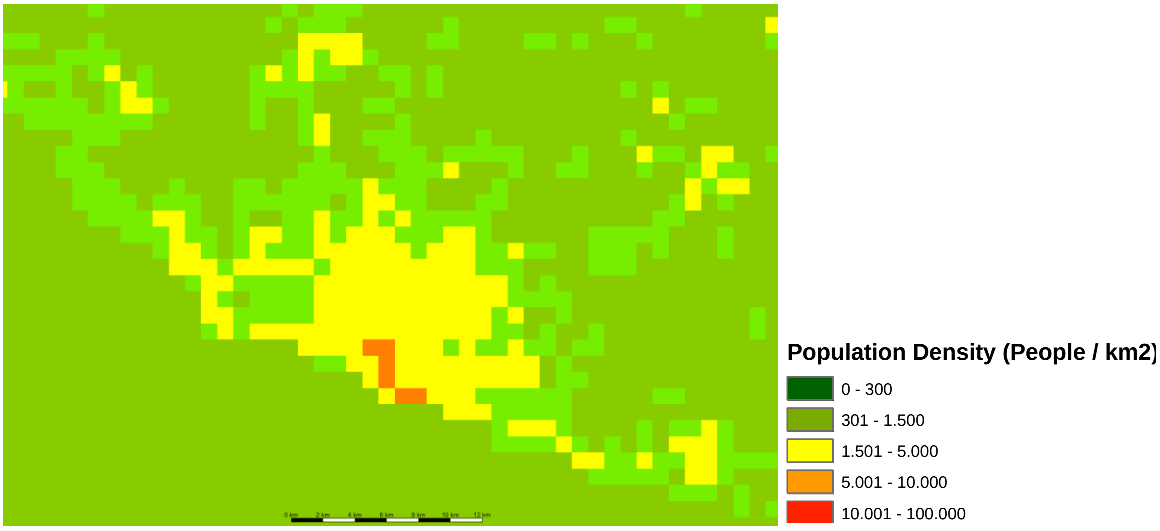

Figure 53: Global Human Settlement Population Layer (spatial resolution of 1 km).

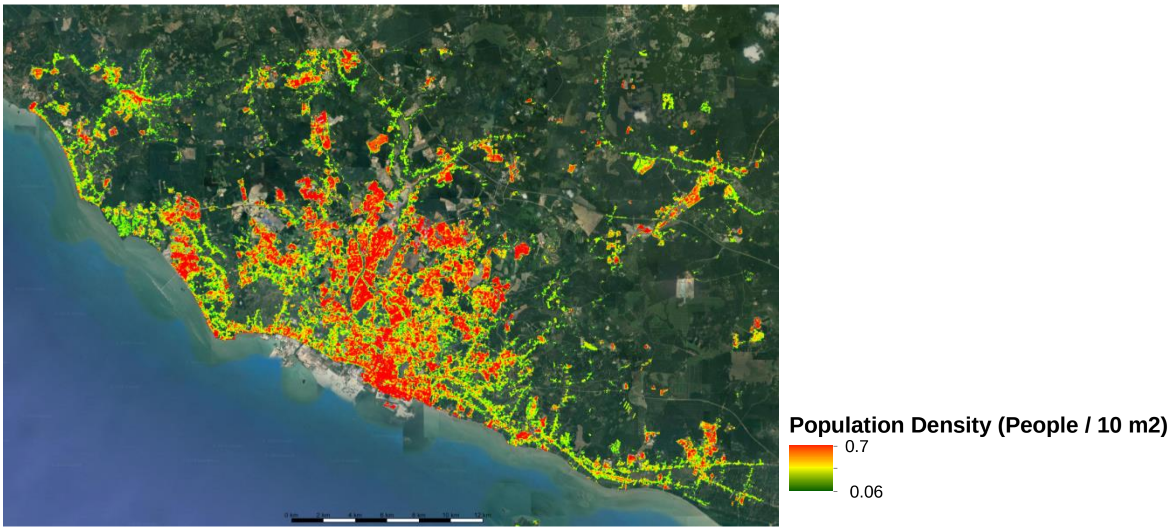

Figure 54: DLR population layer (spatial resolution of 10 m).

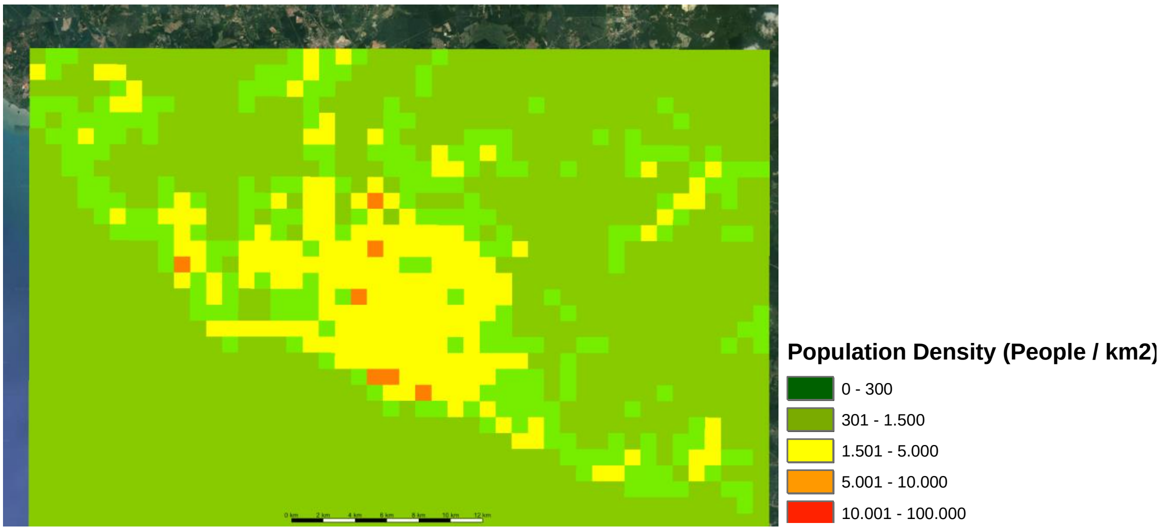

Figure 55: Aggregated DLR population layer (spatial resolution of 1 km).

The High Density Core AOI for a city is created by merging the contiguous grid cells of 1 km^2 with a density of at least 1500 inhabitants per km^2 and a minimum population of 50 000. In the definition of the High Density Core the contiguity is only allowed via a vertical or horizontal connection. In a next step, gaps are filled. Due to the coarse resolution of the population grid cells additional grid cells were in a last step added for under estimated settlement areas. The same was done for over estimations, here grid cells were removed.

Figure 56 shows the High Density Core AOI (red line) overlaid on the DLR population layer (left) and on a RGB satellite image (right).

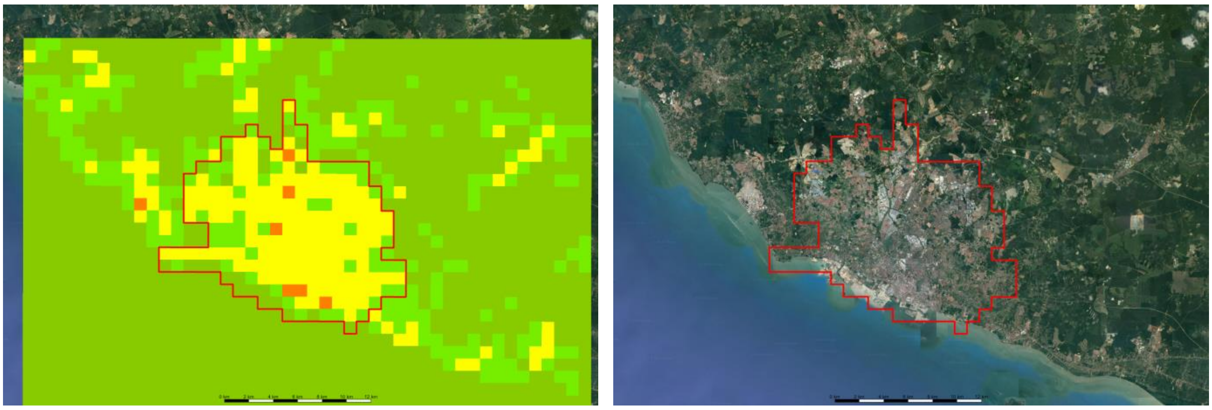

Figure 56: High Density Core area of Melaka calculated based on the aggregated DLR population layer. The image on the left shows the AOI overlaid on the DLR population layer. On the right, the AOI is overlaid on a RGB satellite image.

The Urban Cluster is created very similar to the High Density Core. Continuous grid cells of 1 km^2 with a density of at least 300 inhabitants per km^2 and a minimum population of 500 are merged together to form the Urban Cluster. The contiguity within the Urban Cluster can also be diagonal. After gaps are filled, areas, which were over or under estimated by the population grid were removed or added to the AOI. Figure 57 shows the Urban Cluster AOI (magenta line) overlaid on the DLR population layer (left) and on a RGB satellite image (right).

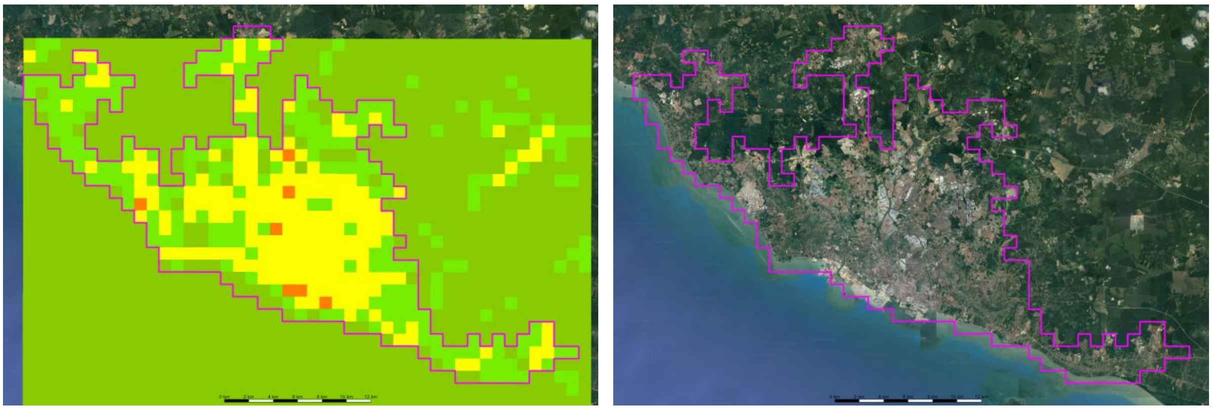

Figure 57: Urban Cluster area of Melaka calculated based on the aggregated DLR population layer.

In some cases, the city counterparts requested that the AOIs for the High Density Core and the Urban Cluster follow the municipal or administrative boundary of the city. In this case, the municipal/administrative boundary was used but enlarged in areas where the AOI created according to the adjusted DG Regio approach was bigger.

This page is intentionally left blank!

Annex 2 – Processing methods for EO4SD-Urban products

This page is intentionally left blank!

Summary of Processing Methods

Urban and Peri-Urban Land Use/Land Cover and Change

The input includes Very High Spatial Resolution (VHR) imagery from different sensors acquired at different time. The data is pre-processed to ensure a high level of geometric and radiometric quality (ortho-rectification, radiometric calibration, pan-sharpening).

The complexity when dealing with VHR images comes from the internal variability of the information for a single land-use. For instance, an urban area is represented by a high number of heterogeneous pixel values hampering the use of automated pixel-based classification techniques.

For these VHR images, it is possible to identify textures (or pattern) inside an entity such as an agricultural parcel or an urban lot. In other words, whereas pixel-based techniques focus on the local information of each single pixel (including intensity / DN value), texture analysis provides global information in a group of neighbouring pixels (including distribution of a group intensity / DN values but also spatial arrangement of these values). Texture and spectral information are combined with a segmentation algorithm in an Object Based Image Analysis (OBIA) approach to reach a high degree of automation for most of the peri-urban rural classes. However, within urban land, land use information is often difficult to obtain from the imagery alone and ancillary/in situ data needs to be used. The heterogeneity and format of these data mean that another information extraction method based on Computer Aided Photo-Interpretation techniques (CAPI) need to be used to fully characterise the LULC classes in urban areas. Therefore, a mix of automated (OBIA) and CAPI are used to optimise the cost/quality ratio for the production of the LULC/LUCC product. The output format is typically in vector form which makes it easier for integration in a GIS and for subsequent analysis.

Level 4 of the nomenclature can be obtained based on additional information. These can be generated by more detailed CAPI (e.g. identification of waste sites) or by an automated approach based on derived/additional products. An example is illustration by categorising the density of the urban fabric which is related to population density and can then subsequently used for disaggregating population data.

Information on urban fabric density can be obtained through several manners with increasing level of complexity. The Imperviousness Degree (IMD) or Soil Sealing (SL) layer (see separate product) can be produced relatively easily based on the urban extent derived from the LULC product and a linear model between imperviousness areas and vegetation vigour that can be obtained from Sentinel 2 or equivalent NDVI time series. This additional layer can be used to identify continuous and discontinuous urban fabric classes. Five urban fabric classes can be extracted based on a fully automated procedure:

- Continuous Dense Urban Fabric (Sealing Layer-S.L. > 80%)
- Discontinuous Dense Urban Fabric (S.L. 50% - 80%)
- Discontinuous Medium Density Urban Fabric (S.L. 30% - 50%)
- Discontinuous Low Density Urban Fabric (S.L. 10% - 30%)
- Discontinuous Very Low Density Urban Fabric (S.L. < 10%)

Manual enhancement is the final post-processing step of the production framework. It will aim to validate the detected classes and adjust classes' polygon geometry if necessary to ensure that the correct MMU is applied. Finally, a thorough completeness and logical consistency check is applied to ensure the topological integrity and coherence of the product.

Change detection: Four important aspects have to be considered to monitor land use/land cover change effectively with remote sensing images: (1) detecting that changes have occurred, (2) identifying the nature of the change, (3) characterising the areal extent of the change and (4) assessing the spatial pattern of the change.

The change detection layer can be derived based on an image-to-image approach provided the same sensor is used. An original and efficient image processing chain is promoted to compare two dates' images and provide multi-labelled changes. The approach mainly relies on texture analysis, which has the benefits to deal easily with heterogeneous data and VHR images. The applied change mapping approach is based on spectral information of both dates' images and more accurate than a map-to-map comparison.

Summary of Processing Methods

World Settlement Extent

The rationale of the adopted methodology is that given a series of radar/optical satellite images for the investigated AOI, the temporal dynamics of human settlements are sensibly different than those of all other land-cover classes.

While addressing settlement-extent mapping for the period 2014-2015 multitemporal S1 IW GRDH and Landsat-8 data acquired at 10 and 30m spatial resolution were taken into account. Concerning radar data, each S1 scene is pre-processed by means of the SNAP software available from ESA; specifically, this task includes: orbit correction, thermal noise removal, radiometric calibration, Range-Doppler terrain correction and conversion to dB values. Scenes acquired with ascending and descending pass are processed separately due to the strong influence of the viewing angle in the backscattering of built-up areas. As a means for characterizing the behaviour over time, the backscattering temporal maximum, minimum, mean, standard deviation and mean slope are derived for each pixel. Texture information is also extracted to ease the identification of lower-density residential areas. As regards optical data, only Landsat-8 scenes with cloud cover lower than 60% are taken into consideration (indeed, further rising this threshold often results in accounting for images with non-negligible misregistration error). Data are calibrated and atmospherically corrected using the LEDAPS tool available from USGS and the CFMASK software is applied for removing pixels affected by cloud-cover and cloud-shadow. Next, a series of 6 spectral indices suitable for an effective delineation of settlements (identified through extensive experimental analysis) are extracted; these include – among others – the Normalized Difference Built-Up Index (NDBI), the Modified Normalized Difference Water Index (MNDWI) and the Normalized Difference Vegetation Index (NDVI). For all of them, the same set of 5 key temporal statistics used in the case of S1 data are generated for each pixel in the AOI. Moreover, to improve the detection of suburban areas, for each of the 6 temporal mean indices also here texture information is computed. For matching the spatial resolution of Sentinel data, the whole stack of Landsat-based features is finally resampled to 10m spatial resolution.

To identify reliable training points for the settlement and non-settlement class, a strategy has been designed which jointly exploits the temporal statistics computed for both S1 and Landsat data, along with additional ancillary information. In the case of optical data, in general the most of settlement pixels can be effectively outlined by properly jointly thresholding the corresponding NDBI, NDVI, and MNDWI temporal mean; likewise, this holds also for non-settlement pixels. Regarding radar data, it generally occurs that the temporal mean backscattering of most settlement samples is sensibly higher than that of all other non-settlement classes. Nevertheless, in complex topography regions: i) radar data show high backscattering comparable to that of urban areas; and ii) bare rocks are present, which often exhibit a behaviour similar to that of settlements in the Landsat-based temporal statistics. Accordingly, to exclude these from the analysis, all pixels are masked whose slope - computed based on SRTM 30m DEM for latitudes between -60° and +60° and the ASTER DEM elsewhere - is higher than 10 degrees.

Support Vector Machines (SVM) are used in the classification process. However, as the criteria defined above for outlining training samples might results in a high number of candidate points, for AOIs up to a size of ~10000 sqkm the most effective choice proved extracting 1000 samples for both the settlement and non-settlement class. Nonetheless, since results might vary depending on the specific selected training points, as a means for further improving the final performances and obtain more robust classification maps, 20 different training sets are randomly generated and given as input to an ensemble of as many SVM classifiers; then, a majority voting is applied. Afterwards, the stacks of Landsat-8-based and S1-based temporal features are classified separately as this proved more effective than performing a single classification on their merger. In both cases, a grid search with a 5-fold cross validation approach is employed to identify for each training set the optimal values for the learning. Here, those resulting in the highest cross-validation overall accuracy are then selected and used for classifying the corresponding study region.

A final post-classification phase is dedicated to properly combining the Landsat- and S1-based classification maps and automatically identifying and deleting potential false alarms. To this purpose, an advanced post-editing object-based approach has been specifically designed.

The above-described methodology has been further adapted for outlining the settlement extent in the past solely based on Landsat-5/7 imagery available since 1984; indeed, no long-term SAR data archive at comparable spatial resolution is freely accessible for the same timeframe (e.g., ESA ERS-1/2 data are available from 1991 without systematic world coverage and often proved too complicated to pre-process). In particular, for the given target period and AOI, all available Landsat imagery with cloud cover lower than 60% is pre-processed in the same fashion as described in the previous paragraphs and the same set of temporal statistics and texture features are extracted. Based on the hypothesis that settlement growth occurred over time (meaning that a pixel cannot be marked as settlement at an earlier time if it has been defined as non-settlement at a later time), all pixels categorized as non-settlement in the 2014-2015 extent map are excluded from the analysis. Then, training samples are derived by thresholding the temporal mean NDBI, MNDWI and NDVI; specifically, a dedicated strategy has been implemented for automatically determining the thresholds for the 3 indices by comparing their cumulative distribution function (CDF) for the target period with that exhibited for the period 2014-2015. Also in this case, an ensemble of 20 SVMs is used, each one trained on a different subset of 2000 samples (i.e., 1000 for the settlement and 1000 for the non-settlement class) and majority voting is then employed for generating the final map. It is worth noting that, when deriving the past settlement extent for multiple times, both the masking and threshold adaptation are performed on the basis of the results derived for the next target period.

Summary of Processing Methods

Percentage Impervious Surface

Imperviousness product is intended to represent the impervious surfaces because of urban development, layers of completely or partly impermeable artificial material (asphalt, concrete, etc.) and infrastructure construction. Therefore, the Imperviousness Degree (IMD) or Soil Sealing (SL) information can be produced relatively easily based on the Urban Extent derived from the baseline LULC information product and the linear model between impervious areas and vegetation presence that can be determined and characterized from Landsat or Sentinel-2 NDVI time series.

More precisely, the raster product is generated at 10m - 30m spatial resolution by properly exploiting Landsat-4/5/7/8 or Sentinel-2 multitemporal imagery acquired over the study area within a given time interval of interest in which no relevant changes are expected to occur (typically a time period of 1-2 years allows to get very accurate results). Each acquired EO data is pre-processed (ortho-rectification, radiometric calibration, pansharpening, cloud-masking). Then, the Normalized Difference Vegetation Index (NDVI) is extracted for each image within the urban mask (corresponding to Urban Extent product). NDVI is inversely correlated with the amount of impervious areas, i.e. the higher the NDVI is, the higher the expected presence of vegetation, hence the lower the corresponding imperviousness degree. The core idea is to compute per each pixel its temporal maximum which depicts the status at the peak of the phenological cycle. It is worth noting that for different pixels in the study area, different number of scenes might be available.

However, in the hypothesis of sufficient minimum number of acquisitions unavailable for computing consistent statistics, this does not represent an issue. Indeed, in this framework, it is also possible to get spatially consistent datasets useful for the desired analyses, even when investigating large territories. Areas associated with different levels of impervious surfaces are then extracted by visual interpretation from data sources with higher spatial resolution (e.g. VHR imagery, Google Earth imagery). OSM layers or information derived from in-situ campaigns are other auxiliary data sources which can also be used for this purpose. At the end, reference data are extracted in various parts of the study region and then rasterized and aggregated at the spatial resolution of input EO data.

A support vector regression SVR module is then used for properly correlating the resulting training information with the temporal maximum NDVI to finally derive the Percentage of Impervious Surface (PIS) or Imperviousness Degree (IMD) for the entire AOI. Specifically, 8bit integer values from the raster product range from 0 (no impervious surface in the given pixel) to 100 (completely impervious surface in the given pixel).

Summary of Processing Methods

Urban Green Areas

The location and extent of green areas are determined within the product of urban land use/ land cover at Level I. Urban green areas refer to land within and on the edges of a city that is partly or completely covered with grass, trees, shrubs, or other vegetation. This includes public parks, private gardens, cemeteries, forested areas as well as trees, river alignments, hedges etc. The product delivered within EO4SD-Urban project thus provides accurate information (1 m resolution) on the spatial location and extent of the green areas located within the Urban Extent (Level I class: 1000) derived from the baseline LULC information product.

Detecting and monitoring urban green coverage needs very high resolution optical satellite images, which explains the product generation over the Core Urban Area of AOI only. The same images have been logically used for generating the LULC information product. Consequently, the usual preliminary quality check and pre-processing tasks were already implemented.

Urban Green Areas have been detected using automated supervised classification method. More precisely, each single multispectral VHR scene has been classified by specifying the most appropriate algorithm and class number. Then, pixel units from the classes considered as representing green areas have been combined into 1 single class. From this operation results the required binary raster product. At this stage, it only remains necessary to apply some post-processing steps:

- Morphological filter is applied to fill small gaps within the green areas (caused by shadow)
- Resampling of the data to the provided spatial resolution of 1m
- Removing small pixel groups under the minimum mapping unit.
- Integrating the information provided by the LULC product (e.g. class Urban Parks, Cemeteries).
- Validation of Mapping results

Furthermore, using archive very high resolution images, current and historic extent of urban green areas are compared to identify their temporal evolution – extent growth or reduction. Quality control and accuracy assessment tasks are performed by means of visual interpretation considering also the LULC dataset.

Summary of Processing Methods

Flood Risk

Historic flood extent mapping

The flood extent is derived from historical optical satellite imagery of 30-meter resolution (Landsat 5 and Landsat 8) and 10-meter resolution (Sentinel 2).

The relevant datasets were corrected atmospherically applying the Dark Object Subtraction (DOS) approach.

For defining the water extent the water cover was classified by applying the Automated Water Extraction Index AWEIsh (Feyisa et al. 2014) which makes use of the reflectance values of Blue, Green, Near Infrared and Shortwave Infrared spectral bands of the Landsat 5, Landsat 8, and Sentinel-2 sensors. The AWEIsh is an index formulated to effectively eliminate non-water pixels, including dark built surfaces in areas with urban background. The equation is intended to effectively eliminate shadow pixels and improve water extraction accuracy in areas with shadow and/or other dark surfaces.

The delimitation of permanent water cover (representing a high water-level during the rainy season) is based on the EO4SD LULC classification.

Finally, mapping of flood extents by visual interpretation of VHR imagery as available in Google Earth was done.

Flood hazard mapping

The flood hazard map was generated based on the occurrence of flood events during the past 10 years. The map aims to give an idea about the flood presence in terms of both frequency and extent in the city, and illustrates which part is in generally flooded more often than other areas.

Water extents representing floods triggered by the small watercourses as well as rainwater stagnation after heavy rains are based on

- data from Landsat 5, Landsat 8 (provided by the US Geological Survey), and Sentinel-2 (provided by the European Space Agency)
- and on visual interpretation of VHR data as available in Google Earth

The flood hazard classification was done according to the approach selected by NEO on Cambodia cities during EO4SD Phase 1: a "number of occurrences" was calculated by combining flood extents as derived from HR imagery and from visual interpretation of VHR imagery. This data was classified according to the following specifications for the hazard definition:

- area flooded once between 2009 and 2018: low hazard
- area flooded twice or three times: medium hazard
- area flooded more than three times: high hazard

It has to be underlined that both approaches for the flood extent identification differ significantly and that the analysis of VHR data does not cover the peri-urban area. Furthermore, in some cases, the areas identified as flooded in HR and VHR data respectively refer to the same event.

Flood risk mapping

Risk is defined as a combination of probability and consequences. A detailed and uniform land-use map is an important prerequisite to perform flood risk calculations, since it determines what is damaged in case of flooding.

Two different datasets regarding the urban LULC were made available for this analysis:

- LULC product generated by NEO through EO4SD-Urban based on VHR data (Mosaic: Pleiades recorded on 01/03/2018 and 02/03/2018) covering the core city area (approx. 422.4 sqkm)
- LULC product generated by NEO through EO4SD-Urban based on HR data (Sentinel 2 data recorded on 27/02/2018) covering the larger urban area (approx. 823.4 sqkm)

The exposition is classified following an approach developed by NEO (based on: Dasgupta et al. 2015) integrating economic costs, social damage, physical damage and flood duration. Four land use damage levels are defined based on this estimation.

Both land-use classification results were recoded to pre-defined categories and merged after categorization.

The flood risk product is a combination of hazard with Land Use / Land Cover (LULC) information. The Flood Risk matrix is generated based on the classification of exposition and flood hazard. The flood risk level is classified in four qualitative classes based on the combination of flood hazard and land use damage.

This page is intentionally left blank!

Annex 3 – Filled Quality Control sheets

Quality Control Sheets for the following products are provided in the form of independent documents:

- Urban and Peri-Urban Land Use / Land Cover
- Urban Green Areas
- Flood History and Risk
  - Flood Extent
  - Flood Hazard
  - Flood Risk