Land Cover Classification 2020 and analysis historical land cover changes since 1900 on Aruba

C.A. Mücher, P.J.F.M. Verweij, H. Kramer, D. Thomas, R.J.H.G. Henkens

WAGENINGEN
UNIVERSITY & RESEARCH

Land Cover Classification 2020 and analysis historical land cover changes since 1900 on Aruba

C.A. Mücher, P.J.F.M. Verweij, H. Kramer, D. Thomas, R.J.H.G. Henkens

The authors would like to acknowledge funding from the Wageningen Research University Knowledge Base programme KB36 Biodiversity in a Nature Inclusive Society (project number KB36-005-016, KB-36-008-002) and the Statutory Research Tasks WOT-04 Nature & Environment (project number WOT-04-009) – both of which are supported by finance from the Dutch Ministry of Agriculture, Fisheries, Food Security and Nature.

Wageningen Environmental Research
Wageningen, November 2024

Reviewed by:
Lawrence Jones-Walters, Programme Director Nature Inclusive Transitions (Wageningen Environmental Research)

Approved for publication:
Sander Janssen, Team Leader of Earth Observation and Environmental Informatics (Wageningen Environmental Research)

Report 3389
ISSN 1566-7197

Mücher, C.A., P.J.F.M. Verweij, H. Kramer, D. Thomas, R.J.H.G. Henkens, 2024. *Land Cover Classification 2020 and analysis historical land cover changes since 1900 on Aruba.* Wageningen, Wageningen Environmental Research, Report 3389. 48 pp.; 36 fig.; 8 tab.; 27 ref.

Aruba is rijk aan natuurlijke terrestrische ecosystemen, variërend van droge tropische bossen, grotten en stranden tot zoutmeren en mangroves. De interactie van menselijke activiteiten met de natuurlijke ecosystemen wordt weerspiegeld in de landbedekking. Inzicht in de huidige landbedekking en hoe het land wordt gebruikt is essentieel voor het beheer en de ruimtelijke ordening. In deze studie hebben we een ruimtelijke landbedekkingsclassificatie van Aruba ontwikkeld op basis van zeer hoge resolutie multi-spectrale satellietbeelden, veldwaarnemingen en aangevuld met lokale kennis. Daarnaast hebben we op basis van historische luchtfoto's en de oude Werbata topografische kaarten de veranderingen in landbedekking in kaart gebracht over de periode 1900-2020. Een van de belangrijkste landgebruiksveranderingen op Aruba is dat de stedelijke gebieden sinds 1900 ruim honderd keer zo groot zijn geworden, grotendeels ten koste van landbouwgrond en natuurgebieden, en het stedelijk gebied nu bijna 50% van Aruba beslaat.

Aruba is rich in natural terrestrial ecosystems that range from dry tropical forest, caves and beaches to salt lakes and mangroves. The interaction of natural ecosystems with human activities is reflected in the land cover. Understanding current land cover and how the land is being used is elementary for land management and land use planning. In this study, we developed a land cover classification of Aruba based on very high-resolution satellite imagery, field observations, supplemented with local knowledge. Alongside this, we have analysed historical aerial photographs and the Werbata topographical maps to outline the changes in landcover from 1900 to 2020. The most significant land use change on Aruba is that urban areas have expanded more than 100 times since 1900 and now cover nearly 50% of Aruba. This land use change has taken place largely at the expense of agriculture and natural areas.

Keywords: land cover, satellite imagery, Worldview, field surveys, Werbata, habitat, mapping

The pdf file is free of charge and can be downloaded at https://doi.org/10.18174/679738 or via the website www.wur.nl/environmental-research (scroll down to Publications – Wageningen Environmental Research reports). Wageningen Environmental Research does not deliver printed versions of the Wageningen Environmental Research reports.

In 2003 Wageningen Environmental Research implemented a quality management system according to the ISO 9001. Since 2006 Wageningen Environmental Research has been working with the ISO 14001 environmental care system. By implementing the ISO 26000 guideline, Wageningen Environmental Research can manage and deliver its social responsibility.

Wageningen Environmental Research Report 3389 | ISSN 1566-7197

Photo cover: Panoramic view from highest point of Aruba at Mount Hooiberg taken on 20th November 2020, by Sander Mücher

Contents

Verification

Report: 3389
Project number: KB36-005-002

Wageningen Environmental Research (WENR) values the quality of our end products greatly. A review of the reports on scientific quality by a reviewer is a standard part of our quality policy.

Approved reviewer who stated the appraisal,

position: Programme Director Nature Inclusive Transitions

name: Lawrence Jones-Walters

date: 24-10-2024

Approved team leader responsible for the contents,

name: S. Janssen

date: 7 November 2024

1 Introduction

Aruba is a small island of approximately 180 km^2 located in the Southern Caribbean Sea 30 km north of the Venezuelan coast. It is characterised by semi-arid climate with an average rainfall of 500 mm per year, but this can vary significantly annually. As well as its coral reefs and sea grass beds, Aruba is rich in natural terrestrial ecosystems ranging from dry tropical forest, caves and beaches to saliñas, mangroves and fresh water wetlands, despite its small size. These ecosystems provide a range of ecosystem services to Aruba's population, including food provision, recreation opportunities for tourists, cultural heritage and habitat provision. Of the 14,408 hectares now safeguarded under the Ramsar Convention, 6,020 hectares are terrestrial (Henkens, 2023; Ramsar, 2023), there are also Important Bird Areas (DCNA, 2004) and 16 official protected nature reserves (whenInAruba, 2020).

Aruba is relatively densely populated with around 108,000 inhabitants in 2024. The well-being and prosperity of the island's population depends highly on the quality of the natural environment. Aruba, therefore, faces major challenges in the areas of: managing urban expansion, (mass) tourism and population growth, local food production, adaptation to climate change and halting biodiversity loss.

The land cover reflects the interaction of the natural ecosystems with human activities (Mücher & Verweij, 2020). Surveying the current land cover and how the land is used, especially with regard to the current challenges, is, therefore, a basic requirement for land management and land use planning. The measurement of current conditions was achieved through land cover mapping.

Satellite images are often used as the basis for land cover mapping as they allow a measured synoptic snapshot that covers the entire island at a single moment in time. Multiple images through time can reveal how the land cover changes (Saah et al., 2019). Since most very high-resolution satellite imagery sources do not date back much, old topographic maps, such as the Werbata maps and historic aerial photographs, were used to analyse the changes in land cover on Aruba since 1900.

In this study, we first implemented a land cover classification at one metre spatial resolution for the whole of Aruba for 2020. This was based on very high-resolution multispectral satellite imagery, field observations, supplemented by additional GIS sources, and local knowledge. Chapter 2 discusses the materials used for the land cover classification for 2020. Chapter 3 discusses the methodology developed for the land cover classification. Chapter 4 discusses the resulting high resolution land cover classification 2020 for Aruba and also includes an accuracy assessment. Chapter 5 discusses the historic land cover changes for Aruba over the period 1900 – 2020 and includes an overview of the sources of information that were used in the analysis, the method used for change analyses, and the results and conclusions from the analysis of historic land cover changes.

2 Materials

2.1 Worldview-3 very high-resolution satellite imagery

Very high-resolution satellite imagery has been acquired for Aruba, consisting of highly detailed ortho-rectified images from the Worldview-3 satellite. These Worldview satellites are owned by DigitalGlobe. The first, Worldview-1 satellite, was launched in 2007. WorldView-3, which was launched on 13 August 2014, is a multi-payload, multi-spectral, high-resolution commercial satellite sensor that operates at an altitude of 617 km. It provides 30 cm panchromatic resolution (450-800 nm) and 1.2 m multispectral resolution across eight spectral bands (see Table 1). It offers the highest spatial resolution of all satellites available for civil applications and is especially suited for studying the terrestrial and marine environment of the Caribbean Islands.

Table 1 *Spectral characteristics of Worldview-3.*

Band nr	Spectral band name	Wavelength (nm)
1	Coastal blue	400 - 450 nm
2	Blue	450 - 510 nm
3	Green	510 - 580 nm
4	Yellow	585 - 625 nm
5	Red	630 - 690 nm
6	Red Edge	705 - 745 nm
7	Near-IR1	770 - 895 nm
8	Near-IR2	860 - 1040 nm

The satellite has a daily revisit time and can collect up to 680,000 km^2 per day (SIC, 2022). However, obtaining cloud-free Earth Observation (EO) data for Aruba remains challenging, as clouds often form in the early afternoon when the satellite passes over the island. Consequently, the final selection of WV-3 imagery for Aruba comprised mainly of data collected on May 20, 2020 that covered the Northern and Southern regions. And for some minor parts, March 20, 2020 due to cloud cover or some missing scan lines, that covered the Southernmost region (see Figure 1).

A pan-sharpened mosaic with a 30 cm resolution was created for the entire island based on this data. It includes the coastal marine zone (see Figure 2 and Figure 3). This 30 cm resolution pan-sharpened mosaic was also used to digitize the coastline in greater detail (CoastlineAruba2020v2.shp), enabling the separation of terrestrial land from the surrounding marine environment. The scope of this report focuses solely on terrestrial land cover and the clipped terrestrial satellite image (based on newly digitized coastline), formed the basis for further image classification using field observations as training data.

The newly created 2020 land cover database has a spatial resolution of one metre and can serve as a basis for further monitoring and spatial modelling of specific natural habitats and their services (e.g. Mahamane et al., 2017; Kapetanaki et al., 2017; Dick et al., 2017; Verweij et al., 2016; Schep et al., 2013; Burkhard et al., 2009).

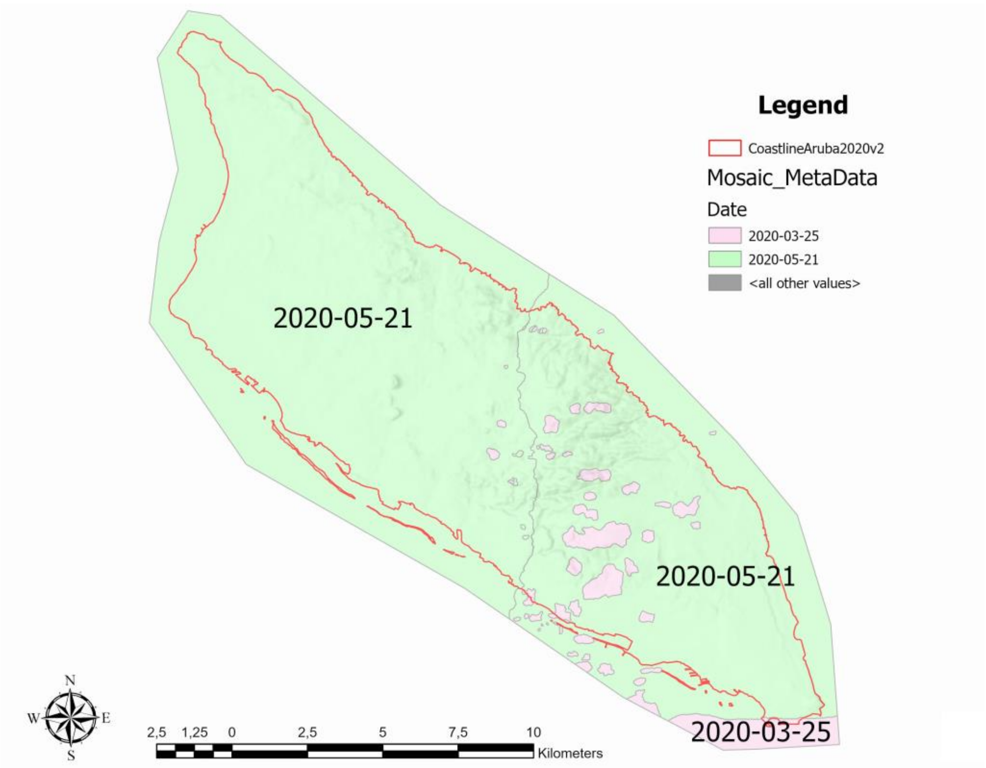

Figure 1 *Sources of Worldview-3 satellite imagery from two dates used within this study.*

Figure 2 *Pan-sharpened Worldview mosaic with 30 cm resolution based on the two above-mentioned dates. It could be said, mainly based on May 21st, 2020.*

Figure 3 *Example of a detail of the pan-sharpened Worldview-3 mosaic at 30 cm resolution at Spanish Lagoon.*

2.2 Fieldwork

Fieldwork was conducted between November 16th to 24th 2022. It also included a benthic survey of the Southern and Western coasts for another project (Thomas, 2024). However, the benthic habitat mapping is not included in this report and was published separately as part of a Master's Degree thesis (Thomas, 2024).

Terrestrial field observations of the land cover types, used as training data for the land cover classification, were collected with a Trimble TDC600, with a spatial accuracy of one metre across the entire island. All land cover classes were documented, and for any under-sampled land cover classes, additional fieldwork was conducted in the final days of November 2022 to gather more data. Most georeferenced observations were supplemented with photographs taken by the Trimble TDC600, mobile phones, and a GoPro 10 (with the GoPro primarily used for the benthic survey).

Figure 4 *Main tools used for the survey: A mobile phone with camera, Trimble TDC600 as a GPS for recording ground truth information, and a GoPro.*

In total, 1,097 ground observations related to the actual land cover were recorded across Aruba between 16th and 24th November, 2022 (see Figure 5). All associated photographs were stored as geotagged images in a file geodatabase in ArcGIS. In most instances, multiple photographs were taken at each location from different directions/angles, and additional images were captured from the car in areas where no ground truth data was yet recorded.

Figure 5 *Location of the 1097 ground truth point data and photographs collected in the period 16th to 24th November 2022.*

One of the challenges we faced, which could potentially impact the accuracy of the image classification, was the difference in time and vegetation development between the field survey (November 2022) and the WV-3 image acquisition time of May 2020 (see Figure 6). Ideally, the timing of the image acquisition should coincide with the field survey to ensure optimal data alignment. While May 2020, (the month of the image acquisition) was still a very dry month, the field survey was conducted after heavy rains that caused the vegetation to bloom.

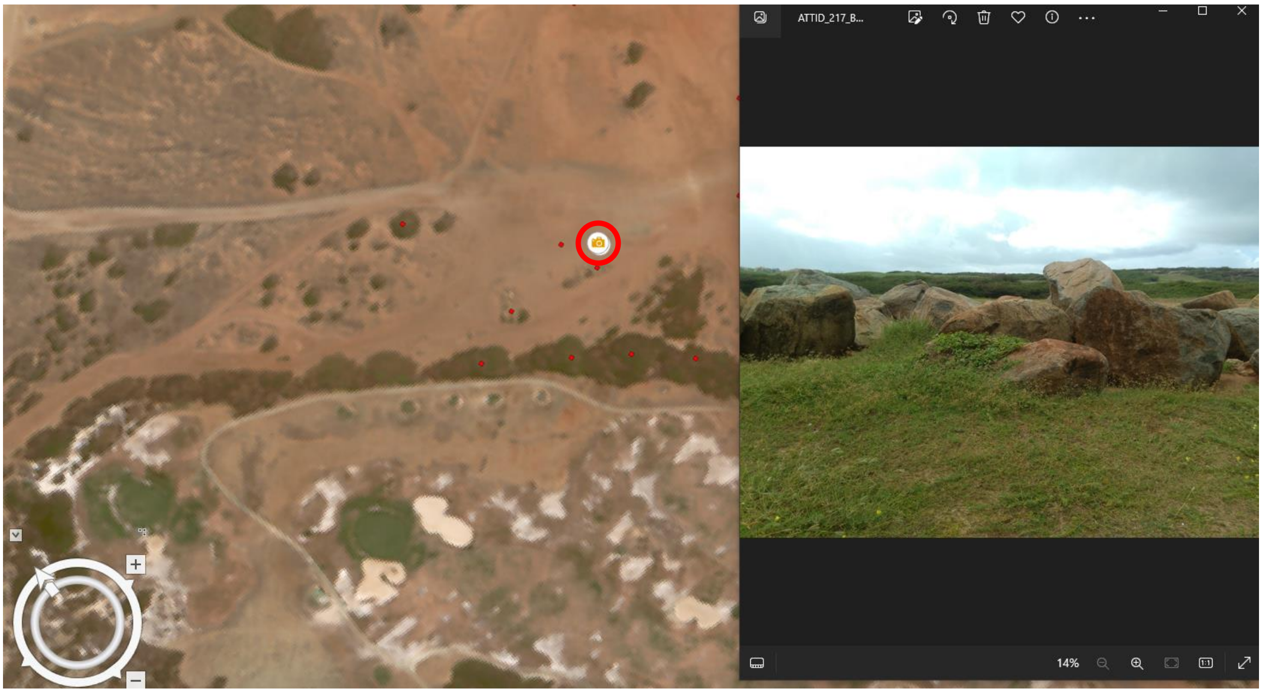

Figure 6 *Difference in acquisition time and phenology between the field survey (November 2022) and the image acquisition date (May 2020) might have caused some problems in the image classification. May 2020 was a very dry month as can be seen in the WV-3 image, while the field survey was conducted after heavy rains that caused the vegetation to bloom. The mixed grass cover shown in the photograph (right) displays lush growth, whereas the satellite image shows bare soil.*

Figure 7 below shows the land cover types that were recorded in the field survey between 16th and 24th November 2022.

Built-up

Urban bare and pavement

Road

Urban green

Bare rock

Bare soil

Bare soil sparsely vegetated

Bare sand

Grassland (mixed grass and herbaceous)

Low scrub with cacti

Low scrub

High scrub with cacti

High scrub

Woodland

Mangroves

Wetland - reed

Wetland – water hyacinth

Saliñas

Fresh water

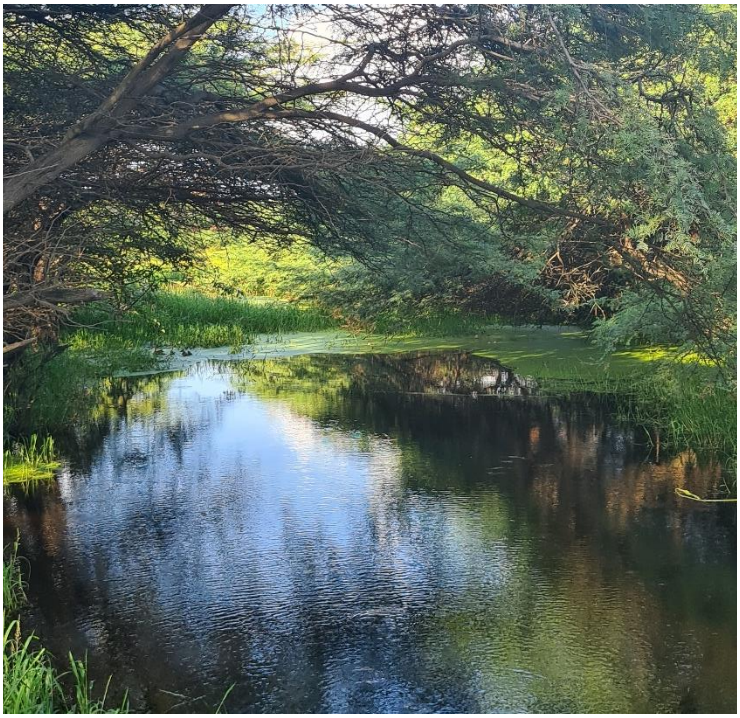

Figure 7 *The different land cover types that have been observed and recorded in a GIS during fieldwork in November 2022. In total, 1,097 ground observations related to the different land cover types were recorded across Aruba in November 2022.*

3 Method land cover classification

The land cover nomenclature for Aruba was influenced by the land cover classification developed for Bonaire (Mücher and Verweij, 2020), and the CORINE land cover typology (Bossard et al., 2000; CEC, 1994). Additionally, it draws partly from Stoffers (1956) for major land cover types, such as mangrove, wetlands and saliñas, scrub, woodland and bare and sparsely vegetated areas (vegetation on rock pavement). Table 2 begins with the primary land cover classes, which include: 1) Urban; 2) Agriculture; 3) Bare soil; 4) Grassland; 5) Scrub; 6) Woodland; 7) Mangroves; 8) Wetlands; and 9) Water.

However, after discussions with colleagues interested in habitat modelling (Smith et al., 2013; Opdam et al., 2003) and ecosystem service modelling for Aruba, additional land cover classes were added. These include columnar cactus (a food source for bats) and green- and open urban areas. As a result, a more detailed land cover legend was created at Level 2 (Table 2).

Table 2 *Land cover typology.*

Level 1	Level 2	Class description	Unique Value
1 Urban	11	Built-up	1
	12	Urban bare and pavement	2
	13	Roads	3
	14	Urban green	4
	15	Urban concrete	5
2 Agriculture	-	Cultivated and semi-cultivated areas	-
3 Bare soil	31	Bare rock	6
	32	Bare soil	7
	33	Bare soil sparsely vegetated	8
	34	Beach bare	9
	35	Bare sand	10
	37	Dunes bare	11
	38	Dunes sparsely vegetated	12
	39	Dunes vegetated	13
4 Grassland	41	Grassland (mixed grass and herbaceous)	14
5 Scrubs	51	Low scrub with cacti	15
	52	Low scrub	16
	53	High scrub with cacti	17
	54	High scrub	18
	57	High cacti	19
6 Woodland	63	Woodland	20
7 Mangroves	70	Mangroves	21
8 Wetlands	81	Wetland – reed	22
	82	Wetland – water hyacinth	23
	83	Saliñas	24
9 Water	91	Fresh water	25

The initial land cover classification for Aruba was explored using an Isodata clustering method (Memarsadeghi, 2007), generating 25-50 spectral classes of the Worldview-3 pan-sharpened multispectral mosaic at a 30 cm spatial resolution, based on four spectral bands (blue, green, red and near-infrared) (Figure 2). However, it became clear that a supervised classification using all eight spectral bands (Table 1) at a slightly lower resolution of 1.2 m provided better results. Additionally, the maximum likelihood classification gave better results than the Spectral Angle Mapper (SAM) in the ENVI remote sensing software. It was also determined that performing a supervised classification for the entire island, instead of classifying the individual regions separately (P1, P2, and P3), would provide better results by utilising the complete training dataset, as some land cover classes were only recorded in a few specific regions and not well distributed across the island. At the same time, it became clearer that both the four-band pan-sharpened mosaic at 30 cm resolution and the eight-band mosaic at 1.2 m still contained significant cloud cover and cloud shadows, particularly over the northern half of the island. These clouds and cloud shadows were visually interpreted and removed from the eight-band mosaic at 1.2 m resolution (Figure 8). The eight-band multispectral mosaic on the right (mosaic_Aruba_WV3_2020_MS8b.tif) was used as the input for the maximum likelihood classification in conjunction with the full ground truth data set.

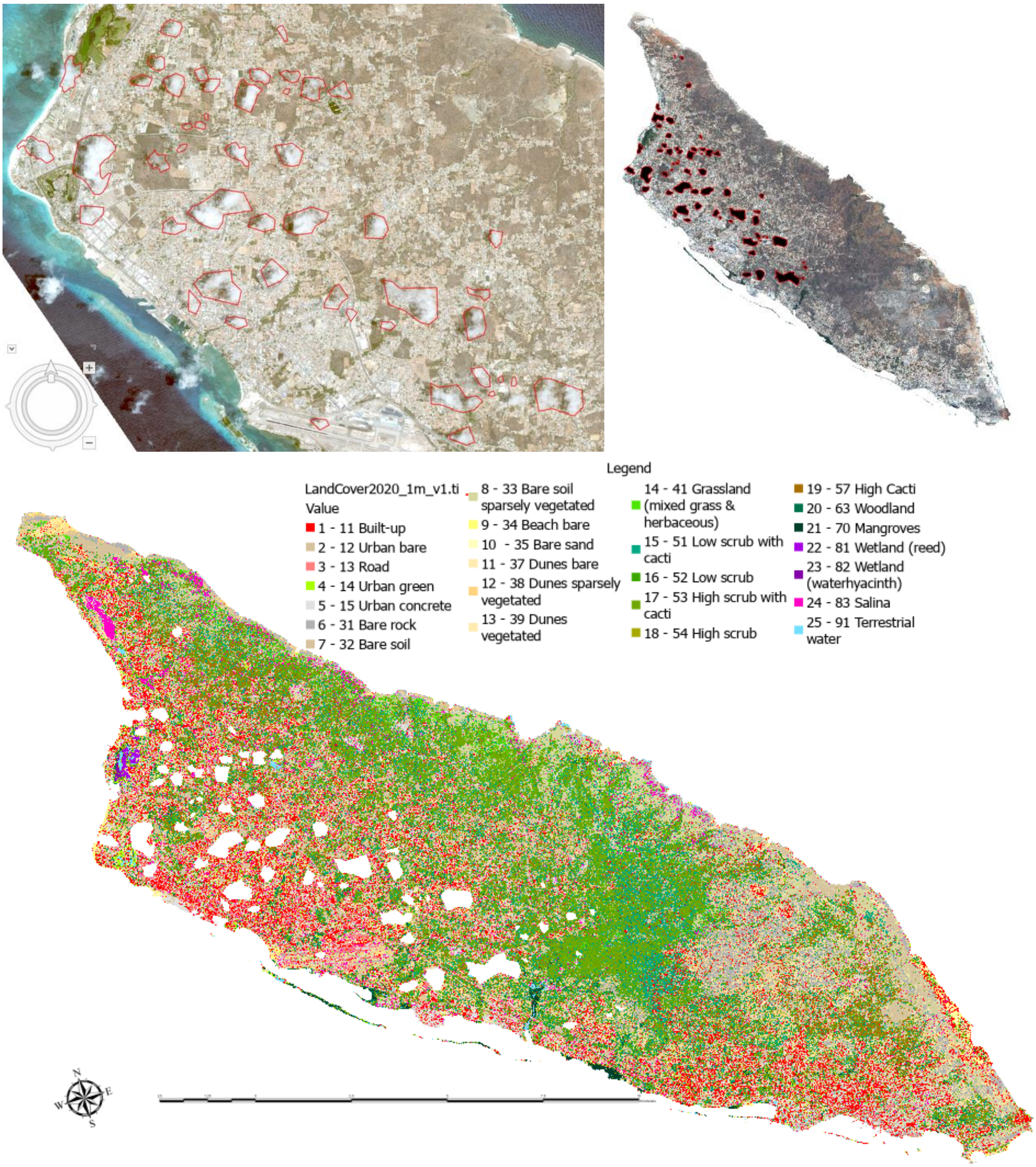

Figure 8 *Visual identification of clouds (left), the resulting eight-band multispectral mosaic at 1.2 m resolution (mosaic_Aruba_WV3_2020_MS8b.tif) and the result of the maximum likelihood classification.*

In a second stage, several additional geographic databases were incorporated to fill gaps and improve thematic accuracy as part of post-processing steps. This began with identifying individual houses and roads from OpenStreetMap (OSM, 2023) and filling cloud contaminated holes using the ESA World Cover dataset (ESA, 2021). The Spatial Plan (DIP, 2019) was used to distinguish urban regions from rural areas. Additionally, the saliñas were digitised with assistance from local experts. Figure 9 shows all the post-processing steps taken after the maximum likelihood land cover classification.

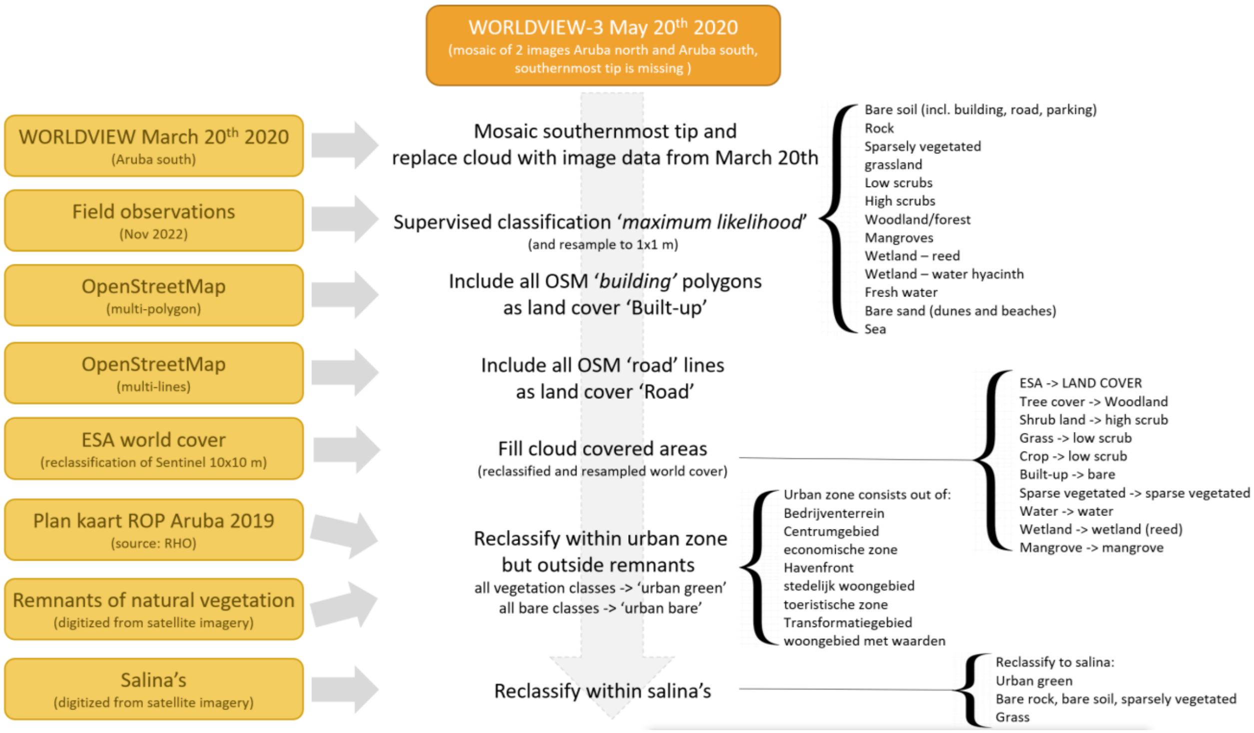

Figure 9 *Overview of maximum likelihood classification and all post-processing steps.*

Figure 10 visualises the post-processing steps, in which cloud covered areas (gaps) in the maximum likelihood classification were filled with data from OSM and ESA WorldCover (ESA, 2021).

The ESA WorldCover data was integrated after recoding some of its classes to better align with Aruba's land cover categories (Figure 9). Figure 10 also shows that the gaps in the land cover classification were filled in a consistent and effective manner.

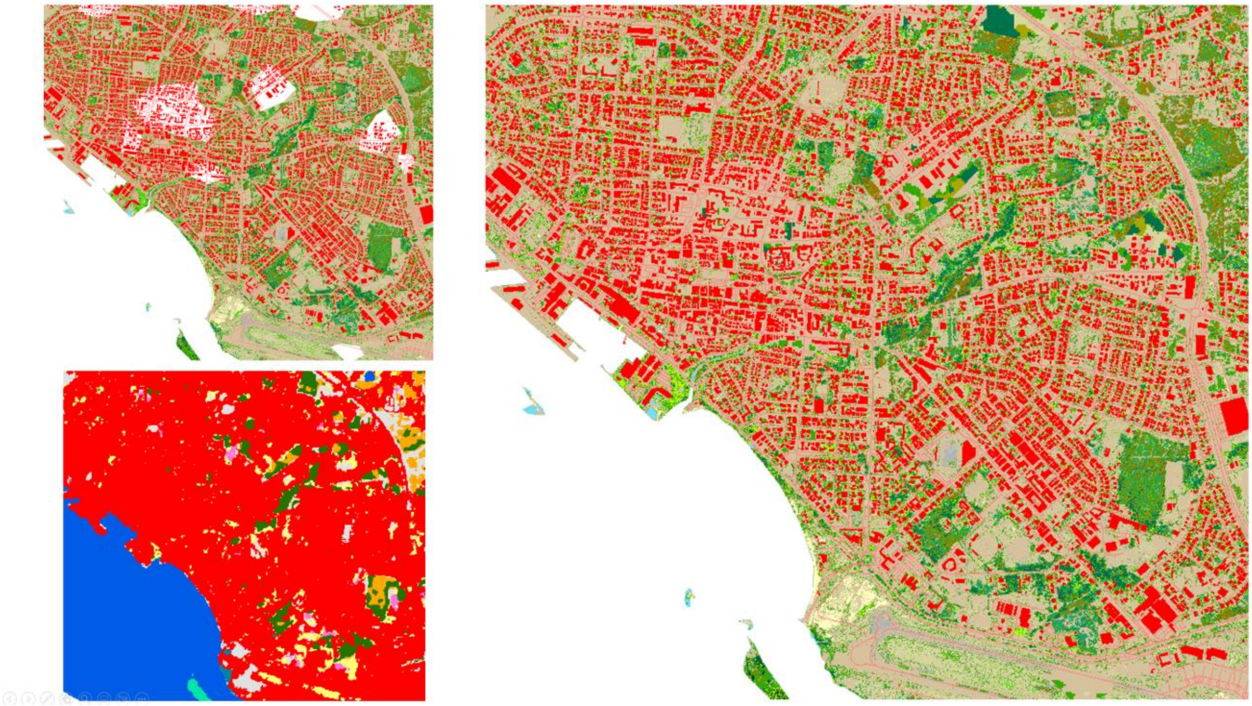

Figure 10 *The process of filling the cloud covered areas (gaps) of the maximum likelihood classification with data from OSM and ESA World Cover (ESA, 2021, on lower left.*

Figure 11 illustrates how urban regions were distinguished from rural areas using the Spatial Plan of Aruba (DIP, 2019). Within the urban areas, four specific categories were identified: 1) built-up; 2) urban bare and pavement; 3) roads; and 4) urban green.

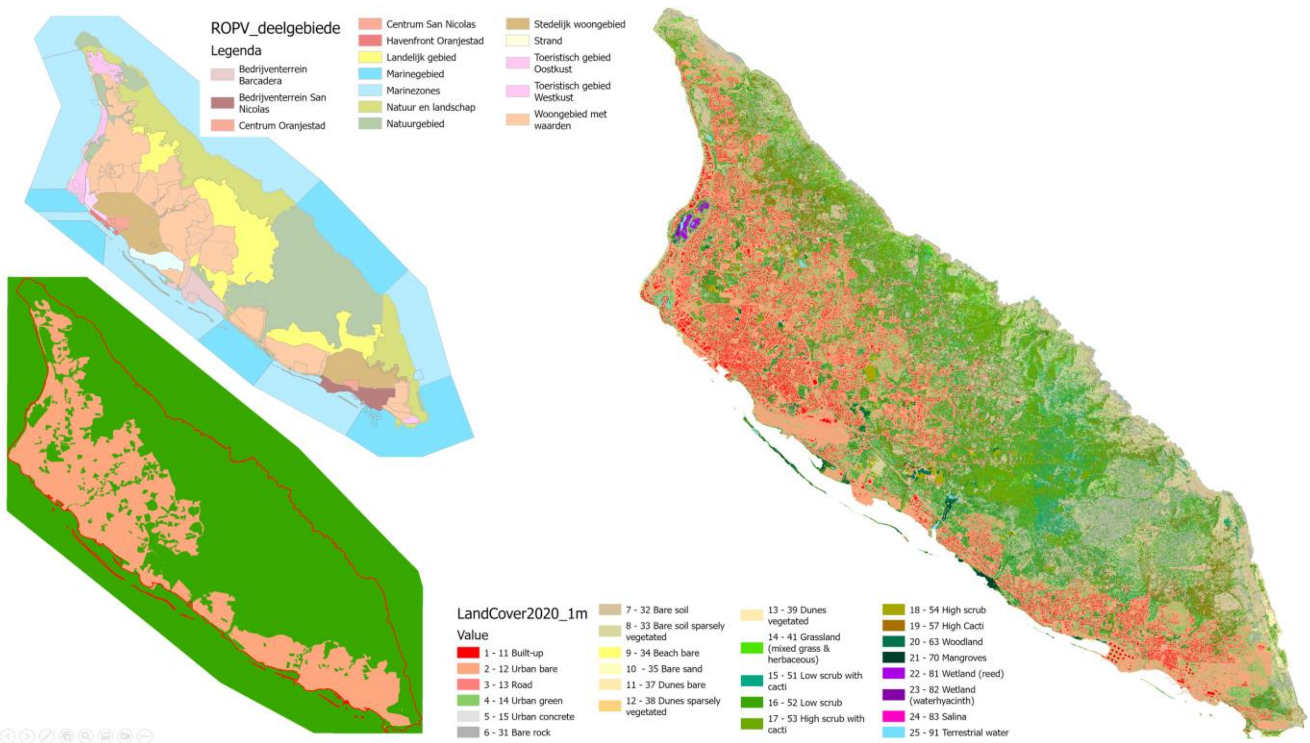

Figure 11 *Distinguish urban zones (orange) from rural zones (green, lower left figure) based on the spatial plan (upper left). Within the urban zones, four specific land cover categories were identified: 1) built-up; 2) urban bare and pavement; 3) roads; and 4) urban green, as show in the land cover classification on the right side.*

In a final stage, the identification of the saliñas was improved by visual delineation with the assistance of local experts. Most of the existing land cover types within the saliñas (e.g. bare soil, grassland etc.) were recorded into the new, unified overall land cover class: 'saliña' (Figure 12). This has improved the accuracy and consistency of the saliñas classification.

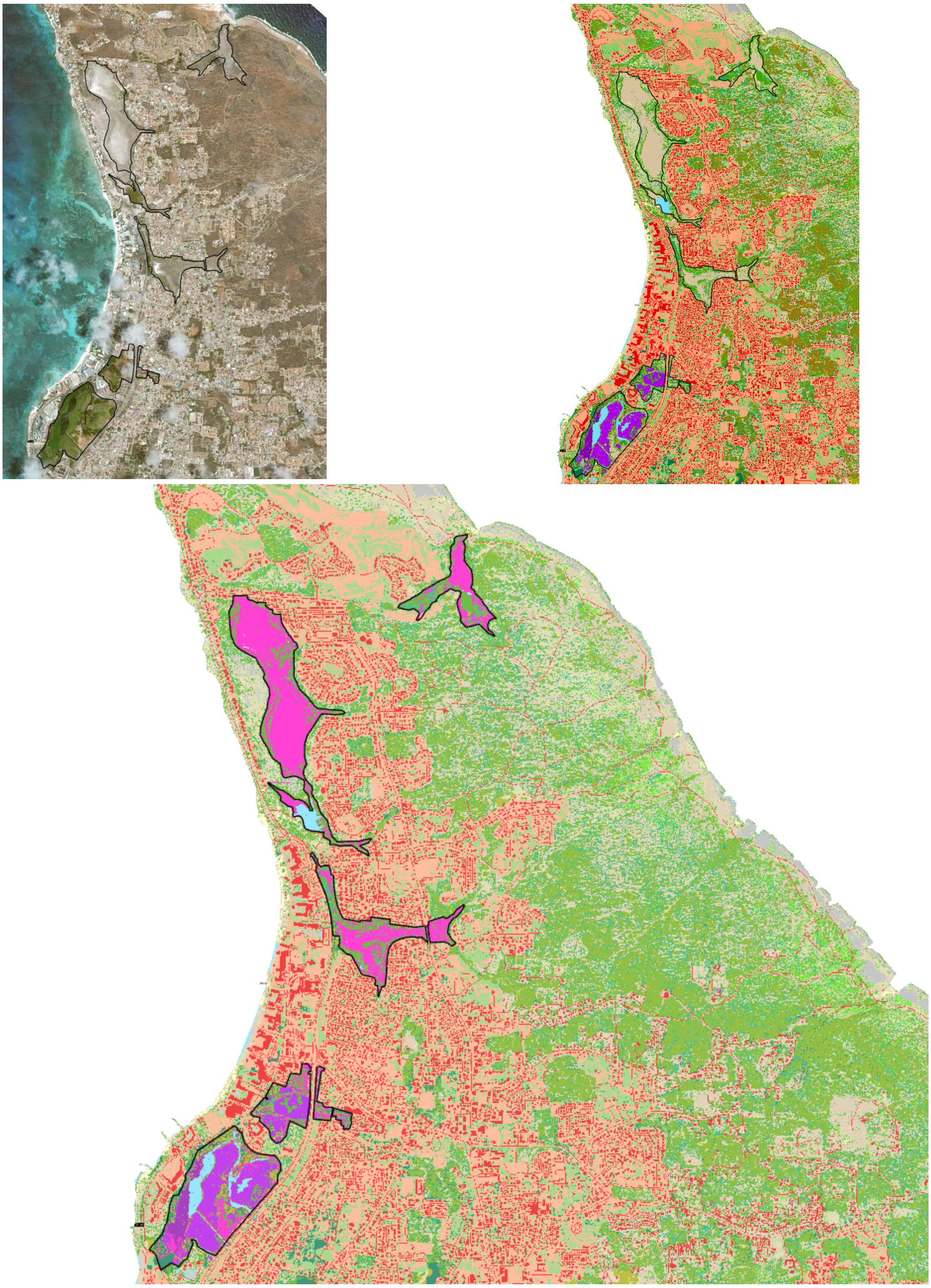

Figure 12 *Including saliñas and recoding some of the land cover classes such as bare soil (Value 7) within the delineated saliñas into the land cover class saliñas (Value 24).*

4 Results

4.1 Land cover classification 2020

The resultant land cover database, now version 10 (LandCover2020_1m_v10.tif), was resampled to a 1 m resolution (instead of the original 1.2 m) and covers an area of 177 km^2. This database focusses exclusively on terrestrial land cover, while the benthic habitat mapping will be addressed in another report (Thomas, 2024). The Aruba land cover database now has a total of 19 land cover classes, which are listed in Figure 13 and Table 3.

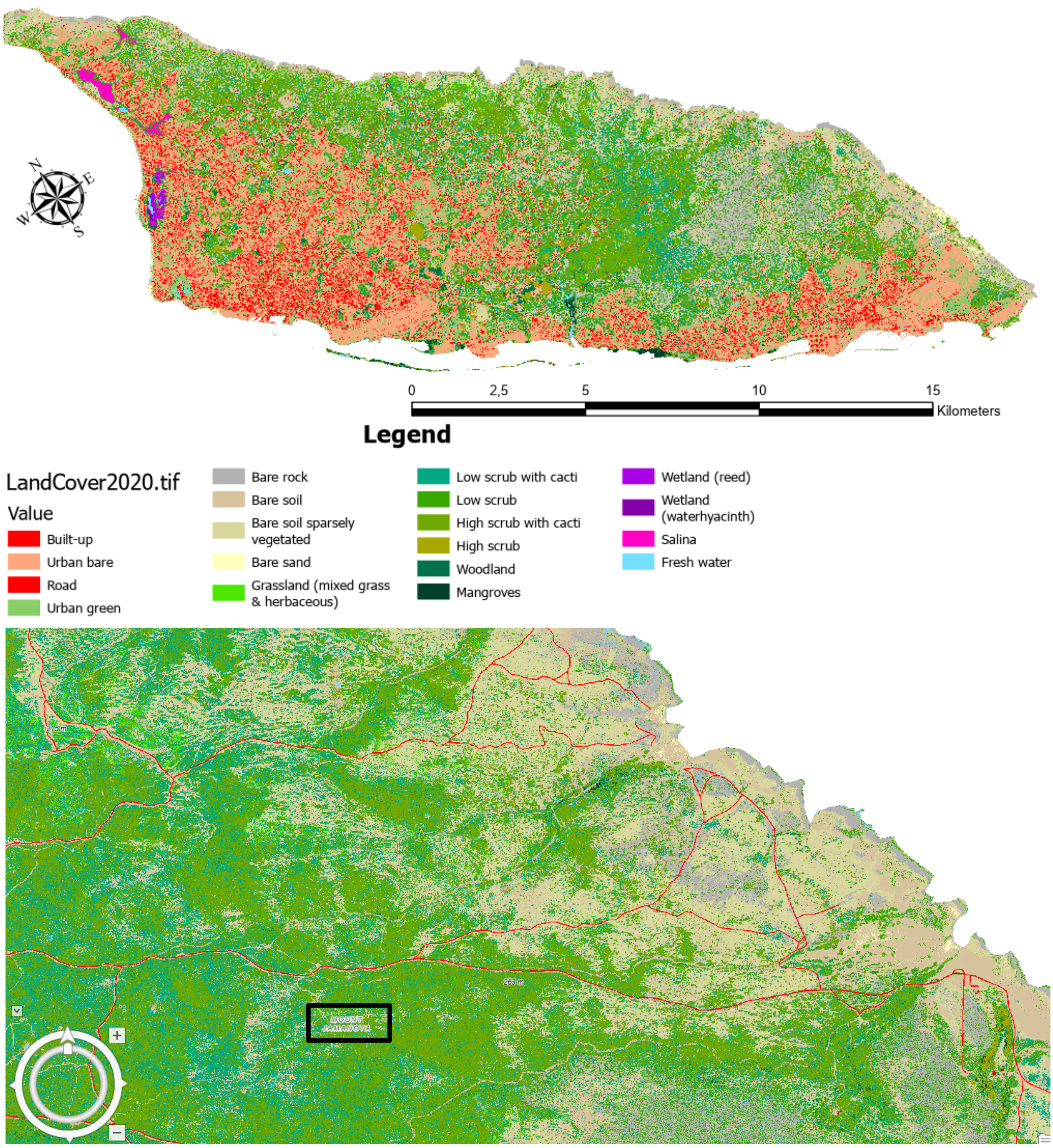

Figure 13 *Land Cover Map Aruba (LandCover2020_1m_v10.tif) with an example of the details around Mount Jamanota (black box) at scale 1:12.000.*

The land cover classes vary significantly in their extent (Table 3). The most dominant land cover types are i) urban bare and pavement, covering 34 km^2 (19,3% of the terrestrial surface); ii) High scrub with cacti, covering 29 km^2 (16,2%), iii) bare soil, covering 20 km^2 (11,2%), and iv) bare soil sparsely vegetated, covering 18 km^2 (10,3% of the terrestrial surface). The smallest land cover classes are the wetland classes water hyacinth covering 4.4 ha and reed covering 25.9 ha.

Table 3 *Land cover statistics (LandCover2020_1m_v10.tif).*

Class Name	**Pixel count (1m²)**	**Area (ha)**	**Area (km²)**	**Percentage**
Built-up	10485536	1048.6	10.5	5.94%
Urban bare and pavement	34038964	3403.9	34.0	19.28%
Road	5588930	558.9	5.6	3.17%
Urban green	16508678	1650.9	16.5	9.35%
Bare rock	7034608	703.5	7.0	3.99%
Bare soil	19785166	1978.5	19.8	11.21%
Bare soil sparsely vegetated	18214889	1821.5	18.2	10.32%
Bare sand	636003	63.6	0.6	0.36%
Grassland	2212624	221.3	2.2	1.25%
Low scrub with cacti	13781052	1378.1	13.8	7.81%
Low scrub	11833130	1183.3	11.8	6.70%
High scrub with cacti	28586256	2858.6	28.6	16.20%
High scrub	1971771	197.2	2.0	1.12%
Woodland	3474765	347.5	3.5	1.97%
Mangroves	684245	68.4	0.7	0.39%
Wetland - reed	259399	25.9	0.3	0.15%
Wetland – water hyacinth	43553	4.4	0.0	0.02%
Salina	714593	71.5	0.7	0.40%
Fresh water	650948	65.1	0.7	0.37%
	176505110	**17650.5**	**176.5**	**100.00%**

4.2 An accuracy assessment

For the accuracy assessment an independent validation point dataset was created through visual interpretation of the 30 cm resolution pan-sharpened WV-3 mosaic, while also considering local insights from the ground survey. The validation dataset consisted of 556 points, covering most land cover types. However, for scrub areas, no distinction could be made between low- and high scrub or between scrub with or without cacti. Additionally, grassland and woodland were not identified. This approach carries some risk, as errors can occur during visual interpretation of the Worldview-3 imagery. Ideally, a separate ground truth validation dataset would have been used, but this was considered too costly to gather. Based on Table 4, an overall accuracy of 71.6% was calculated, which is reasonable, but not excellent. Some confusion arose due to the spectral overlap between urban pavement and roads, as well as between bare soil and sparsely vegetated bare soil (Table 4). This negatively impacted overall user and producer accuracy but is quite common in remote sensing land cover classifications. The most surprising was the confusion between scrub and sparsely vegetated areas.

Table 4 *Confusion matrix of the Land Cover Classification (LCC) and the validation points (#556).*

	Validation															
		1	**2**	**3**	**4**	**6**	**7**	**8**	**10**	**18**	**21**	**22**	**23**	**24**	**25**	**Grand Total**
LCC	1	**45**			4											49
	2	5	**44**	22				2	1						5	79
	3			**22**	1											23
	4		2		**34**			1								37
	6		1			**26**		2		1						30
	7		3	5		13	**30**	3	16		1			1		72
	8					6	18	**10**								34
	10								**33**							33
	18			1	1	4	1	19		**48**	5	1		5		85
	21				3						**20**					23
	22											**20**				20
	23												**9**			09
	24											2		**21**		23
	25					1								2	**36**	39
	Grand Total	50	50	50	43	50	49	37	50	49	26	23	9	29	41	**556**

Value	**Class Name**	**User Accuracy**	**Producers accuracy**
1	Built-up	92	90
2	Urban bare and pavement	56	88
3	Road	96	44
4	Urban green	92	79
6	Bare rock	87	52
7	Bare soil	42	61
8	Bare soil sparsely vegetated	29	27
10	Bare sand	100	66
18	Scrub	56	98
21	Mangroves	87	77
22	Wetland - reed	100	87
23	Wetland – water hyacinth	100	100
24	Salina	91	72
25	Fresh water	92	88

Overall accuracy of 71.6%.

5 Historic land cover changes Aruba

5.1 Sources of information

Various sources were used for analysing the historic land cover changes, starting with the vegetation map of Stoffers (1956). The vegetation map of Stoffers was aggregated into broader land cover classes as shown in Table 5.

Table 5 *Summary generalisation of vegetation classes (Stoffers, 1956) into land cover classes.*

Vegcode	Vegname	Land cover
1	Mangrove	70 Mangrove
2	Strand vegetation	32 Strand vegetation
3	Vegetation of salt flats and saliñas	80 Wetlands and saliñas
4	*Hippomane* woodland	60 Woodland
5	Settlement and urban areas	10 Urban and built-up areas
6	Cultivated and semi-cultivated areas	20 Cultivated and semi-cultivated land
A	Cactus thorn scrub	50 Scrub
A-1	Cactus-scrub	50 Scrub
A-2	Thorny woodland (Shrubland)	60 Woodland
A-4	Croton Lantana thicket	50 Scrub
B	Desert	30 Bare and sparsely vegetated
C-2	Thorny woodland (Shrubland)	60 Woodland
C-4	Croton Lantana thicket	50 Scrub
D	Vegetation of the rock pavement	30 Bare and sparsely vegetated
D-2	Littoral woodland	60 Woodland

For this reason, the following land cover classes were used to analyse the historic land cover changes between 1900 and 2020:
10) Urban and built-up.
20) Cultivated and semi-cultivated areas.
30) Bare and sparsely vegetated.
32) Strand vegetation.
50) Scrub.
60) Woodland.
70) Mangrove.
80) Wetlands and Saliñas.

The following maps and image data sources have been processed, see Table 6, and are discussed in more detail in the following sections.

Table 6 *Summary of sources used for analysing historic land cover changes between 1900 and 2020.*

Year of acquisition	Source
1912	Werbata topographic map
1948	Historic aerial photographs (Black and white)
1953	Vegetation map Aruba of Stoffers (1956)
1987	Historic aerial photographs (RGB colours)
2020	WV3 high resolution multispectral satellite imagery

Table 6 shows significant variations in the sources of information over time, making the interpretation of the land cover and its changes quite challenging.

5.1.1 Werbata topographic map (1912)

The old topographic maps of Aruba, published by Werbata and Jonckheer in 1912, were remarkably detailed for their time. The series consisted of eight individual maps at a 1:20,000 scale. These maps are named after Johannes Gijsbertus Hendrikus Werbata, a Dutch military officer and Cartographer who played a key role in their development. Created primarily to support military operations and colonial administration, the maps provided essential geographical information for planning, infrastructure development, and governance. Between 1911 and 1915, Werbata surveyed five islands: Aruba, Curaçao, Bonaire, Sint Maarten and Sint Eustatius (excluding Saba). The maps, printed in colour at a scale of 1:20,000, included a variety of geographical features, such as:

- Vegetation types and land use patterns.
- Water bodies, such as rivers, lakes, and coastlines.
- Contour lines to represent elevation and topography.
- Settlements, including cities, towns, and villages.
- Roads, railways, and paths.
- Administrative boundaries.

For Aruba, all eight individual maps were georeferenced to current high-resolution satellite imagery using ESRI ArcGIS. The resulting georeferenced data were transformed to a GeoTIFF with a raster resolution of 1.5 m. Figure 14 illustrates significant changes in the southwestern coastline of Aruba since 1900, including alterations to the barrier islands along the coast. Figure 15 highlights the remarkable level of detail captured in the topographic features of these historic maps. The map’s legend is displayed separately in Figure 16 and shows the detail and richness of the mapped elements.

Figure 14 *The resulting georeferenced Werbata map of Aruba was created by stitching together eight individual sheets, each georeferenced separately. The red line represents the modern coastline, digitized from Worldview-3 imagery from 2020. It is clearly visible that that the southwestern coastline has undergone significant changes.*

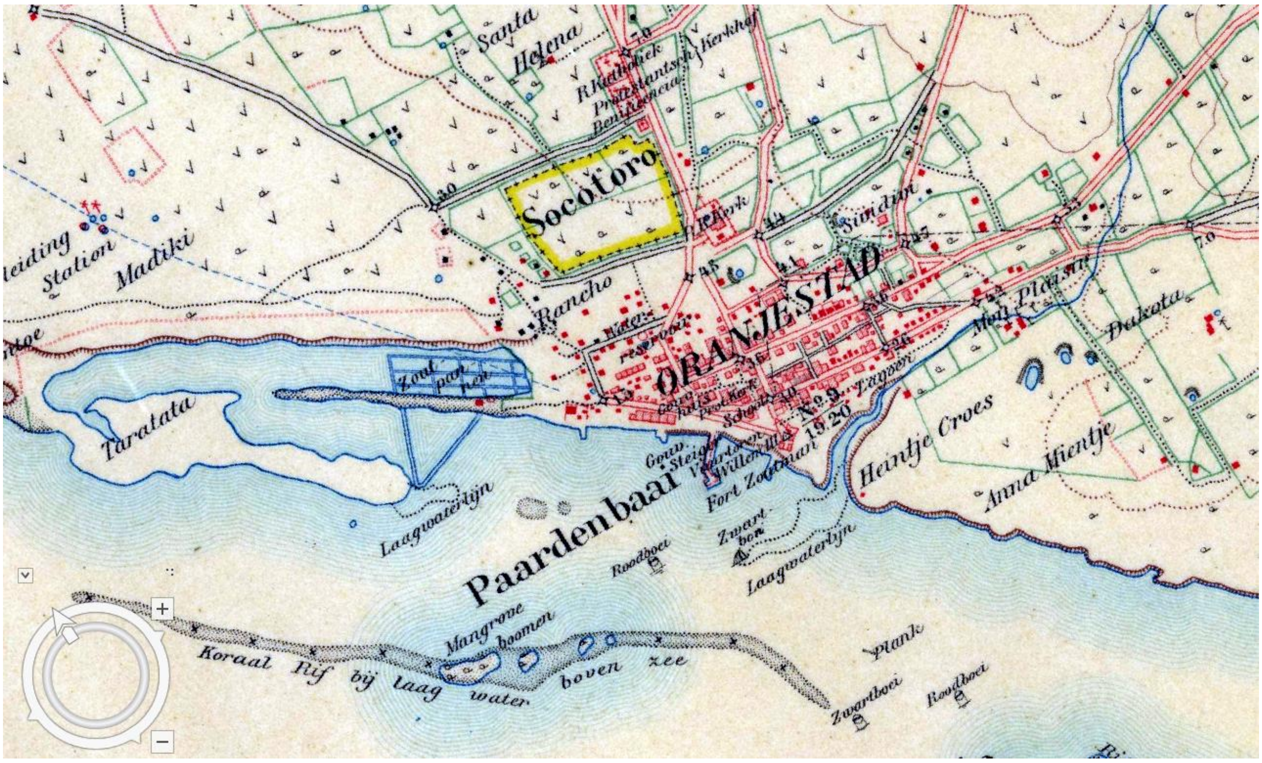

Figure 15 *Details of the Werbata map of Aruba (1912) at a scale 1:10.000 for Oranjestad and Paardenbaai.*

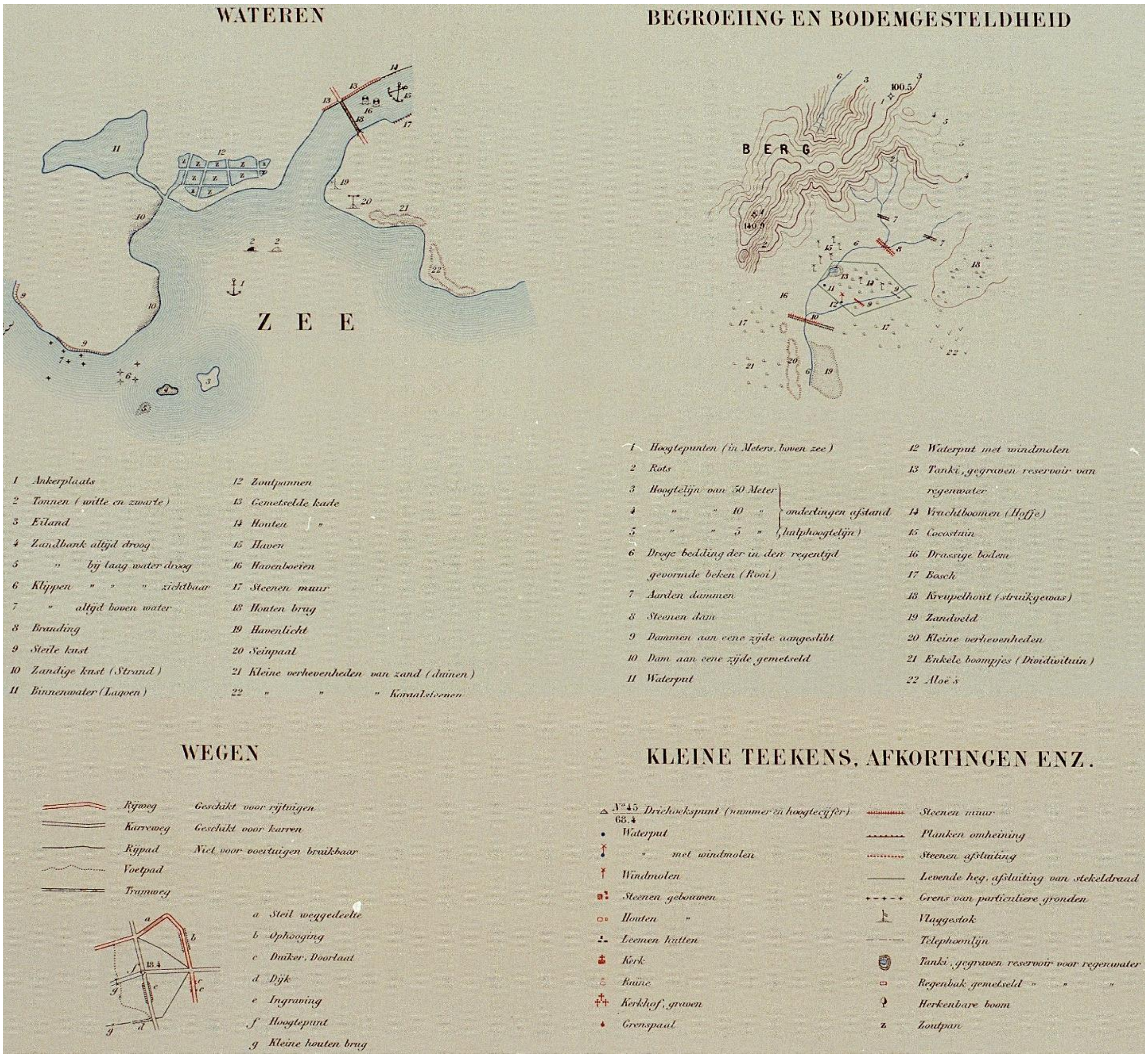

Figure 16 *Legend from the Werbata map for Aruba.*

5.1.2 Historic aerial photographs (1948)

The aerial photographs were provided by the Aruba Conservation Foundation (ACF) as a non-georeferenced mosaic (JPEG file). They were georeferenced in ArcGIS Pro using the Georefence tool, using the ortho-rectified WV3 high resolution image from 2020 (30 cm resolution) as a reference. Although the quality of the scanned aerial photographs is relatively poor (scanned at 200 dpi), they remain a valuable source of information, as no other image data source is available for the 1940s. Figures 17 and 18 provide an overview and shows some details of the 1948 mosaic.

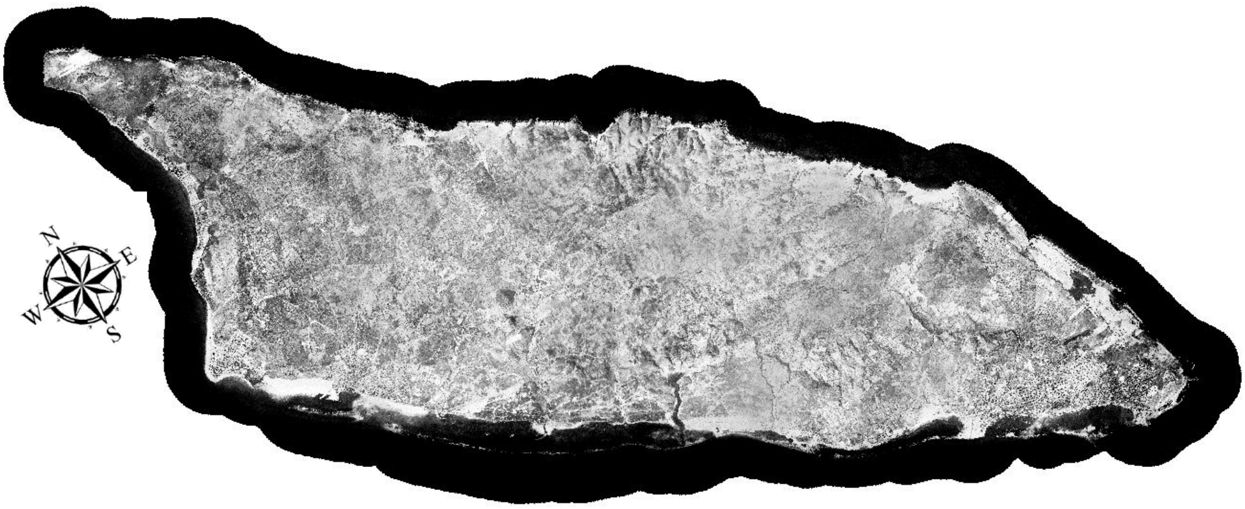

Figure 17 *Georeferenced mosaic of aerial photographs from 1948 (Source: Aruba Conservation Foundation).*

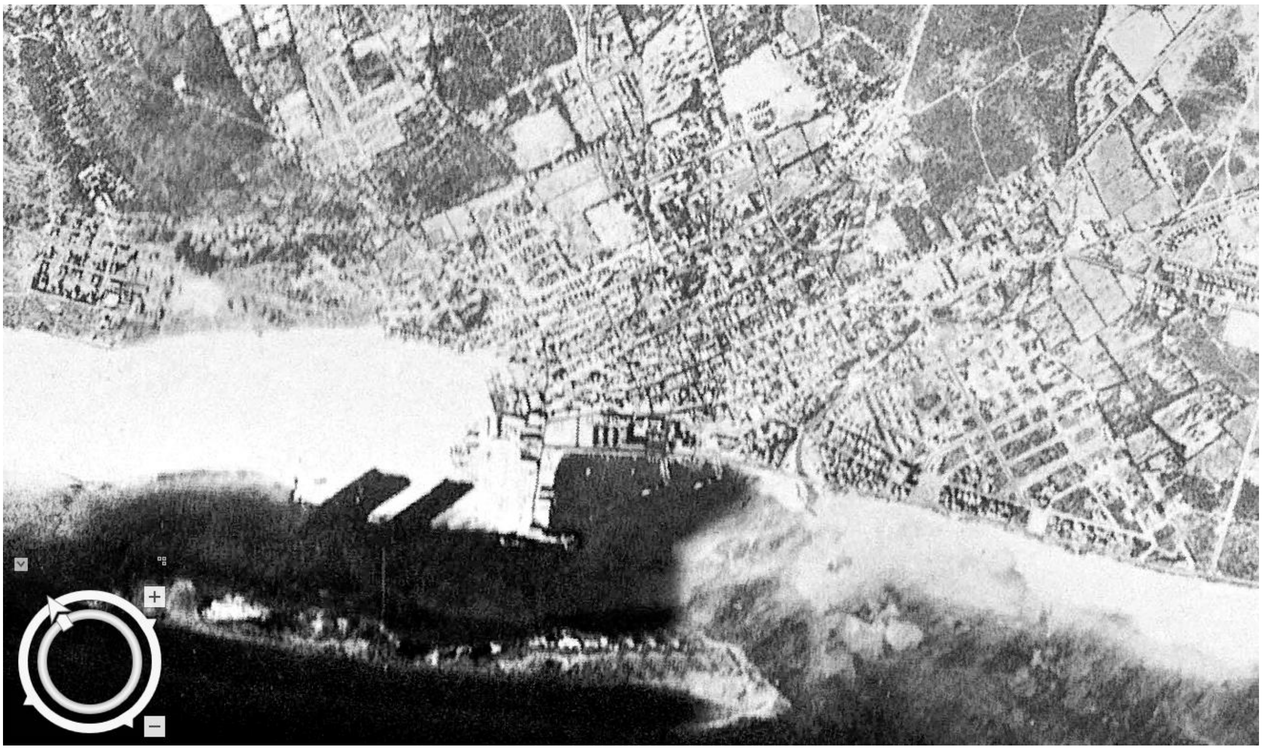

Figure 18 *Example of detail of the aerial photographs of 1948 at a scale 1:10.000 for Oranjestad and Paardenbaai. The image is noticeably lacking in sharpness.*

5.1.3 Vegetation Map (1953)

The vegetation map of Aruba, derived from Stoffers' study (Stoffers, 1956), offers a detailed overview of the island's plant communities and their distribution. Stoffers' work is considered foundational for understanding the flora of Aruba and other islands in the region. The original map scale is 1: 50.000, based on field surveys conducted from September 1952 to October 1953. During this period, Stoffers and his team mapped the vegetation of Curaçao, Bonaire, Aruba, St. Martin, Saba and St. Eustatius, culminating in 1956 publication: *The vegetation of the Netherlands Antilles* (Stoffers, 1956). For Aruba it is assumed that fieldwork was carried out in 1953. However, verifying Stoffers' findings is challenging due to the lack of aerial photographs from that year. In order to improve consistency across the time series, small adjustments were made in the vegetation map with regard the delineations and derived land cover classes using aerial photographs from 1948 and 1987.

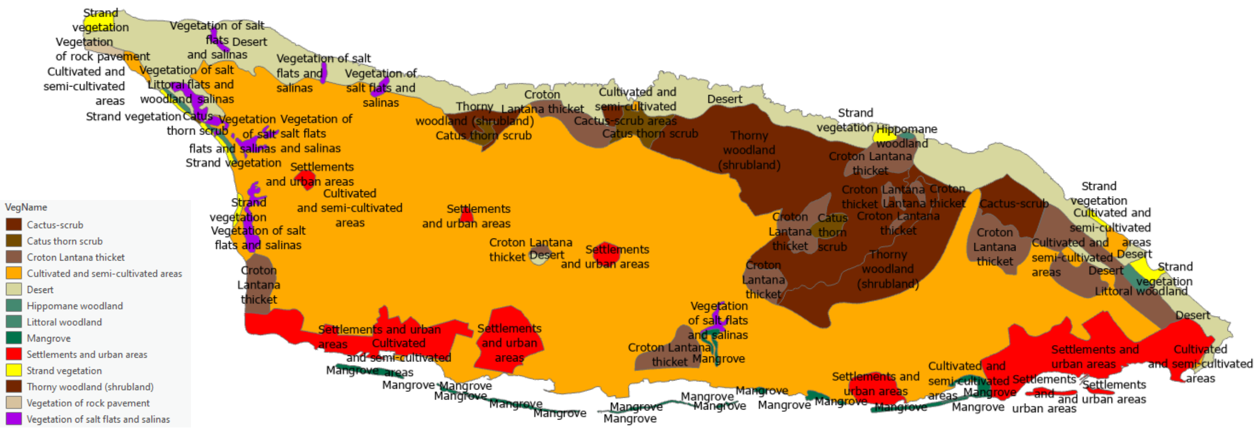

Figure 19 *Vegetation map of Aruba (Stoffers, 1956).*

The derived land cover map has been slightly modified, as shown below.

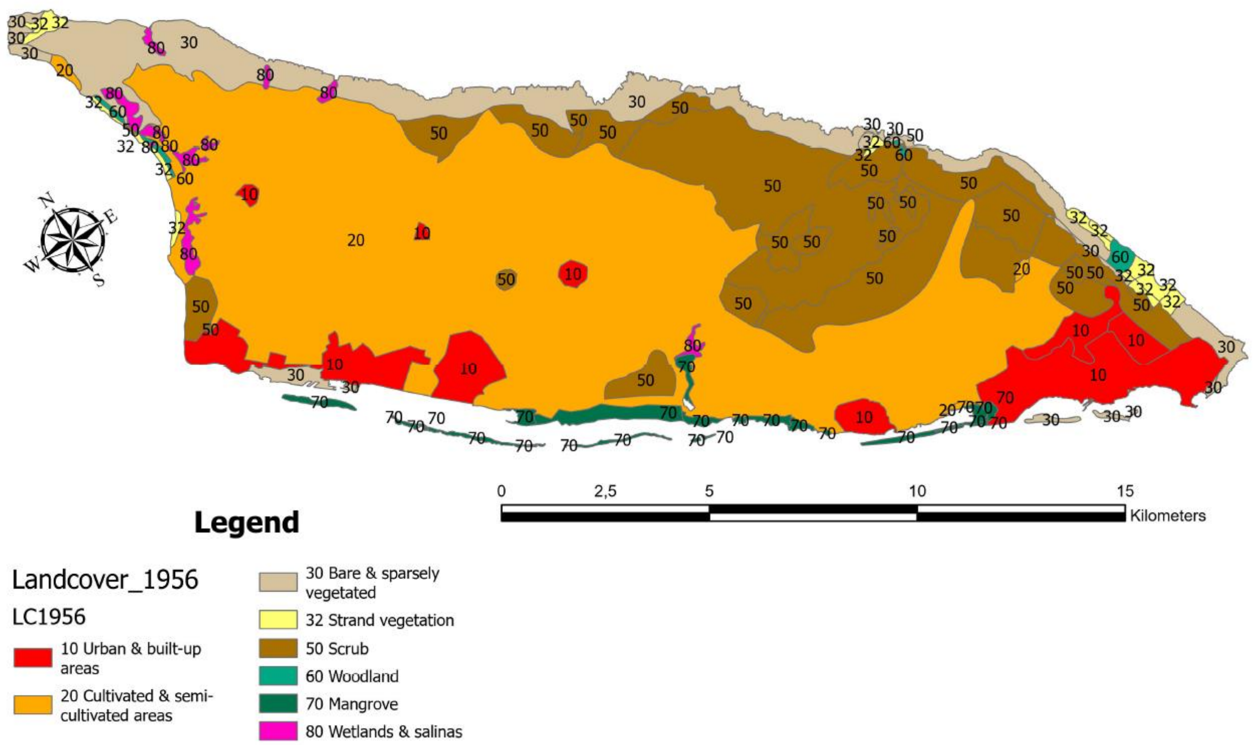

Figure 20 *Derived land cover from the vegetation map of Stoffers (1956), slightly adjusted based on aerial photographs 1948 and 1987. This was required to make the time series more consistent.*

5.1.4 Historic aerial photographs (1987)

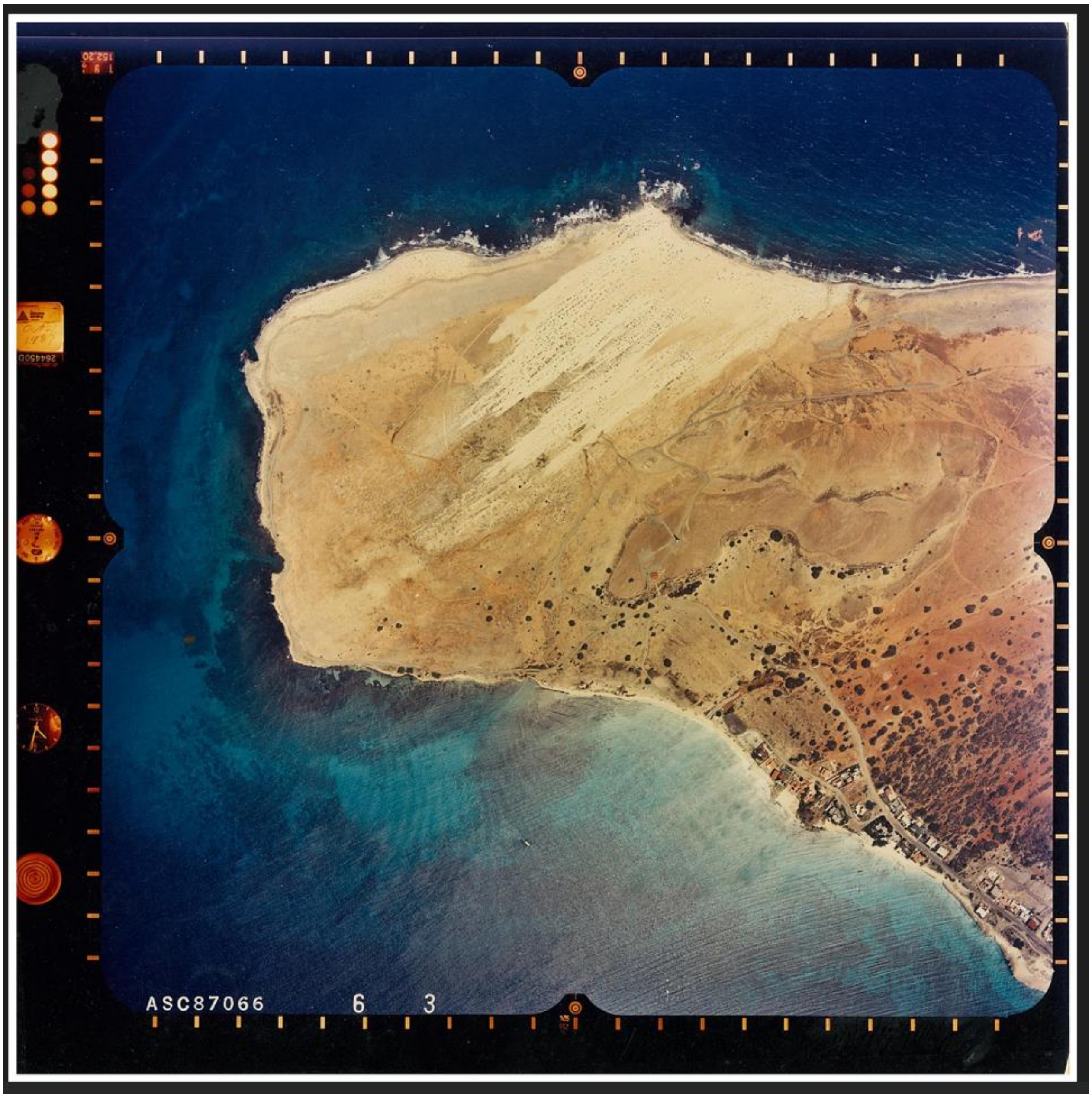

Figure 21 *Example of the aerial photographs of October 1987 for Aruba with a spatial resolution of approximately 50 cm.*

The 1987 aerial photographs were obtained from Carmabi and consist 214 images taken on October 21, 1987. Although it is likely that KLM Aerocarto captured these photographs, this cannot be confirmed. The images have an approximate resolution of 50 cm.

Agisoft Metashape was used to build a stitched mosaic out of all individual aerial photographs. Processing with Agisoft Metashape was possible as there was sufficient overlap between the individual aerial photographs. The resulting mosaic, in GeoTIFF format, still required georeferencing. This was performed in ArcGIS Pro using the Georeference tool, with the ortho-rectified multispectral WV-3 image from 2020 as a reference, similar to the approach used for the 1948 aerial photographs. The final georeferenced mosaic is shown in Figure 22.

Figure 22 *Mosaic with a spatial resolution of 50 cm, out of 214 aerial photographs of 1987, processed in Agisoft Metashape and georeferenced in ArcGIS Pro.*

5.1.5 WV3 high resolution multispectral satellite imagery (2020)

The data with the highest quality is from May 21, 2020, consisting of ortho-rectified multispectral Worldview-3 imagery. This dataset includes an 8-band multispectral image with a 1.2 m resolution and a panchromatic image with a 30 cm resolution (see also Section 2.1).

To illustrate the level of detail in the pansharpened multispectral WorldView-3 image at a scale 1:5.000 for Oranjestad and Paardenbaai, a snapshot is provided in Figure 23.

Figure 23 *Details of the pansharpened multispectral WV-3 image (30 cm resolution) at a scale 1:5.000 for part of Oranjestad and Paardenbaai.*

5.2 Method change detection

All data sources from the years between 1900 and 2020 have been visually interpreted into the following broad land cover classes:
10) Urban and built-up.
20) Cultivated and semi-cultivated areas.
30) Bare and sparsely vegetated.
32) Strand vegetation.
50) Scrub.
60) Woodland.
70) Mangrove.
80) Wetlands and Salinas.

The vegetation map of Aruba (Stoffers, 1956), originally at scale 1:50.000, was translated into broad land cover classes, using the 1953 vegetation map (the date of Stoffers' survey) as the starting point. Due to the poor topology of the original vegetation map, it was necessary to improve the derived land cover map by removing slivers, not closing border polygons, and empty island polygons. Subsequently, visual interpretations were made at a scale of 1:50.000 for historical aerial photographs from 1948 (closest to 1953) and 1987 (second closest to 1953). Initially, the 1953 land cover map was copied to the 1948 and 1987 maps. Based on visual interpretation of the specific aerial photographs, the borders of the polygons and/or their thematic classes were changed when needed. Next, a visual land cover interpretation for 2020 was performed at the same scale, using the pixel-based land cover map (Figure 24) described in Chapter 1 as a reference. It is important to note that a visual interpretation at a scale of 1:50,000 differs significantly from pixel-based classification. The visual approach (Figure 25) focuses on broad land cover patterns at the landscape level rather than individual pixels.

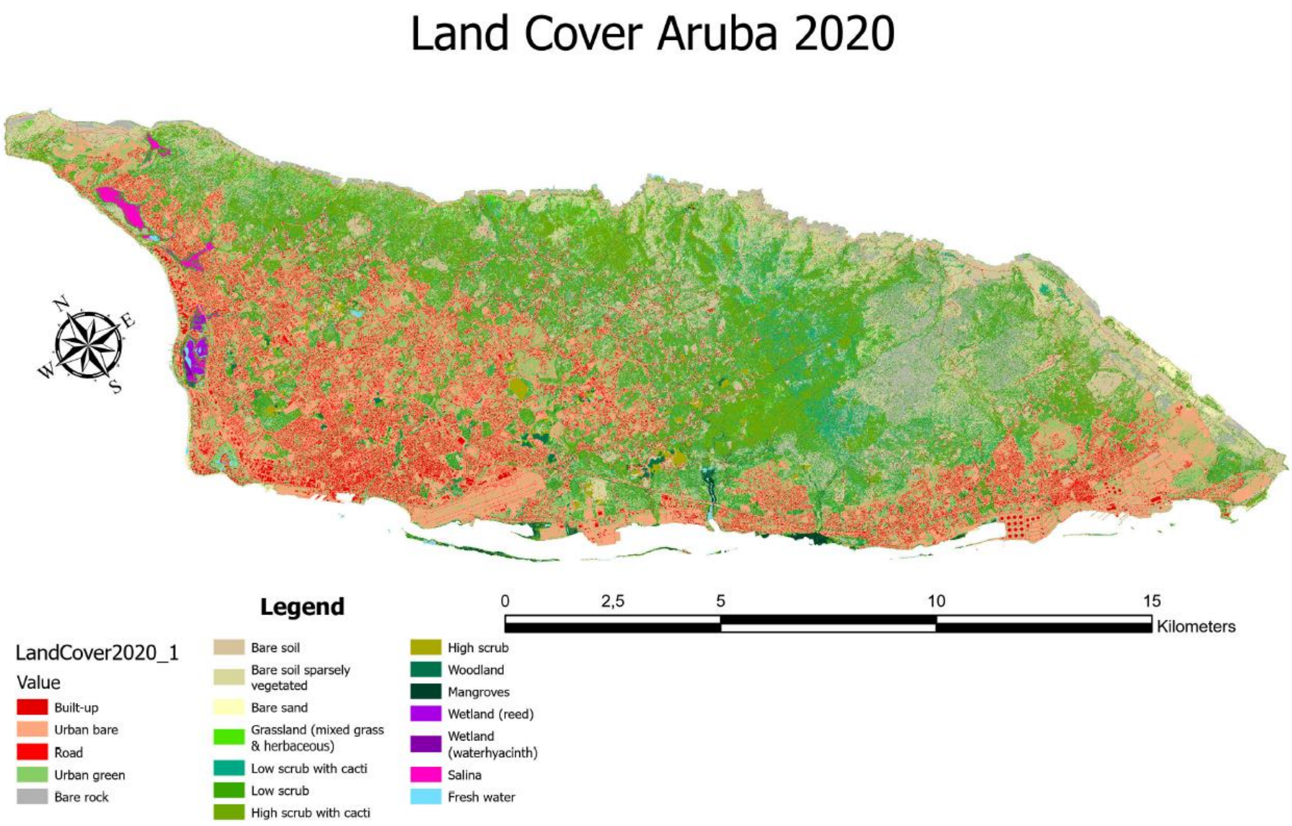

Figure 24 *The pixel-based land cover classification of Aruba for 2020 at 1 m resolution.*

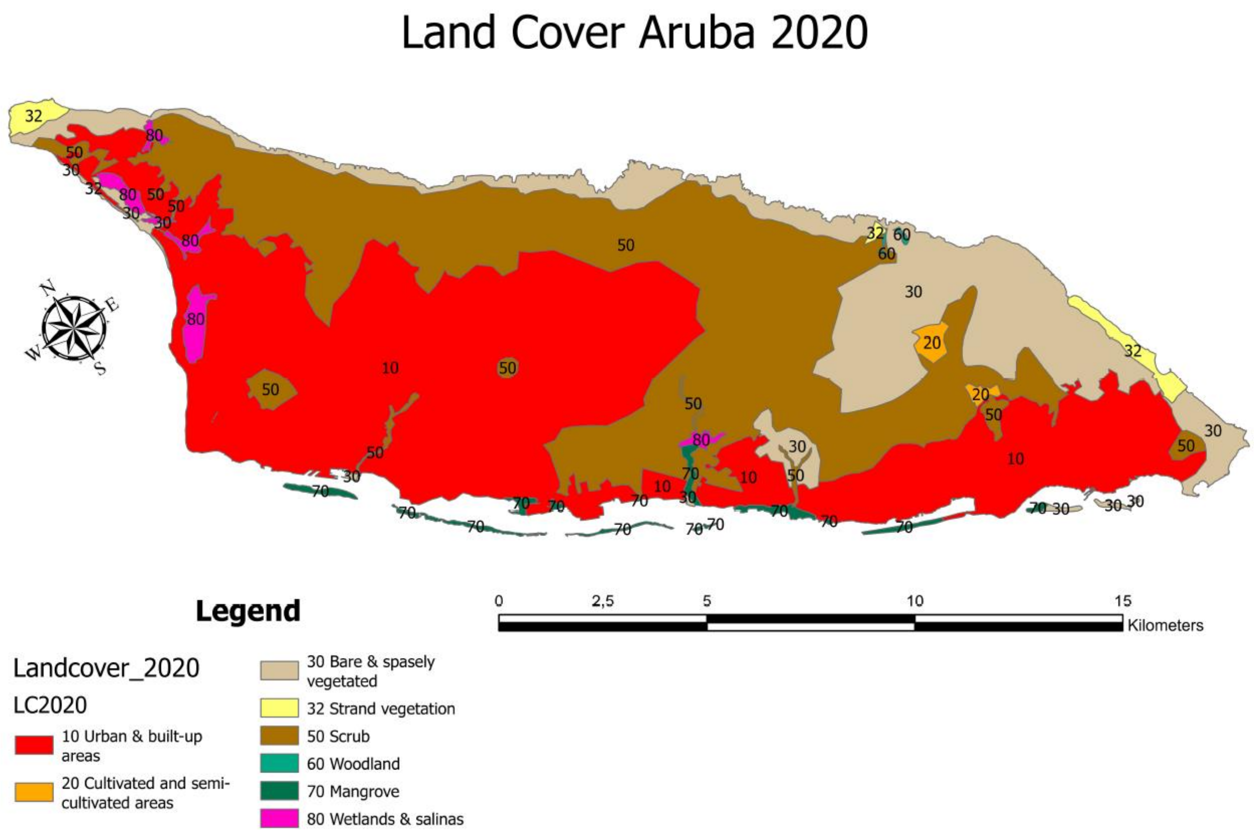

Figure 25 *The visual interpretation of the broad land cover types at the landscape level (interpreted at scale 1:50.000).*

In the final stage, the Werbata topographic map was interpreted into broad land cover types at a scale of 1:50.000. Although the map is quite detailed, translating these into broad land cover classes was sometimes challenging due to ambiguity in the interpretation of the map. For example, in the north-eastern wetlands, the Werbata map indicated sand fields, which, based on internal discussions with vegetation experts were interpreted as strand vegetation. Since it is impossible to verify the land cover around 1900, some misinterpretations may have occurred. Nonetheless, the Werbata map remains a very valuable source of information that could not be overlooked.

Following this, we analysed the time series for consistency across different years and made some additional corrections to the 1953 land cover map (Stoffers, 1956) particularly for woodland and scrub *versus* sparsely vegetated for some of the polygons. In these cases, we relied sometimes more on the aerial photographs from adjacent years for a correct interpretation of 1953 land cover map.

5.3 Results

Figures 26 to 30 present the visual interpretation of the land cover for the years 1912, 1948, 1953, 1987 and 2020, respectively, at a scale 1:50.000.

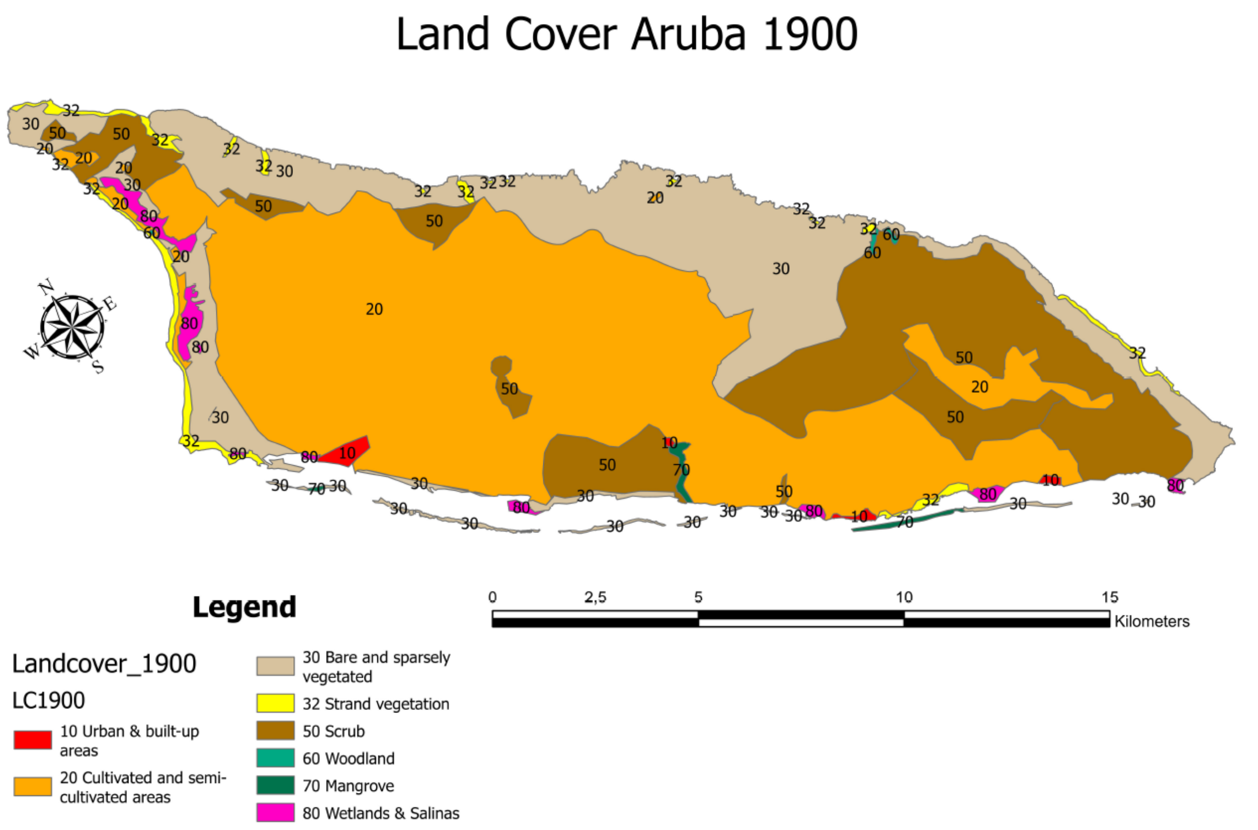

Figure 26 *Land cover 1900, or more precisely from around 1912, based on the Werbata maps of Aruba.*

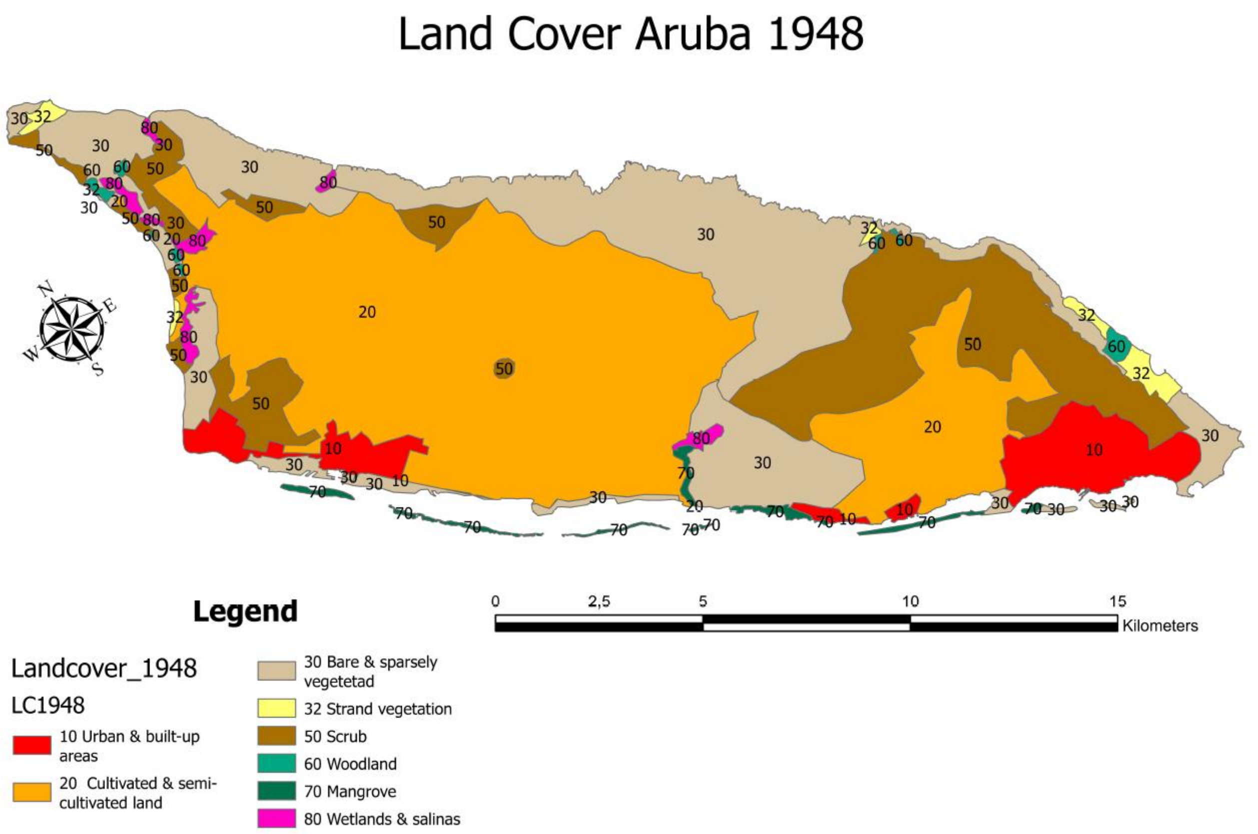

Figure 27 *Land Cover Aruba in 1948.*

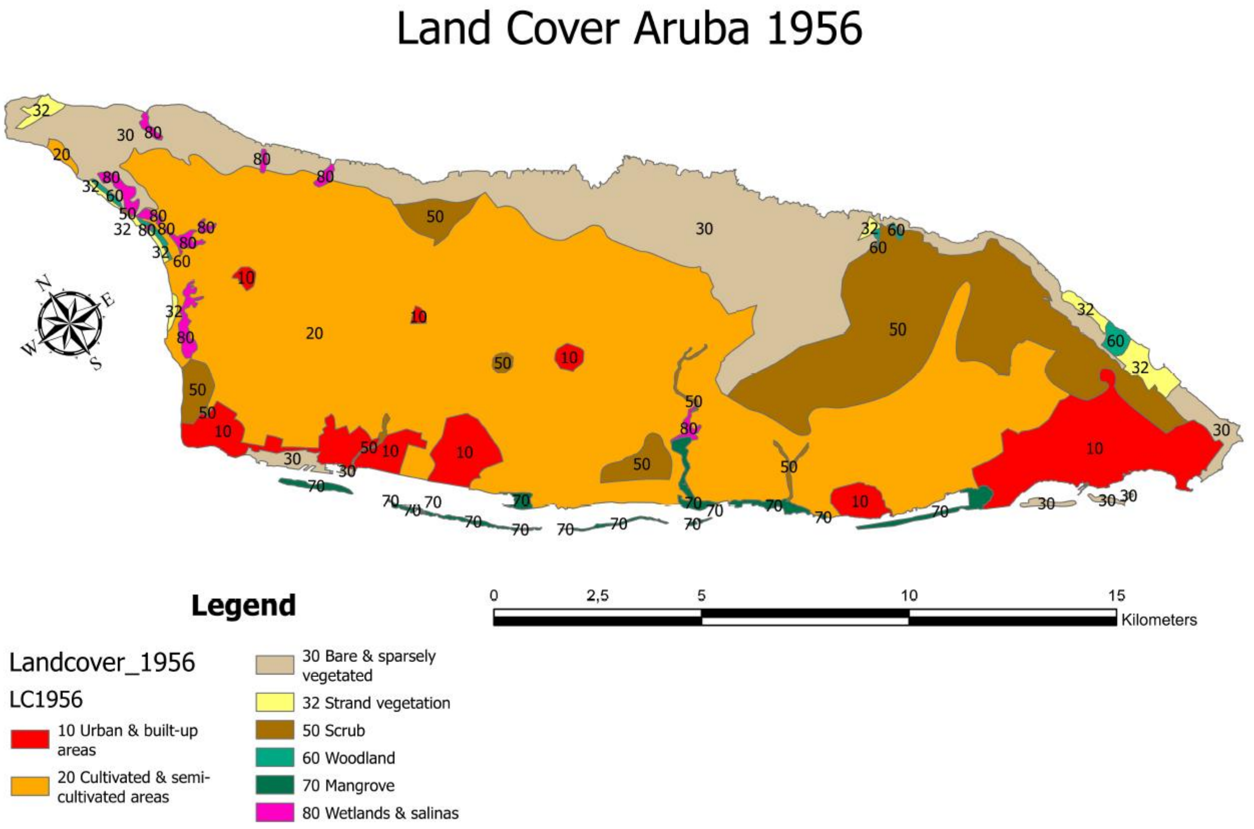

Figure 28 *Land cover Aruba in 1956.*

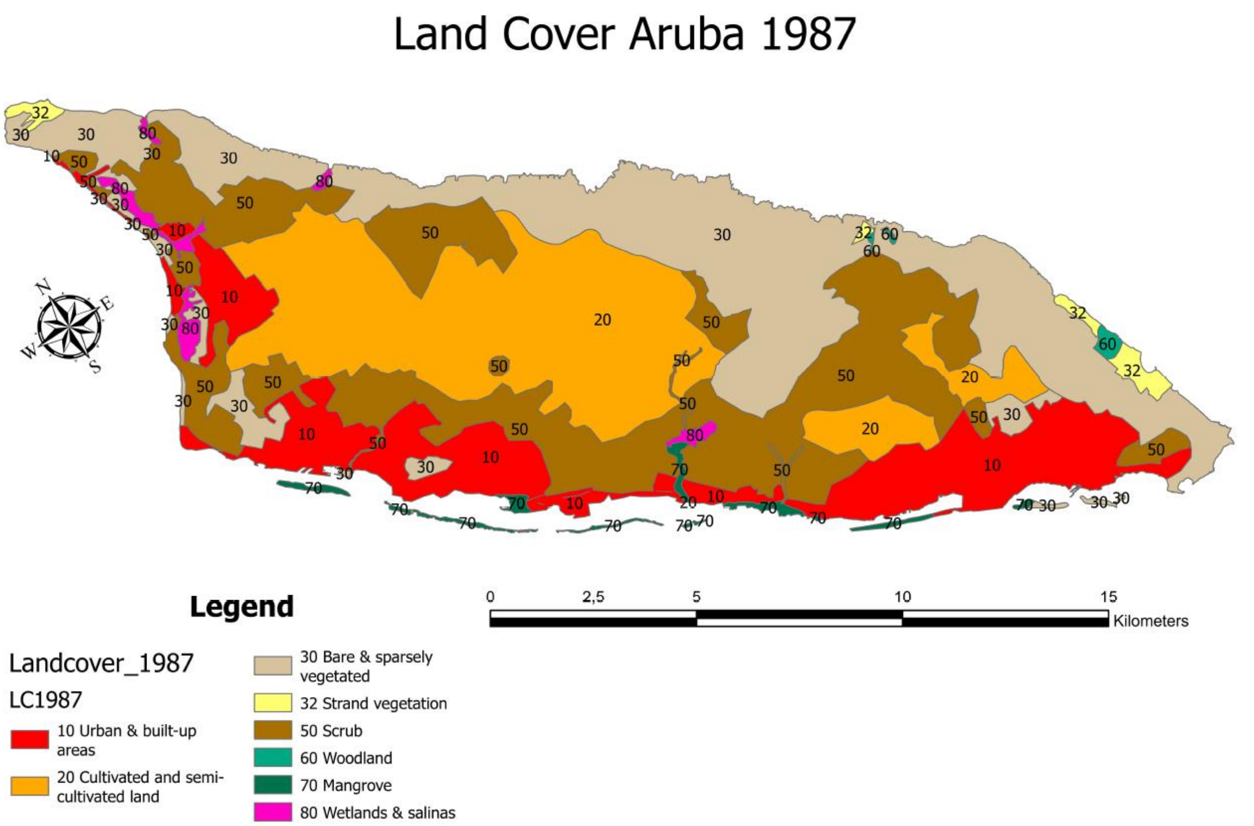

Figure 29 *Land cover Aruba in 1987.*

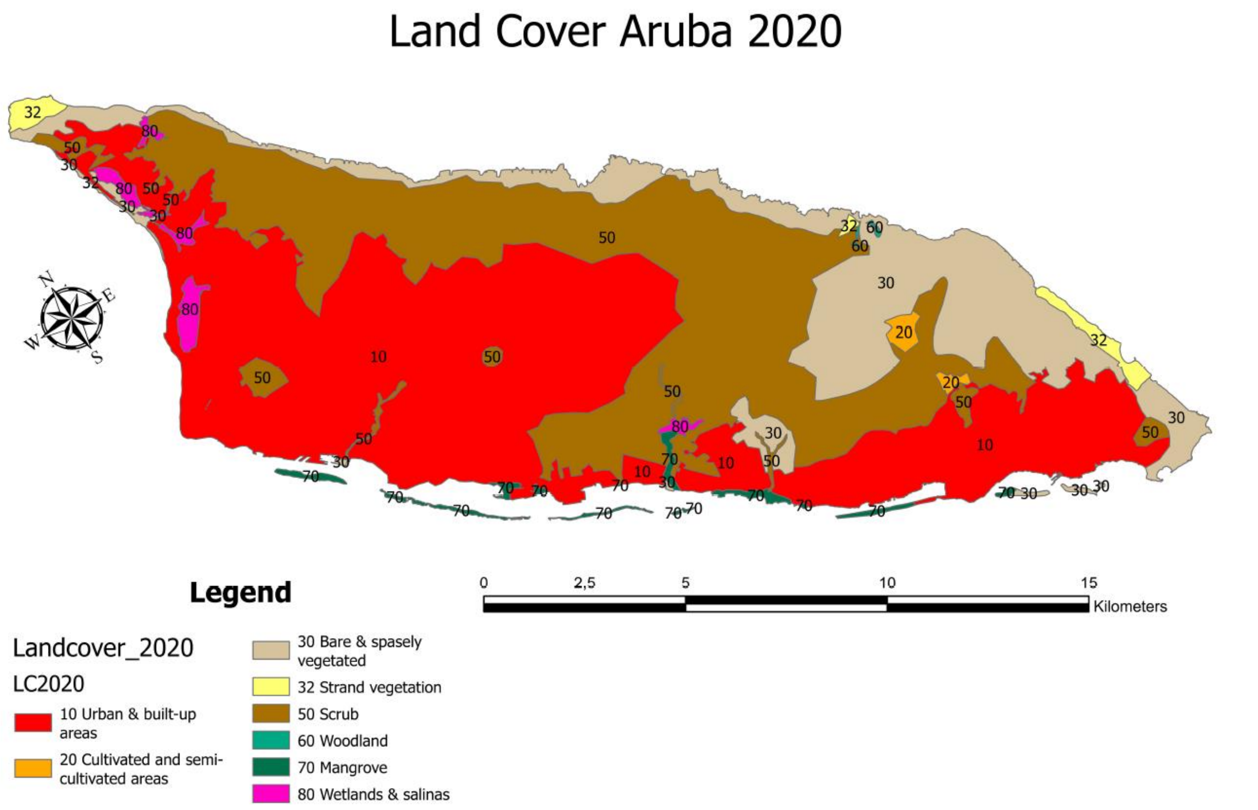

Figure 30 *Land cover Aruba in 2020.*

We summarised the above figures in Tables 7 and 8, to analyse the land cover trends in the period 1900 – 2020.

Table 7 *Summary of the land cover trends for Aruba between 1900 and 2020 in hectares.*

		Area_ha				
LC	**Land Cover Class**	**1912**	**1948**	**1956**	**1987**	**2020**
10	Urban and built-up area	74	1124	1611	2956	8262
20	Cultivated and semi-cultivated areas	9051	8303	9713	4494	80
30	Bare and sparsely vegetated	4230	4910	3573	5184	3038
32	Strand vegetation	294	184	206	186	199
50	Scrub	3865	3004	2455	4791	6066
60	Woodland	13	78	66	43	9
70	Mangrove	58	160	212	174	168
80	Wetlands and saliñas	214	181	165	197	199
		17798	**17944**	**18000**	**18025**	**18022**

Table 8 *Summary of the land cover trends for Aruba between 1900 and 2020 in percentages.*

		Percentages				
LC	**Land Cover Class**	**1912**	**1948**	**1956**	**1987**	**2020**
10	Urban and built-up area	0	6	9	16	46
20	Cultivated and semi-cultivated areas	51	46	54	25	0
30	Bare and sparsely vegetated	24	27	20	29	17
32	Strand vegetation	2	1	1	1	1
50	Scrub	22	17	14	27	34
60	Woodland	0	0	0	0	0
70	Mangrove	0	1	1	1	1
80	Wetlands and saliñas	1	1	1	1	1
		100	**100**	**100**	**100**	**100**

Figures 26-30, along with Tables 7 and 8, clearly illustrate the rapid urbanisation of Aruba, particularly since the late 1980s. This trend over the years is summarised in Figure 31.

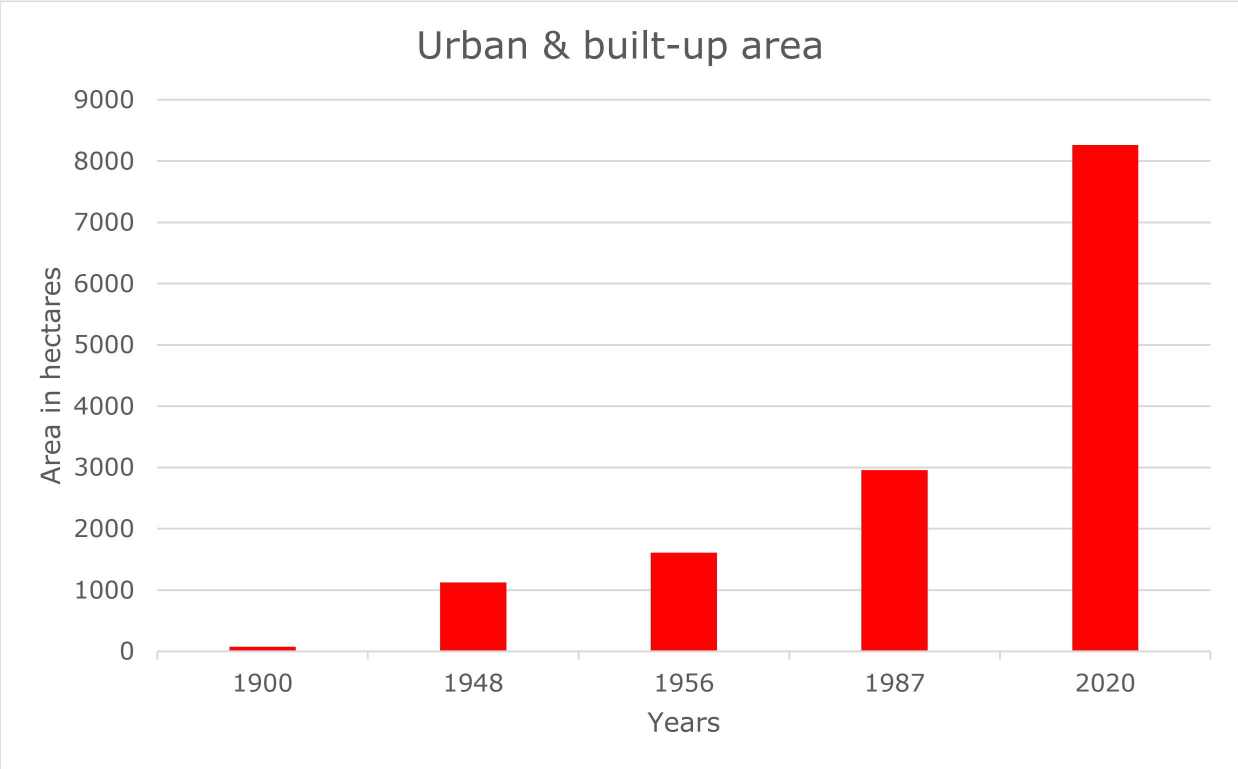

Figure 31 *Bar diagram of the steep increase of urbanisation on Aruba, especially since the late 1980s.*

It is also striking that agriculture has nearly disappeared on Aruba since the late 1980s. (Figure 32).

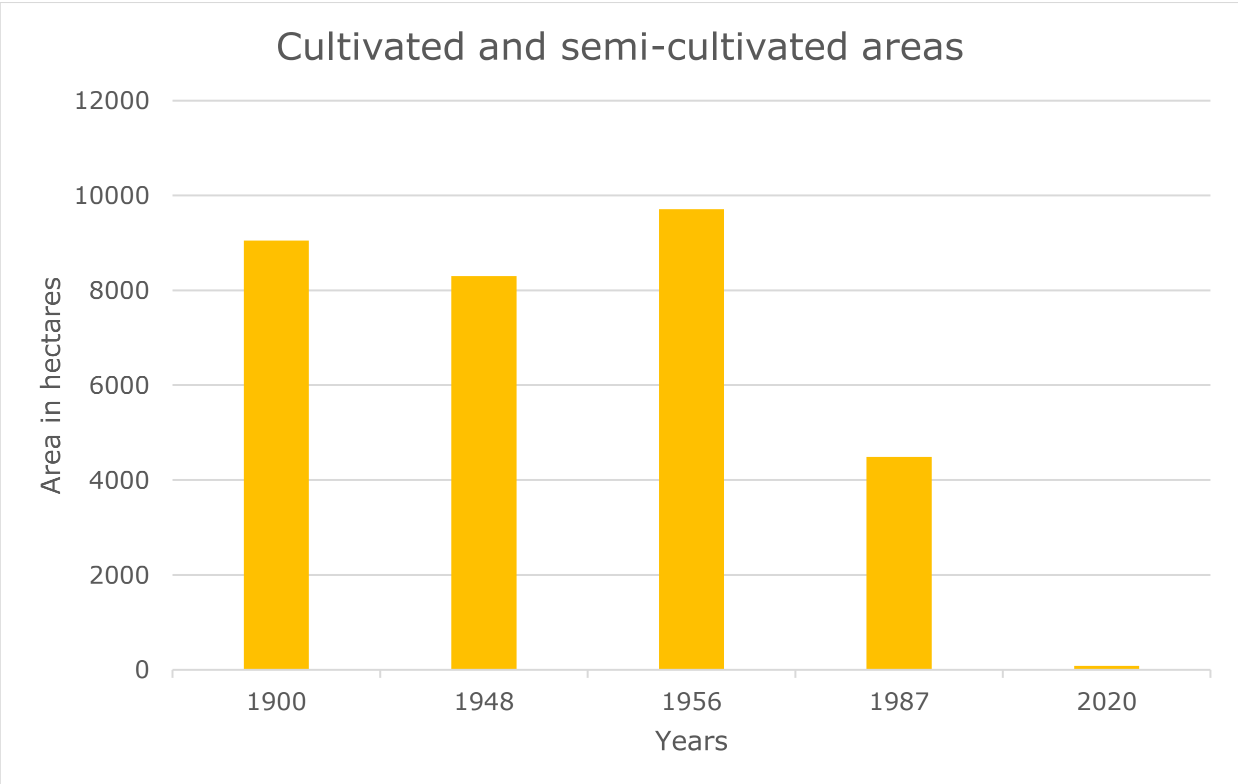

Figure 32 *Bar diagram of the steep decrease of Agriculture on Aruba, especially since the late 1980s.*

One trend that remains somewhat ambiguous in our data analysis is the development of scrub. While the expansion of scrub is clearly visible in the aerial photographs since 1948, it is difficult to verify using the 1956 land cover map (Stoffers, 1956), where the extent of scrub may have been underestimated, (see also Figure 33). However, it is evident that the expansion of scrub has primarily occurred at the expense of 'bare and sparsely vegetated' areas. This change is further illustrated in Figure 34, which features pictures taken at approximately the same locations in the 1950s and in 2022. Figures 35 and 36 clearly show the expansion of scrub at the expense of 'bare and sparsely vegetated' areas. The removal of goats could also have contributed to this process (personal communication Gian Nuñes, Aruba Conservation Foundation).

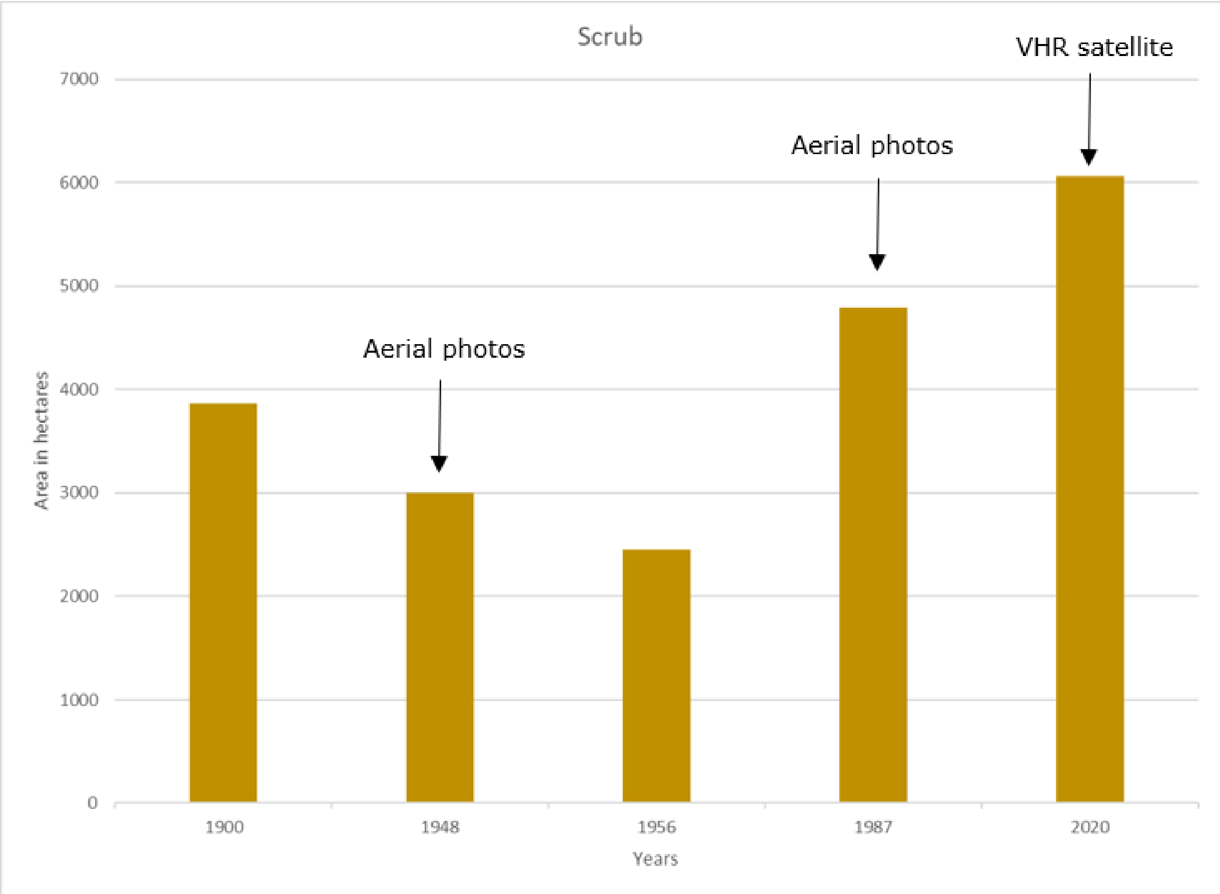

Figure 33 *Bar diagram of the scrub development on Aruba.*

Figure 34 *Pictures taken from similar places around 1950 and in 2022, showing the scrub encroachment on 'bare and sparsely vegetated' areas.*

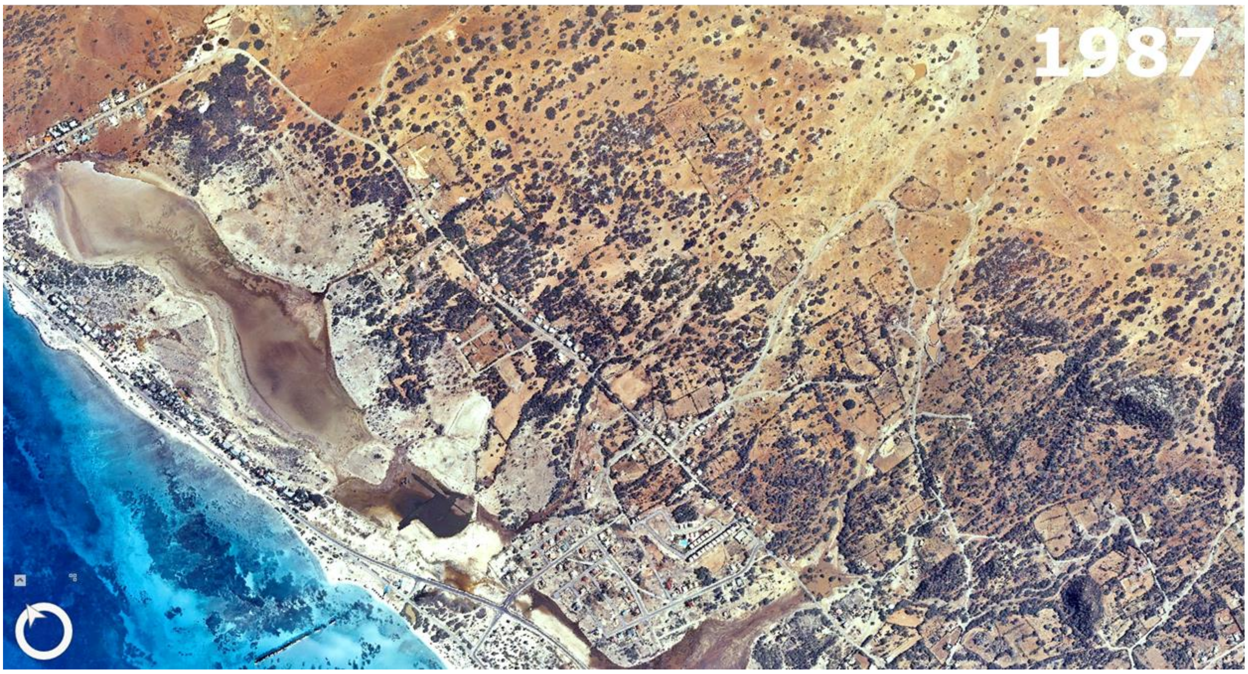

Figure 35 *Detail of aerial photographs 1987 and compare the scrub development with Figure 36.*

Figure 36 *Detail of aerial photographs 2020 for the same area shown in Figure 35. It can clearly be seen that the amount of scrub has expanded at the expense of 'bare and sparsely vegetated' area.*

5.4 Conclusions

- Although different sources of information have been used over time, the resultant analysis of land cover changes is still very valuable.
- Overall aerial photographs and similar very high-resolution satellite imagery are preferable as they can be interpreted in the same manner, so the assessment is not dependent on the interpretations of others.
- The land cover change analysis shows that urban areas have expanded dramatically (more than 100 times since 1900) largely at the expense of cultivated land and natural areas, that now cover nearly 50% of Aruba.
- Cultivated and semi-cultivated areas (read agriculture), which covered about 50% of the island in 1900, have almost completely disappeared. The decline started after 1956.
- In the remaining natural areas, the amount of scrub has significantly increased, replacing bare and sparsely vegetated areas, likely due, in part, to the removal of goats in specific areas.
- Historical aerial photographs are a powerful tool for analysing landscape changes in full details.

Acknowledgements

We want to extend our gratitude to Natasha Silva and Gian Nunez (the Aruba Conservation Foundation (ACF)), Gisbert Boekhoudt, Oriana Wouters and Nadine Da Silva (Department Nature and Environment (DNM)) for their feedback on an early draft of the land cover map. Also, Lawrence Jones-Walters for completing a native-speaker's edit of the whole document. Finally we would like to thank Erik Houtepen from CARMABI for providing aerial photographs from 1987, and the Aruba Conservation Foundation for providing the aerial photographs from 1948.

References

Bossard, M., Fernanec, J., Otahel, J., 2000, *CORINE landcover technical guide*, European Environmental Agency, technical report No 40.

CEC, 1994, *CORINE landcover*, Luxembourg, retrieved in December 2020 from https://www.eea.europa.eu/publications/COR0-part1.

Burkhard, B., Kroll, F., Müller, F., Windhorst, W., 2009, *Landscapes' Capacities to Provide Ecosystem Services - A Concept for Land-Cover Based Assessments*, Landscape Online, 15, pp. 1-22.

DCNA, 2004, Important Bird Areas in the Dutch Caribbean, retrieved from www.dcnanature.org on January 2024.

DIP (Directie Infrastructuur en Planning), 2019, Spatial Development Plan with regulations, kindly provided by RHO adviseurs, www.rho.nl on October 2023.

ESA WorldCover project / Contains modified Copernicus Sentinel data (2021) processed by ESA WorldCover consortium, Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N.E., Xu, P., Ramoino, F., Arino, O., 2022. ESA WorldCover 10 m 2021 v200.

De Freitas, J., Rojer, A., Houtepen, E., Debrot, A., 2023, *Landscape ecological vegetation map of Aruba (southern Caribbean)*, Royal Netherlands Academy, the Netherlands.

Dick, J., Verweij, P., Carmen, E., Rodela, R., Andrews, C., 2017, *Testing the ecosystem service cascade framework and QUICKScan software tool in the context of land use planning in Glenlivet Estate Scotland*, International Journal of Biodiversity Science, Ecosystem Services & Management, 13:2, 12-25, DOI: 10.1080/21513732.2016.1268648.

Henkens, R., 2023, Extension of protected wetlands on Aruba, retrieved from https://www.wur.nl/nl/nieuws/grote-uitbreiding-beschermde-wetlands-aruba-onder-het-ramsar-verdrag.htm January 2024.

Kapetanaki, P., Verweij, P., Jones, L., Simoes, M., Winograd, M., 2017, *An application framework for exploring the sustainability limits: the case of climate change impacts in Brazil*, Agile conference, Wageningen, May 2017.

Mahamane, M., Zorilla-Mirras, P., Verweij, P., Sitoe, A., Ryan, C., Patenaude, G., Grundy, I., Metzger, M., Ribeiro, N., Baumert, S., Vollmer, F., 2017, *Understanding landuse, land cover and woodland-based ecosystem services change*, Mabalane, Mozambique, Energy and Environment Research, 7(1).

Memarsadeghi, N., Mount, D., Netanyahu, N., Le Moigne, J., 2007, *A fast implementation of the isodata clustering algorithm*, International journal of computational geometry & applications, 17(1), pp. 71-103.

minLNV, minI&W, minBUZA, 2020, Plan voor land en water.

Mücher, C.A., Verweij, P., 2020, Land cover classification Bonaire: mapping the land cover of Bonaire based on very high resolution PLEIADES satellite data of 2014-2016. Wageningen Research report 3050.

OLB – Openbaar Lichaam Bonaire, 2015, *Ruimtelijk ontwikkelingsplan Bonai*re, accessed from https://www.dcbd.nl/document/zonal-plan-map-ruimtelijk-ontwikkelingsplan-bonaire-rob on January 2020.

Opdam, P., Verboom, J., Pouwels, R., 2003, *Landscape cohesion: an index for the conservation potential of landscapes for biodiversity*, Landscape ecology, 18, pp. 113-126.

OSM – OpenStreetMap, 2023, Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org.

RAMSAR, 2023, Four new wetlands of international importance on Aruba, retrieved from https://www.ramsar.org/news/four-new-wetlands-international-importance-aruba January 2024.

Saah, D., Tenneson, K., Matin, M., Uddin, K., Cutter, P., Poortinga, A., Nguyen, Q., Patterson, M., Johnson, G., Markert, K., Flores, A., Anderson, E., Weigel, A., Ellenberg, W., Bhargava, R., Bhandari, B., Khanal, N., Housman, I., Potapov, P., Tyukavia, A., Maus, P., Ganz, D., Clinton, N., Chishtie, F.,2019, *Land Cover Mapping in Data Scarce Environments: Challenges and Opportunities*, Frontiers in environmental science, 5, https://doi.org/10.3389/fenvs.2019.00150.

Schep, S., van Beukering, P., Brander, L., Wolfs, E., 2013*, the tourism value of nature on Bonaire, Institute for environmental studies*, report number R-13/02.

SIC, 2022, Worldview-3 satellite sensor, retrieved from www.satimagingcorp.com on January 2024.
Smith, S.R., Mücher, C.A., Debrot, A.O., Roupioz, L., Meesters, H.W.G., Hazeu, G.W, Davaasuren, N., 2013. *Use of satellite data for the monitoring of species on Saba and St. Eustatius*. Wageningen Research report C124/13 (BO-11-011.05-019), 86 pp.
Thomas, D., 2024. From sky to Aruba's benthic habitats: a comprehensive evaluation of classifier performance using multi-scale imagery. MSc thesis, VU Amsterdam, UNIGIS, June 2024, Amsterdam.
Stoffers, 1956. The vegetation of the Netherlands Antilles. Published on 8 October 1956 by Botanisch Museum en Herbarium Utrecht.
Ukrainski, P., 2016, *classification accuracy assessment – confusion matrix method*, SCGIS on 50 degrees north.
Verweij, P., Janssen, S., Braat, L., van Eupen, M., Perez Soba, M., Winograd, M., de Winter, W., Cormont, A., 2016, *QUICKScan as a quick and participatory methodology for problem identification and scoping in policy processes*, Environmental Science & Policy, 66, pp. 47-61.
WhenInAruba, 2020, Aruba proudly introduces 16 official protected nature reserves, retrieved from www.wheninaruba.org on January 2024.

Wageningen Environmental Research
P.O. Box 47
6700 AA Wageningen
The Netherlands
T 0317 48 07 00
wur.eu/environmental-research

Report 3389
ISSN 1566-7197

The mission of Wageningen University & Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR's Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.

To explore the potential of nature to improve the quality of life

Wageningen Environmental Research
P.O. Box 47
6700 AB Wageningen
The Netherlands
T +31 (0) 317 48 07 00
wur.eu/environmental-research

Report 3389
ISSN 1566-7197

The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.