Extent and health of mangroves in Lac Bay Bonaire using satellite data

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Summary

Remote sensing is an important tool for monitoring the environment. In this report we investigate the use of satellite images from two different satellites for monitoring the extent and health of the mangrove forests in Lac Bay, Bonaire. The different satellite bands were used to produce the Normalized Differential Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), the Atmospherically Resistant Vegetation Index (ARVI), and the Red Edge index. The above indices, the results from a Principal Components Analysis (PCA), an unsupervised, and supervised classification were used to classify extent and health of the mangroves.

The image from the RapidEye satellite with a spatial resolution of 5 meters in multispectral bands, covering the whole island produced vegetation indexes that generally were able to distinguish broader classes such as mangroves, water, and land. The high resolution image from the WorldView-2 satellite covering only Lac Bay with a spatial resolution of 2 meters in multispectral and 0,5 meters in panchromatic was able to distinguish between different species of mangrove and also appeared to be able to detect differences in health of the different species. Both satellite images can be used to estimate the extent of the mangroves, but only WorldView2 has a resolution that enables the detection of unhealthy (i.e. lower values for certain indices mostly related to chlorophyll content) areas with sufficient confidence. Apart from the technical characteristics, the RapidEye image is cheaper and covers the whole island of Bonaire, providing a full synoptic view.

We conclude that:

1. Satellite images are a well suitable for monitoring areal extent, species composition, and health of mangrove areas in Lac Bay, Bonaire.
2. RapidEye satellite images are usable for broad classification, whereas Worldview2 gives better resolution to also include species differences and health assessments.

1 Introduction

Any sensor deployed from a ship (acoustic), aircraft (imaging spectrometers, laser) or satellite (microwave, multispectral, hyperspectral) can be considered remote sensing. In this report we investigate the use of satellite observations for monitoring the extension and health of mangrove forests of Lac Bay Bonaire. Remote sensing is an important tool for monitoring the environment. Advantages of using remote sensing techniques are low costs of data acquisition and repeated coverage of difficult to access areas. The satellite records reflectance of man-made and natural features in different wavelengths. The information is presented in multi-spectral images and stored in the different bands. Monitoring of mangrove forests by remote sensing is based on the detection of biomass and chlorophyll, structural appearance and extent of spatial coverage. The level of detail which can be seen on the satellite image depends on the resolution of the image. The information in the satellite images is retrieved using image processing methods combined with ground-truthing data, information from maps, results of statistical analysis and similar studies.

Satellites are being used to monitor many different aspects of the environment. An incomplete list is given below:

- Habitat extension and land use
- Vegetation cover and health
- Land cover
- Sea surface temperature
- Bathymetry
- Photosynthetically active radiation
- Light attenuation coefficients
- Cloud cover
- Chlorophyll a concentration
- Algal blooms
- Suspended sediment concentrations

Monitoring of the mangrove forests using satellite data have been used in Indonesia, Malaysia and some areas on the African continent by optical (multi-spectral) Landsat TM (30 meters), ASTER (15 meters) and radar SAR (Synthetic Aperture Radar) of 15 and 20 meters (Howari et al. 2009, Kuenzer et al. 2011). Remote sensing has limitations in terms of data availability (not all areas can be regularly imaged), availability of cloud free coverage, and variability related to growth season. However, as vegetation shows less variation in the tropics (e.g. no shedding of leaves) the main limitations will be the availability of data and cloud free images.

In our study WorldView-2 and RapidEye satellite data were used because of their high resolution and almost cloud free coverage.

1.1 Lac Bay mangroves

Bonaire is an island that forms part of the so-called ‘Caribbean dry region’ (Sarmiento 1976) situated between the Araya Peninsula in Venezuela (64° W long., 11° N lat.) and Cartagena in Colombia (75° W long., 10.5 N lat.). This region is characterized by the presence of semi-arid areas with rainfall below 800mm/y and arid areas with rainfall below 500mm/y. With its 30y average of 463mm/y (1971-2000; Meteorological Service of Curaçao, pers. Comm). Bonaire belongs to the latter category. Rainfall on the island is seasonal, with the last three months of the year accounting for 51% of the long-term annual average.

The Lac Bay mangroves are located in the largest lagoon of Bonaire, in the lower southern part of the island (Figure 1). The area has been declared a protected Ramsar site.

Figure 1. Location and satellite image of Bonaire and location of Lac Bay (yellow circle).

Lac Bay is a large lagoon in the south-eastern part of Bonaire (Fig. 1). The northern part of the bay is covered by mangroves and the southern part is an open lagoon that is protected from incoming waves by a coral reef barrier (Fig. 5). In the northern part of the bay the mangroves are mainly dry and dead (Fig. 2). The mangrove area of Lac bay covers approximately 700 ha and includes four mangrove species. The Lac mangrove community is dominated by red (*Rhizophora mangle*) and black mangrove (*Avicennia germinans*, Fig. 3) with a clear zoning in distribution.

Figure 2. Northern part of Lac with dead mangroves in the background.

Another species, buttonwood (*Conocarpus sp.*), is growing in relatively dry areas outside of the small lakes and wet muds often next to the red mangrove on the sides of the lakes and sea, and in more inland areas with black mangrove, and mixtures of *Avicennia* and white mangrove (*Laguncularia sp.*) in high saline and muddy soils.

Figure 3. Black mangrove (left) and Red mangrove (right)(© Tranquilometro's photostream; Reid Moran)

The south-western part of Lac is extensively used for recreation such as windsurfing, canoeing, swimming, sunbathing with a resort and several restaurants. The overgrazing by roaming livestock and human activities increase the rate with which sediment (runoff) is filling up Lac in the northern part of the bay, where mangroves are dying.

The lagoon area is quite shallow, with depths down to 3 meters and an 8m deep and narrow exit in the north to the open sea. The lagoon contains sea grasses (*Thalassia testudinum, Syringodium filiforme, Diplanthera wrightii, Ruppia maritime*) and macro-algae (e.g. *Halimeda Opuntia, Avrainvillea nigricans, Acetabularia crenulata, Batophora oerstedi*).

1.2 WorldView-2 Satellite

WorldView-2 is the first commercial high-resolution satellite from the Digital Globe company (U.S.A) to provide 8 spectral sensors in the visible to near-infrared range (Fig. 4, Digital Globe 2010). Each sensor is narrowly focused on a particular spectrum of the electromagnetic range that is sensitive to a selected feature on the ground, or a property of the atmosphere. Together they are designed to improve the segmentation and classification of land and aquatic features beyond most other space-based remote sensing platforms. The high spatial resolution of WorldView-2 enables the discrimination of fine details, like vehicles, shallow reefs and even individual trees in an orchard, and the high spectral resolution provides detailed information on diverse areas such as the quality of the road surfaces, the depth of the ocean, and the health of plants.

The two red and two infra-red channels of WorldView-2 are useful for detecting biomass and chlorophyll content in vegetation. The additional infra-red edge channel is less disturbed by atmospheric effects from aerosols and moisture evaporation, which is high in humid tropical regions. The additional coastal band can detect more details in water, in particular the water features (corals, seagrass, etc.) in shallow depths in addition to the blue band. The distinct advantage of the WorldView-2 data is 50 cm panchromatic channel, which can improve the resolution of the multi-spectral bands of lower resolution and capture more details. A description of channels and detectible features is given in table 1.

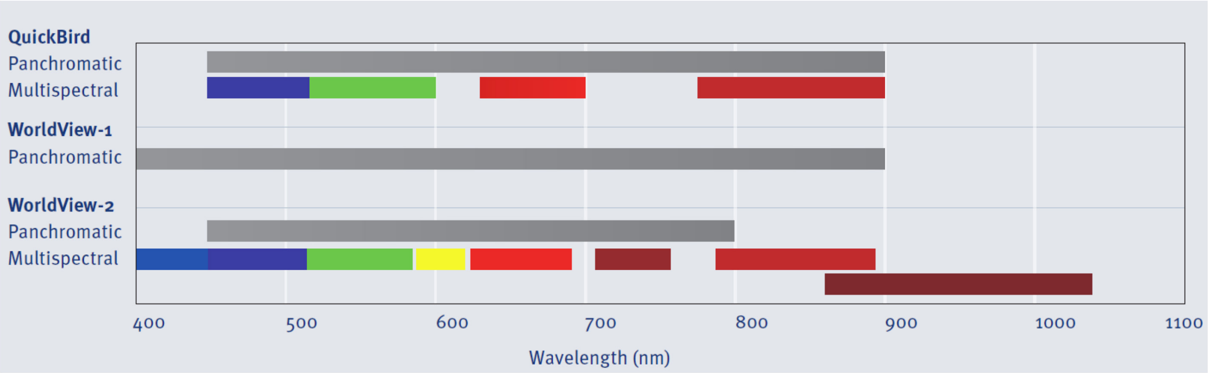


Figure 4. Comparison of WorldView-2 satellite with other satellites.

Each spectral band has certain characteristics that make it useful for certain applications (Table 1). The WorldView-2 satellite has 4 additional spectral bands that increases its capabilities.

Table 1. Characteristics of the 8 spectral bands of WorldView-2. New bands are underlined.

<u>Coastal Blue</u> (400-450 nm) • Absorbed by chlorophyll in healthy plants and aids in conducting vegetative analysis • Least absorbed by water, and will be useful in bathymetric studies • Substantially influenced by atmospheric scattering and has the potential to improve atmospheric correction techniques
Blue (450-510 nm) • Readily absorbed by chlorophyll in plants • Provides good penetration of water • Less affected by atmospheric scattering and absorption compared to the Coastal Blue band
Green (510-580 nm) • Able to focus more precisely on the peak reflectance of healthy vegetation • Ideal for calculating plant vigor • Very helpful in discriminating between types of plant material when used in conjunction with the Yellow band
<u>Yellow</u> (585-625 nm) • Very important for feature classification • Detects the "yellowness" of particular vegetation, both on land and in the water
Red (630-690 nm) • Better focused on the absorption of red light by chlorophyll in healthy plant materials • One of the most important bands for vegetation discrimination • Very useful in classifying bare soils, roads, and geological features
<u>Red-Edge</u> (705-745 nm) • Centred strategically at the onset of the high reflectivity portion of vegetation response • Very valuable in measuring plant health and aiding in the classification of vegetation
NIR1(770-895 nm) • Very effective for the estimation of moisture content and plant biomass • Effectively separates water bodies from vegetation, identifies types of vegetation and also discriminates between soil types
<u>NIR2</u> (860-1040 nm) • Overlaps the NIR1 band but is less affected by atmospheric influence • Enables broader vegetation analysis and biomass studies

The original WorldView-2 image is shown below.

Figure 5. The original WorldView-2 image of the Lac Bay Bonaire (true colours composite).

1.3 RapidEye Satellite

RapidEye is a European satellite (RapidEye company, Germany), with a resolution of 5 meters in the blue, green, two red and infra-red bands. The two red bands can detect vegetation biomass and chlorophyll content (Fig. 6). Compared with WorldView-2, RapidEye has a lower resolution, but because the obtained image covers the whole of Bonaire and was much cheaper we decided to test whether it could fulfil the requirements to measure extent and health of the mangroves of Lac Bay. The two sets of satellite data enabled the comparison of the final results and finding the most cost-effective way for mangrove monitoring.

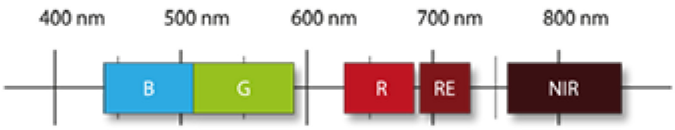


Figure 6. Spectral bands of the RapidEye satellite.

The advantage of the RapidEye satellite compared to many other satellites is the additional red-edge band. Compared with WorldView-2, both red bands of these satellites cover almost the same spectrum. The satellite data are already corrected for terrain distortions. It is possible to perform additional terrain corrections (e.g. in mountainous areas), but in the case of Lac Bay, such additional corrections are not necessary, because Lac Bay is almost at sea level surrounded by relatively flat terrain with maximum heights of approximately 1.5 meters above sea level.

Figure 7. The original RapidEye image of the Lac Bay Bonaire (true colours composite).

1.4 Vegetation Indexes

The basis of vegetation indexes (VIs) is the measurement of the amount of sun light reflected by leafs. Leaf reflectance properties, controlled by properties of pigments, water, and carbon, play a significant role in reflectance at the canopy level. Healthy vegetation strongly absorbs the sun light and reflects it back. The reflection of vegetation can be recorded in the red and infra-red wavelengths. The strength of the vegetation reflectance depends on chlorophyll content and structural appearance (e.g. density of the vegetation). Very dense areas appear as very dark with transitions to more light and to very bright for sparsely vegetated areas. The vegetation reflectance can be disturbed by soil background of the vegetation and, in areas of dry land, this will reduce the reflectance of the sparse vegetation. Huete and Jackson (1988) found that soil type has the greatest effect on vegetation index values between 40% and 75% of the vegetative cover. The final accuracy of the derived vegetation indexes depends on the resolution of the satellite images.

Vegetation indexes provide information on vegetation characteristics by calculating ratios from combinations of red, infra-red and blue channels. The results of such ratios will for example show index

values that are related to chlorophyll content, starting from minimum of 0.1 to a maximum of 1. Negative values indicate no vegetation.
Reflection from vegetation can also be disturbed by effects from the atmosphere, such as haze, originating from water evaporation. Another disturbance of vegetation reflectance is the problem of the mixed pixels: in satellite images with low resolution, small areas of for example forest will be mixed with neighbouring pixels of land, urban areas, etc. All VIs require high-quality reflectance data of vegetation as input. Therefore, the satellite data need to be corrected first for atmospheric disturbances and other effects to guarantee correct interpretation.

A description of common used vegetation indexes is given in Table 2 below.

Table 2. Vegetation indexes used in this study

Index	**Purpose**
Normalized Difference Vegetation Index (NDVI)	To detect chlorophyll a, biomass, plant health. Ratio of red and infra-red bands, showing amount of biomass, depending on health of the vegetation.
The Enhanced Vegetation Index (EVI)	Like NDVI, but corrects for soil background (dry, wet soil) and reduces atmospheric influences (moisture, evaporation, and aerosols).
The Atmospherically Resistant Vegetation Index (ARVI)	Like EVI, but very useful in tropical regions, since it is resistant to atmospheric effects (high humidity, moisture)
Vegetation delineation tool (VD)	Detects the structural appearance of vegetation and groups into classes of No Vegetation, Sparse Vegetation, Moderate Vegetation and Dense Vegetation
Red Edge index	Very sensitive to differences in health. It is the ratio between red and red-edge extended red channel, showing the differences in chlorophyll and biomass between two channels. Very sensitive to changes over the chlorophyll content and biomass.

2 Assignment

Conservation and protection of the biodiversity of the Dutch Caribbean is part of the responsibility of the Ministry of Economic Affairs, Agriculture and Innovation. The Lac Bay area is declared as RAMSAR site and used by many birds and other species for nesting, breeding and foraging and therefore the health of the mangrove ecosystem is very important to preserve the biodiversity of the region. The main question to be answered in this study, and which was formulated by the Ministry, concerns the use of Remote sensing data and methods to detect the extent and health of the mangroves. For this purpose one image from RapidEye and one from WorldView-2 were purchased, and selected image processing techniques for vegetation indexing and classification were used to analyse whether satellites can be used for monitoring the extent and health of mangrove areas, and which techniques are most promising.

3 Materials and Methods

3.1 Satellite data

The RapidEye image was acquired on 09 March 2011, with some cloud cover (about 10-15%) in the northern part. The image has 5 multi-spectral bands with 5 meters resolution (resampled from original 6.5m). The 3 data tiles were merged to cover the entire Bonaire Island with a total area of 1,000 km^2. The Worldview-2 data was acquired on 28 October 2010 and has some cloud patches in the northern part of the bay. The data format is a standard archive image, containing an 8 band multispectral image with 2 meters resolution resampled from original 1.8m resolution and a 50cm panchromatic image, covering the 25 km^2 of Lac Bay. A summary of the characteristics of each image is given in the table below (Table 3).

Table 3. Satellite image specifications.

Data	Bands		Resolution	Corrections	Costs per image
RapidEye level 3A	Blue: Green: Red: Red Edge: Near-IR:	440-510 nm 520-590 nm 630-685 nm 690-730 nm 760-850 nm	5 m	Geometric, projected to UTM/WGS84; resampled to 5 m	800 US$ (whole island)
WorldView-2	Panchromatic: Coastal: Blue: Green: Yellow: Red: Red Edge: Near-IR1: Near-IR2:	450-800 nm 400-450 nm 450-510 nm 510-580 nm 585-625 nm 630-690 nm 705-745 nm 770-895 nm 860-1040 nm	0.50 m 2 m	Geometric, projected to UTM/WGS84; resampled to 2m from 1.8m	850€ (only Lac Bay Area)

The images were pre-processed using geometric and radiometric (sensor) corrections at the reseller of WorldView-2 and RapidEye data, Geoserve BV, Marknesse, the Netherlands. Further pre-processing steps included atmospheric correction using the ENVI spectral tool. The atmospheric correction is important in removing the atmospheric effects during data acquisition and it is especially important in tropical coastal areas which are strongly influenced by high moisture content and humidity of the tropical climate. The spectral radiance was corrected for the effect of the atmosphere to retrieve true values of the surface reflectance. The next procedure was to subtract the dark pixels from each band, to remove the effect of the reflectance of the water.

3.2 Auxiliary data

The landscape-ecological map (1:50.000) showing the vegetation classes in accordance with the landscape types are used as additional reference during the classification (Appendix 2). However, because of the map scale, the mangrove areas were represented in a very general manner, without distinction of mangrove classes.

3.3 Ground-truthing data

The ground data is collected as GPS points during June-July 2011 field campaign. The locations of different mangrove areas with a short description and detailed video of 5-10 min, showing a panoramic view of the each point, were recorded. All points were used as input in image classification and verification of the final results. The additional field campaign in September 2011 provided extra ground-truthing points and verification of earlier points.

3.4 Methodology

An overview of the processing steps of the images is detailed below and in Figure 8. The method includes three main steps: pre-processing, data processing, and classification. During pre-processing radiometric and atmospheric corrections for WorldView-2 and RapidEye data are applied. In the next step, data processing, the different vegetation indexes are calculated and spectral analysis is performed. In the last step, reflectance values of ground-truthed mangrove areas, information from vegetation indexes together with information on vegetation density are combined and used as additional input in mangrove classification. In this step the atmospherically corrected images of the WorldView-2 and RapidEye are classified in vegetation indexes and to classes of red and black mangroves. Neighbouring areas are assigned to separate classes of surrounding Lac Bay areas of dry land with some bushed vegetation, area of lagoon and open sea.

Finally, the information from classification and vegetation indexes is analysed to determine the mangroves health in terms of healthy (relatively high biomass), less healthy (low biomass) and not healthy (very low and or almost no biomass). The biomass values derived from vegetation indexes and additional information from vegetation density used to quantify health of the mangroves. The assumptions on the mangrove health are described in a separate chapter.

For the assignment of the class names (classification legend) for the mangroves the international Global Land Cover classification from the Food and Agriculture Organization (FAO) of the United Nations was used. The reason for selecting classification for mangroves of Lac Bay is to adopt the harmonization approach of the Global Land Cover, so that assigned classes for mangroves of the Lac Bay can be understood, interpreted and compared with other mangrove areas on the globe.

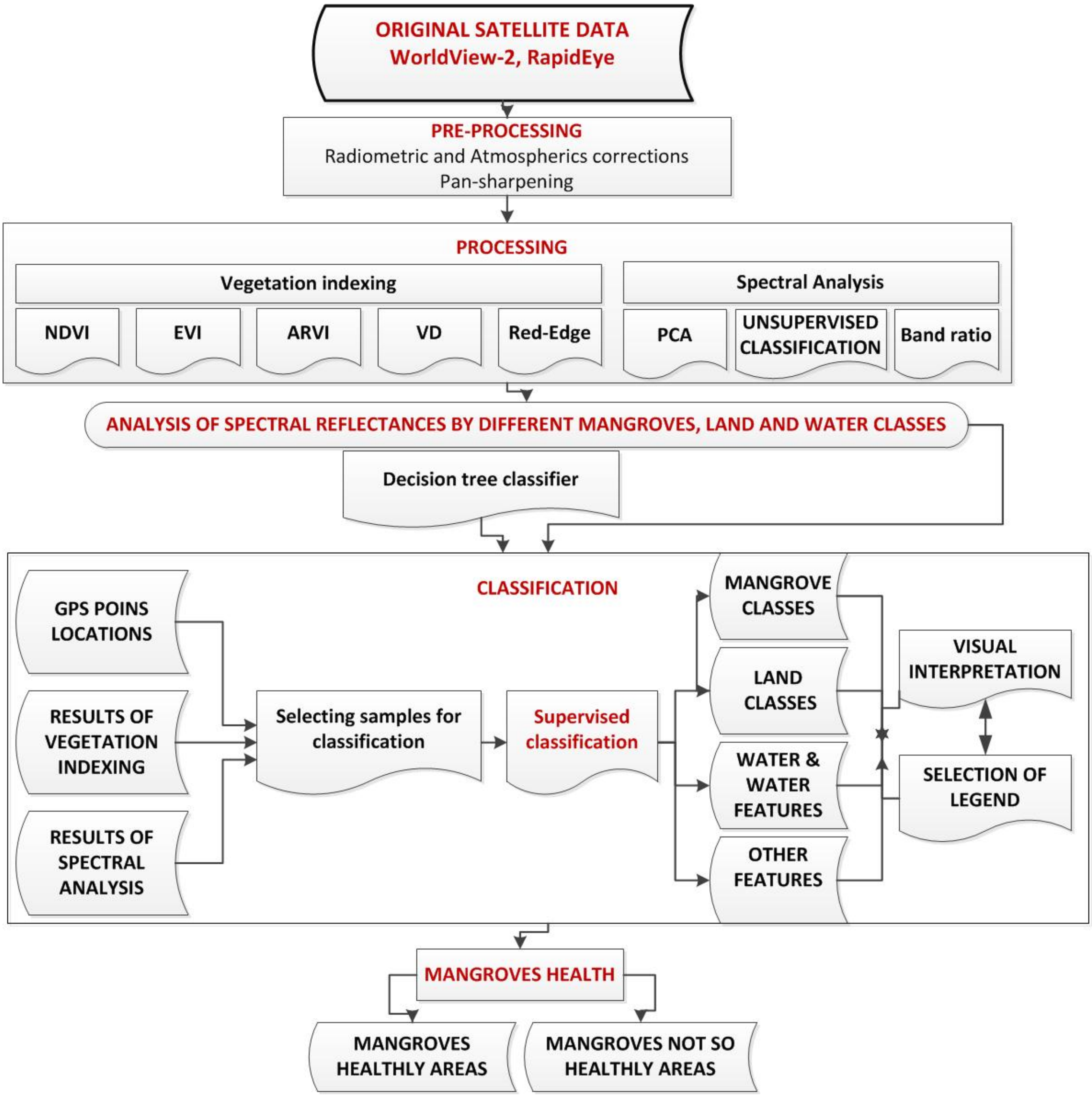


Figure 8. Processing steps for satellite data followed for this report.

3.5 Pre-processing

3.5.1 Atmospheric correction

3.5.1.1 Conversion to Top-of-Atmosphere (ToA) Spectral Reflectance

This conversion followed the methods described in the Technical note of Worldview-2 imagery (Updike and Comp, 2010), using the radiometrically (see Radiometric resolution in Glossary) corrected image pixels. Radiometrically corrected image pixels are converted to spectral radiance. The required parameters, absolute radiometric calibration factor and effective bandwidth, were taken from the metadata file. Next, Band-Integrated Radiance was defined for each band, using the corresponding effective bandwidth values. Solar Geometry, such as Earth-Sun Distance and solar zenith angle were estimated. The final equation solving the surface reflectance results for each band is:

$$L'_{\lambda_{\text{Pixel,Band}}} = \frac{L_{\lambda_{\text{Pixel,Band}}} \cdot d_{ES}^{2}}{\cos(\theta_S)}$$

Where- $L'_{\lambda\text{Pixel,Band}}$ are top-of-atmosphere band-averaged spectral radiance image pixels; d_{ES}^2, the Sun-Earth distance computed for the image acquisition date and cos (θ_s) is the solar zenith angle [degrees] during the image acquisition. The solar geometry is independent of wavelength, so the same geometry factors are applied to each band. The corrected image will present the best "possible" reflectance with least disturbance from the atmosphere.

Atmospheric correction for the RapidEye image was slightly different. The equation used for solving the atmospheric correction for the RapidEye image is:

$$REF(i) = RAD(i)\frac{\pi * SunDist}{EAI(i) * \cos(SolarZenith)}$$

With i, the number of the spectral band; REF, the reflectance value (values without atmospheric disturbance); RAD, the radiance value (radiance value of the original image); SunDist, the Earth-Sun Distance at the day of the image acquisition in Astronomical Units.

The next procedure was to subtract the dark pixels from each band, to remove the effect of the reflectance of the dark pixels in the image, such as dark pixels from the shadows of clouds and water objects (sea, deep river).

3.5.1.2 Pan-sharpening

To improve the visual interpretation of the images pan- sharpening was used next. Pan-sharpening is the process of merging the low resolution bands with a higher resolution band. The pan-sharpening technique was applied to both the WorldView-2 and the RapidEye images. The WorldView-2 multi-spectral channels of 2 meters were merged with panchromatic 0.5 meter (black and white) channel, using the Gram-Schmidt method, within the ENVI program image sharpening tool. The fusion process was done by dividing each pixel and overlaying the result with the pixel containing more details. The new pan-sharpened image of WorldView-2 has a new resolution of 1.5 meters and for the RapidEye image of 2 meters (Fig. 9).

Figure 9. Uncorrected image on the left and atmospherically corrected and pan sharpened image on the right (RapidEye image)

The result presents a significant improvement of spatial resolution of the RapidEye image, producing more details (as can be seen on the right part of Figure 9) for the delineation of objects and much improving the visibility of objects. The images were later used in the visual interpretation when checking whether areas with dense and high biomass appear similar in all mangrove areas and in assessing the relationship between the density of the mangroves and the amount of biomass. A subset for the Lac Bay mangrove area from the RapidEye image was made, matching the same size as WorldView-2 image.

3.6 Processing

3.6.1 Vegetation indices

A healthy green leaf will have low reflectance in the red range of the electromagnetic spectrum because of the strong absorption of the sun light and high reflectance in the infra-red range. In order to assess the differences in spectral reflectance of the mangrove forest and to determine the amount of biomass in different areas of Lac Bay, several vegetation indices were calculated and compared.

3.6.1.1 Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is one of the oldest, most well-known, and most frequently used vegetation indexes (Rouse et al. 1973, Sellers 1985). The main advantage of NDVI index is retrieval of information on chlorophyll and vegetation biomass using near-infrared and red bands. The index is defined as bands ratio and retrieves information on chlorophyll from near-infrared and biomass from red band.

NDVI is defined by the following equation:

$$\mathrm{NDVI} = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$$

Values for the NDVI are between -1 and 1, presenting high biomass ranging from 0.7 to 1 and low or almost no biomass starting from 0.3 to 0 The -1 value indicating no biomass.

3.6.1.2 The Enhanced Vegetation Index (EVI)

The Enhanced Vegetation Index (EVI) was developed to improve the NDVI by optimizing the vegetation reflectance , enhancing the NDVI index by adding vegetation reflectance from the blue band, correcting for soil background. The Enhanced index is useful in not so dense and sparse vegetated areas and also in detecting biomass for tree species with small leafs. The index is defined as a band ratio in near-infrared, red and blue bands, and pre-defined coefficient of 2.5, to compensate for extra low values. The following equation applies to EVI index:

$$\mathrm{EVI} = 2.5\left(\frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + 6\rho_{RED} - 7.5\rho_{BLUE} + 1}\right)$$

The value of this index ranges from -1 to 1. The common range for vegetation biomass is 0.2 to 0.8, for high biomass from 0.6 to 1, and very low biomass from 0.3 to 0. The -1 value indicates that there is no biomass.

3.6.1.3 The Atmospherically Resistant Vegetation Index (ARVI)

The Atmospherically Resistant Vegetation Index (ARVI) is an enhancement of the NDVI index, providing additional correction from atmospheric effects. In this case the subtraction of values from red band using the values from the blue band with additional subtraction from the near-infrared band will enhance the information on vegetation biomass which might be disturbed by atmospheric effects.
ARVI is defined by the following equation:

$$\mathrm{ARVI} = \frac{\rho_{NIR} - (2\rho_{RED} - \rho_{BLUE})}{\rho_{NIR} + (2\rho_{RED} - \rho_{BLUE})}$$

The value of this index ranges from -1 to 1. The common range for vegetation biomass is 0.2 to 0.8, with high biomass from 0.6 to 1, very low or no biomass from 0.3 to 0. The -1 value indicates no biomass.

3.6.1.4 Vegetation delineation tool (VD)

This index is based on result from NDVI index and basically it groups the biomass values into following classes:

- No Vegetation (very low or no biomass) (-1<NDVI<0.249);
- Sparse Vegetation (low biomass) (0.2<NDVI<0.3);
- Moderate Vegetation (between low and high biomass) (0.3<NDVI<0.6);
- Dense Vegetation (high and very high biomass) (0.6<NDVI<0.8).

3.6.1.5 Red-Edge Index

While the traditional Normalized Difference Vegetation Index (NDVI of measuring vegetation biomass can provide sufficient information, the Red-Edge index can enhance information about biomass, since it is uses the ratio of red and red-edge bands. In our case, the both images of RapidEye and WorldView-2 have additional red-edge bands, providing extended range of spectrum to record. Scientists have been evaluating the Red-Edge region of the spectrum (between 680 nm and 750 nm), which is the transition region between the minimum and maximum reflectance. Researchers have shown that a RED to Red-

Edge comparison is more sensitive to subtle changes in plant health than NDVI. Several Red-Edge indices are possible. Here we use:

$$REI = \frac{\rho_{Red} + \rho_{RedEdge}}{\rho_{Red} - \rho_{RedEdge}}$$

For the WorldView-2 data the red band is the band of 630-690 nm and the Red Edge band is from 705-745 nm. For the RapidEye image these values are 630-685 nm 690-730 nm respectively.
Using the ratio of red and red-edge bands is beneficial in terms of providing better distinction and details on vegetation biomass compared to the NDVI index.

3.7 Spectral analysis

The spectral analysis is necessary in order to determine the separability of the spectral reflectance of the features in the satellite image, including the different mangrove species. The most commonly used tools are Principal Components Analysis (PCA), Unsupervised Classification, and Band Rationing. Spectral reflectance is a dimensionless ratio of sun light energy absorbed and reflected back by mangrove crown, land and water features. Every object has its distinct spectral reflectance, called spectral signature. Due to peculiarities of the area and the spatial resolution of the image, spectral signatures can mix, especially in areas with high variations and combinations of water, land, swamps and mangroves in a relatively small area. One of the tools used in the analysis of spectral reflectance of different features is Decision Tree classification.

3.7.1 Principal Component Analysis (PCA)

PCA is used to produce uncorrelated output bands, to segregate noise components, and to reduce the dimensionality of data sets. Because multispectral data bands are often highly correlated, PCA is used to produce uncorrelated output bands. This is done by finding a new set of orthogonal axes (linear combinations of the original spectral bands) that have their origin at the data mean and that are rotated so the data variance is maximized. The first PC band contains the largest percentage of data variance and the second PC band contains the second largest data variance, and so on. The last PC bands appear noisy because they contain very little variance, much of which is due to noise in the original spectral data. Principal Component bands produce more colourful colour composite images than spectral colour composites and can be used for classification, to check the spectral separability of all features, and to get a first impression about the possible number of classes that can be detected.

3.7.2 Unsupervised classification

Unsupervised classification was used to distinguish land cover, vegetation and mangrove classes, and water features. It is an automated process requiring minimal input from the user but the number of classes must be defined a priori by the user. Based on PCA we decided to start with 30 different classes, specifically because of high variation in type and structural appearance within the mangrove groups, and other natural features inside the mangrove areas, such as water, dry land, etc. The final result was visually interpreted, using ground-truthed data, vegetation indices and PCA image analysis. Similar classes that could not be separated by available data or expert knowledge were grouped together. The ISODATA algorithm was used for the classification.

3.7.3 Decision Tree classification

Decision tree classification is a type of multi-step classifier that can be applied to a single image or a stack of images. It is made up of a series of decisions that are used to determine the category for each pixel. The decision tree uses as input several images, with predefined rules. The rules are defined for each image in order to extract the features from each image. In our case, the decision tree classifier was used to test its applicability for classifying heavy mixed and small areas of mangrove of Lac Bay. Several vegetation indexes, together with the PCA image and results from the unsupervised classification were used as input.

3.8 Final Classification

Classification methods are necessary to group pixels with similar characteristics into groups that can then on the basis of ground-truthing data be assigned to, for example, vegetation classes.

3.8.1 Supervised Classification

The final mangrove classification map was derived using supervised maximum likelihood classification (ENVI version 4.9 trial software from ITT solution, the Netherlands). The initial object classes were determined using previously collected GPS points, indicating red and black mangroves, and other herb vegetation groups, and expert knowledge of the area. As input for this classification technique, we used a combination of the vegetation indexes, the results from the Principal Component Analysis, the unsupervised (automated) classification, and the decision tree analysis.

3.8.2 Mangroves Health

In our study mangrove health was assessed using information from the supervised classification showing the location and extent of the mangrove species, vegetation indexes (e.g. amount of biomass) and results from the Vegetation delineation VD tool, presenting vegetation density (No vegetation, Sparse, Moderate and Dense)

In practice this meant that healthy mangroves were selected from areas with high biomass. The density of vegetation were used to further subdivide groups of not so healthy and unhealthy mangroves, as values for these two groups were very close. It was assumed that not so healthy mangroves are sparsely dense. Such assumptions were based on ecological peculiarities of the mangroves, which must grow in dense groups for better survival, accumulation of moisture and protection from the sun.

4 Results

4.1 Atmospheric correction

Atmospheric correction improved the visibility of features, providing more details, and enhanced contrast especially for fine details for the WorldView-2 image (Fig. 10). Statistical information of uncorrected and corrected Worldview-2 images is presented below (Table 4 and 5). The standard deviation for uncorrected WorldView-2 image present a high numbers for each band, meaning, that values are spread out over a large interval and the information contains a lot of noise. For the classification it will result in creating high number of mixed classes or wrongly classified pixels, since the spectral signatures in the uncorrected image are not well separated.

Table 4. Summary statistics for each band of the uncorrected WorldView-2 image

Band	Min per band	Max per band	Mean per band	Standard deviation per band
Coastal	0.00	1940	450.30	171.74
Blue (450 - 510 nm)	0.00	1506	281.19	145.26
Green (510 - 580 nm)	0.00	1943	363.64	226.87
Yellow (585 - 625 nm)	0.00	2047	410.34	310.17
Red (630 - 690 nm)	0.00	1950	279.66	245.54
Red Edge (705 - 745 nm)	0.00	20	392.67	316.13
Near-IR1 (770 - 895 nm)	0.00	1979	444.03	373.98
Near-IR2 (860 - 1040 nm)	0.00	1805	375.03	323.71

The low standard deviation table 5 indicates that the values of the bands tend to be very close to the mean and therefore there is less scattering of values within each band, improving the classification results.

Table 5. Summary statistics for each band of the corrected WorldView-2 image

Band	Min per band	Max per band	Mean per band	Standard deviation per band
Coastal (400-450 nm)	0.00	0.77	0.18	0.07
Blue (450 - 510 nm)	0.00	0.89	0.17	0.09
Green (510 - 580 nm)	0.00	0.81	0.15	0.09
Yellow (585 - 625 nm)	0.00	0.65	0.13	0.10
Red (630 - 690 nm)	0.00	0.86	0.12	0.11
Red Edge (705 - 745 nm)	0.00	0.71	0.14	0.11
Near-IR1 (770 - 895 nm)	0.00	0.82	0.18	0.15
Near-IR2 (860 - 1040 nm)	0.00	0.68	0.14	0.12

The effect of atmospheric correction (removal of noise) can be visually seen in improved contrast of the image, easier visual identification of features, and will improve classification, by reducing the number of mixed and wrongly classified pixels.

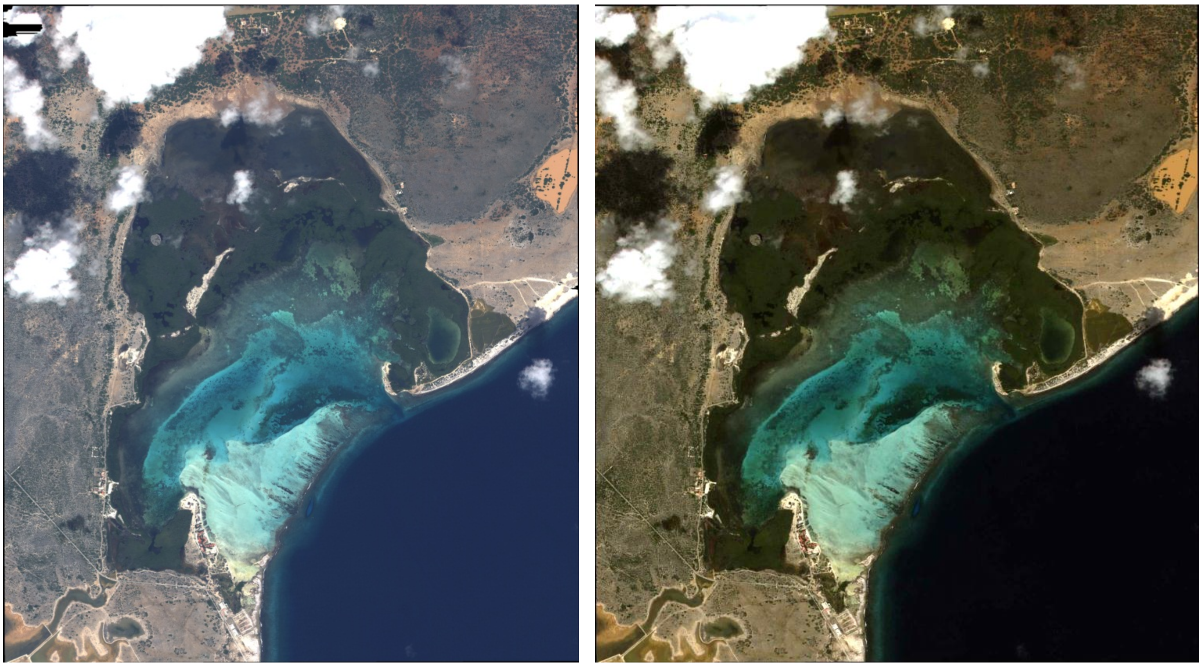


Figure 10. WorldView-2 image: Before (left) and after (right) atmospheric correction and filtering (contrast enhancement).

The atmospheric correction and contrast enhancement removed the haze, improved contract of the image and visibility of features. The same improvements were observed in the RapidEye image (Fig. 11). The image has a lower resolution of 5 meters compared to the WorldView-2 data, but the corrected image produced relatively more details, especially in delineating the lagoon shore zone.

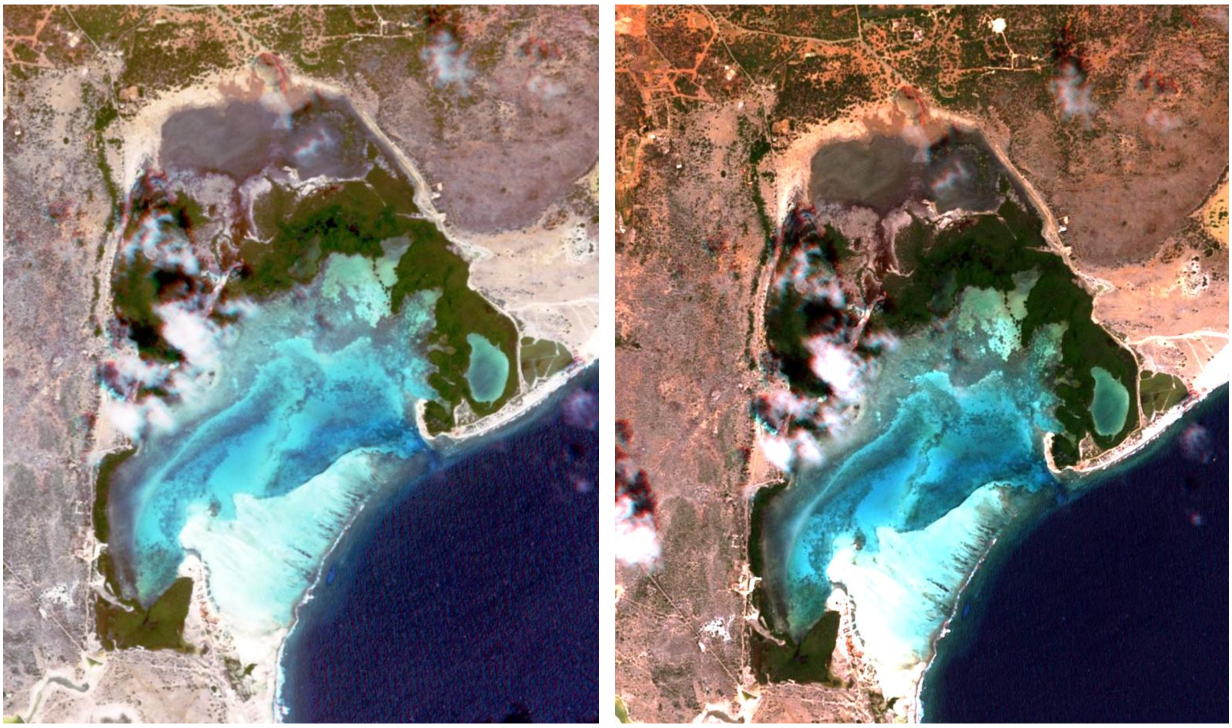


Figure 11. RapidEye image: Uncorrected (original) image on the left and Atmospherically corrected and filtered (contract enhancement) image on the right.

4.2 Vegetation indexes

Values for vegetation indices of known locations (Fig. 12, red dots) were compared. The yellow pushpins were added to identify lagoon, open sea, dry land outside of the Lac Bay, coral area in the lagoon, and locations of known dry (dead) mangroves within Lac Bay.

Figure 12. The location of known GPS points (red) and additional points (yellow pushpins) (© 2011 Google)

The normalized vegetation index (NDVI) for both satellite images is shown in Figure 13. The land areas with high vegetation biomass are very bright and areas with low biomass are dark grey. The transition from high to low biomass are greyish.

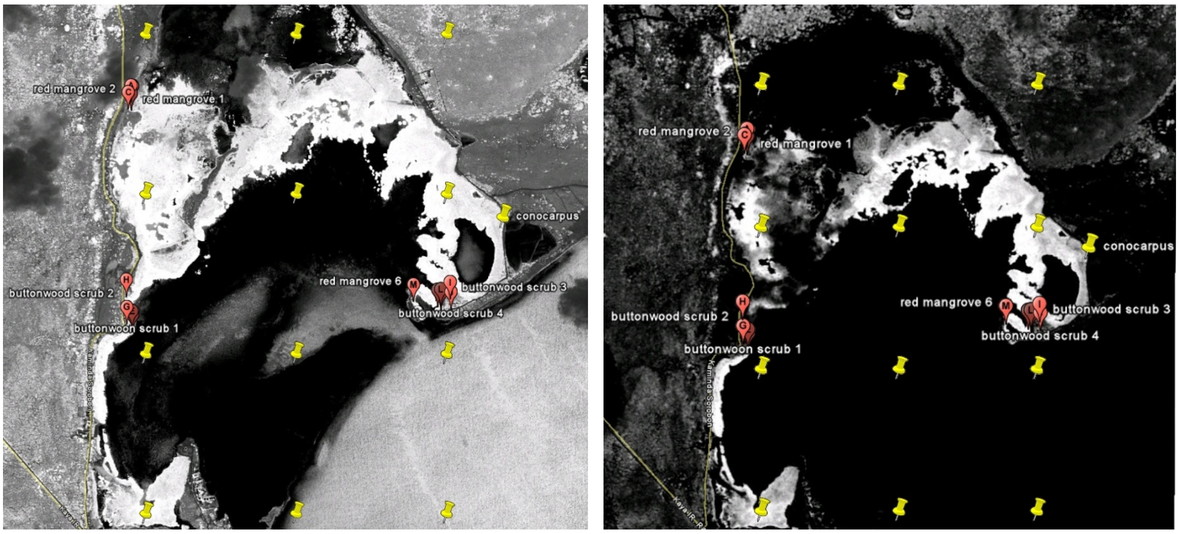


Figure 13. NDVI image WorldView-2 data (left) and NDVI image, RapidEye data (right). Locations that were used to investigate the index values are shown by pin and balloon symbols.

EVI and ARVI index results are shown in Figure 14. Note some more detail in the EVI image in the bright areas of the NDVI image. The ARVI index appears to perform similar as the EVI index, but has more detail in the shallow water areas.

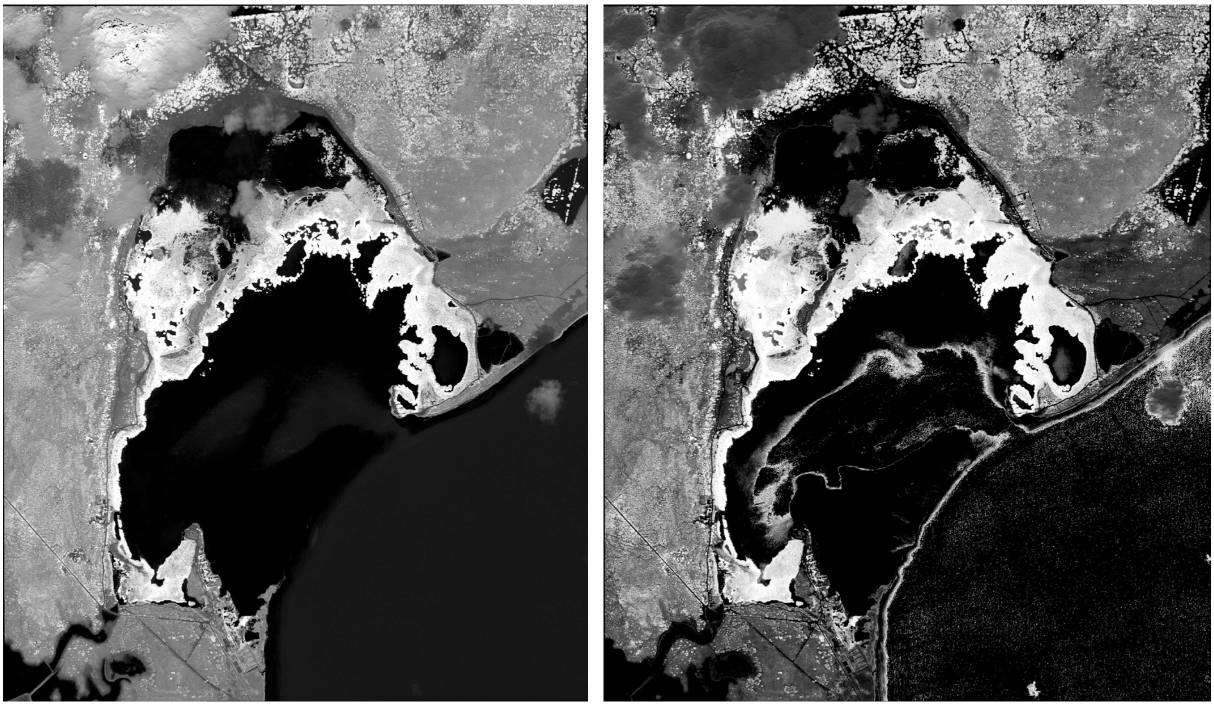


Figure 14. EVI index on left and ARVI on right image for WorldView-2 data.

From the images it is difficult to visually assess how the indices perform and whether they are able to distinguish areas with no vegetation from areas with sparse vegetation. Pixel values for known locations are given in the table below. Locations are shown in Figure 13. Large pictures of vegetation indices are shown in Appendix 4.

Table 6. Vegetation index values for known locations. For geographic coordinates of locations see appendix 3.

Mangrove types & Features	**NDVI**	**EVI**	**ARVI**	**VD**
Red mangrove open 1	0.80	0.79	0.82	Dense Vegetation
Red mangrove open 2	0.89	0.83	0.84	Dense Vegetation
Red mangrove 1	0.87	0.80	0.80	Dense Vegetation
Red mangrove 2	0.42	0.11	0.27	No vegetation
Red mangrove 5	0.65	0.26	0.53	Sparse Vegetation
Red mangrove 6	0.87	0.78	0.81	Dense Vegetation
Red mangrove 7	0.81	0.75	0.73	Sparse Vegetation
Red mangrove 8	0.83	0.83	0.84	Dense Vegetation
Red mangrove 9	0.80	0.80	0.83	Dense Vegetation
Red mangrove 10	0.61	0.61	0.72	Moderate Vegetation
Black mangrove Avicennia 1	0.78	0.78	0.82	Dense Vegetation
Black mangrove Avicennia 2	0.26	0.26	0.40	No vegetation
Black mangrove Avicennia 3	0.73	0.73	0.43	Sparse Vegetation
Black mangrove Avicennia 4	0.73	0.73	0.43	Moderate Vegetation
Black mangrove Avicennia 5	0.68	0.68	0.68	Moderate Vegetation
Black mangrove Avicennia 6	0.90	0.90	0.90	Dense Vegetation
Black mangrove Avicennia 7	0.45	0.45	0.45	Sparse Vegetation
Black mangrove Avicennia 8	0.57	0.57	0.57	Moderate vegetation
Button wooden scrub 1	0.68	0.68	0.75	Moderate Vegetation
Button wooden scrub 2	0.46	0.46	0.54	Sparse Vegetation
Button wooden scrub 3	0.46	0.46	0.54	Sparse Vegetation
Button wooden scrub 4	0.67	0.67	0.79	Moderate Vegetation
Button wooden scrub 5	0.47	0.47	0.60	Moderate Vegetation
Button wooden scrub 7	0.57	0.57	0.67	Moderate Vegetation
Button wooden scrub 8	0.70	0.70	0.69	Moderate Vegetation
Dry land 1	0.22	0.22	0.03	No vegetation
Dry land 2	0.20	0.20	0.01	No vegetation
Dry land 3	0.25	0.25	0.06	No vegetation
Dry land 4	0.26	0.26	0.07	No vegetation
Dry land 5	0.18	0.18	0.02	No vegetation
Dry (dead) mangroves on high water 1	0.01	0.01	-1	No vegetation
Dry (dead) mangroves on high water 2	0.03	0.03	-1	No vegetation
Dry (dead) mangroves on high water 3	0.00	0.00	-1	No vegetation
Dry (dead) mangroves on high water 4	0.02	0.02	-1	No vegetation
Dry (dead) mangroves on high water 5	0.05	0.05	-1	No vegetation
Marine areas (lagoon) 1	-1	-1	-1	No vegetation
Marine areas (lagoon) 2	-1	-1	-1	No vegetation
Swamp (high water content)	0.045	0.013	-1	No vegetation
Urban settlements areas	-1	-1	-1	No vegetation
Roads (linear features	-1	-1	-1	No vegetation
Man-made features (recreation)	-1	-1	-1	No vegetation
Open sea	0.069	0.0064	-1	No vegetation
Corals 1	0.019	0.03	0.02	No vegetation
Corals 2	0.03	0.006	-1	No vegetation
Corals 3	0.01	0.001	-1	No vegetation

The highest biomass values were observed in areas with dense vegetation. The very dark almost black areas in open sea and lagoon are areas with zero NDVI values, bright white areas are areas with high biomass. The areas on grey outside of Lac Bay are areas of dry land.

The vegetation index values show a large amount of overlap between the different mangrove species (Fig. 15), making it difficult to separate species on the basis of these 3 indices.

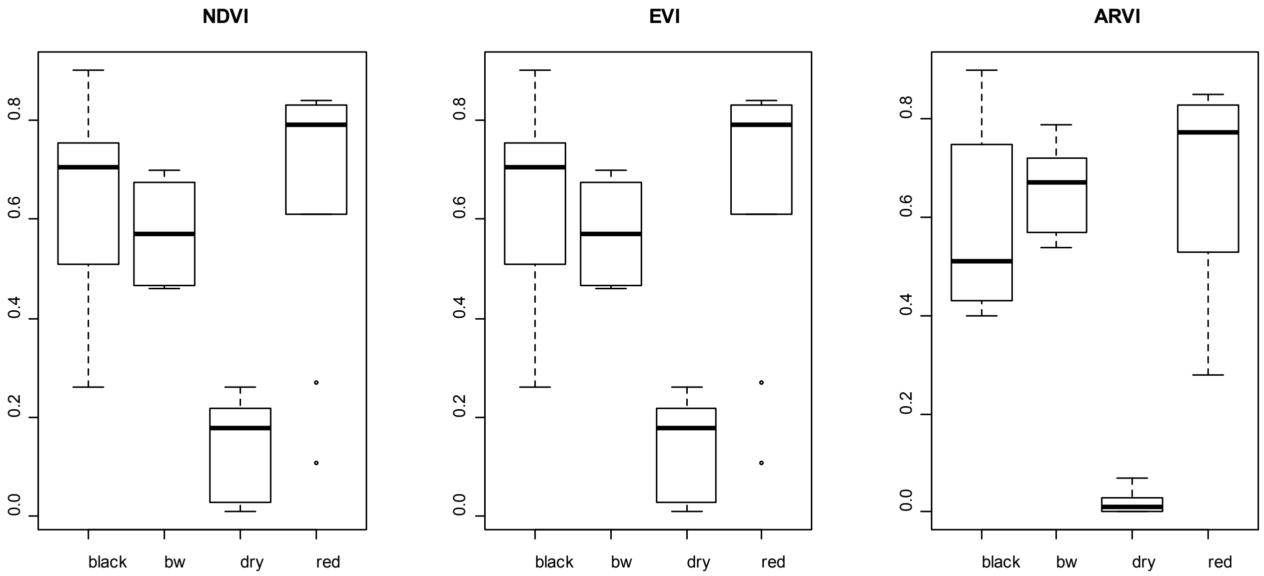


Figure 15. Variation in index values for NDVI, EVI, and ARVI. Values range maximally from 0-1; categories are Black, Red, and white mangrove, and dry land.

The results of Red-Edge and Vegetation delineation tool are shown in Figure 16. The Red-Edge index image appears to give many different grey intensities in the mangrove area, probably related to vegetation health. The Vegetation delineation image (right) showing the very dense areas in blue, with average density in green and very low density areas in red colour. Vegetation close to the fresh water supply and known channels is all very dense which is comparable to the Red Edge image, but the latter shows much more detail in these areas.

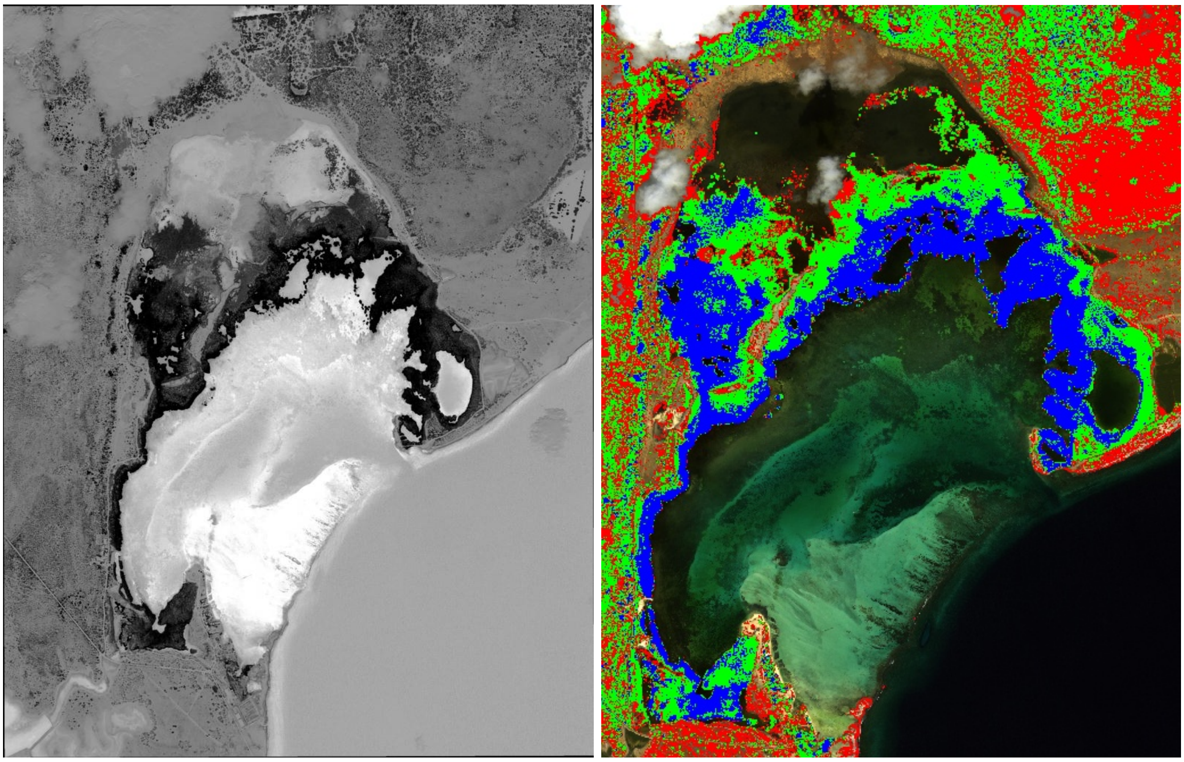


Figure 16. Red-Edge index (left) and Vegetation delineation image (right) for WorldView-2 data. Very dense areas blue, average density in green and very low density areas red.

4.3 Spectral analysis

4.3.1 PCA

Principal Component Analysis indicated that the first three principal components explained 80% of the total variation in the 8 multi-spectral bands. The resulting image using only the first 3 axes (Figure 17) shows a clear spatial distinction: areas with mangroves, water or land all very well-defined, with much detail in the mangrove areas. The WorldView2 image has more detail than the RapidEye image.

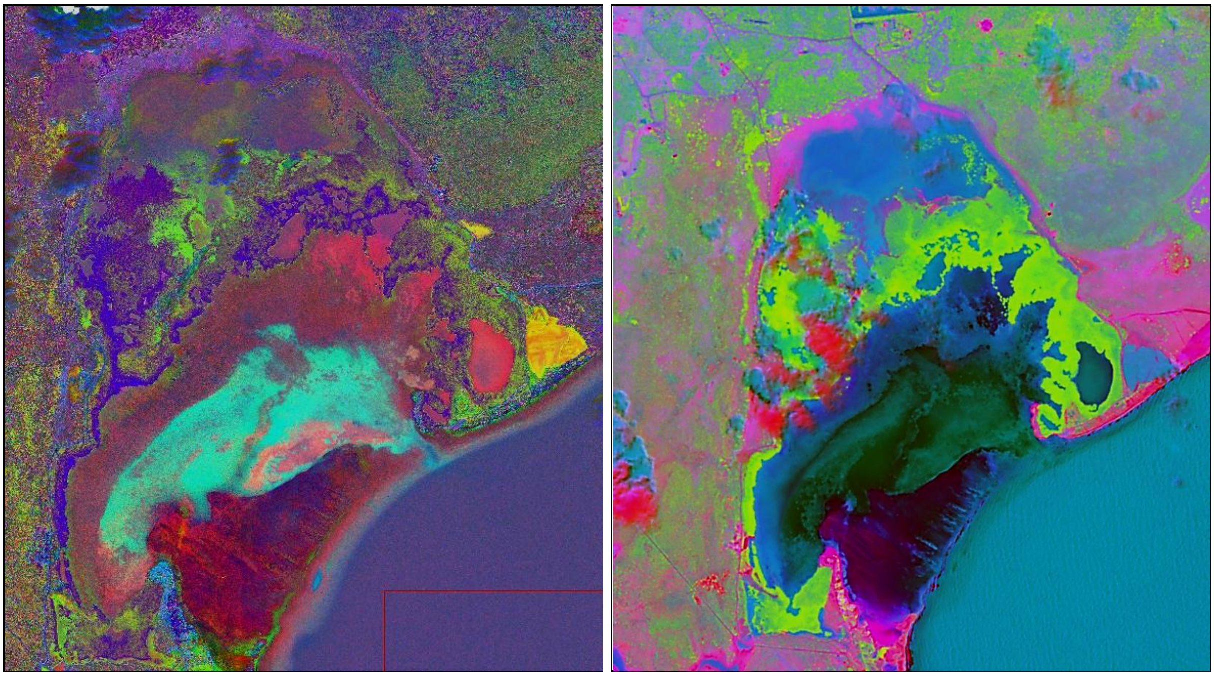


Figure 17. PCA results WorldView-2 data (left) and RapidEye data (right).

4.3.2 Unsupervised classification

The result of the unsupervised classification in the WorldView-2 image is presented in Figure 18 below. We used 30 classes based on PCA and the categories that we expected.

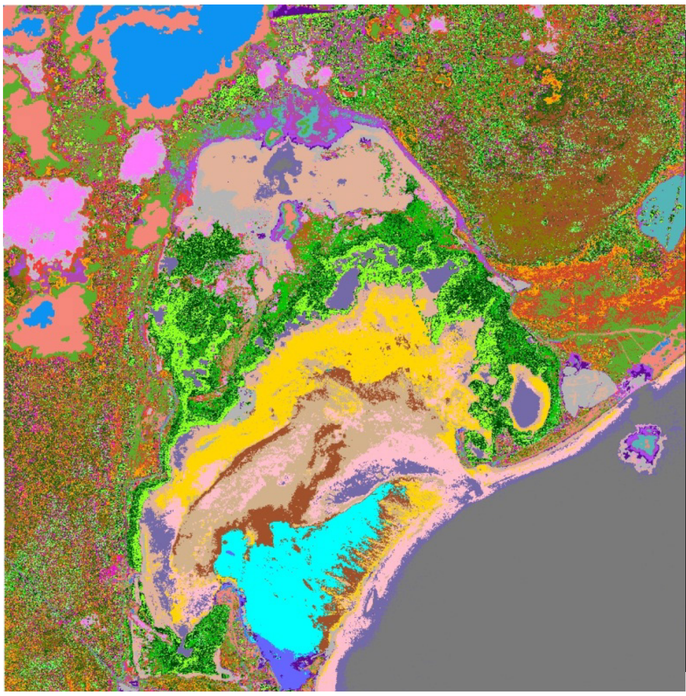


Table 7. Area for each class of Figure 18

Class	Area (ha)	Class	Area (ha)	Class	Area (ha)
Class 1	504.2	Class 11	32.4	Class 21	83.7
Class 2	27.4	Class 12	17.0	Class 22	113.9
Class 3	94.1	Class 13	63.7	Class 23	99.3
Class 4	129.4	Class 14	31.9	Class 24	49.1
Class 5	90.1	Class 15	52.0	Class 25	87.7
Class 6	74.8	Class 16	97.6	Class 26	117.7
Class 7	39.2	Class 17	74.7	Class 27	27.1
Class 8	47.9	Class 18	101.7	Class 28	119.4
Class 9	24.9	Class 19	94.3	Class 29	87.9
Class 10	30.3	Class 20	60.8	Class 30	55.9
Unclass.	12.6688				

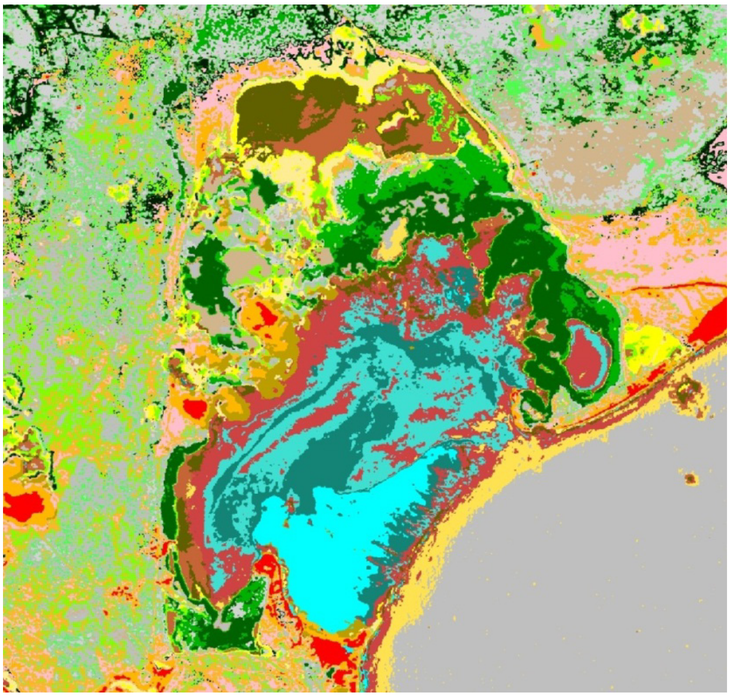
Figure 18. Unsupervised classification WorldView-2 image.

Areas (ha) for each class in the WorldView2 image (Figure 18) are given in Table 7. Areas (ha) for each class of the RapidEye image (*Figure 19*) are given in Table 8. Unsupervised classification gives a fairly good separation of land and water features. The distinction of red and black mangroves is quite clear, probably related to specific growth differences of the red and black mangroves. The black mangroves grow close to areas with higher elevation (called dry land), away from permanently flooded areas, or areas with high water content such as mud flats and swamps. The red mangroves occur next to areas with high water content and permanently or frequently flooded areas. Mixed forest areas are represented in small irregular patches. Corals and seagrass classes are included in the shallow submerged habitats.

Comparing the classification of the WorldView-2 image with the RapidEye image indicates that the lower resolution of the RapidEye image leads to a decreased ability to distinguish details. Especially in the shallow water areas, the RapidEye image seems to mix dry land and a sandy shallow area

Table 8. Area for each class of Figure 19.

Class	Area (ha)	Class	Area	Class	Area
Class 1	340.8	Class 11	30.3	Class 21	18.7
Class 2	83.4	Class 12	69.1	Class 22	94.5
Class 3	61.8	Class 13	70.9	Class 23	71.0
Class 4	58.3	Class 14	23.1	Class 24	84.8
Class 5	57.3	Class 15	69.2	Class 25	71.9
Class 6	95.9	Class 16	43.6	Class 26	77.6
Class 7	54.5	Class 17	74.7	Class 27	52.5
Class 8	69.2	Class 18	79.0	Class 28	109.4
Class 9	66.3	Class 19	64.0	Class 29	99.2
Class 10	36.6	Class 20	90.6	Class 30	65.9
Unclassified	0.04				



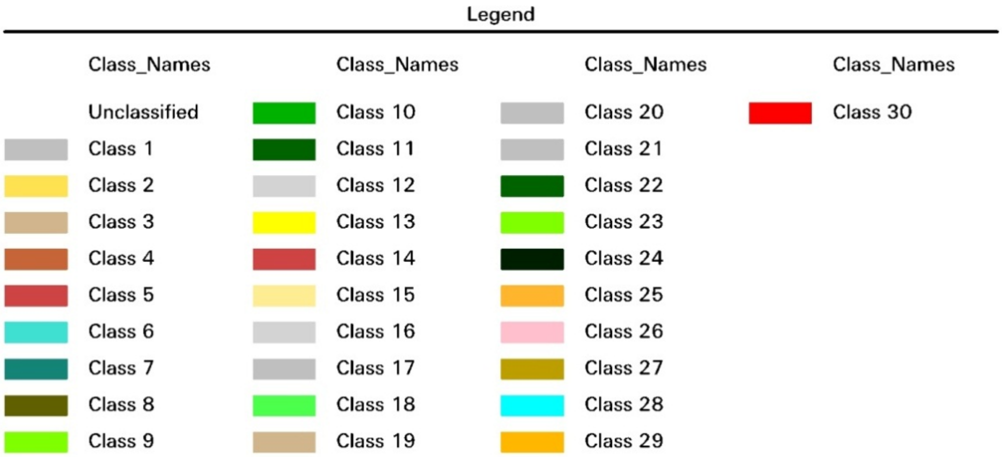


Figure 19. Unsupervised classification RapidEye image.

Pan-sharpening of the image did not much improve the classification results of the WorldView-2 image. The RapidEye image contains a high percentage of small patches of mixed moderate and dense mangrove forests that cannot be separated. The RapidEye image is further complicated by a large cloud area in the northern upper part of the Lac Bay, shadowing a big part of the mangrove forest.

4.3.3 Decision tree classification

As input to the decision tree classification the images from the vegetation indices, the PCA and the unsupervised classification were used (
Figure 20). First, we used the NDVI image to separate mangrove and non-mangrove groups. Next the PCA image was used to separate land from water. NDVI, ARVI, and EVI indices were used to define groups of moderate, sparse, and dense forest.

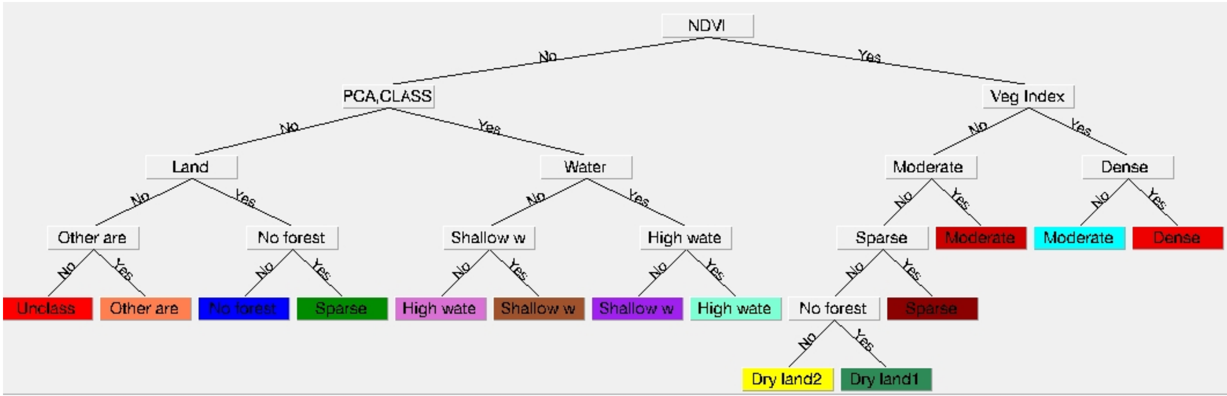


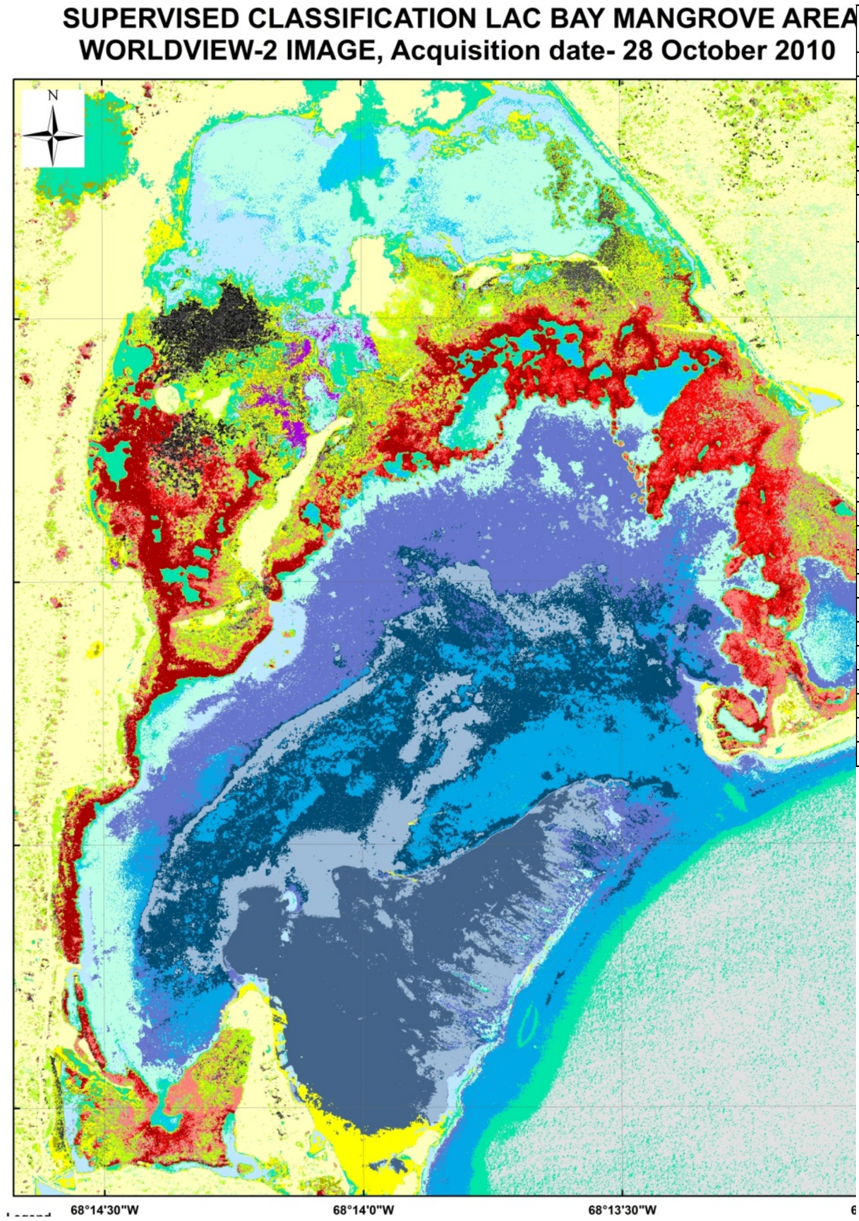
Figure 20. Decision tree model.

The decision-tree classifier showed a high mismatch in areas with high mixes of red and black mangroves and a fairly good match in homogeneous areas. However, due to time constrains the further development of the decision-tree rules were left and classification followed the ISODATA clustering approach.

4.4 Supervised classification

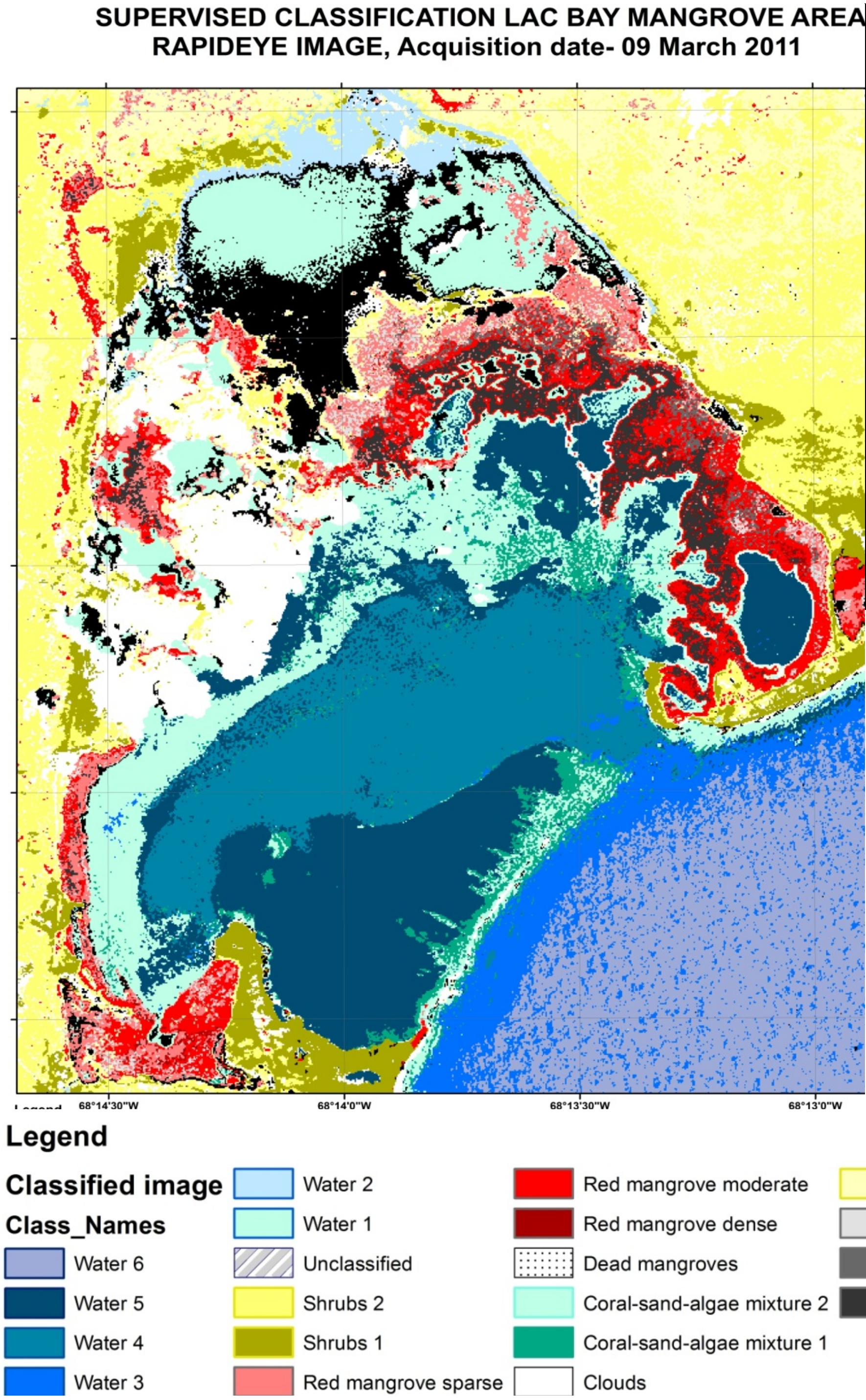
The supervised classification followed ISODATA clustering approach (i.e. based on grouping image pixels into same class based on highest probability).

As input for the supervised classification, the images from the vegetation indices, vegetation density, PCA and unsupervised classification were used. Dry land and water within the mangrove area together with dead mangrove were classified based on the PCA image. Sea grass and coral were assigned based on visual interpretation, as was cloud which is especially significant in the RapidEye image. The final results for the WorldView-2 data are presented in figures 21 and 22. The pixel based classification had shown quite good distinction between dense, moderate and sparse mangrove forest and water and land areas. The mangrove forest in the WorldView-2 image in total occupies about 1,7km^2, the mangrove mixed areas 1.23km^2 and dead mangrove areas 0.028km^2. Unclassified pixels are mainly located outside of Lac Bay and therefore not included in the area calculations.



Class	Area (ha)
Black mangrove dense	8.4
Black mangrove moderate	19.3
Black mangrove sparse	30.4
Bush areas	34.5
Conocarpus	2.1
Coral-sand-algae mixture 1	97.5
Coral-sand-algae mixture 2	69.0
Coral-sand-algae mixture 3	52.1
Coral-sand-algae mixture 4	61.0
Dead mangroves	2.8
Mangrove mix	123.4
Red mangrove dense	36.7
Red mangrove moderate	26.2
Red mangrove sparse	49.2
Sea	377.3
Shrubs 1	947.7
Shrubs 2	95.9
Shrubs 3	15.4
Unclassified	12.7
Very shallow area	93.2
Water 1	90.5
Water 2	64.6
Water 3	0.05
Water 4	221.5
Water 5	11.6

Figure 21. Image for supervised classification of WorldView2 data.



Classes	**Areas (ha)**
Unclassified	0
Shrubs 1	111.5
Black mangrove sparse	15.9
Black mangrove dense	26.9
Red mangrove moderate	73.8
Red mangrove dense	4.0
Coral-sand-algae mixture 1	27.9
Black mangrove moderate	8.7
Red mangrove sparse	51.7
Water 1	78.4
Shrubs 2	471.7
Bush	421.4
Dead mangroves	74.3
Coral-sand-algae mixture 2	92.7
Water 2	27.7
Water 3	104.3
Clouds	188.2
Water 4	117.7
Water 5	148.4
Water 6	238.8

Figure 22. Supervised classification of RapidEye data.

In the RapidEye image resolution is lower, and the distinction between red and black mangroves is not so clear. Moreover, there is high information loss from clouds (more than 1.88 square km). The total mangrove area in the RapidEye picture is less compared to the WorldView-2 image (about 1.29 square km for Red mangroves and 0.5 for the Black mangrove). The dead mangroves occupy approximately 0.74 km^2.

4.5 Mangrove Health

The healthy vegetation strongly absorbs the sun light and has low reflectance in the red bands and high chlorophyll content detectable in infra-red.

The health of the mangroves in Lac Bay is described qualitatively (in terms of healthy and less healthy) based on vegetation indices, structural appearance, and density. The main assumption for healthy mangroves is that healthy vegetation will strongly absorb sun light with strong reflection in the red and infra-red bands. The deterioration of vegetation health can be detected by decreased reflectance in the near-infrared (lower chlorophyll production) and increased reflectance in the red (only weak absorption of sun light). Dead mangroves were included as a separate class. Figures 23 and 24 present results on mangrove health. Areas with dense and high density mangroves are located along and close to the water sources (the lagoon) and channels.

The total area of healthy mangroves in WorldView-2 image is 0.82 km^2 (56%) and unhealthy mangroves 0.63 km^2. The healthy mangrove in the RapidEye image is about 1.14 km^2 (60%) of a total of 1.9 km^2.

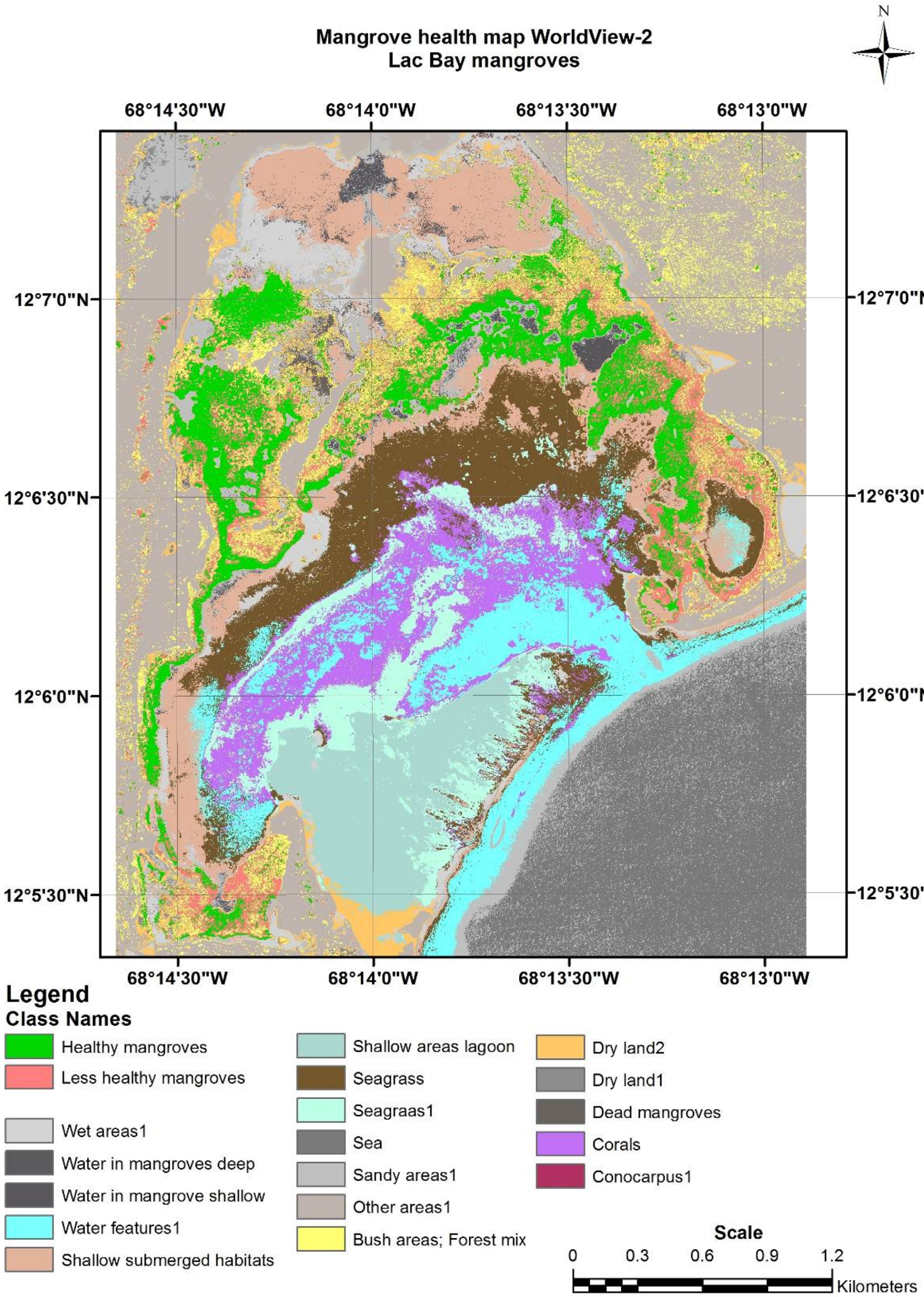


Figure 23. Mangrove health, WorldView-2 data

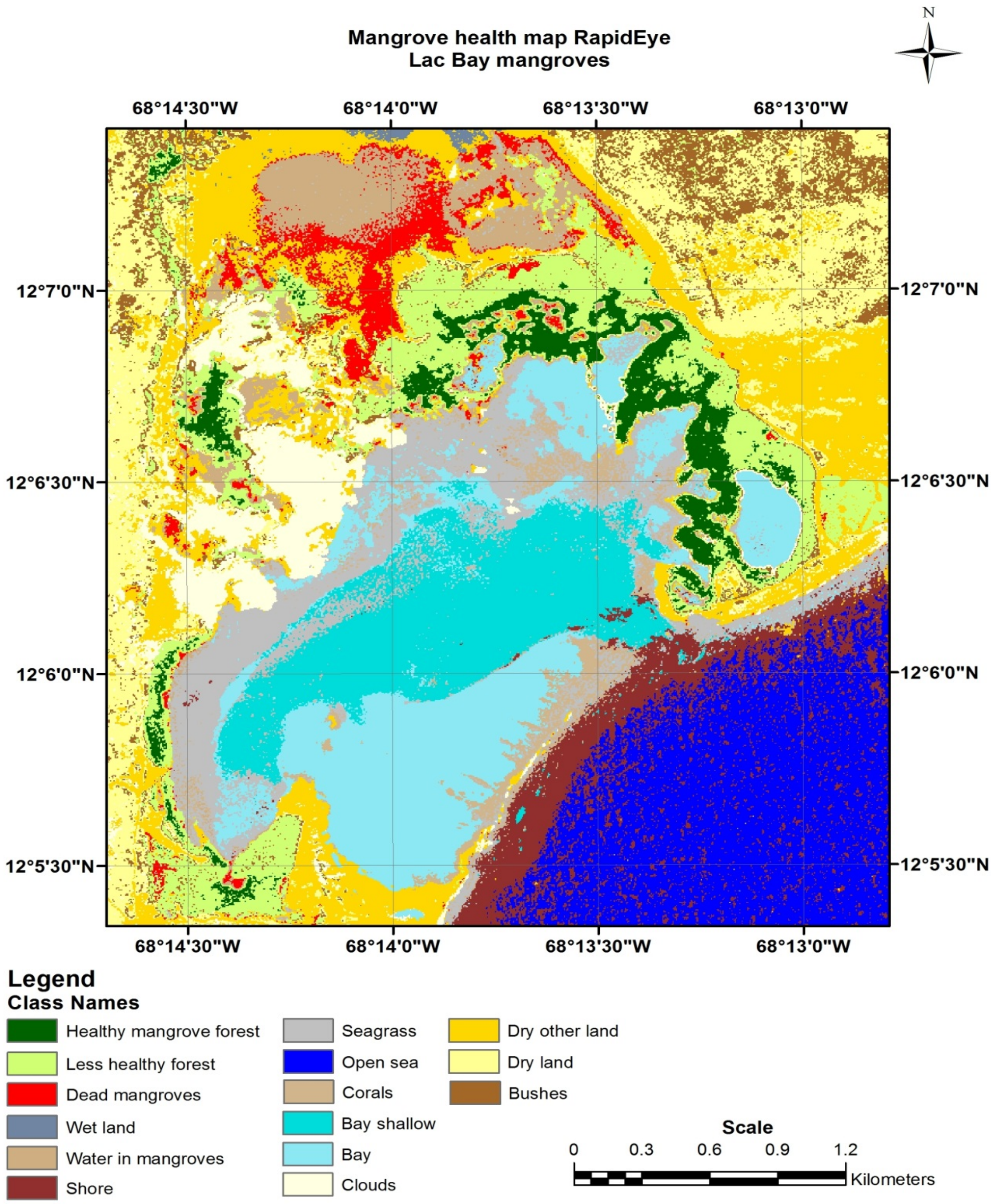


Figure 24. Mangrove health, RapidEye data

5 Discussion and conclusions

Satellite data can be used to accurately measure the extent and density of the mangroves in Lac Bay, Bonaire. This can be achieved to a reasonable degree of confidence with relatively low-cost data (RapidEye). To be able to detect different species and to derive more details in vegetation indexing, the higher resolution data are needed (WorldView2). The Normalized Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), the Atmospherically Resistant Vegetation Index (ARVI), and vegetation delineation provided information on amount of biomass and chlorophyll. The red and black mangroves were classified using the unsupervised and supervised classification. The health state of the mangroves can be related to chlorophyll content and biomass, which can be detected in red, red-edge and near-infrared bands. The structural appearance in dense and moderate red and black mangrove forest showed high NDVI, EVI and ARVI values ranging from 0.89 to 0.54, which indicates healthy vegetation, and sparse red and black mangrove areas in the upper part of the Lac Bay with lower water and nutrients supply ranging from 0.36 to 0.20 indicating less healthy vegetation. The areas with dead mangroves in the upper part of the bay are between 0.32 and 0.002. The comparison of waters with dead mangroves and water areas without dead mangrove can be clearly seen in PCA and unsupervised classification images. It seems that NDVI index overestimates biomass values, while the Enhanced Vegetation Index and Atmospherically Resistant Vegetation Index and Red Edge index appear to have much better precision, however, more ground-truthing is necessary to develop accurate models to estimate mangrove health.

Lac Bay contains within a relatively small area a highly variable mix of mangroves, and dry, wet and swamp areas. This creates a variable spectral mix, which cannot be always well separated by a classification routine and especially in the lower resolution image (RapidEye) details are obscured. Supervised classification which was combined with visual interpretation and ground data showed good results. However, the mangrove area available for interpretation was reduced because of a large cloud in the area of interest. Availability of the cloud-free satellite images will be an issue in selecting data for monitoring. Since the Lac Bay is relatively small (only 700 hectares) and contains a large amount of mixed mangroves a high resolution image appears necessary for efficient monitoring.

Mangrove health can be related to vegetation indexes (vegetation biomass) and structural appearance (density). In Lac Bay the healthy mangroves have dense and moderate structural appearance and vegetation index values ranging from 0.95 to 0.65. The areas with less healthy mangroves ranged index values starting from 0.5 to 0.3.

The main conclusion from this study is that Remote Sensing data and methods can be a good way to measure the extent of the mangroves in Lac Bay and can be used to measure mangroves health through vegetation indexing. Comparing the two data sets, the higher resolution of WorldView-2 provides better results than the RapidEye satellite. The advantage of RapidEye image is its lower costs and if the interest is mainly in vegetation indexing will render results that are largely comparable to the WorldView-2 data.

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Quality Assurance

IMARES utilizes an ISO 9001:2008 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organization has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Environmental Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

Justification

Rapport C190/11
Project Number: 430.82010.79

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Drs. A.J. Paijmans
Researcher

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Date: January 2012

Approved: Drs. J. Asjes
Head of Department

Signature:

Date: 31 March 2012

Appendix 1. Glossary

GLOSSARY OF TECHNICAL TERMS

- **Remote sensing**- Remote sensing can be defined as the collection of data about an object from a distance. Humans and many other types of animals accomplish this task with aid of eyes or by the sense of smell or hearing. Geographers use the technique of remote sensing to monitor or measure phenomena found in the Earth's lithosphere, biosphere, hydrosphere, and atmosphere. Remote sensing of the environment by geographers is usually done with the help of mechanical devices known as remote sensors. These gadgets have a greatly improved ability to receive and record information about an object without any physical contact. Often, these sensors are positioned away from the object of interest, features (see Features) by using helicopters, planes, and satellites. Most sensing devices record information about an object by measuring an object's transmission of electromagnetic energy from reflecting and radiating surfaces (Pidwirny, 2006).
- **Features**- features can be objects of nature- forest, land, water, etc. and artificial, man-made- e.g., urban structures, artificial mountains, structures in the sea, ships, platforms, etc. Objects of the nature and man-made objects can be detected from the space and recorded on satellite images, based on reflectance or spectral signature(see Reflectance).
- **Reflectance (spectral signature)**- when sun light hits any surface on earth, the sun light can be absorbed (for example by water), transmitted back (dry soil), reflected in full extent (house roof, ice and snow cover) or partially- forest, land, etc. The strength of the transmition, absorption and reflection is depend from the texture and type of the surface (see Texture; Surface types). The satellite sensors records the transmitted and reflected signals. Reflectance value (Spectral signature) is a number, presented in bits and stored as numerical values in the image (see 8 bit, 16 bit, 32 bit).
- **Texture (of the feature)**- the real objects often do not exhibit regions of uniform intensities. For example, the image of a wooden surface is not uniform but contains variations of intensities which form certain repeated patterns called visual texture. The patterns can be the result of the physical surface properties such as roughness or oriented strands which often have a tactile quality, or they could be the result of reflectance differences such as the colour on a surface. In remote sensing the texture of the surface is used in image classification (see Image classification).
- **Surface types (of the features)**- can be smooth, rough, geometrically shaped, irregular. In remote sensing the surface types of the features is used in image classification (see Image classification) and visual interpretation.
- **Image**- image is representation of captured signal or sun light. The features are shown in colours if image is in colours (see Colours) or in black and white (see Panchromatic image). The image can be analogue- printed, or digital- stored in the computer. In Remote sensing, image has two dimensional function- X and Y coordinates, and size of the image consists from Row and Columns (Height and Width). Such image is called raster image (see Raster). Each pair of coordinates has reflectance values of the objects, expressed in number (value) (see Image, 8 bits, 11 bit, 16 bit, 32 bit).
- **Raster (image)** – raster (image) consists from the squares (grid). Each cell of the grid (see Grid) is represented by a pixel (see Pixel), also known as a grid cell.
- **Grid**- square in the image, representing the smallest element of the image. In remote sensing, the grid is called Pixel (see Pixel).
- **8 bit image**- the values of the image start from 0 to 255. Zero (0) is for black and 255 is for white color (see Look up table).
- **11 bit image**- the values of the image start from 0 to 2047. Zero (0) is for black and 2047 is for white color (see Look up table).

- **16 bit image**- the values of the image start from 0 to 65,536. Zero (0) is for black and 65,536 is for white color (see Look up table)
- **32 bit image**- the values of the image start from 0 to 4,294,967,295. Zero (0) is for black and 4,294,967,295 is for white color (see Look up table).
- **Look up table**- this term used in computer science to describe a data structure (see Image, 8 bit, 11 bit, 16 bit, 32 bit). The each value in the image is assigned a colour, starting from zero (0) as a black and stretching to the white (see Colours).
- **Colours**- the colours are continuous range, starting from Black to Red, Magenta, Yellow, Green, Blue, Violet to White. The colours used in images as a mixtures. Each feature on image has colour with different intensity, hue and saturation (see Intensity, Hue, Saturation).
- **Panchromatic image**- it is black and white image and image values (see Image) are represented in range from black (zero value) to the white (see 8 bit, 11 bit, 16 bit, 32 bit). The image values in between from black to white are represented in shades of grey, in different saturation, hue and intensity (see Saturation, Hue and Intensity).
- **Multispectral image**- it is image containing several bands (see Bands) and it can present features in colours, depending what bands combination were used. There are two types of the colour system which is used to display the multispectral image. One colour system is called true colours composite (see True colours composite) and Pseudo colours composite (see Pseudo colours composite).
- **Saturation-** is how pure the colour is. A fully saturated colour is the truest version of that colour. Primary colours (Red, Yellow, and Blue) are "true", so they are also fully saturated. The saturation of colours in the computer system and in digital image is presented by number. The number can be positive- high saturation and negative- minimum saturation.
- **Hue**- is what most of people think of when they think of "colour." It is the generic name used to describe a colour, e.g. red, green, yellow, orange, etc. The hue of colour in computer system and in digital image is presented by number. The number can be positive- high hue and negative- minimum hue.
- **Intensity**- how much of "true" colours are in image. The higher intensity of the "true" colour, the more "intense" is colour. The intensity of the colour in computer system and in digital image is presented by number. The number can be positive- high intensity and negative- less intensity.
- **True colours composite-** the composite present the main features of land, water and vegetation in "true" colours, like the original subject would, and it is dark brown colour for land (depending from soil moisture and vegetation cover), all vegetation in green and water in dark or light blue. The combination of bands to display image in such true colour composite is called RGB (Red, Green, Blue).
- **Pseudo colours composite-** will not necessarily present features in colours like the original object would, and the purpose to use such pseudo-colouring is to make some details more visible, for instance by highlighting the water from land, presenting the water in red and land in black or in green. The colour combination in this case is selected randomly as a free choice by the user.
- **Wavelengths-** are the distances between repeating units of a propagating wave of a given frequency. The light, microwaves, x-rays, and TV and radio transmissions are all kinds of electromagnetic waves. They are all the same kind of wavy disturbance that repeats itself over a distance called the wavelength.
- **Electromagnetic spectrum**- it is physical definition of wavelengths, expressed in nanometers (see Nanometers). The spectrum used in Remote sensing starts from infrared region (near, middle and far infrared), visible region (Red, Green, Blue) and thermal.
- **Nanometers**- a nanometer is 0.000000001 meters, equal to 10^{-13} meters .
- **Infrared** region of wavelengths- starts from 0,7 to 5,0 nanometers.

- **Visible region** (Red, Green and Blue). The Blue region starts from 0,4 to 0,5; Green region from 0,5 to 0,6 and Red from 0,6 to 0,7 nanometers.
- **Satellite sensor**- is a camera mounted on satellite, which records the reflected and transmitted reflectance's of features in selected wavelengths. The each satellite has range of electromagnetic spectrum which can record.
- **Image Processing-** is a process which extracts information about features based on their reflectance, transmission and absorption property (see Reflectance, Electromagnetic spectrum) of the sun light.
- **Resolution of the satellite image**- is a broad term commonly used to describe the number of pixels you can display on computer, or area on the ground (in meters, centimeters, etc.), often called a pixel (see Pixel) that a pixel represents in an image. The resolution is fixed for each satellite. For instance the resolution of the Landsat satellite is 30 meters; the WordView-2 is 2 meters and RapidEye is 5 meters. Resolution can be spectral, spatial, radiometric and temporal.
- **Pixel**- it is area on the ground which represents is a single point on a raster image, or the smallest addressable screen element on a display device; it is the smallest unit of picture that can be represented or controlled. In satellite image the pixel is related with resolution (see Resolution of the satellite image) and satellite sensor (see Satellite sensor).
- **Spectral resolution**- the specific wavelength intervals that a sensor can record and it is fixed for each satellite. For example for the WordView-2 satellite, the spectral resolution is starts from Blue wavelength (see Wavelengths) and includes another blue wavelength, green, yellow, 2 red and 2 infrared wavelengths of the spectrum (see Electromagnetic spectrum) . Often these wavelengths are called bands of the image (see Bands).
- **Bands (of image)**- bands are recorded range of Electromagnetic spectrum by satellite sensor of reflectance's of the features. The range of the bands are expressed in nanometers (see Nanometers) and they limited by satellite sensor mounted on satellite.
- **Spatial resolution**- the area on the ground represented by each pixel (in meters, see the Resolution) and it is fixed for each satellite.
- **Radiometric resolution**- the number of possible data file values in each band (see the Image, 8 bit, 11 bit, 16 bit, 32 bit, Bands). For example the original WorldView-2 data has radiometric resolution of 11 bits, which can be changed (resampled, see Resampling) to other resolution, in our case it was resampled to 8 bits.
- **Temporal resolution**- it is refers to how often a sensor obtains imagery of a particular area. For example, the Landsat satellite can view the same area of the globe once every 16 days. The WorldView-2 satellite every 1,1 day.
- **Resampling (image)**- it is process of changing the number of pixels in the original image. In Remote sensing it is process of changing from 11 bit to 8 bit- resampling, e.g. densifying the values, from 8 bit to 11 or 32 bit- stretching the values (see Stretching). The resampling of the image should not be confused with resizing (see Resizing).
- **Resizing (image)**- changing the size the image, e.g. making number of columns and rows (see Image) larger or smaller, without changing the number of pixels (see Pixel) in the image.
- **Stretching-** stretching is process of changing the hue, intensity and saturation into increasing or decreasing. The result is different from original image and in remote sensing it is used to highlight the features. In computer system for stretching the several options are used- so called filters (see filters) and process is called image stretching and filtering.
- **Filters (image processing) –** the filters in image processing of satellite images are processes in computer system to remove the noise (see Noise) from a digital image, for the purpose to improve the visibility of the features on the image. The filters can smooth the image, sharpen the image and highlight the features.

- **Noise (image)-** it is variation of hue, intensity or saturation in brightness or colour in the image. On satellite image noise is recorded by satellite sensor from originated haze (moisture), blocking the visibility of the features or can be produced by satellite sensor itself.
- **Accuracy (of the image)**- accuracy of the image is comparison of how well (accurate) the features are positioned in the image compare with real situation (on the ground). The comparison of image accuracy is made by measuring by GPS (see GPS) the vertical position of the features (see Vertical accuracy) and horizontal position of the features (see Horizontal accuracy). The vertical and horizontal accuracy is expressed in meters. In satellite images, the shift in vertical and horizontal accuracy can be improved by using ground control points (see Ground Control Points) measured by GPS (see GPS) or by using the Digital Elevation Model DEM (see Digital Elevation Model).
- **GPS**- it is device to record the position in two- dimension, X and Y coordinates, using the Global Positioning System, called GPS system. The GPS device captures the signal from the GPS satellites and estimates the average of the feature position in degrees, minutes, etc. depending what coordinate system are used in the GPS device (see Coordinate system). The GPS systems have Horizontal and Vertical accuracy. There are different GPS systems, like in Europe it is Galileo system, GLONASS in Russia and GPS in USA. It is also possible to measure the height of the position, but such height measurements are accurate only in commercial GPS systems.
- **Horizontal accuracy**- it is the assessment of how much is the features are shifted (in meters), horizontally, compare with exact location on the ground measured by GPS . The accuracy is expressed in meters. For the WorldView-2 image the horizontal accuracy is less than 1 meter. To improve the horizontal accuracy is required by using the image processing software to move the pixels into a referenced exact location of the Earth.
- **Vertical accuracy**- it is accuracy of heights on DEM image, produced from image pair. It will show the differences in height (in meters) between the estimated (from image) height and on measured on the ground (by GPS).
- **Ground Control Points** – it is points of X and Y location of particular feature measured by GPS. The Ground Control Points GPC are used in image Georeferencing (see Georeferencing) and in improving the horizontal and vertical accuracies. The GPC is also used in image classification (see Image classification) and in verification of the classified image (see Image classification).
- **Georeferencing-** Georeferencing refers to the process of assigning map coordinates- X and Y to image values (pixels).
- **Digital Elevation Model DEM**- it is three dimensional representation of a terrain's surface and it is usually expressed as a series of points with X,Y, and Z values (heights), stored in image values.
- **Resolution accuracy-**it is related with resolution of the satellite image (see Resolution). The higher the resolution, the higher is accuracy of the final results. The comparison on resolution accuracy is very important in comparison of two satellite images with different resolution, for instance, in comparison of WorldView-2 image with resolution of 2 meters and RapidEye with 5 meters.
- **Image classification-** it is process of image processing (see Image processing), in detecting and separating the features from each other. The image classification uses radiometric (see Radiometric resolution) properties of the satellite sensor. The main principle of the image classification is that different objects (features) have different spectral signatures (see Reflectance) and it is based on probability (see Probability), that each pixel belongs to particular class. The image classification can be supervised classification (see Supervised classification) and 67Unsupervised (see Unsupervised classification).
- **Supervised classification**- it is process of detecting features on the image, selecting the features and setting up classes. The process is "supervised", and based on knowledge of the computer analyst in detection of the features and assigning them categories and names. For

detection of the feature classes the Ground Control Points can be used (see Ground Control Points). Common Classifiers includes- Parallelepiped, Minimum distance to mean and Maximum likelihood (see Parallelepiped, Minimum distance to mean, Maximum likelihood).

- **Unsupervised classification –** in this process every individual pixel is compared to each other and automatically groped into classes. Such automated process is based on reflectance (spectral) property of the each feature. The features are simply clusters of pixels with similar spectral characteristics (see Reflectance). The automated process can be co-called Maximum Likelihood (see Maximum Likelihood) or ISODATA clustering (see ISODATA). The process takes maximum "advantage" of spectral variability (see Reflectance) in an image. The unsupervised classification is separate process and it should be not mistaken with PCA (see PCA) and or other pixel grouping processes.
- **PCA-** Principal Component Analysis. It is used to compress information from multi-spectral bands to fewer bands. The first 3 principal components are contains most of the information and normally, the PCA is computed for the first 3 bands. In image processing (see Image processing), the PCA will compress information from 8 bands into 3 bands.
- **Parallelepiped**- it is statistical (see Statistic) process of analyzing pixels on the image. The process is automated and done by image processing software. The process makes few assumptions about character of the classes, based on texture (see Texture), surface type (see Surface type), reflectance (see Reflectance) classifying the image using the "Parallelepiped" (see Parallelepiped) shaped box.
- **Minimum distance to mean**- it is statistical process to find the mean (see Mean) of each pixel (see Pixel). The process is automated and done by image processing software. All pixels in the image are classified according to the class mean to which they are closest.
- **Maximum Likelihood** (image processing)- it is statistical process on grouping the pixels into classes, to which pixel of most likely to belong, e.g. the highest probability (see Probability) of the membership. The process is automated and done by image processing software.
- **Parallelepiped-** it is geometrical three-dimensional figure, the shape is like a cube and it is related to a square. The shape of the Parallelepiped is depends from number of sides. In image processing the parallelepiped window is refer how the computer using image processing software groups the pixels. In this process the pixels groped in shape of parallelepiped.
- **Statistic-** is science on methods on collection, organization, analysis, and interpretation of the data. In remote sensing, statistic is used in data analysis and interpretation of the classified image (see Image classification).
- **ISODATA clustering-** it is special case of Minimum distance to mean (see Minimum distance to mean). The difference with Minimum distance to mean is that user (person operating computer and doing image processing) enters the desirable number of classes of the features (see Features). The desirable number of classes depends from the user's knowledge.
- **Mean (signature)-** ideally, the spectral signatures (see Reflectance) of the features are different from each other, related with the spectral reflectance, wavelengths (see wavelengths) and radiometric (see Radiometric resolution), spatial resolution (see Spatial resolution) and temporal resolution (see Temporal resolution). The mean is sum of the values divided by the number of values, in image processing the mean of signature values will be the sum of the reflectance (see Reflectance) values to the total number of the values.
- **Mean (pixel)-** mean of pixel will be total sum of counted pixel's divided by number of the pixels. Each image consist from number of pixels (see Image, Pixels). The number of pixels are depends from Resolution accuracy of the satellite image (see Resolution accuracy).
- **Probability**- branch of mathematics concerned with analysis of random events. It is analysis whether the occurred event is either single occurrence or will evolve over the time. In image processing, the probability is used in image processing software to analyse the image in image

classification (see Image classification), to assign each pixel to most “probable”, “possible”, “most likely” class.

- **Index**- it is a quantitative measure used to measure biomass (see Biomass) of vegetation or any other properties of the features, usually by using the combination of several spectral bands (see Bands), whose values are added, divided, or multiplied in order to obtain a single value that will indicate the amount of biomass or will characterize the feature.
- **Biomass-** it is amount of standing crop, grass, forest etc. expressed in kg/m^2. The biomass for crop and grass is different from the forest biomass. The forest biomass is expressed as kg/m^2 of the total crown- and includes only leafs, without including the weight of branches and stem. In remote sensing, since it can only measure the reflected (see Reflectance) sun light, the forest biomass will be expressed as measured area (in ha, km^2, m^2) of the crown, the top of the forest. The information about biomass of the crown in kg/m^2 can be added to estimated area for the total count.
- **Vegetation indexing-** The simplest form of vegetation index is a ratio between near infrared and red reflectance. For healthy living vegetation (see Vegetation health), this ratio will be high due to the inverse relationship between vegetation brightness in the red and infrared regions of the spectrum.
- **Coordinate system-** The location of a pixel in a file or on a displayed or printed image is expressed using a coordinate system. In two-dimensional coordinate systems, locations are organized in a grid of columns and rows. Each location on the grid is expressed as a pair of coordinates known as X and Y. The X coordinate specifies the column of the grid, and the Y coordinate specifies the row. Image data organized into such a grid are known as image (raster) data.
- **Vegetation health-** we might consider a forest unhealthy if it loses the ability to maintain or replace its unique species or functions. One way scientists have assessed whether a system is unhealthy is by comparing current conditions with the normal range of dynamics the system has experienced through the past. This concept is referred to as the historic range of variability. Change can be determined using techniques such as permanent monitoring plots, fire history analyses, old historical photo records or studies of pollen and charcoal layers in bogs or lakes. These various pieces of information are then integrated with our understanding of the dynamics of the ecosystem. The ability of the forest to sustain itself ecologically and provide what society wants and needs is what defines a healthy forest. Maintaining the balance between forest sustainability and production of goods and services is the challenge for owners and managers of the state's forests.

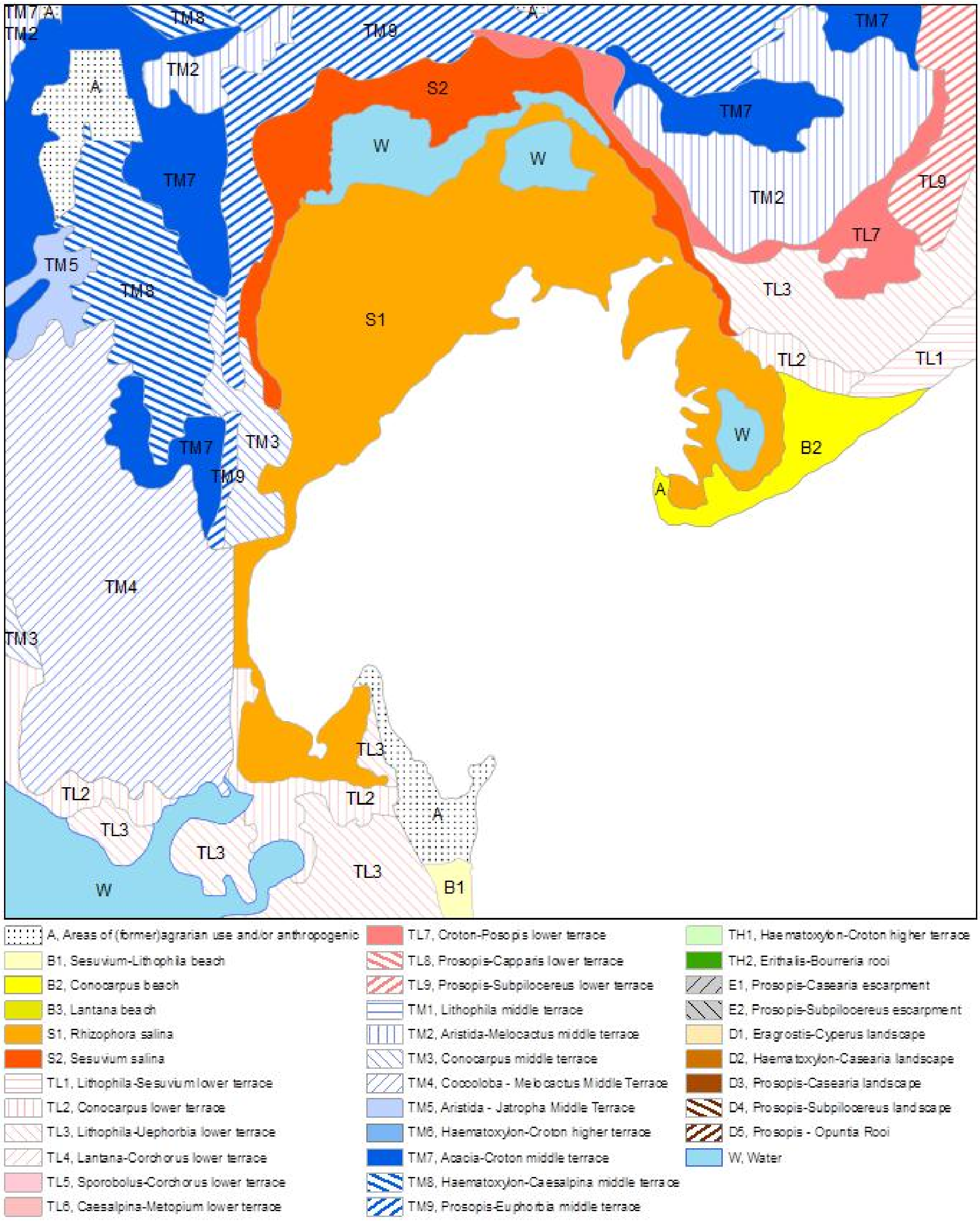
- Ecological health: A healthy forest maintains its unique species and processes, while maintaining its basic structure, composition and function.
- ◦Social health: A healthy forest has the ability to accommodate current and future needs of people for values, products and services. (USDA Forest Service, 2011).

- **Vegetation growth season**- An irreversible increase in the size of the plant, which happen in particular period of the year. Vegetation growth is affected by internal and external factors, which may include the climatic factors (e.g. sun light, rainfall amount, wind, temperature). During vegetation growth season, the new leaves are continuously or seasonally produced. At the same time the older leaves are shed because newer leaves are metabolically more efficient in the production of photosynthesis.
- **Chlorophyll production**- Chlorophyll is the green coloration in leaves and it is molecules in the plant, which actively absorbs the sunlight, in order to produce the energy for the vegetation growth. The chlorophyll production in known as a basis for sustaining the life processes of all plants.
- **Delineation**- it is process of drawing or tracing the outline of an area, in our case it is outline (boundary) of the forest. Outline, e.g. tracing of areas of features is done during image

classification by computer, when image processing sorts and groups the pixels into different classes.

- **Forest mix, vegetation mix**- a forest consisting of two or more types of trees, with no more than 80% of the most common tree. If the mix of one tree or vegetation specie will be 80% or more than that, then forest will be not considered as mix (USDA Forest Service, 2011).
- **Contract enhancement**- it is one of the filters (see Filters) used in image processing. The contract enhancement reduces the lowest grey values to black and the highest to white, it is similar to process of resampling- e.g. densifying the values, from 16 bit image to 8 bit image (see 16 bit, 8 bit).
- **Ancillary data-** data from sources other than remote sensing, for example vector (see Vector) data from GIS (Geographic Information system) used to assist in analysis and image classification.
- **Vector data-** it is data stored in computer, with structure consisting from geometrical (see Geometry) line, point and polygon (see Line, Point, Polygon).
- **Geometry-** is a branch of mathematics concerned with questions of shape, size and relative position of figures.
- **Line-** mathematical definition- a geometric figure formed by a point moving along a fixed direction and the reverse direction. In GIS and Remote sensing, line consist from points and connecting lines and each starting and ending point and points forming the line has X and Y coordinates.
- **Point-** mathematical definition- a dimensionless geometric object having no properties except location. In GIS and Remote sensing, each point has X and Y coordinates.
- **Polygon-** mathematical definition- closed plane figure bounded by three or more straight sides that meet in pairs in the same number of vertices, and do not intersect other than at these vertices. The sum of the interior angles is $(n-2) \times 180°$ for n sides; the sum of the exterior angles is 360°. A regular polygon has all its sides and angles equal. Specific polygons are named according to the number of sides, such as triangle, pentagon, etc. In GIS and Remote sensing each polygon is consists from starting and ending points and lines connecting the points in between. Each point has X and Y coordinates.

Appendix 2. Landscape-ecological map



Appendix 3. Ground-truthing points

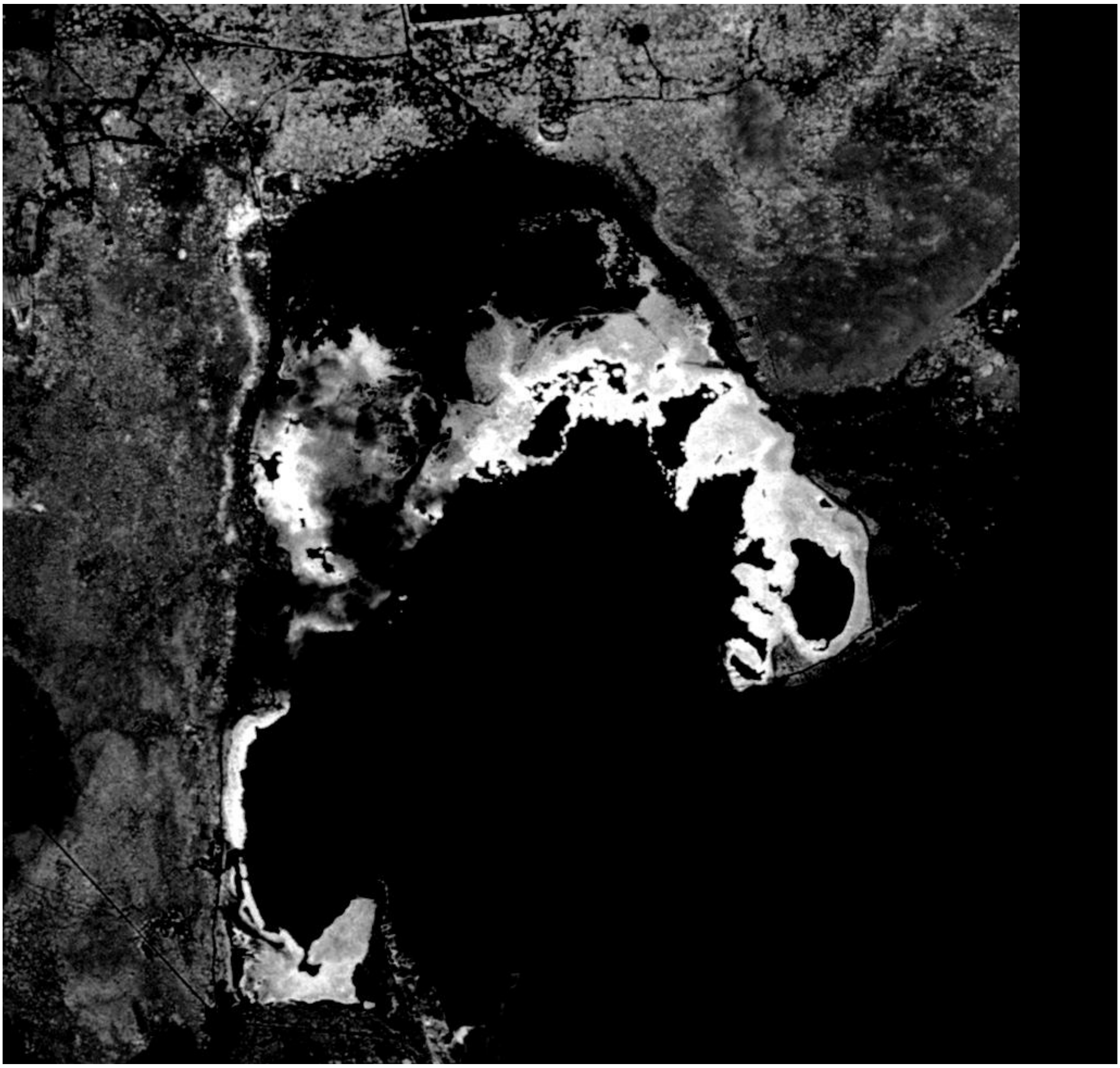
Table 9. GPS points of known locations of the mangroves, land and water features (the Latitudes and Longitudes in decimal numbers)

Species	**Latitude**	**Longitude**
Red mangrove open 1	12.10221111	68.24071944
Red mangrove open 2	12.10198333	68.24068333
Red mangrove 1	12.11633889	68.24078611
Red mangrove 2	12.11591111	68.24097500
Red mangrove 5	12.10354167	68.22040833
Red mangrove 6	12.10386389	68.22201667
Red mangrove 7	12.11387232	68.24189526
Red mangrove 8	12.09349624	68.23745029
Red mangrove 9	12.11464491	68.22695122
Red mangrove 10	12.11679651	68.22676124
Black mangrove Avicennia 1	12.10386389	68.22201667
Black mangrove Avicennia 2	12.11583056	68.24076667
Black mangrove Avicennia 3	12.10332778	68.22019444
Black mangrove Avicennia 4	12.10332778	68.22019444
Black mangrove Avicennia 5	12.11589151	68.23957384
Black mangrove Avicennia 6	12.11077425	68.23988238
Black mangrove Avicennia 7	12.11825405	68.22412887
Black mangrove Avicennia 8	12.12077515	68.22673141
Buttonwood scrub 1	12.10357222	68.22019444
Buttonwood scrub 2	12.10416944	68.24109444
Buttonwood scrub 3	12.10416944	68.24109444
Buttonwood scrub 4	12.10340000	68.21953333
Buttonwood scrub 5	12.10504735	68.21606232
Buttonwood scrub 6	12.10971285	68.21590169
Buttonwood scrub 7	12.12541125	68.22899710
Buttonwood scrub 8	12.12544462	68.23451082
Dry land 1	12.12234821	68.23968421
Dry land 2	12.12019806	68.24040708
Dry land 3	12.11481289	68.24194775
Dry land 4	12.10298713	68.24266108
Dry land 5	12.09436281	68.23689651
Dry (dead) mangroves on high water 1	12.12076481	68.23604963
Dry (dead) mangroves on high water 2	12.11979166	68.23730217
Dry (dead) mangroves on high water 3	12.11998770	68.22971108
Dry (dead) mangroves on high water 4	12.12058435	68.22965423
Dry (dead) mangroves on high water 5	12.11925737	68.23373817
marine areas (lagoon) 1	12.09549504	68.23430209
marine areas (lagoon) 2	12.09389329	68.21763851
swamp (high water content	12.11915985	68.23772668
urban settlements areas	12.08795439	68.23461757
roads (linear features	12.10448458	68.24133365
man-made features (recreation)	12.10929502	68.21524129
other areas	12.11988135	68.21756287
Open sea	12.09389329	68.21763851
Corals 1	12.09881492	68.22659703
Corals 2	12.09824993	68.22665838
Corals 3	12.09903968	68.22612776
Corals 4	12.09435162	68.22956401

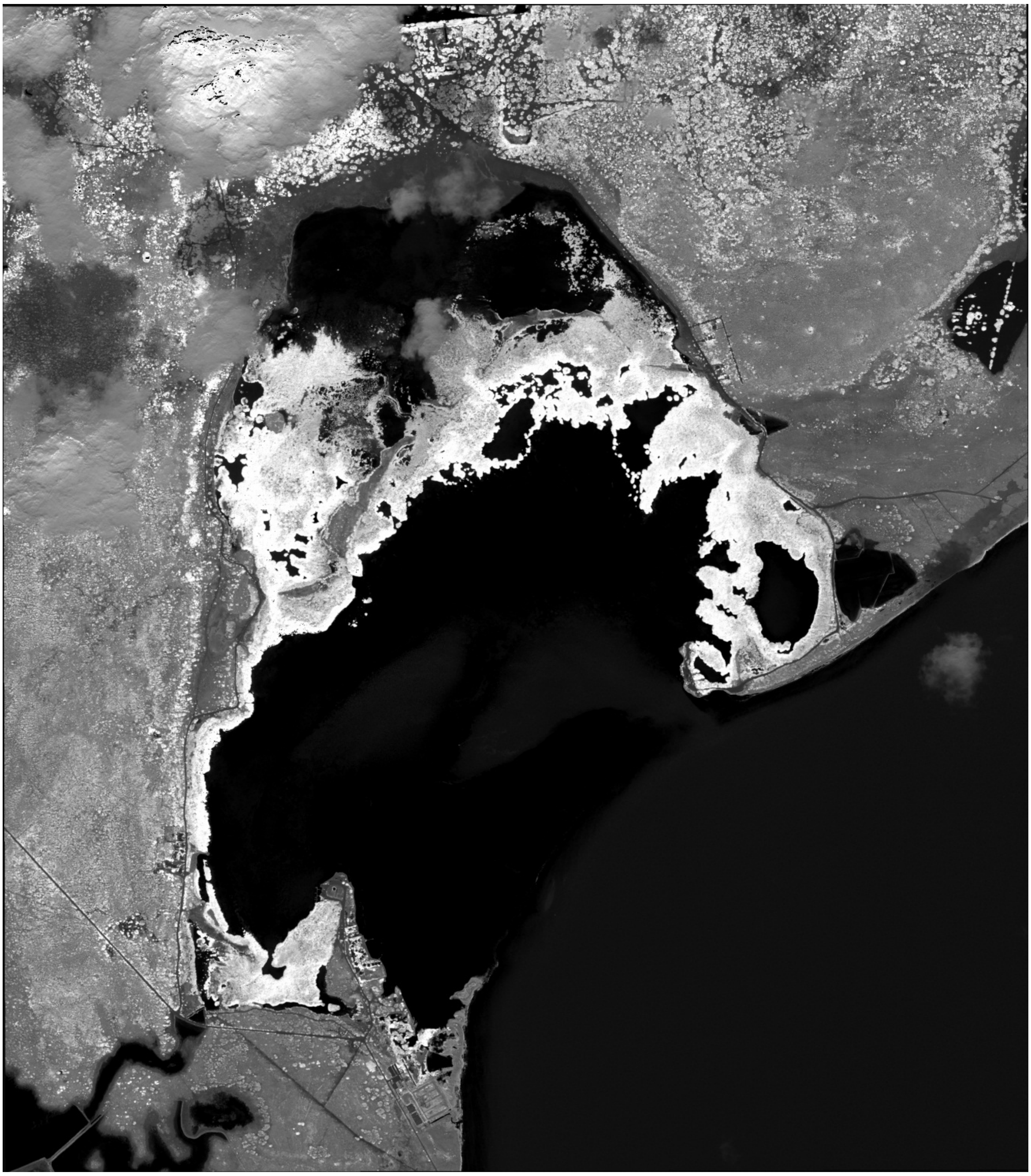
Appendix 4. Index pictures

NDVI WorldView2

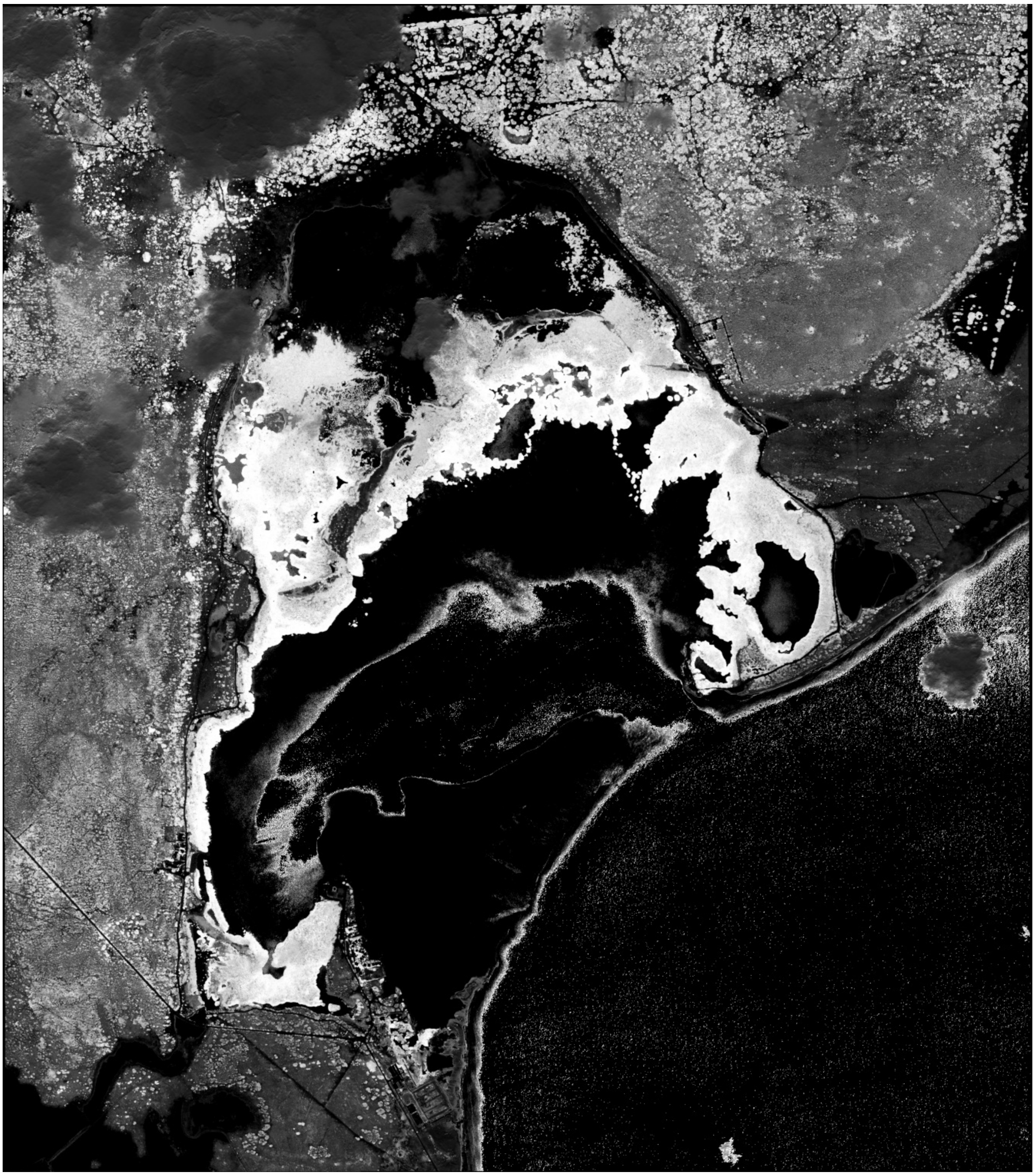
NDVI RapidEye



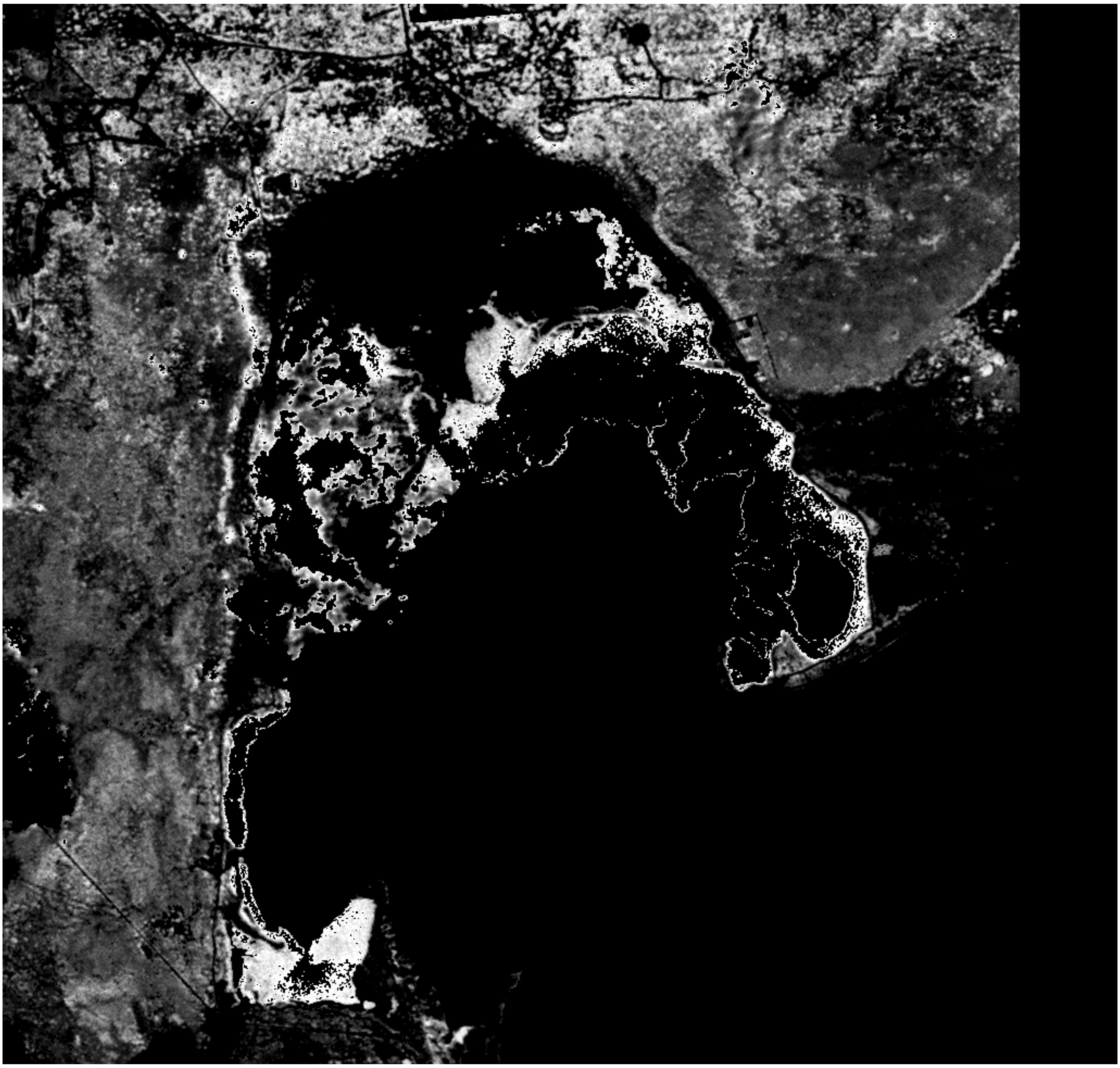
EVI WorldView2



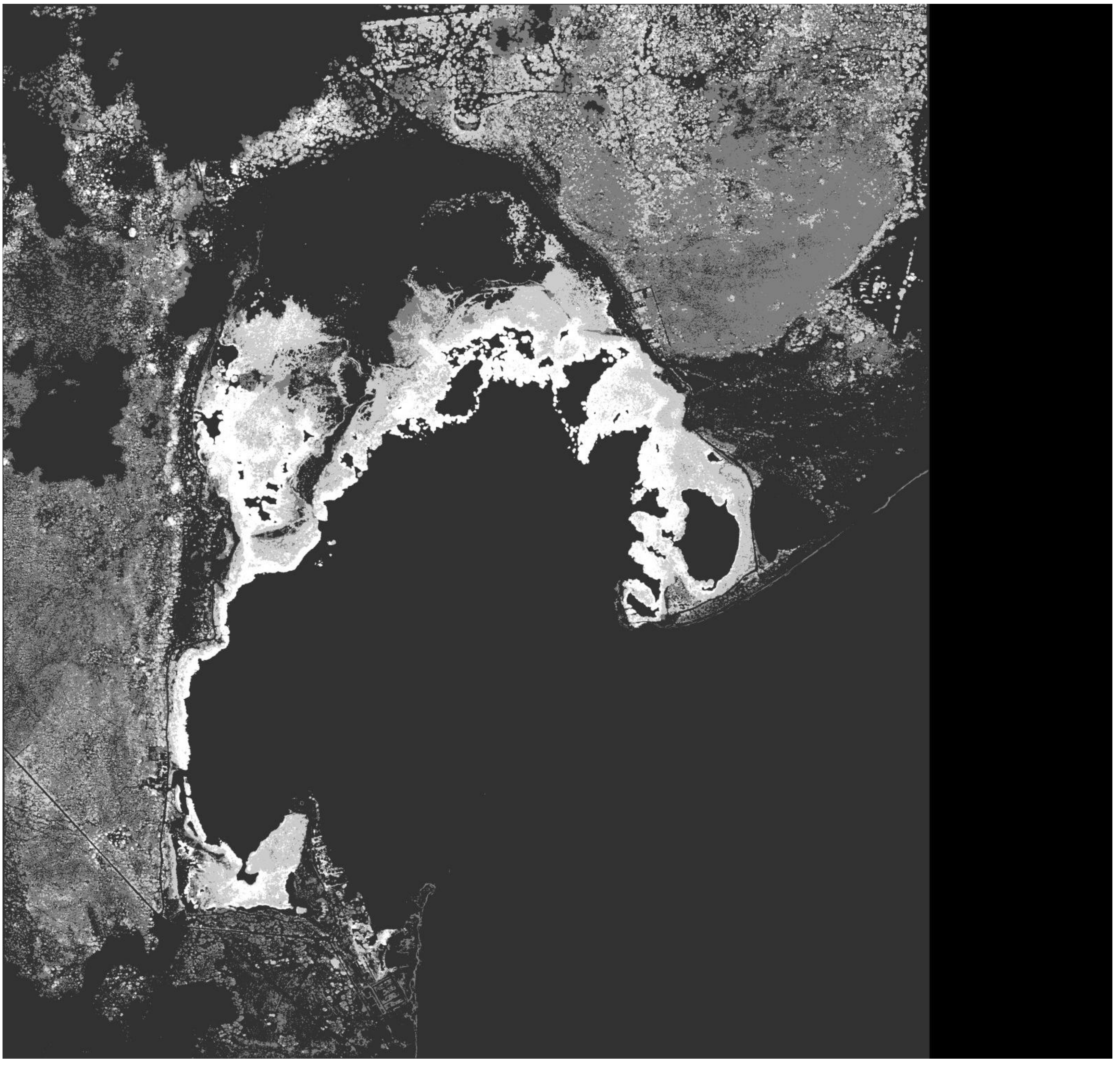
ARVI WorldView2



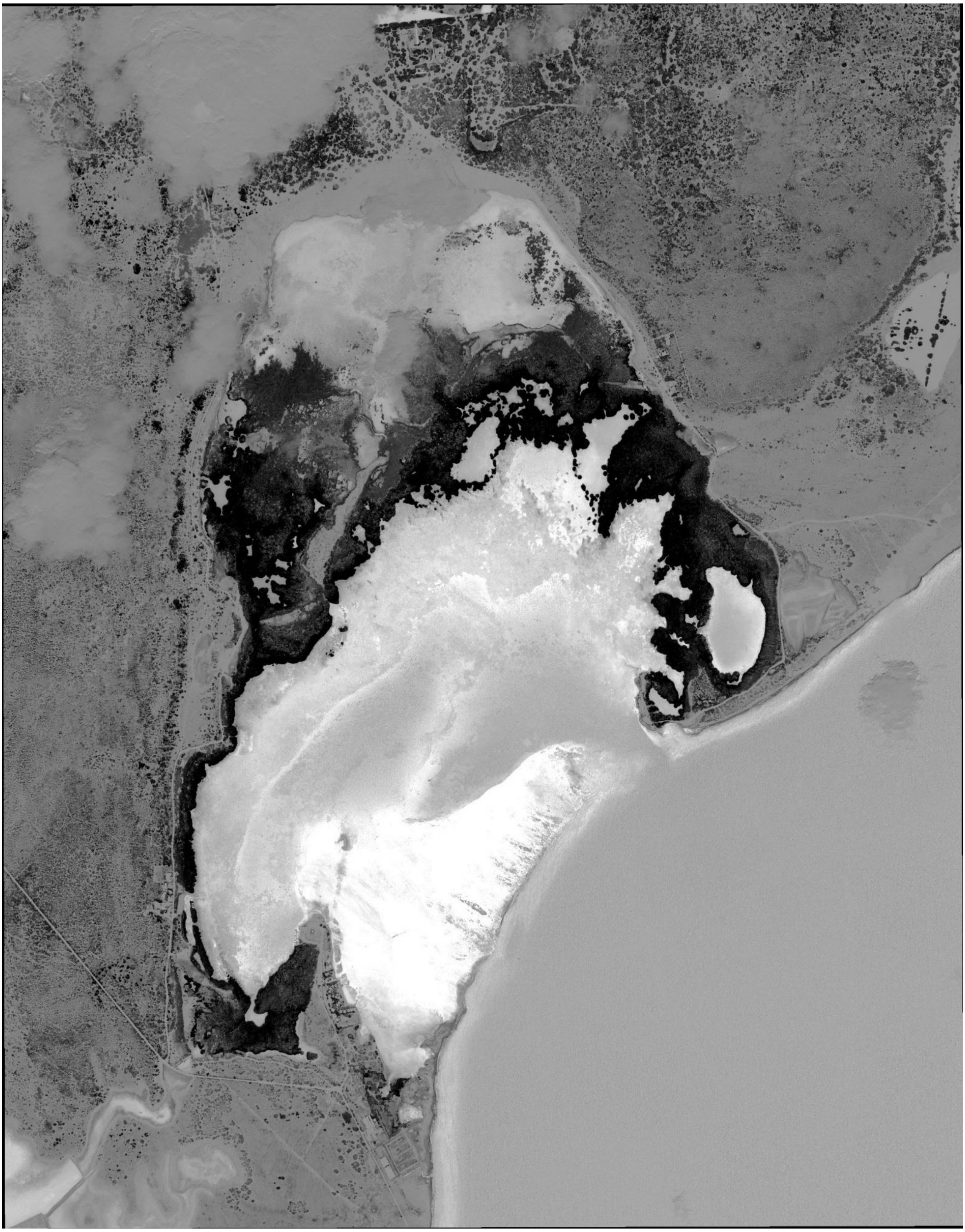
ARVI RapidEye



Vegetation Delineation WorldView2

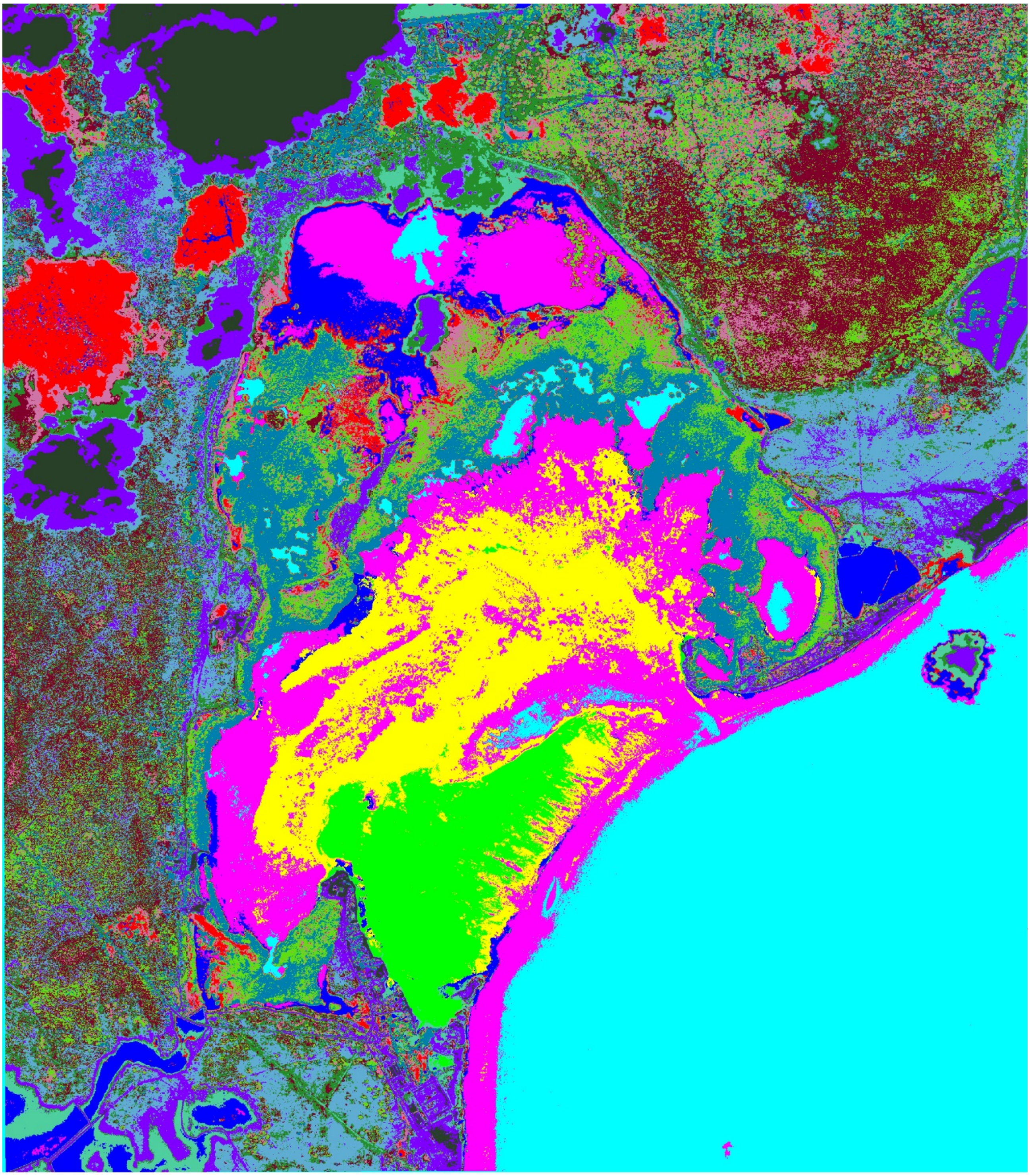


Red Edge Index

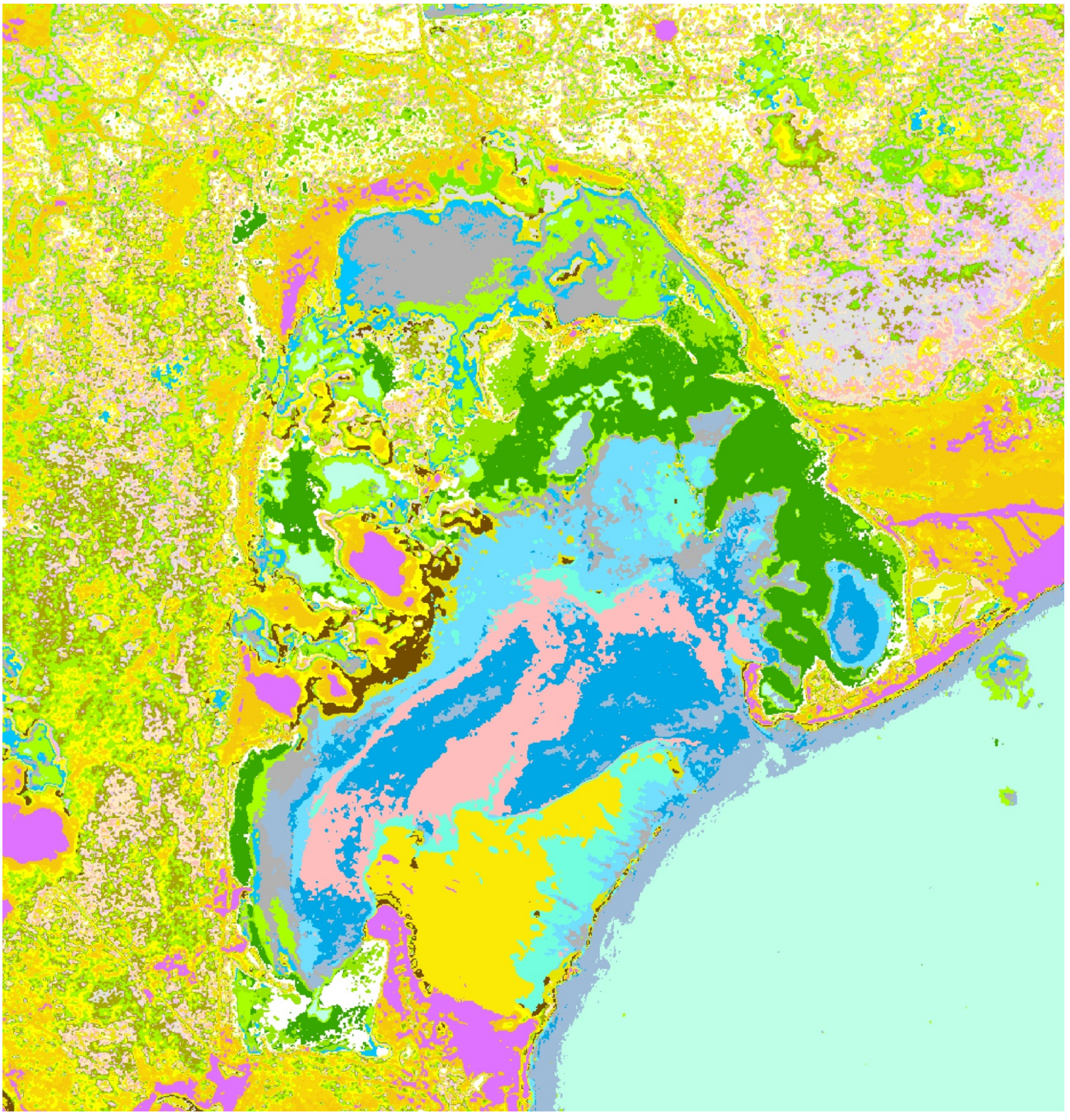


Appendix 5. Classification results

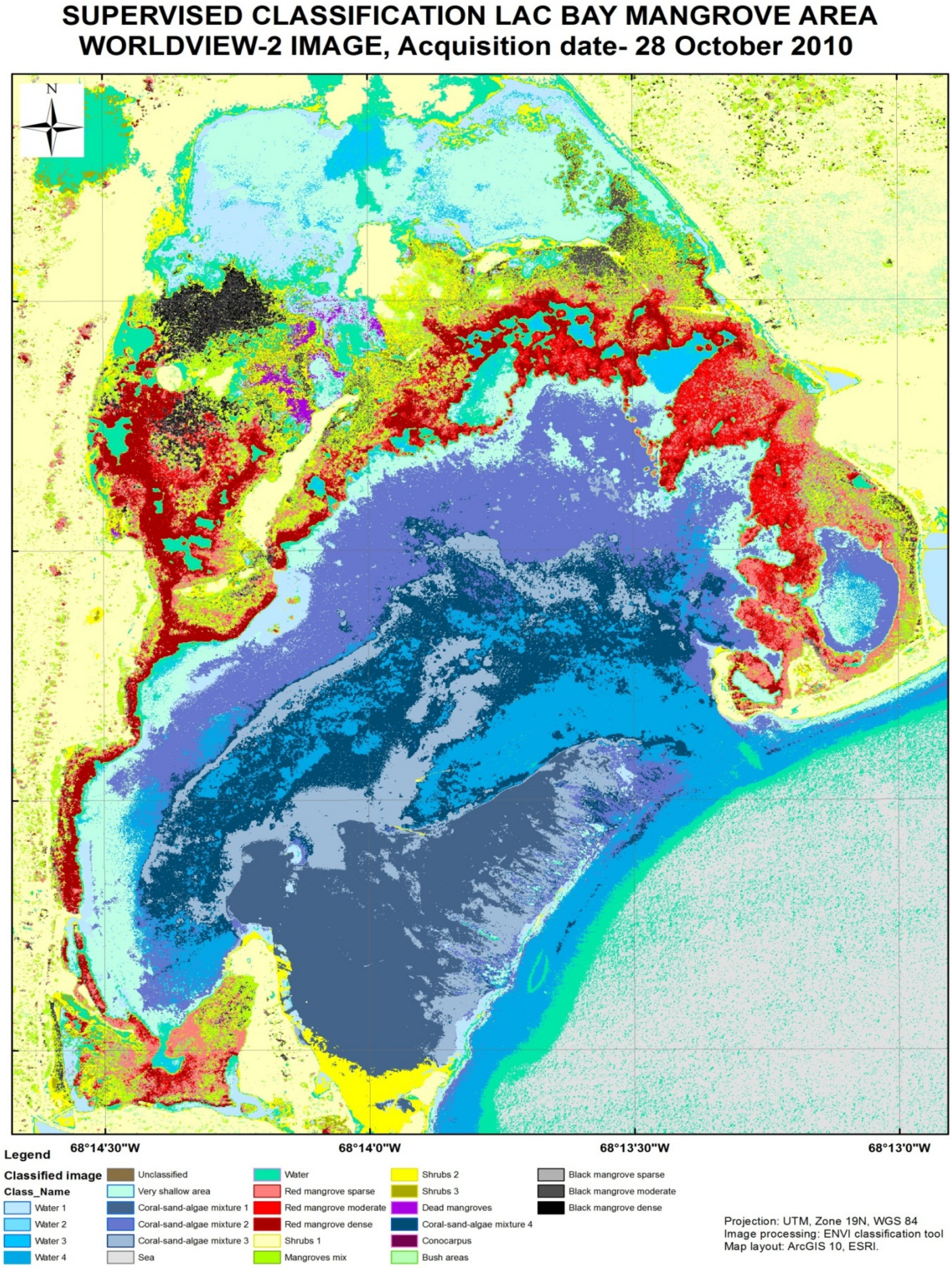
Unsupervised classification WorldView-2 image



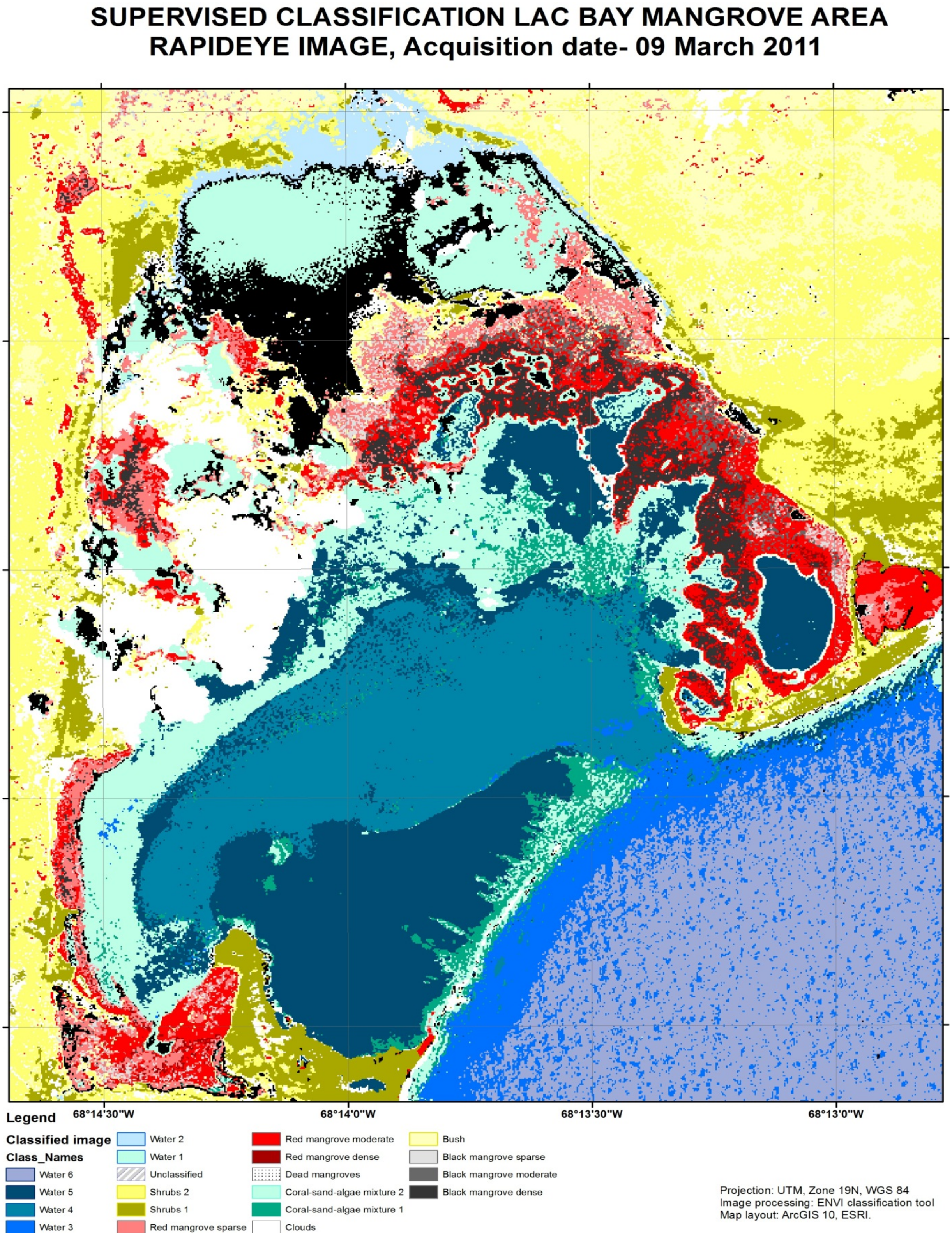
Unsupervised classification RapidEye image



Supervised Classification of WorldView2 image

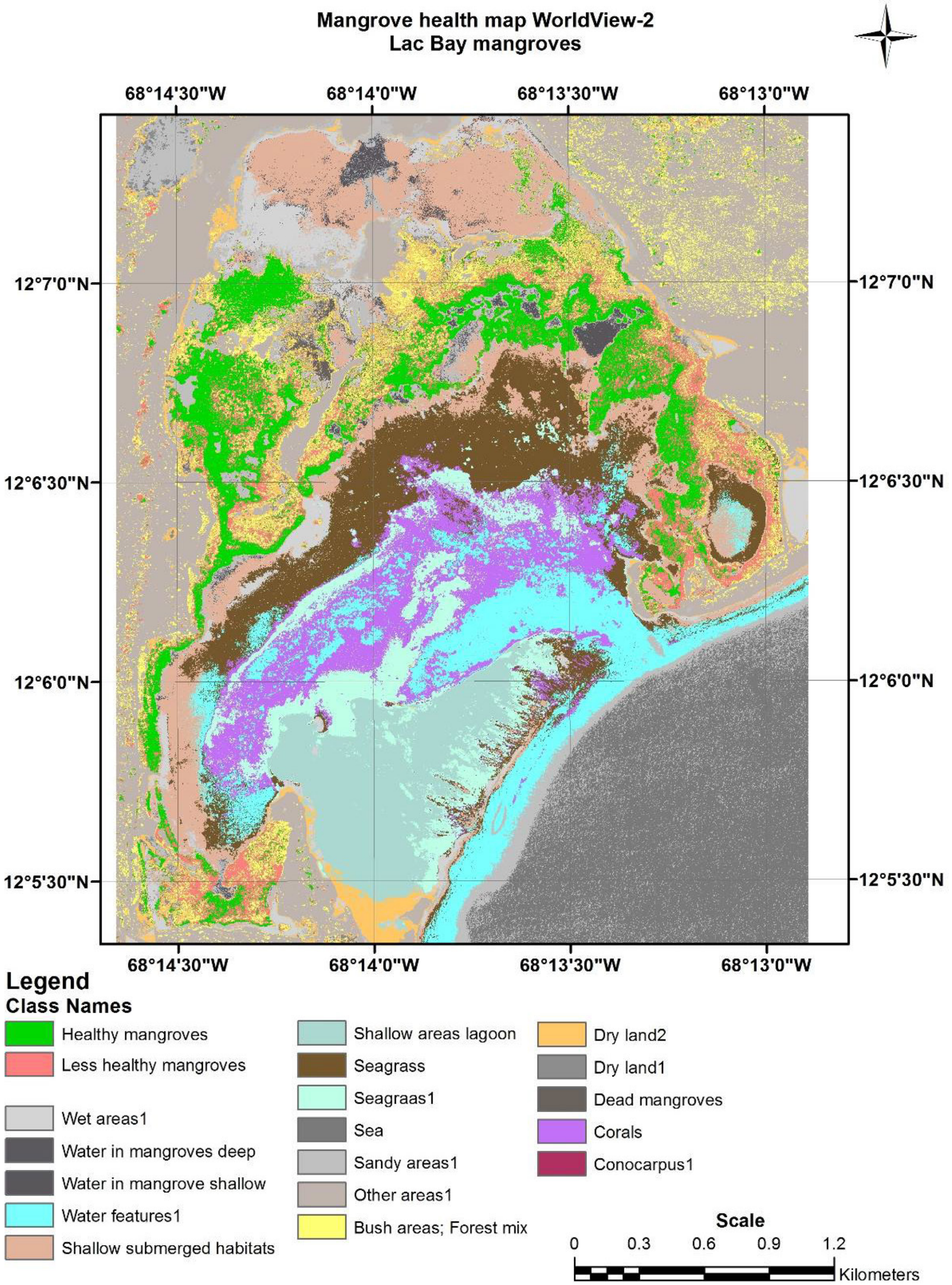


Supervised classification RapidEye data

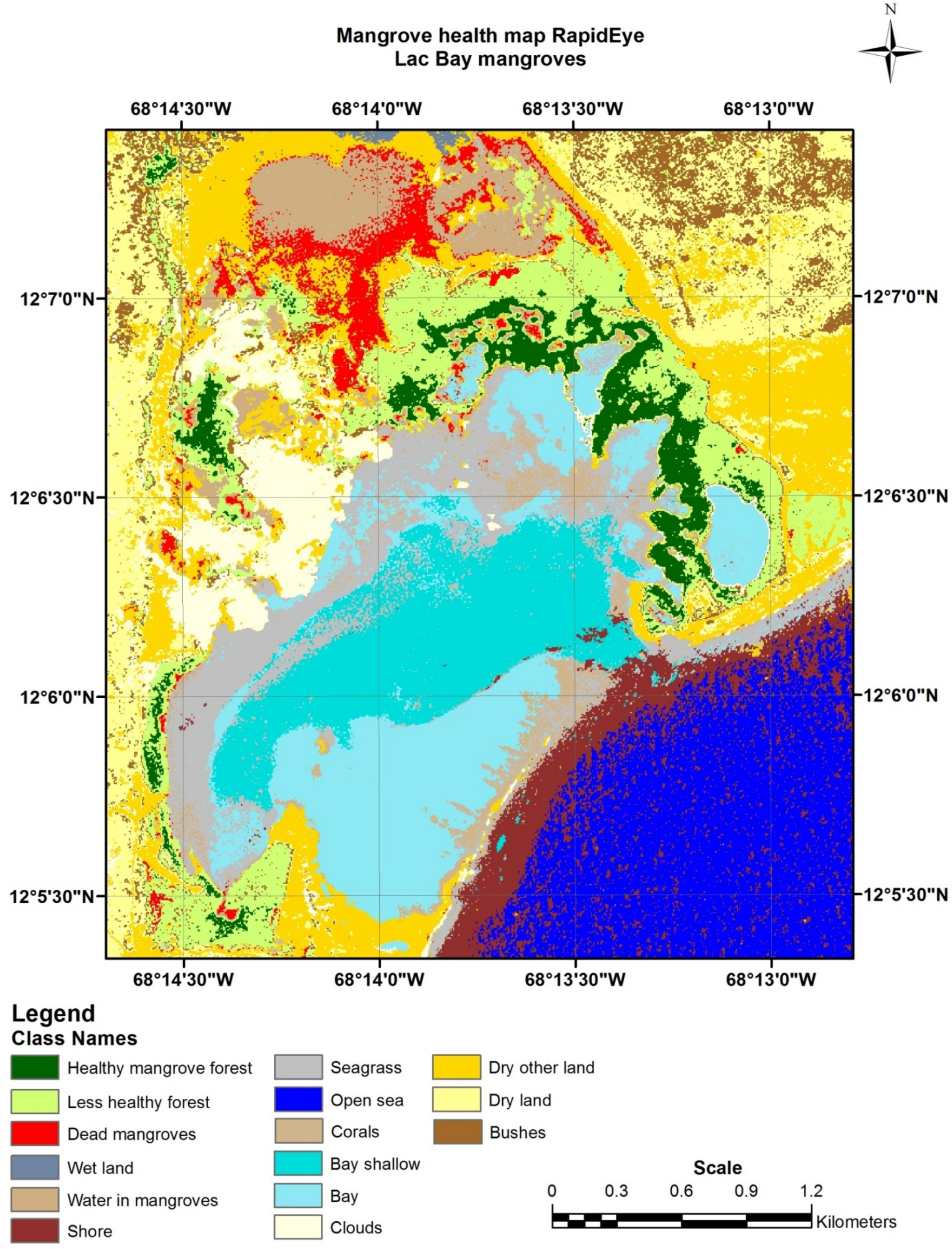


Appendix 6. Mangrove Health

WorldView2



RapidEye


Mangrove health map RapidEye
Lac Bay mangroves
N
68°14'30"W
68°14'0"W
68°13'30"W
68°13'0"W
12°7'0"N
12°6'30"N
12°6'0"N
12°5'30"N
Legend
Class Names
Healthy mangrove forest
Less healthy forest
Dead mangroves
Wet land
Water in mangroves
Shore
Seagrass
Open sea
Corals
Bay shallow
Bay
Clouds
Dry other land
Dry land
Bushes
Scale
0
0.3
0.6
0.9
1.2
Kilometers

Appendix 7. Factors used for atmospheric correction in WorldView-2 and RapidEye image

Absolute scale factors

Band	Absolute scale factor	Effective band width	Conversion factor
WorldView-2			
Coastal: 400-450 nm	0.0092957	0.0473000	0.19652545
Blue: 450 - 510 nm	0.0178357	0.0543000	0.32846556
Green: 510 - 580 nm	0.0136420	0.0630000	0.21653921
Yellow: 585 - 625 nm	0.0058298	0.0374000	0.15587741
Red: 630 - 690 nm	0.0110362	0.0574000	0.19226882
Red Edge: 705 - 745 nm	0.0051881	0.0393000	0.13201364
Near-IR1: 770 - 895 nm	0.0122438	0.0989000	0.1237998
Near-IR2: 860 - 1040 nm	0.0090422	0.0996000	0.09078548
	0.0567835	0.2846000	0.1995202
RapidEye			
Blue: 440-510 nm	0.010000	Not applicable	Not applicable
Green: 520-590 nm	0.010000	Not applicable	Not applicable
Red: 630-685 nm	0.010000	Not applicable	Not applicable
Red Edge: 690-730 nm	0.010000	Not applicable	Not applicable
Near-IR:760-850 nm	0.010000	Not applicable	Not applicable

Acquisition date conversion factors

Universal time UT date of acquisition	Solar zenith angle	Cosines solar zenith angle	Earth sun distance des	Des2
WorldView-2				
15.26795791	29.4	0.871341482	0.99512799	0.990279716
RapidEye				
15.9668405	69.758	0.004149712	0.993814129	0.987666523