2. Theoretical Background

2.1 Optical water quality variables

Water remote sensing is based on the observation and measurement of the light reflected from the water bodies. The most important optical water quality variables which can be estimated with remote sensing are mainly chlorophyll pigments (Chl-a), suspended particulate matter (SPM), dissolved organic matter and secchi disk (turbidity) (Laanen, 2007). The color of surface waters is determined by the concentrations and color spectral characteristics of these constituent compounds, which constitute also the most important water quality parameters. Figure 1, gives us a general overview of the typical reflectance spectrum from a eutrophic lake, showing how different water quality parameters influence water reflected spectrum. We see that in the visible and Near Infra-red (NIR) region (~400-900 nm), active water quality parameters interact with the received radiation, influence and modify the shape and amount of reflected signal. Radiation with wavelengths longer than 900 nm is mostly absorbed by water. Thus, our zone of interest stays in the visible spectrum.

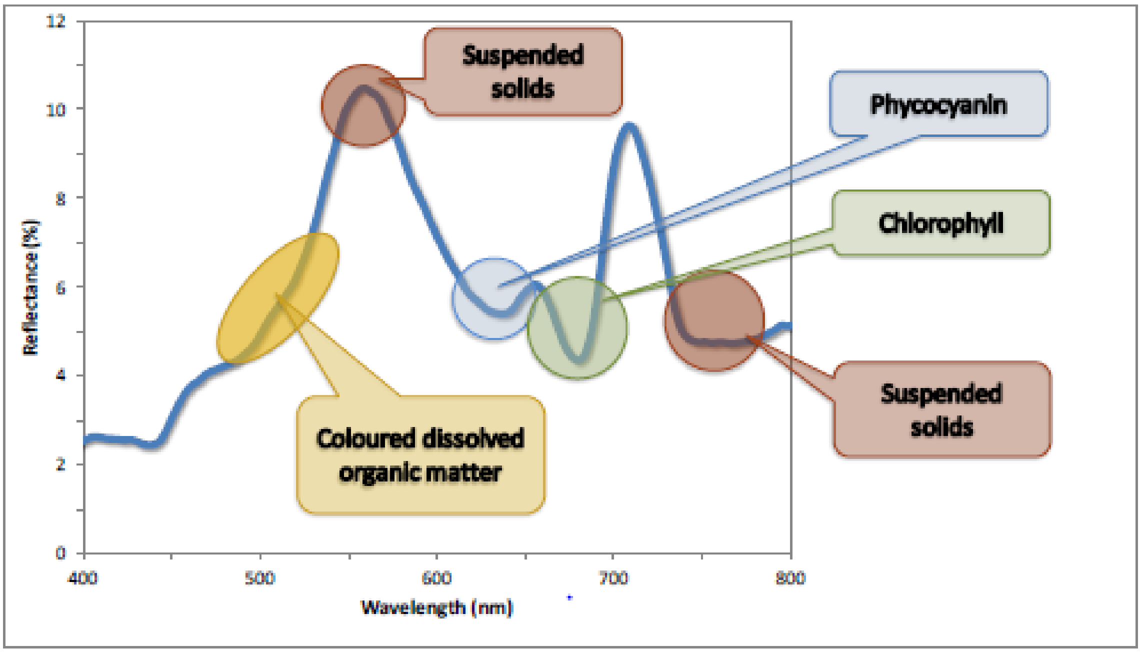

Figure 1: General overview of a typical reflectance spectrum from a eutrophic inland water body showing spectrum influence of different optical active constituent in waters (García, et al., 2016)

Chlorophyll-a, the main constituent of phytoplankton and very important bioindicator of water quality, which will be under the microscope in this study, exhibits a unique spectral absorption signature. This latter is marked by two distinctive peaks, one in the blue region of the spectrum (~433 nm) and another in the red region of the spectrum (~686 nm) (Kirk, 1994). Figure 2 gives the pattern of absorption spectrum of Chl-a and b.

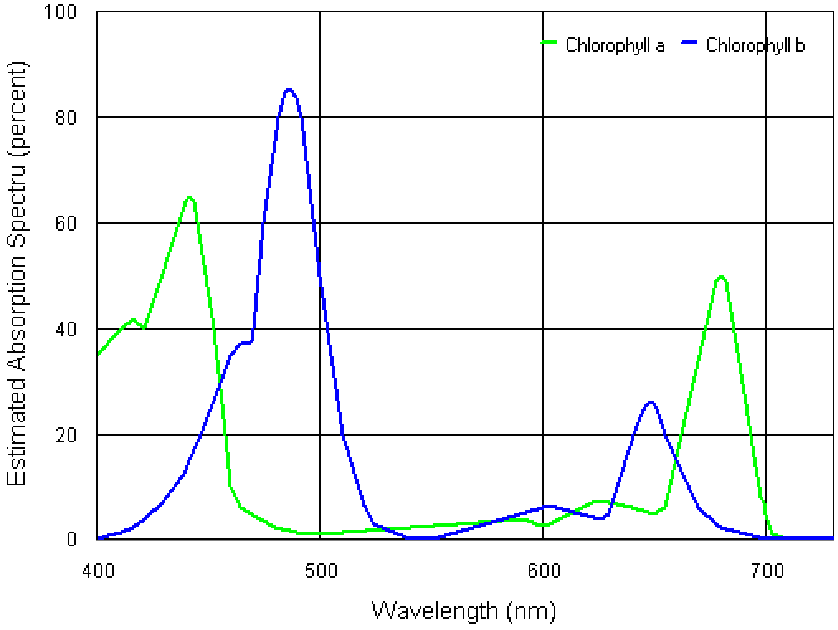

Figure 2: Absorption spectra of Chl-a and b (Raven, et al. , 1976).

Another important point is that we refer to surface waters signal of reflectance. When light passes through water becomes attenuated by interaction with the water column. Penetration of light in the water depends on its wavelength. Figure 3 gives us an overview of light penetration of different wavelengths (blue, green, red). Red light is attenuated quite rapidly reaching max 10-15 meters deep, while blue light penetrates much further reaching up to 30 m deep.

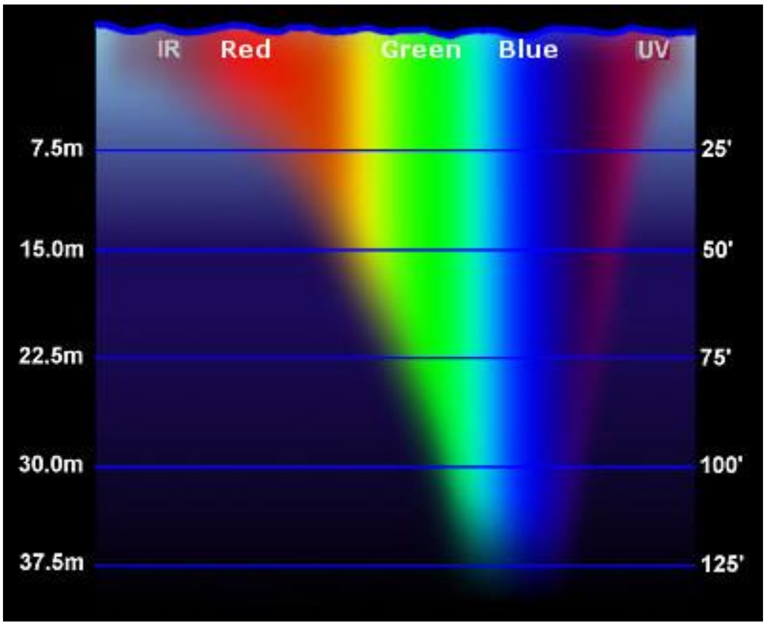

Figure 3: Depths of light penetration into the water (source Tom Morris, Fullerton University, http://goo.gl/hEbSxg)

2.2 Water remote sensing

Water remote sensing refers to water observation from distance in order to describe its color or temperature. This is succeeded with the use of earth observations sensors or satellites. Objects' information is acquired via reflected electromagnetic signals. However, light and color, to which we focus here, are complex features, influenced by absorption, scattering, and emission. The light reaching water surface consists of direct sun light and diffused light after interaction with the atmosphere. At the surface of the water this light is either reflected or refracted. In the water column, the water itself and the different constituents of the water column will interact and transform the light by transmission, absorption, and scatter. Proportion of scattered light upwards, is captured and observed by satellite sensors. Figure 4 gives a schematic illustration of various light interactions involving air, water and substrate.

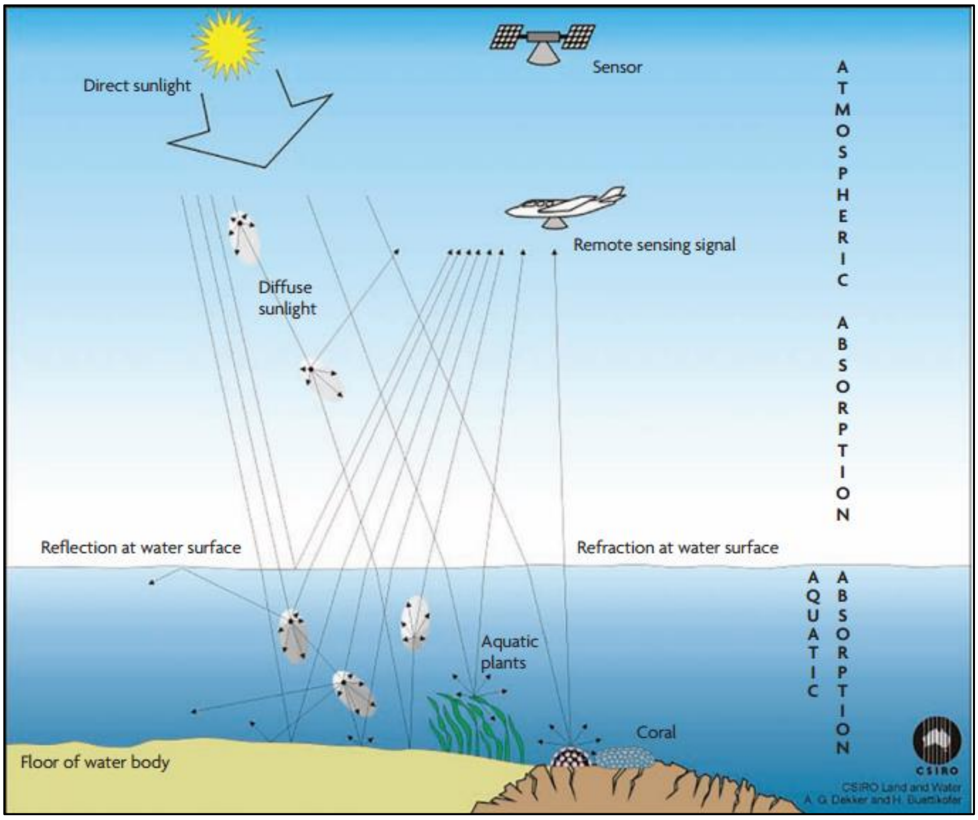

Figure 4: Illustration of light interactions before it is captured by satellite sensors (Dekker, 1993).

As explained in 2.1, in the visible range of light, chlorophyll, suspended particulate matter and other optical quality parameters, interact and modify the shape and amount reflected signal (Dekker, 1993). On the other hand, the received signal from satellites is strongly dependent on the type of satellites, spectral response and band placement. In Figure 5 we can see an indicative schematic illustration of satellites Landsat and MODIS spectral extent, resolution and density. We can see along in the figure the reflectance of different kinds of observed objects (water, soil, vegetation). As explained, for water observation we stay in the visible range of wavelengths. We realize then, that different technical characteristics, resolution, band number and placement between satellites play a key role on the received information.

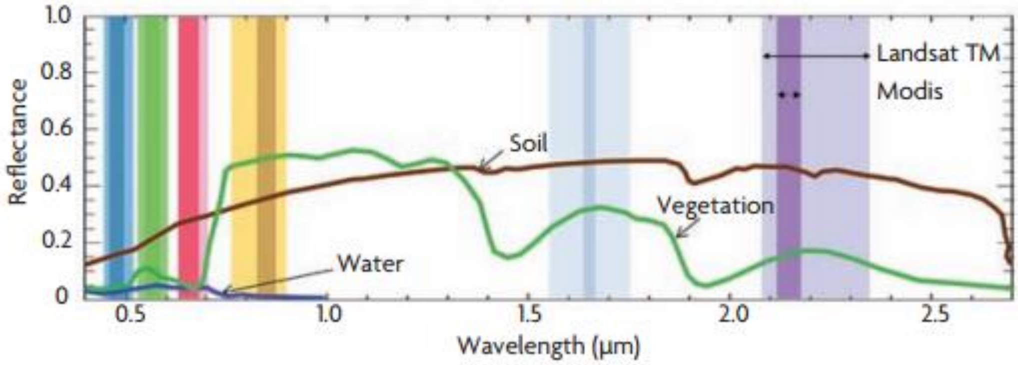

Figure 5: Indicative illustration of spectral extent, resolution and density for Landsat and MODIS satellites superposed to reflectance of different observed objects (Dekker, 1993).

In order to translate measured spectral reflectance received from water bodies, into concentrations of water quality variables, there has been developed a series of satellite images algorithms (Laanen, 2007). These algorithms consist of multispectral transformations of satellite data, whose aim is to convert measured radiances to thematic variables. The idea is to decrease the quantity of available data by keeping only the useful proportion, according to what we need to observe. These tools use radiances or reflectance of different channels, which are represented by the different bands of multispectral satellite data. With reference to the different observed objects' reflectance proprieties, the different algorithms look for the best combination of bands that will give the best possible and most accurate translation of information. With respects to water observation, as discussed in 2.1, the bands of the visible range of the spectrum (~400-700 nm) interests us the most, with respects to light interaction with the constituent optical active components. However, a large number of multispectral transformation are based on the bands corresponding to red (600-700 nm) and near infrared (NIR) (700 nm-1mm) spectrum (Figure 6), since it's between those two bands that we can observe the biggest reflectance differences between vegetation and ground or water.

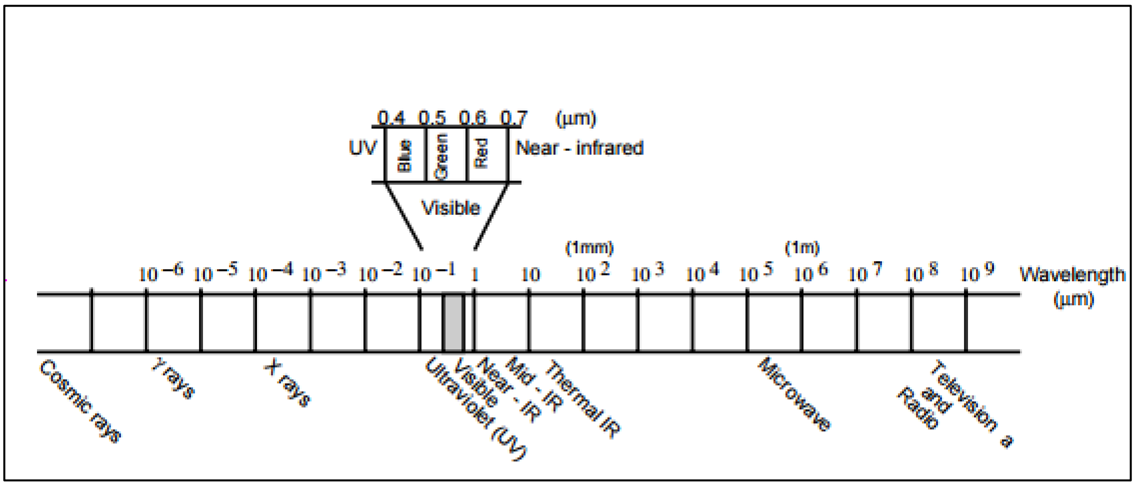

Figure 6: The electromagnetic spectrum (Lillesand & Kiefer, 1987).

In Figure 7 we can see an indication of reflectance spectra of chlorophyll and water, amongst other features. The reflectance of clear water is generally low. Nonetheless, the reflectance is maximum at the end of blue and decreases as the wavelengths increase. Water constituents mostly interact with light in the visible range and water completely absorbs light for wavelength longer than 900 nm. Turbid water, with dissolved non algal particles interacts with light increasing the reflectance, which is higher outside the blue region that mostly absorb. Reflectance of bare soil depends on its composition. Vegetation, whose main constituent is Chl-a, has a unique spectral signature. Reflectance is low on both red and blue regions (as chlorophylls have two absorption peaks between 400-500 nm, the blue region, and 600-700 nm, the red region as seen in Figure 2 before) and high at the green region (500-600 nm). Reflectance of vegetation in the NIR is much higher than in the visible due to its cellular structure, which do not use wavelengths longer than 700 nm (Chin, 2001). Generally, reflectance differences between the Visible and NIR can distinguish different vegetation types. Finally, overlapping absorptions of dissolved non algal particles of the water and Chl-a in the blue region, renders the blue to green bands inaccurate for evaluation of Chl-a. Hence, relevant assumptions are based mainly on the red and NIR channels.

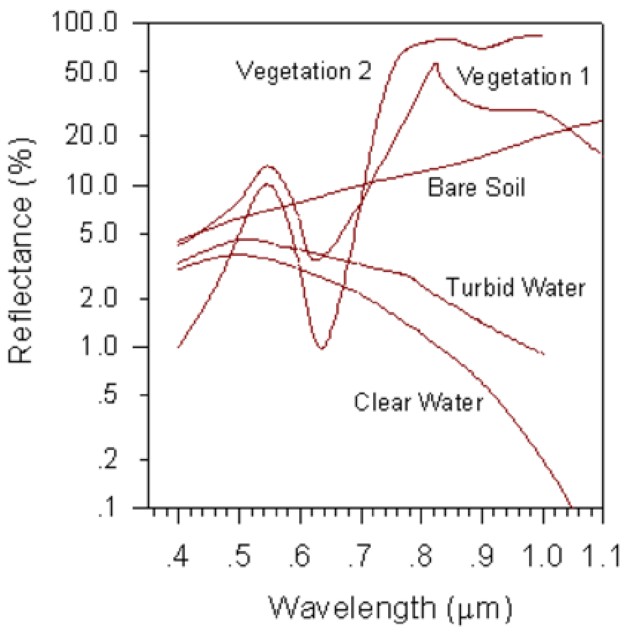

Figure 7: Reflectance spectra of various types of land cover (Chin, 2001)

In the current study we included two main satellite algorithms, the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI) and some specific chlorophyll indexes based on literature. Besides these wildly used indexes, there is the possibility to reveal required information from the arithmetic combination (division or other) of different canals in the form of band ratios. Moreover, there is the possibility to use band combinations in order to create RGB color composites, which are specifically tailored to facilitate the identification of features of interest. Using these, we will tend to analyze data received from satellites Sentinel-2A and Landsat, whose technical characteristics and details are given hereafter.

2.3 Sentinel-2 satellite missions

The European Space Agency is developing a new series of seven satellite missions under the Sentinel program. The Sentinel missions consist of next-generation earth observation missions with radar and multi-spectral imaging instruments, each focusing on a different aspect, atmospheric, oceanic or land monitoring. Each mission is based on the implementation of two sets of satellites in order to fulfill best revisit and coverage requirements, providing this way robust datasets for use in many applications.

Sentinel-2 is a multispectral high-resolution imaging mission whose objective is land monitoring, including vegetation, soil and coastal areas. It will be composed of two polar-orbiting satellites, with the first Sentinel-2A having been already launched in June 2015 and Sentinel-2B following, in the second half of 2016 (ESA, European Space Agency , 2016). The twin satellites will be flying in the same orbit phased at 180º to each other, designed to give high revisit frequencies. The mean orbital altitude of the satellites is 786 km and they will acquire data over land and coastal areas including islands, the Mediterranean Sea, inland water bodies and closed seas (Figure 8).

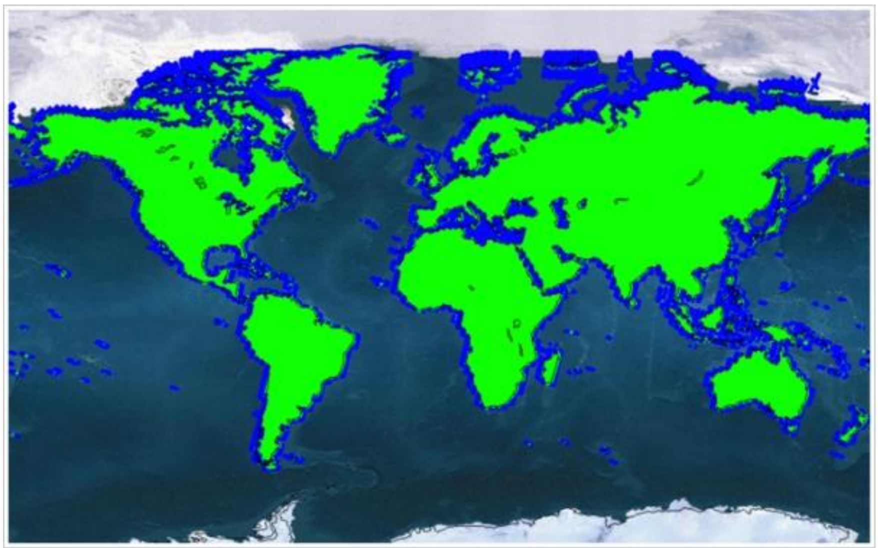

Figure 8: Modelled Sentinel 2 coverage at full operation (ESA, European Space Agency , 2016)

The Multispectral Instrument they use works passively collecting sunlight reflected from earth. Thereafter, the incoming light beam is separated in two different assemblies one for the visible and for the NIR bands and another one for the Short Wave Infra-Red (SWIR) bands.

High spatial and spectral resolutions of Sentinel satellites are of great interest, as their combination is the most important advantage they have over heritage satellites. To be more precise, Sentinel-2A, already in orbit, using as described a MSI sensor, measures earth reflected radiance in 13 spectral bands, spanning from the visible and NIR to SWIR. The spatial resolution of bands, meaning the detail in a photographic image visible to the human eye, varies from 10 to 60 m as follows (Gatti & Bertolini, 2015):

- 4 bands at 10 m: blue (490 nm), green (560 nm), red (665 nm) and NIR (842 nm)
- 6 bands at 20 m: 4 narrow bands for vegetation characterization (705nm, 740nm, 783 nm and 865 nm
- 2 larger SWIR bands (1610 nm and 2190 nm), for snow, ice, cloud detection or vegetation moisture stress assessment
- 3 bands at 60m for cloud screening and atmospheric corrections (443 nm for aerosols, 945 for water vapor and 1375 nm for cirrus detection)

Table 1 provides a detailed description of spectral resolutions (bandwidth) and their ability to resolve features in the electromagnetic spectrum.

Table 1: Wavelengths and bandwidths of the MSI system of Sentinel-2 (ESA, 2016).

Spatial Resolution (m)	Band Number	Central Wavelength (nm)	Bandwidth (nm)
10	2	490	65
	3	560	35
	4	665	30
	8a	842	115
20	5	705	15
	6	740	15
	7	783	20
	8b	865	20
	11	1 610	90
	12	2 190	180
60	1	443	20
	9	945	20
	10	1 380	30

Figure 9 shows MSI spectral bands of Sentinel-2A versus their spatial resolution.

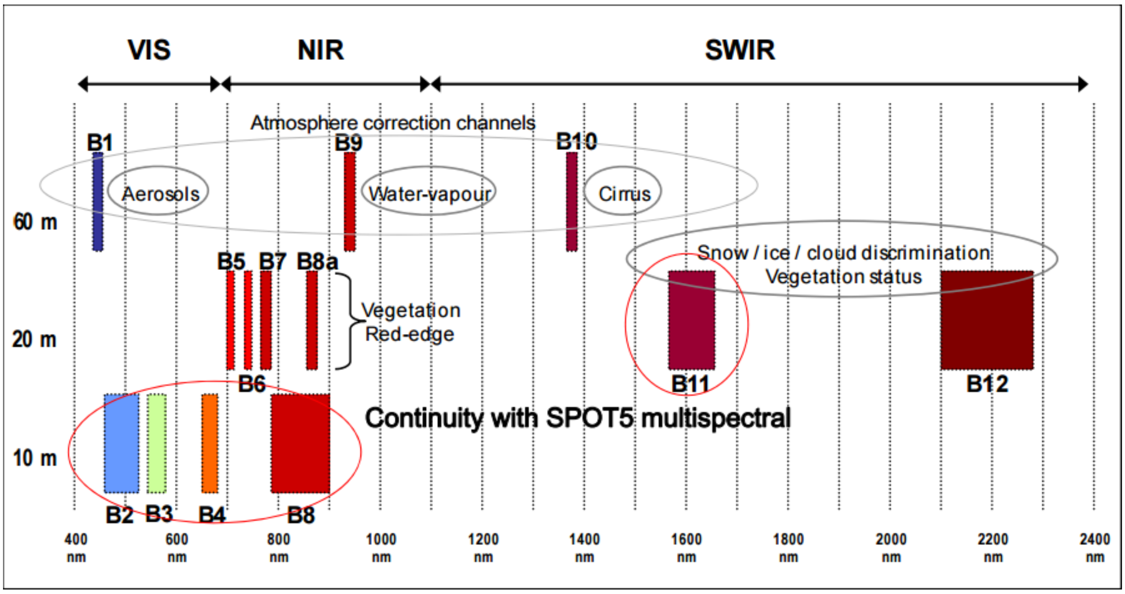

Figure 9: MSI spectral bands distribution and width along with their spatial resolution. (Gatti & Bertolini, 2015)

The system uses 12 optical detectors whose configuration results to a ground coverage swath width of 290 km. Radiometric resolution, which is the capacity of the instrument to distinguish light reflectance differences, is 12 bit, which enables an acquired image with a range of 0 to 4095 light intensity values or pixels.

Temporal resolution is another important aspect of Sentinel-2 satellites, as mentioned. All areas indicated before (Figure 8), will be revisited every 5 days in full operation of the two satellites. Currently Sentinel-2A is in a 10-day repeat cycle.

Sentinel-2 missions build directly on a unique and proven heritage of Landsat missions orbiting for more than 40 years. Spectral bands' configuration of the Sentinel-2 satellites is developed around services provided by Landsat 7, 8 and Spot wavelengths. In the next chapter we will give a short comparison's overview of the main characteristics of the two different satellite missions.

2.4 Comparison of Landsat-Sentinel technical characteristics

For more than 40 years, the NASA-USGS (United States Geological Survey) Landsat missions have provided the longest temporal record of earth observation data. Overall they have provided a remarkable unbroken record. Landsat 1 was launched in 1972, with an unstopped continuity from Landsat 1 to 7 (Figure 10).

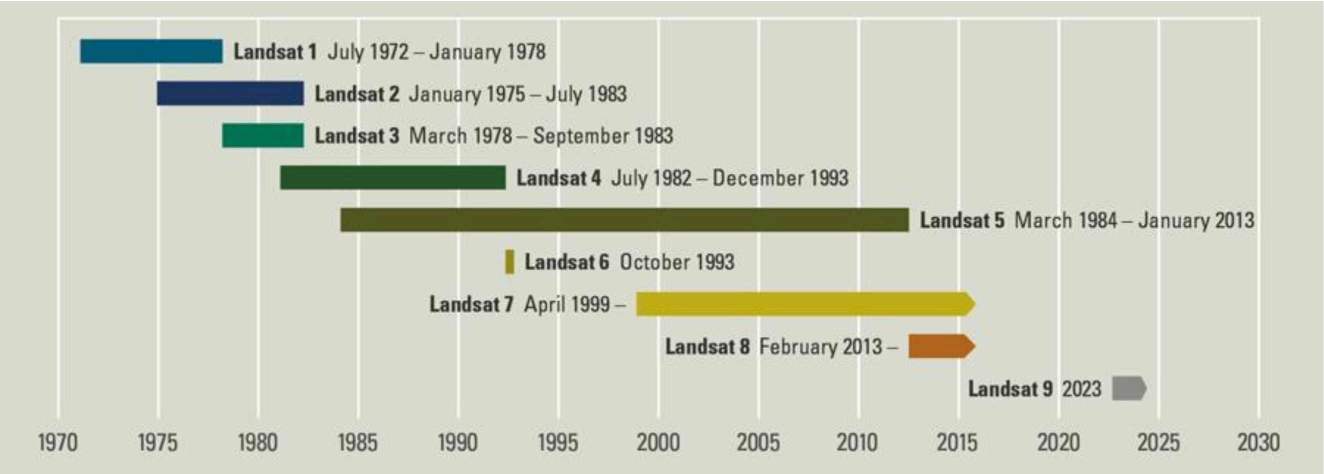

Figure 10: Landsat mission imaging the earth since 1972 until today and future (USGS, Landsat Missions, 2016).

Landsat 7 Enhanced Thematic Mapper (ETM+) launched in 1999, consists of 8 spectral bands with a spatial resolution of 30 m, for bands 1 to 7 and 15 m for band 8 (Table 2).

Table 2: Wavelengths and band resolution of Landsat 7 ETM+ (USGS, Landsat Missions, 2016).

Enhanced Thematic Mapper Plus (ETM+)	Landsat 7	Wavelength (micrometers)	Resolution (meters)
	Band 1	0.45-0.52	30
	Band 2	0.52-0.60	30
	Band 3	0.63-0.69	30
	Band 4	0.77-0.90	30
	Band 5	1.55-1.75	30
	Band 6	10.40-12.50	60 * (30)
	Band 7	2.09-2.35	30
	Band 8	.52-.90	15

Landsat 8 launched in 2013, consists of 9 spectral bands with again a spatial resolution for most bands of 30 m (Table 3). This satellite consists of two sensors providing improved signal-to-noise radiometric performance. Band placement and width were also improved enabling better characterization of land cover condition and changes.

Table 3: Wavelengths and band resolution of Landsat 8 (USGS, Landsat Missions, 2016).

Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)	Bands	Wavelength (micrometers)	Resolution (meters)
	Band 1 - Coastal aerosol	0.43 - 0.45	30
	Band 2 - Blue	0.45 - 0.51	30
	Band 3 - Green	0.53 - 0.59	30
	Band 4 - Red	0.64 - 0.67	30
	Band 5 - Near Infrared (NIR)	0.85 - 0.88	30
	Band 6 - SWIR 1	1.57 - 1.65	30
	Band 7 - SWIR 2	2.11 - 2.29	30
	Band 8 - Panchromatic	0.50 - 0.68	15
	Band 9 - Cirrus	1.36 - 1.38	30
	Band 10 - Thermal Infrared (TIRS) 1	10.60 - 11.19	100
	Band 11 - Thermal Infrared (TIRS) 2	11.50 - 12.51	100

Swath width resolution of both satellites is 185 km and their revisit frequency 16 days. Radiometric performance of Landsat 7 is 8-bit, which translates into 256 levels of grey. Landsat 8 radiometric performance as well as Sentinel-2 series, quantize over a 12-bit dynamic range. This refers to 4096 potential grey levels.

The launch of Sentinel 8 ensured a continuous data availability, which is extremely important for earth observation. Landsat 8 records are comparable to other Landsat records and as stated Sentinel missions were built taking into account this legacy. However, since new missions are relatively new, there are no comparison studies between the two so far. As already seen, satellite sensors operate on different and various spatial, spectral and temporal resolutions. Different band placements and sensitivities and different spatial resolutions may give different results with reference to optical active constituents in the same water bodies. Figure 11 shows the placement of Sentinel-2 bands, compared to Landsat 7 and 8 bands.

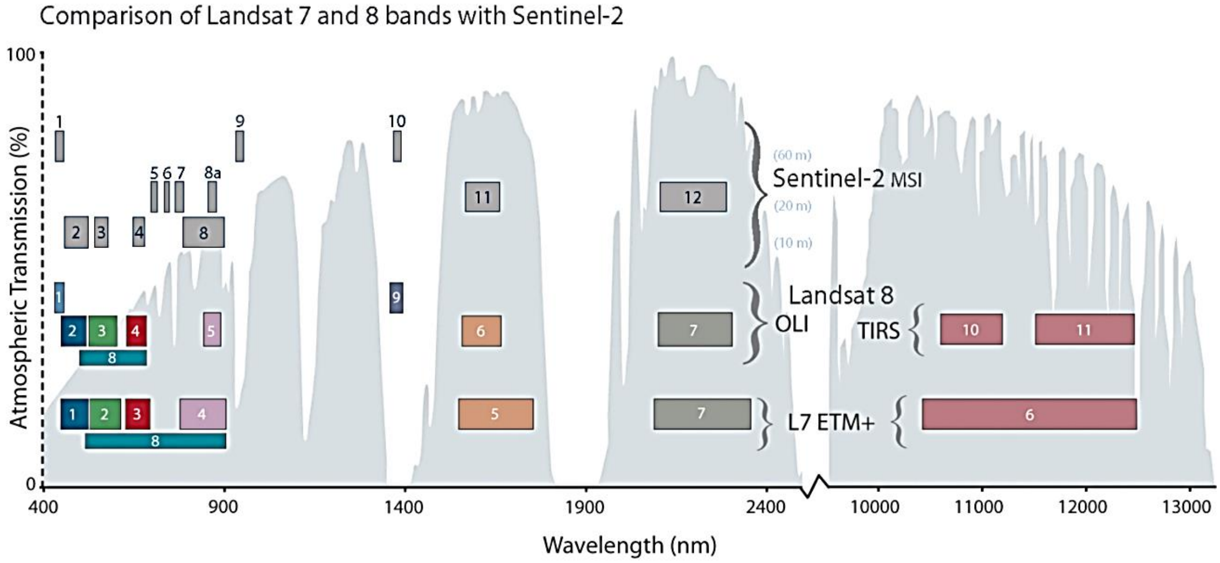

Figure 11: Comparison of Landsat 7 and 8 with Sentinel-2 bands placement (source: http://landsat.gsfc.nasa.gov/)

We can see that band configuration between Landsat 7 and 8 has changed, however with the same spectral resolution. Sentinel-2 compared to Landsat 7 bands placement and spectral resolution is a lot different, with Sentinel-2 having more bands, more careful placement of spectral bands (placement and width), thus higher spectral resolution. A successful application of the above differences in characteristics has the potential to lead on one hand, an increasing number of optical active constituents that can be detected and on the other hand stronger correlations with AOCs concentrations.