POLITECNICO DI TORINO

Faculty of Engineering
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Masters Degree Thesis

Irrigation volume assessment via Remote Sensing and Cloud Engine tools

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Abstract

The agricultural sector has a lead role on most developing countries, being its main source of national income. In Europe, grassland and cropland make up 39% of European land cover *(EEA, 2017) [1]*, playing an important part in land use patterns. In addition to providing food and raw material, agriculture also provides employment opportunities to a large percentage of the population. Furthermore, this sector is highly related to the environment, by being one of the biggest users of natural resources, for example through irrigation, where agriculture consumes more than 50% of the water used in Europe.

On the one hand, agriculture is experiencing a demand increment due to the population growth, which implies a bigger need of resources. On the other hand, because of climate change, rainfall is getting increasingly irregular, leading to droughts and water shortage. Due to all these issues, it is essential to find a way to optimize and control the water used for irrigation. Under this framework, several systems and tools have been evaluated to help facing the problem. Remote sensing resources seems to be able to provide some solutions due to their capacity of global analysis and to the ever-increasing amount of good data, among other benefits.

The main objective of this thesis is to set a base-line from where a soil moisture estimation product can be developed via remote sensing and cloud engines. The soil moisture estimations will be used to control irrigation volumes in the North of Italy, specifically in the Piedmont region. This main objective can be divided into three main tasks: i) analysis of all the technologies and techniques potentially useful in soil moisture estimations; ii) selection of the proposals that better fulfil the requirements of the project and iii) application of the selected technologies to calculate the soil moisture estimations.

The analysis of the first task, which will now be discussed., has been developed in three main areas: remote sensing, both satellites and products, cloud engines and mathematical models and algorithms that can be applied to estimate soil moisture from satellites observations.

Firstly, among all the existing remote sensing technologies, three of them required a special mention because of their contributions, both past, present and future, to the soil moisture estimations field. They are the Soil Moisture Active Passive (SMAP) Satellite launched by the NASA, the Soil Moisture and Ocean Salinity (SMOS) Satellite launched by the European Space Agency (ESA) and the Sentinel Satellite Constellation currently being developed as part of the Copernicus program by the ESA and the European Commission. Agricultural applications need a spatial resolution around the dozens of meters to be able to give useful results. SMOS and SMAP satellites spatial resolution is between 30 to 50 km, therefore, they do not fulfil the spatial resolution requirements of this project. However, Sentinel 1 satellite, which is among the Sentinel constellation the satellite that can be related with soil moisture, has a spatial resolution of 10 meters, and therefore can be used to develop the thesis.

Regarding remote sensing products, though those already developed by Copernicus for soil moisture estimations are commonly used, their spatial resolution is not high enough. Therefore, to achieve the objectives of this project it was necessary to develop, in a cloud engine tool, a method to estimate soil moisture from raw satellite data.

The two main cloud engines available to develop this kind of project, are Google Earth Engine (GEE), developed by Google, and Copernicus Climate Change Service (C3S), developed by the Copernicus program. Both of them, being free of charges, allow the processing of raw data online. However, C3S programming language is less intuitive than GEE, which uses Java. Moreover, the guidelines found for GEE were more complete, with more examples and detailed explanations of the possible functions that could be implemented. Therefore, GEE was the cloud engine selected to develop this thesis. It is important to highlight, that despite all of this, both platforms are barely new, which brings along several restrictions on the possible applications that can be created.

Moreover, the three main methods available to estimate soil moisture from raw satellite data are: Neural Networks (NN), Water Cloud Models (WCM) and Change Detection (CD) methods. NN and WCM are more accurate, but need soil moisture in-situ measurements or previous data of the area in order to train and calibrate the models. Due to the lack of this previous data they cannot be applied in this thesis. CD methods can be divided in two groups, according to the application of the NDVI. Using NDVI in the method will suppose an increase in the accuracy of the results. Due to programming limitations of the Google Earth Engine platform, it was not possible to apply this vegetation index.

Once the selected method was applied in GEE, a soil moisture estimation product (C-SM) was obtained. The next step was the validation of this product, which was carried out using another soil moisture estimation product (2C-SM) from a French project *(Hassan Bazzi, 2019) [61]*. In the validation process, the average of all the RMSD errors obtained was of 8,57 %vol, which has been considered as a correct result, because of the three following reasons: firstly, 2C-SM data have a RMSD error between 6 %vol to 8 %vol. Moreover, the French project had at their disposal in-situ measurements, which allowed them to applied NN and WCM. Finally, the CD method applied did not consider the NDVI, as it was explained previously.

Taking into account all these considerations, the validation errors obtained in this project are considered low enough to perform different analyses on the soil moisture estimations in order to prove the level of accuracy of the method applied. The two-analysis performed to the C-SM were the followings:

1. **Cell analysis.** Its aim was to be able to distinguish between agricultural and non-agricultural areas. In general, it was possible to identify almost all the houses and large tree areas from the agricultural fields.

2. **Irrigation, rainfall and soil moisture comparison.** The aim of this analysis was to understand the variations of soil moisture caused by the irrigation and rainfall water volumes. In overall, the water volumes of both, irrigation and rainfall, were coherent with the soil moisture changes.

As a summary, from the validation process it can be concluded that the RMSD error was inside the limits permitted. In addition, due to the great results of the analysis carried out to these estimations, it can be concluded that applying the selected method to obtained C-SM estimations has led to considerably high accurate soil moisture results.

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Abbreviations and units

Abbreviations

ESA	European Space Agency
SM	Soil Moisture
TDR	Time-Domain Reflectometry
IFOV	Instantaneous Field of View
AATSR	Advanced Along-Track Scanning Radiometer
ASAR	Advanced Synthetic Aperture Radar
DORIS	Doppler Orbitography and Radio-positioning Integrated by Satellite
GOMOS	Global Ozone Monitoring by Occultation of Stars
LRR	Laser Retro Reflector
MERIS	Medium-Resolution Visible and Near-IR Spectrometer
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MWR	Microwave Radiometer
RA-2	Radar Altimeter 2
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SMOS	Soil Moisture and Ocean Salinity
SSS	Sea Surface Salinity
CATDS	Centre Aval de Traitement des Données
MIRAS	Microwave Imaging Radiometer using Aperture Synthesis

❖ SMAP	Soil Moisture Active Passive
❖ SM	Stripmap
❖ IW	Interferometric Wide swath
❖ EW	Extra-Wide swath
❖ WV	Wave mode
❖ OLCI	Ocean and Land Colour Instrument
❖ SLSTR	Sea and Land surface Temperature Radiometer
❖ SRAL	SAR Radar Altimeter Intrument
❖ MWR	Microwave Radiometer
❖ MSI	MultiSpectral Instrument
❖ TROPOMI	TROPOspheric Monitoring Instrument
❖ FAPAR	Fraction of absorbed photosynthetically active radiation
❖ LAI	Leaf Area Index
❖ LCC	Leaf Chlorophyll Content
❖ LWC	Leaf Water Content
❖ SAR	Synthetic Aperture Radar
❖ SST	Sea Surface Temperature
❖ FRP	Fire Radioactive Power
❖ LST	Land Surface Temperature
❖ AOD	Aerosol Optical Depth
❖ SSH	Sea Surface Height
❖ SWH	Significant Wave Height
❖ SRAL	Altimeter

- POD — Precise Orbit Determination
- GNSS — Global Navigation Satellite System
- DORIS — Doppler Orbitography and Radio-positioning Integrated by Satellite
- LRR — Laser Retro reflector
- TOA — Top of Atmosphere
- MEP — Mission Exploitation Platform
- EU — European Union
- GMES — Global Monitoring for Environment and Security
- EUMETSAT — European Organization for the Exploitation of Meteorological Satellites
- CAMS — Copernicus Atmosphere Monitoring Service
- CMEMS — Copernicus Marine Environment Monitoring Service
- CLMS — Copernicus Land Monitoring Service
- C3S — Copernicus Climate Change Service
- CEMS — Copernicus Emergency Management Service
- ETc — Evapotranspiration
- ERC — ERATOSTHENES Research Centre
- CH — Crop Height
- NDVI — Normalized Differentiate Vegetation Index
- ECV — Essential Climate Variables
- GEE — Google Earth Engine
- NN — Neural Network
- WCM — Water Cloud Model
- CD — Change Detection

- ❖ IEM Integral Equation Model
- ❖ ADLC Absolute Difference between like and cross
- ❖ CDF Cumulative Distribution Function
- ❖ RMS Root Mean Square
- ❖ ubRMSD unbiased Root Mean Square Difference

Units

- ❖ Watts (W) Radiance
- ❖ - Reflectance
- ❖ Mm/time unit Evapotranspiration
- ❖ %vol Soil Moisture
- ❖ dB Backscattering

1. Introduction

1.1. Project Motivation

The agricultural sector has a lead role on most developing countries, being its main source of national income. In Europe, grassland and cropland make up 39% of European land cover *(EEA, 2017) [1]*, playing an important role in land use patterns. In addition to providing food and raw material, agriculture also provides employment opportunities to a very large percentage of the population.

Furthermore, this sector is highly related with the environment, by being one of the biggest users of natural resources, for example through irrigation, where agriculture consumes more than 50% of the water used in Europe.

On the one hand, agriculture is experiencing a demand increment due to the population growth, which implies a bigger need of resources. On the other hand, because of climate change, rainfall is getting more and more irregular causing droughts and a lack of water.

Due to all these issues, it is essential to find a way to optimize and control the water used for irrigation. Under this framework several systems and tools have been evaluated to help facing the problem. Remote sensing resources seems to be able to provide some solutions due to their capacity of global analysis and to the ever-increasing amount of good data, among other benefits.

One of the possible ways to face the issue is to create a remote sensing product able to estimate the soil moisture of a region with agriculture fields, to provide a better control over the irrigation process. These estimations, will also give valuable information of the state of the soil crops, as well as the vegetation health. In addition, it can help assessing how much rain has fed the soil *(Brocca, 2014) [2]*.

Figure 1. Open Copernicus Sentinel-2 Data turned into a global mosaic *[3]*

Soil moisture estimations from remote sensing have a long history, see chapter 3. Due to the progress this sector has gone through, it is possible nowadays to fully develop an application working with the necessary data on a Cloud Engine environment, without having to download the satellite data on a personal computer. In addition, it has become possible to automatize this application on several platforms, in order to have a product that can be globally used. Furthermore, it is possible to combine data coming from different satellites in order to obtain a product with a better spatial resolution. This has marked an inflection point for the usefulness remote sensing data can have while designing products.

On the framework of this project, these improvements have come through the Copernicus Program, which is a program created and coordinated by the European Commission in partnership with the European Space Agency (ESA).

The aim of Copernicus program is to achieve a global, continuous, autonomous, high quality, wide range Earth observation capacity and providing accurate, timely and easily accessible information to improve the management of the environment, understand and mitigate the effects of climate change, and ensure civil security *(Copernicus Program) [25] [30]*. It is important to underline that agriculture is considered one of the most promising markets in terms of the impact of Copernicus, which is one of the main reasons of the development of this project. The most promising areas of development of new knowledge and operational products of Copernicus in the agricultural sector are precision farming, helping assessing land use and trends, crop conditions, yield forecast and irrigation management. Furthermore, it is centered in subsidy controls, seasonal maps and water manager and drought monitoring *(Copernicus Impacts in Agriculture [4])*.

The main benefit of the Copernicus program is that the data and information produced in its framework are made available on a free-of-charge basis to all its users. Regarding the agricultural sector, Copernicus information has already been implemented in different projects within different application areas, as documented in *VVAA (2018) [5]*.

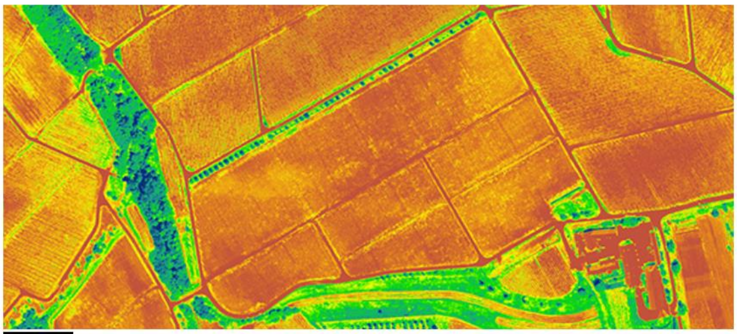


Figure 2. Mapping of vineyards with aerial remote sensing technologies *[6]*

1.2. Objectives

The main objective of this project is setting a base-line from where a soil moisture estimation product can be developed via remote sensing and cloud engines. The soil moisture estimations will be used to control irrigation volumes in the North of Italy, specifically, in the Piedmont region.

This main objective can be divided in three secondary ones:

1. Analysis of all the technologies and techniques that can be useful to achieve the soil moisture estimations. This analysis will be carried out in the areas of remote sensing,

cloud engines and mathematical models and algorithms that can be applied to estimate soil moisture from satellites observations.

2. Selection of the proposals that better fulfil the requirements of the project.

3. Application of the selected technologies to calculate the soil moisture estimations.

1.3. Thesis planning

The document will be organized in the followings nine chapters. The chapter 2 will give an overall view of the applications of remote sensing on the agriculture sector, as well as, a huge number of remote sensing techniques and technologies. Among these techniques and technologies, the ones needed to achieve the objectives of the project will be selected. In addition, in chapter 3, some examples of real applications of the techniques and technologies mentioned above will be shown, in order to demonstrate the scope of remote sensing in agriculture. Chapter 4 corresponds to the analyses of the possible cloud engines platforms that can be used to develop the project. Furthermore, in chapter number 5, the existent mathematical methods and algorithms to estimate soil moisture from satellites measurements will be explained. Moreover, chapter 6 shows the first approach of application of the selected method to estimate soil moisture. All the problems faced while implementing the method are detailed. In chapter 7. the selected method is validated using external data. Additionally, chapter 8 shows the estimations of soil moisture calculated in the Piedmont area, as well as, the analysis carried out to these calculations in order to prove the level of accuracy of the method applied. Finally, chapter 9 contains the conclusion and future lines of the project.

The correspondence between the disaggregated objectives and the chapter organization can be seen in the following table:

Disaggregated Objectives	Chapters
Analysis of all the technologies and techniques & Selection of the proposals	Chapter 2
	Chapter 3
	Chapter 4
	Chapter 5
Calculation of the soil moisture estimations	Chapter 6
	Chapter 7
	Chapter 8

Table 1. Thesis planning

2. Theoretical Background

2.1. Soil Moisture and Remote Sensing

2.1.1. Soil Moisture

Soil Moisture (SM) can generally be described as the water that is held in the spaces between soil particles. Surface soil moisture is the water that is in the upper 10 cm of soil, whereas root zone soil moisture is the water that is available for plants, which is generally considered to be in the upper 200 cm of soil *(Arnold, 1999) [7]*. In this project, the term soil moisture will refer to surface soil moisture.

Soil moisture volume is small while compared to other components of the hydrological cycle. Nevertheless, it is a key variable in the climate cycle, as well as in many hydrological, biological and biogeochemical processes. The following list shows why soil moisture has been proven to be an essential variable for the monitoring and improvement of the agricultural sector:

- Soil moisture regulates soil temperature.
- Soil moisture acts as a nutrient itself.
- Soil moisture is a principal constituent of the growing plant.
- Soil moisture helps in chemical and biological activities of soil.
- Microorganisms require water for their metabolic activities.
- Soil moisture serves as a solvent and carries nutrients for the plant.
- Water is a critical element so the plant can make photosynthesis.

Due to its importance, accurate soil moisture assessment has become a critical task in many operational areas of water resources management. In-situ measurements of soil moisture can be obtained by extracting soil cores, drying, and weighing them, but this way of measuring is not suitable for long-term monitoring. Automated in site measurements can be achieved using different types of devices, such as: tensiometers, various types of electrical resistance sensors or Time-Domain Reflectometry (TDR) sensors.

The tensiometer, se figure 3, is composed of a cylindrical tube, with porous ceramic cups at the bottom. In addition, it has a vacuum gauge, that can be permanent (tensiometer at the right of the image) or not (tensiometer at the left of the image). Its working principle is based on measuring the vacuum inside the tube. The tensiometer is half buried in the soil, the porous ceramics cups allow water to get inside and outside the tube. When the soil is wet water come through this porous, creating a particular vacuum that is measured by the gauge. Meanwhile, if the soil gets drier, water will be sucked out of the tensiometer increasing the vacuum, and therefore the measurement of the gauge. It is important to underline that tensiometers measure how tightly water is held to the soil particles and not how much water is left in the soil.

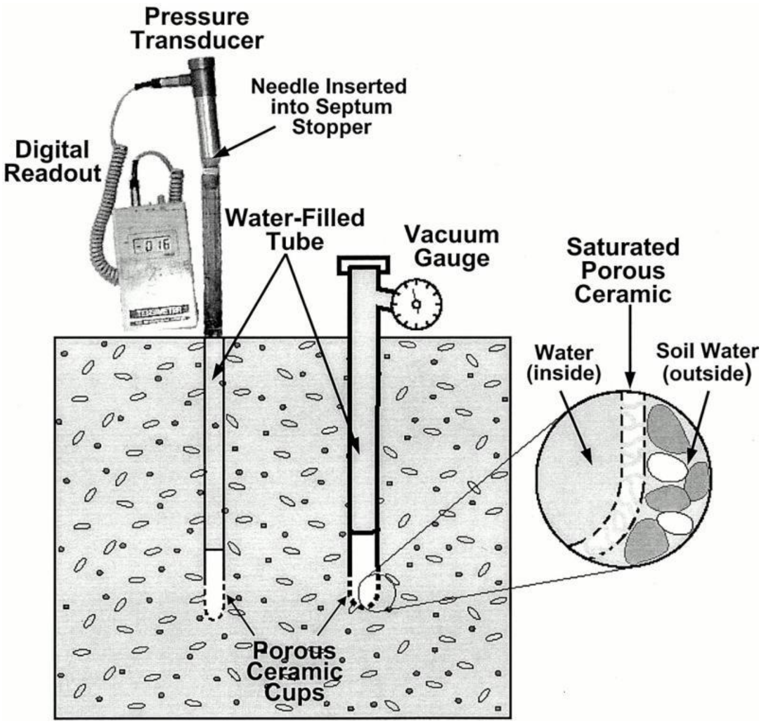


Figure 3. Tensiometers with none-permanent and permanent vacuum gauge *[8]*

The TDR instruments (figure 5) are used to measure soil moisture values indirectly. The device measures the travel time of a high frequency electromagnetic pulse. With this travel time the dielectric constant can be obtain, and from it soil moisture can be calculated *(Topp, 1980) [9]* .The theoretical background of the relation between the dielectric properties and soil moisture values is explained in the chapter 5.

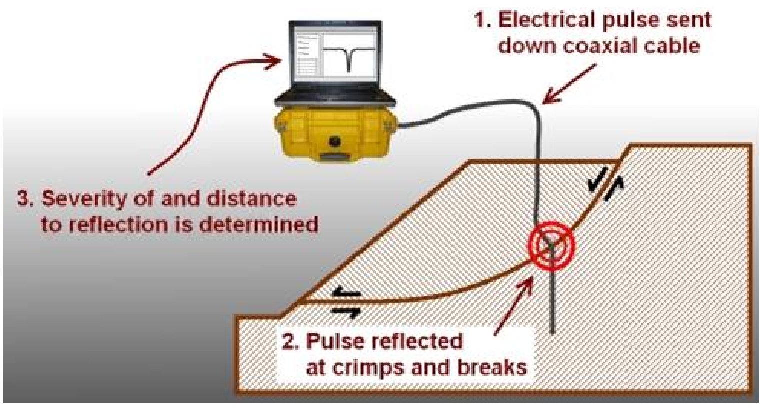


Figure 4. TDR working principle *[10]*

Figure 5. TDR instrument *[9]*

These tools are usually used for irrigation management purposes. All these instruments have in common one big disadvantage, they can only measure soil moisture of a small area around themselves. Therefore, for having an accurate description of the spatial distribution of soil moisture values in large agricultural fields, the number of instruments needed will be extremely high, making these technologies completely inefficient for this type of measuring.

2.1.2. Remote Sensing

In order to solve this problem, soil moisture started being measured through remote sensing. This technology is based on several physical aspects, such as radiance or reflectance.

Radiance is the variable directly measured by remote sensing instruments. Basically, it can be understood as how much light the instrument "sees" from the object being observed. When looking through an atmosphere, some light scattered by the atmosphere will be seen by the instrument and included in the observed radiance of the target. An atmosphere will also absorb light, which will decrease the observed radiance. Radiance most often has units of watts. Meanwhile, reflectance is the ratio of the amount of light leaving a target to the amount of light striking the target. It has no units. Reflectance is a property of the material being observed. Radiance, on the other hand, depends on the illumination (both its intensity and direction), the orientation and position of the target and the path of the light through the atmosphere *(Ray, 2013) [11]*.

One the one hand, observing large areas became possible. On the order hand, a new problem appeared: low spatial resolution. Spatial resolution is a measure of the smallest object that can be resolved by the sensor, or the ground area imaged for the instantaneous field of view (IFOV) of the sensor, or the linear dimension on the ground represented by each pixel *(Advanced Remote Sensing, 2012) [12]*. It depends on various parameters of the satellite sensor. Higher spatial resolution requires a larger diameter antenna which implies a bigger requirement of fuel to maintain the satellite in space. Due to this issue, most sensors have spatial resolutions in 10s of kilometers that are too coarse for catchment hydrology applications. To fulfill the accuracy requirements of the soil moisture applications different approaches can be taken, which are explained on the following chapters [12].

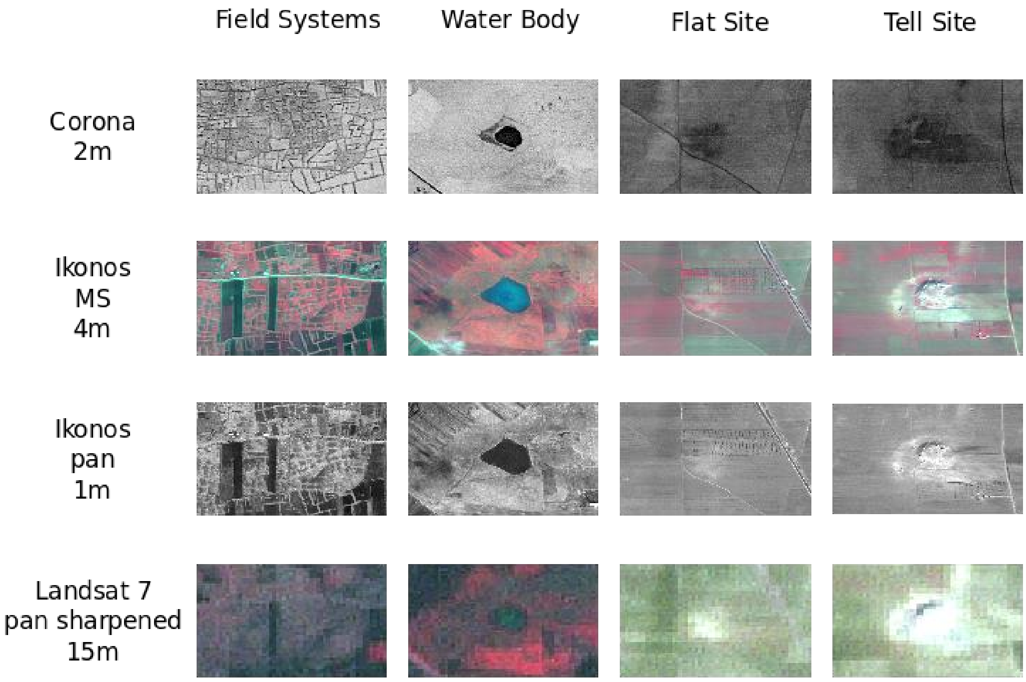


Figure 6. Spatial resolution comparison *[13]*

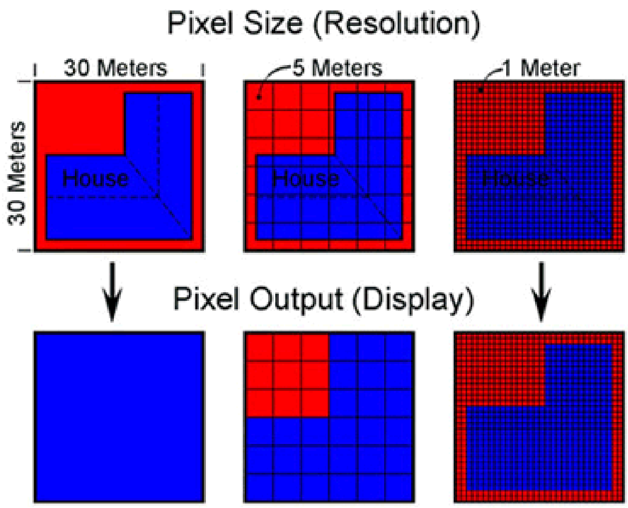


Figure 7. Spatial Resolution graphical definition *[14]*

Applying remote sensing techniques to retrieve soil moisture have increased the accuracy of the data analyzed on several areas. The fields which have made the biggest progress are:

1. **Understanding the climate.** Soil moisture is a main storage element for carbon dioxide, but as well an important source of it, therefore it is a critical variable in Global Warming *(Role of Soil Moisture) [15]*.

2. **Predicting the weather.** Soil moisture is extremely related with temperature and precipitation. A rise in temperature means an increase in the evaporation of soil

moisture. This increase of evaporation of soil moisture will cool down the soil. If there is moisture on the air, coming from the soil, low-pressure systems moving in the area, it will condensate and the precipitations will occur. Meanwhile, having a dry soil means less moisture on the environment, therefore the probabilities of precipitation if a low-pressure system advance in will be much lower.

3. **Forecasting floods.** Floods forecast is a critical task, in order to respond to an emergency situation rapidly. It is based on analyzing both precipitations and water levels, i.e. river weights, and forecasting precipitations for the following days.

4. **Predicting agricultural productivity.** Soil moisture is a key factor on the agricultural sector, having a huge influenced on the outcome of the crops, as it was previously introduced.

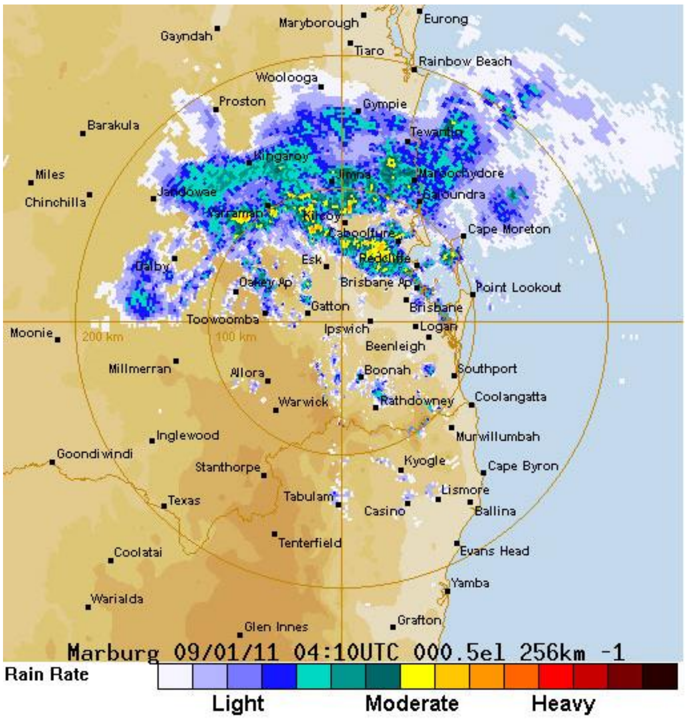


Figure 8. Radar image showing rainfall over the South-East Queensland and New South Wales coast *[16]*

2.2. How to measure soil moisture: Satellites, Sensors and Products

2.2.1. Introduction

As it was previously introduced, various technologies exist while applying remote sensing to measuring soil moisture. Several satellites, sensors and cloud engines have been developed by the space agencies to carry out this task. In this chapter, the most recent satellite platforms and products used for soil moisture estimation are presented.

Before developing the mentioned analysis, some definitions are going to be provided, in order to completely understand the concepts of the chapter.

- **Satellite Platform:** in spacecraft, it in understood as all the components that composed the satellite.
- **Sensor:** it is a device used to detect, measure and record a physical property, depending on the task it was designed for.
- **Satellite Product:** it is the processing of the data obtained by the satellites before arriving to the users. Depending on the grade of processing it has been through the products might have different levels.
- **Latency:** in remote sensing, it is understood as the amount of delay that occurs in a round-trip data transmission.
- **Spatial Resolution:** it can be seen as the smallest size an object can have in order to be represented in an image.
- **Temporal Resolution:** it is defined as the amount of time passed between obtaining data from a location and reobtaining it from the exact same location.

2.2.2. Envisat Mission

Envisat Earth Observation satellite was launched by the ESA on February 2002. The aim of the mission was increasing our knowledge in the Earth sciences and to develop operational applications related to environmental monitoring. On April 2012 there was a failure on the satellite which led to the end of the mission. Figures 9 and 10 show the satellite, as well as its main on-board sensors. Figure 11 explains the working principle of one of these sensors.

Figure 9. Envisat Satellite being assembled *[17]*

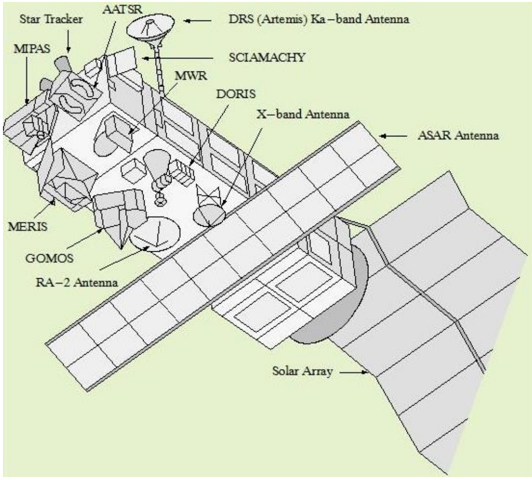


Figure 10. Envisat Satellite main parts and on-board sensors *[17]*

Envisat was composed of 10 sensors which provided different types of information:

Sensors	**Complete name**	**Working principle**	**Spatial resolution**
AATSR	Advanced Along-Track Scanning Radiometer	Optical/IR Radiometer	1km x 1km
ASAR	Advanced Synthetic Aperture Radar	C-Band SAR	Global Monitoring mode: approx1000m x 1000m.
DORIS	Doppler Orbitography and Radio-positioning Integrated by Satellite	Radio Frequency Orbitography	5cm in altitude
GOMOS	Global Ozone Monitoring by Occultation of Stars	Ultra-Violet and Optical Spectrometer	-
LRR	Laser Retro Reflector	Passive Optical Reflector	-
MERIS	Medium-Resolution Visible and Near-IR Spectrometer	Imaging Spectrometer	Ocean: 1040m x 1200m, Land & coast: 260m x 300m
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding	Limb-Viewing Infrared Interferometer	3km x 30km
MWR	Microwave Radiometer	Two-Channel Nadir View Radiometer	20km
RA-2	Radar Altimeter 2	Pulsed Radar	20km
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography	Multi-Channel Nadir + Limb View UV/VIS/IR Spectrometers	32 x 215km

Table 2. On-board sensors of the Envisat and their main characteristics *[17]*

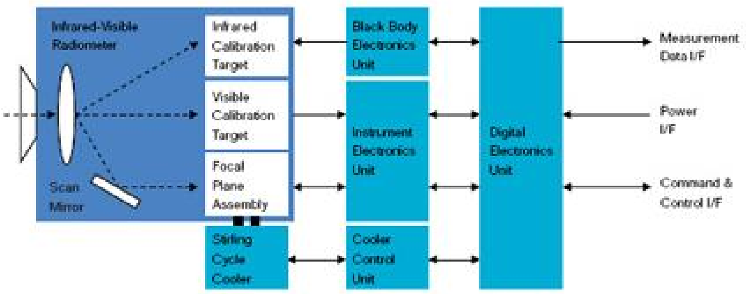


Figure 11. ATTSR Sensor Functional Block *[17]*

Envisat mission aims to replace and enhance the datasets coming from older missions, such as ERS-1 and ERS-2. In addition, the mission looks for covering specifications linked to environmental monitoring and global study in general. Furthermore, Envisat has been considered as crucial, due to the long-term datasets provided, in order to deal with climatological and environmental issues. The mission main objectives are shown in plate 1.

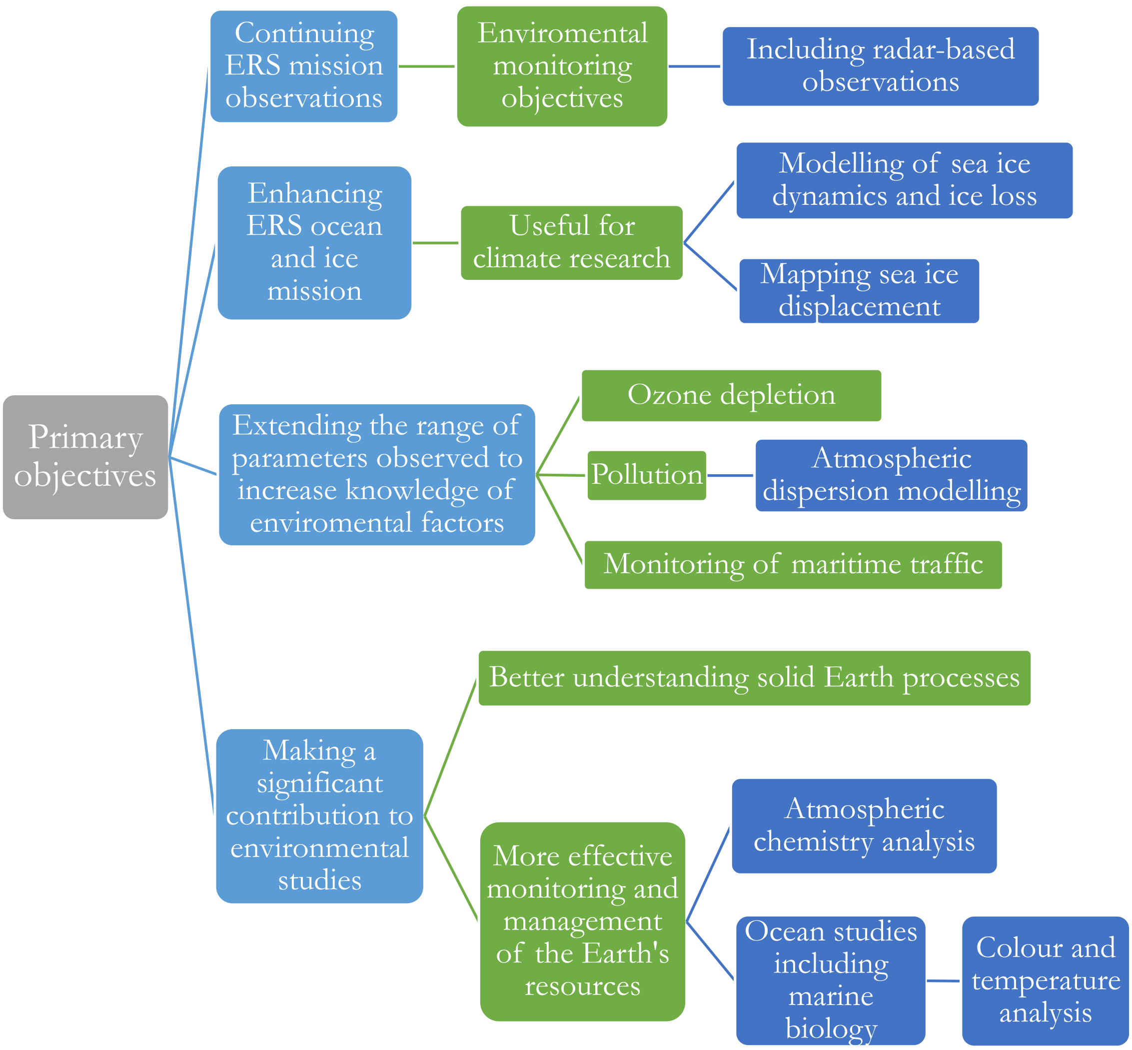


Plate 1. Primary objectives of the Envisat Mission

Due to its large number of sensors, the applications of Envisat were many and very different between each other, its main sectors were: ice, ocean, atmosphere and land. It is important to highlight, that obtaining measurements of soil moisture was not one of its applications, but the variable was achieved applying different and complex algorithms and treatment to captured data.

2.2.3. Soil Moisture and Ocean Salinity Mission

The European Space Agency launched the Soil Moisture and Ocean Salinity (SMOS) mission on November 2009. Its main objective is to provide observations of Sea Surface Salinity (SSS) over oceans and Soil Moisture over land to help develop diverse applications on several fields, such as advance climatologic, meteorological, hydrologic, and oceanographical. It is known as the ESA "Water" mission because it looks to improve our knowledge on the water cycle.

Figure 12. SMOS Satellite *[18]*

SMOS satellite was built with the MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) sensor. The sensor assembly is a dual polarized 2-D interferometer operating at L-band. Its aim is to provide records of pixel brightness temperatures over different incidence angles across a 900 km swath, with a spatial resolution in the range of 30-50 km. From these observed data and auxiliary information, like surface physical temperature and roughness among others, soil moisture and sea surface salinity will be retrieved. Table 3 shows the characteristics of the MIRAS sensor *[18]*.

Characteristics	MIRAS
Frequency	1.41GHz
Polarizations	H & V (polarimetric mode optional)
Resolution	30-50km
Incident angle	0º-55º
Orbit	Sun-synchronous, dawn/dusk
Temporal coverage	Nov 2009-to present
Temporal resolution	3 days revisit at Equator

Table 3. SMOS sensor characteristics *[18]*

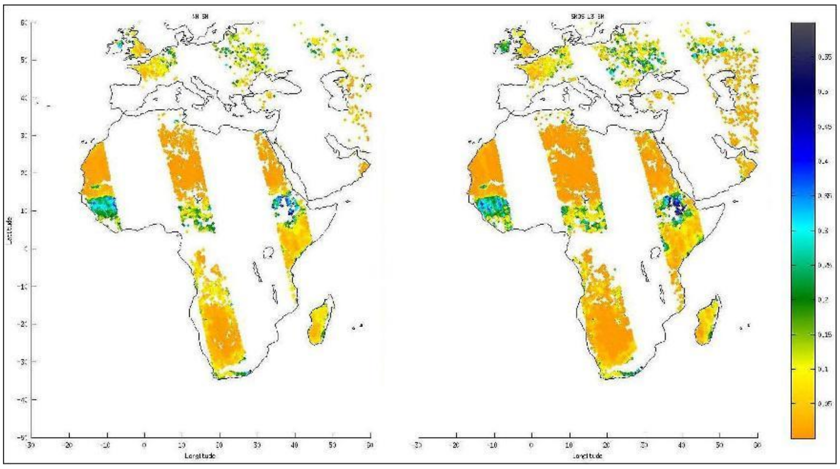


Figure 13. SMOS brightness temperature measurements maps *[18]*

On figure 13, two SMOS brightness temperature measurements maps can be seen. The one on the left was processed using a neural-network algorithm (this method will be fully explained on chapter 5), and therefore is processed in less than a second. The one on the right is processed on the usual way, which takes several hours. Comparing them, it can be seen that the quality between the products is similar. However, the spatial coverage is bigger on the common product, because more measurements form the satellite are used with this methodology.

SMOS products can be divided in four levels, depending or their processing grade, and the final information they give. In this study, only the soil moisture products have been analyzed (table 4).

Product	Resolution	Latency
Level 2	15km	8-12 hours
Level 3	25km	1, 3, 10 days, monthly
Level 4	25 km	1 day

Table 4. SMOS Products characteristics *[18]*

Level 2 products consists on global soil moisture maps and are provided by the ESA. Both level 3 and 4 are provided by CATDS (French ground segment: Centre Aval de Traitement des Données SMOS): Level 3 products consist on global map of soil moisture, vegetation optical depth, surface roughness and dielectric constant; Level 4 provides root zone soil moisture estimations, agriculture drought index, surface roughness and synergy soil moisture *[18]*.

SMOS products have been applied to a huge range of sectors due to its versatility:

- **Detection models:** specially for ocean and fire detection.
- **Weather and Climate Forecasting:** as it has already been explained, soil moisture can give valuable information of both, air temperature and humidity near the surface.
- **Agriculture production:** applying soil moisture in this area seeks to increase the quality of the crops. In this case, the applications are centered on getting data from the root zone, and providing the agriculture drought index.
- **Landscape:** analyzing surface roughness and vegetation index. The relation of this variables with soil moisture values is developed in the chapter 5.
- **Cryosphere:** the products aim in this area is to analyze the ice thickness.
-

2.2.4. Soil Moisture Active Passive Satellite

This specific soil moisture satellite was launched by the NASA in January 2015. The Soil Moisture Active and Passive (SMAP) Satellite mission is to map global soil moisture and detect whether soils are frozen or thawed. Figures 14 and 15 show the satellite and its main parts.

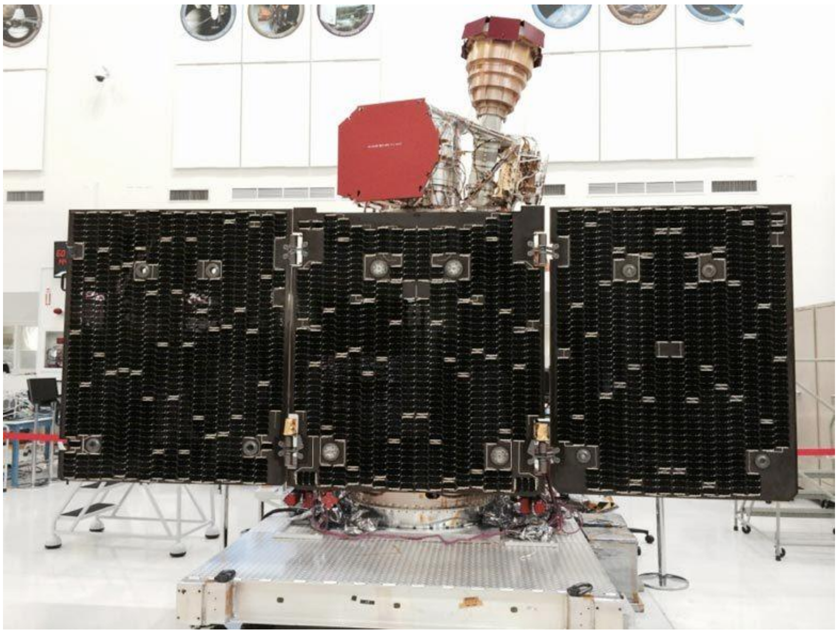


Figure 14. SMAP Satellite assembly *[19]*

The SMAP instrumentation consists on a radiometer (passive) instrument and a radar (active) instrument operating with multiple polarizations in the L-band range. Combining active and passive measurements allows to take advantage of the spatial resolution of the radar and the sensing accuracy of the radiometer. Unluckily, the radar got broken in July 2015, which deteriorates the resolution of the images (see table 5).

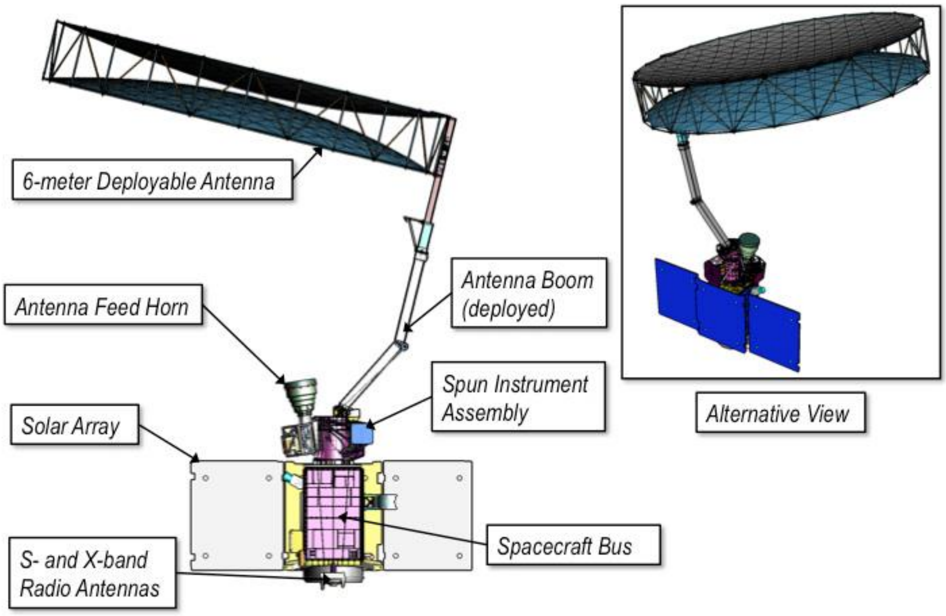


Figure 15. SMAP Satellite main on-board sensors and parts *[19]*

Characteristics	**Radar**	**Radiometer**
Frequency	1.2GHz	1.41GHz
Polarizations	VV, HH, HV	V, H, U
Resolution	1-3km	40km
Incident angle	40º	
Orbit	Polar, Sun-synchronous	
Temporal coverage	Jan 2015-July 2015	2015-to present
Temporal resolution	2-3 days	

Table 5. SMAP characteristics *[19]*

SMAP provides measurements of the surface emission and backscatter, being able to measure the first 5 cm of soil when there is a moderate vegetation cover.

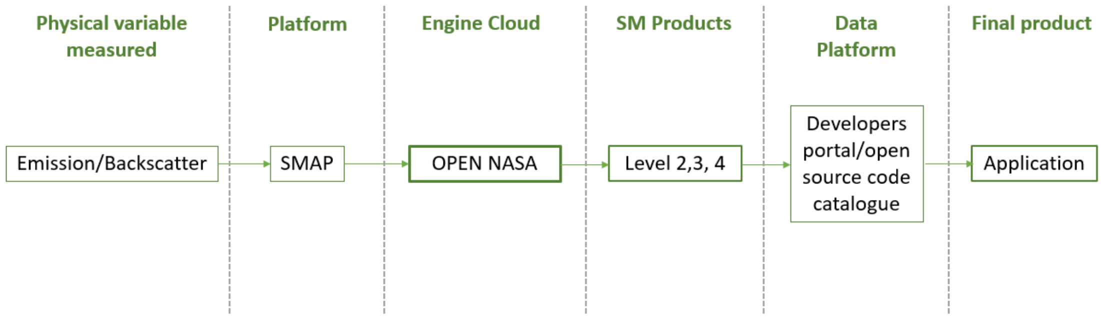


Plate 2. Data Flow for SMAP: from detection to final processing for soil moisture estimations

The previous schema shows the working cycle of the satellite information, from its detection and capture to its final processing. The measured values go through some transformations to become soil moisture data at the first stage. These data can be downloaded from three web sites: WorldView, Earthdata and NSIDC.

The level of the products depends on the grade of transformation the data has gone through. Level 2 products are geophysical retrievals of soil moisture on a fixed Earth grid based on Level 1 products and ancillary information. Level 3 products are daily composites of Level 2 surface soil moisture and freeze/thaw state data. Level 4 products are model-derived value-added data products of surface and root zone soil moisture and carbon net ecosystem exchange that support key SMAP applications and more directly address the driving science questions *(SMAP Satellite) [19]*. The following table shows a list of the products and their main characteristics.

Product	Resolution	Latency
Level 2	3, 9, 36km	24 hours
Level 3	3, 9, 36km	50 hours
Level 4	9km	7 days

Table 6. SMAP Satellite SM Products *[19]*

SMAP applications areas can be directly, or indirectly addressed coupling the data with hydrologic models in order to obtain soil moisture measurements in the root zone.

- **Weather and Climate Forecast:** enhancing prediction skills of numerical models to forecast weather.
- **Droughts:** enhancing droughts model predictions through space-based observations.
- **Floods:** creating hydrological forecast systems.
- **Agricultural Productivity:** giving information of the water available and estimating plant productivity.
- **Human Wealth:** enhancing risk models, especially on the areas of hunger and diseases.
- **National Security:** monitoring mobility and ground trafficability.

2.2.5. Sentinel Satellites

Sentinel is a multi-satellite project. It is being developed by the ESA thanks to the Copernicus program. The goal of the Sentinel program is to substitute the other Earths observational missions that have reached the end or that are near to it. This multi-satellite mission will keep providing data, therefore there are no discontinuities on the existent studies. The objectives of this mission are various, due to the great number of satellites that composed it.

The satellites characteristics, main on-board sensors and objectives are shown on the following tables and figures:

Sentinel 1:

Objective	To provide enhanced revisit frequency, coverage, timeliness and reliability for operational services and applications requiring long time series
Launch	Sentinel 1A: April 2014 Sentinel 1B: April 2016
Sensor	SAR, four acquisition modes: 1. Stripmap (SM) 2. Interferometric Wide swath (IW) 3. Extra-Wide swath (EW) 4. Wave mode (WV)
Spatial resolution	5m x 5m 5m x 20m 20m x 40m 20km x 20km

Table 7. Sentinel 1 Satellite main characteristics *[20]*

Figure 16. Sentinel 1 Satellite *[20]*

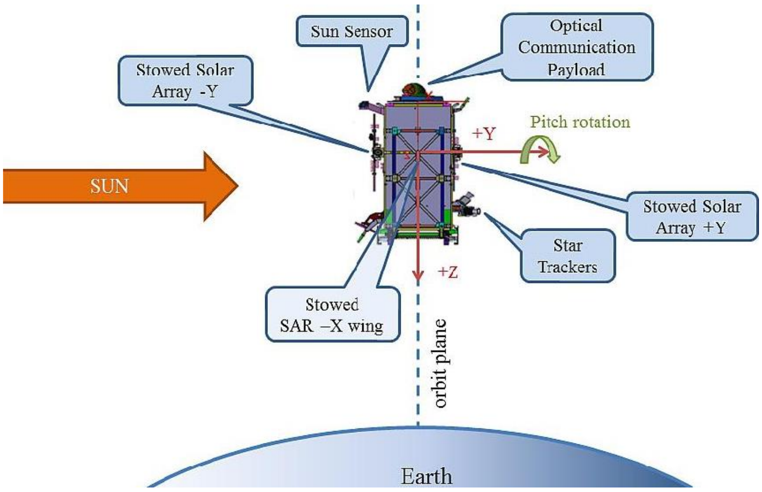


Figure 17. Sentinel 1 Satellite main parts and on-board sensors [20]

Sentinel 2:

Objective	To monitor variability in land surface conditions.
Launch	Sentinel 2A: June 2015 Sentinel 2B: March 2017
Sensor	MultiSpectral Instrument (MSI).
Spatial resolution	10, 20, 60m

Table 8. Sentinel 2 Satellite main characteristics [20]

Figure 18. Sentinel 2 Satellite assembly [20]

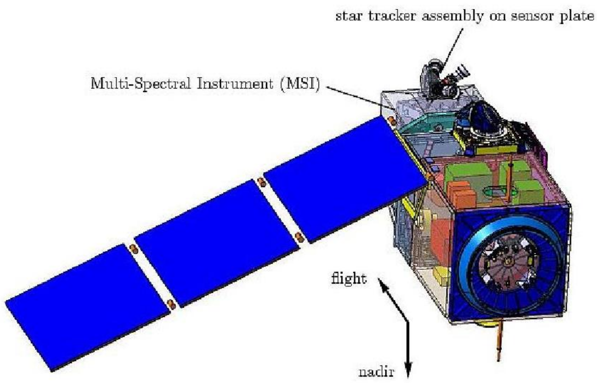


Figure 19. Sentinel 2 Satellite main parts and on-board sensors *[20]*

Sentinel 3:

Objective	Globally monitoring key air quality trace gases and aerosols in support of the Copernicus Atmosphere Monitoring Service (CAMS).
Launch	Sentinel 3A: January 2016 Sentinel 3B: April 2018
Sensor	1. Ocean and Land Colour Instrument (OLCI) 2. Sea and Land surface Temperature Radiometer (SLSTR) 3. SAR Radar Altimeter (SRAL) Intrument 4. Microwave Radiometer (MWR)
Spatial resolution	300m-500m

Table 9. Sentinel 3 Satellite main characteristics *[20]*

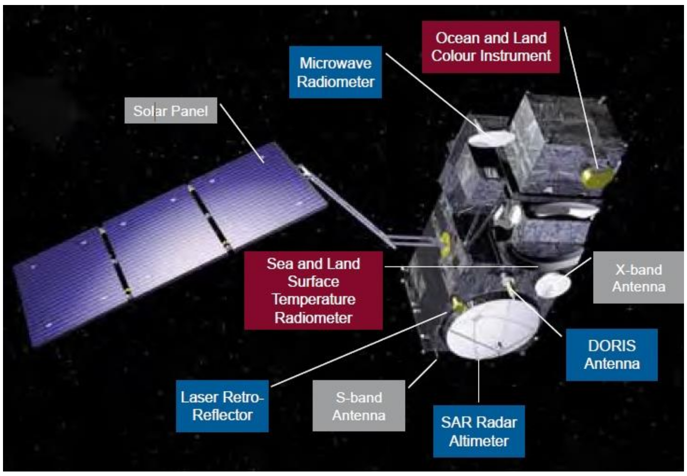


Figure 20. Sentinel 3 Satellite main parts and on-board sensors *[20]*

Sentinel 4:

Objective	To monitor key air quality trace gases and aerosols over Europe
Launch	Predicted in 2019 and 2027
Sensor	8km x 8km
Spatial resolution	Passive imaging spectrometer

Table 10. Sentinel 4 Satellite main characteristics *[20]*

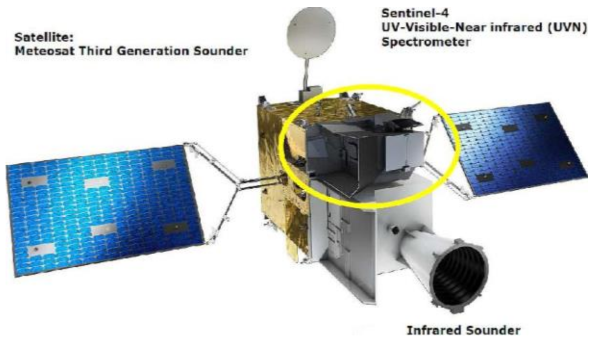


Figure 21. Sentinel 4 Satellite main parts and on-board sensors *[20]*

Sentinel 5:

Objective	To perform atmospheric measurements with high resolution to be used for air quality
Launch	Predicted in 2021
Sensor	Passive grating imaging spectrometer
Spatial resolution	50km x 50km

Table 11. Sentinel 5 Satellite main characteristics *[20]*

Sentinel 5P:

Objective	To perform atmospheric measurements with high resolution to be used for air quality, ozone & UV radiation, and climate monitoring & forecasting.
Launch	October 2017
Sensor	TROPOspheric Monitoring Instrument (TROPOMI)
Spatial resolution	7km x 7km

Table 12. Sentinel 5P Satellite main characteristics *[20]*

2.2.5.1. Sensors

Once having introduce all the satellites from the Sentinel mission, a deeper research of how their sensors work is shown. It has been analyzed the physical principle and the variable measured by all the sensors. Finally, all the possible products that can be obtained have been listed.

Satellite	**Sentinel 1**
Instrument	Synthetic Aperture Radar (SAR)
Objective	Geographical coverage and rapid data dissemination to support operational applications in the priority areas of marine monitoring, land monitoring and emergency services
Physical Principle	Reflectance of micro-wave
Measured Variable	Reflectivity and conductivity (dielectric cte. and roughness)
Products	Type of material (%water, humidity)

Table 13. Sentinel 1, SAR instrument characteristics

SAR instrument is a radar system able to create high resolution images by analyzing the phase and magnitude of consecutive pulses of the signal received.

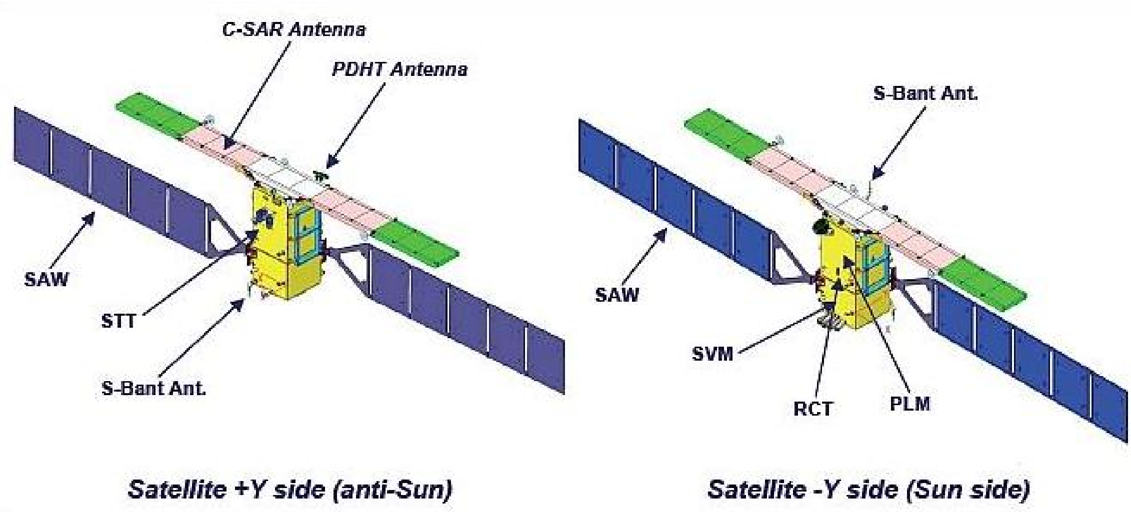


Figure 22. SAR Antenna Satellite examples [20]

From table 7, it can be seen that the SAR instrument can operate in four variation modes. The following picture gives a visual explanation of the differences between these modes.

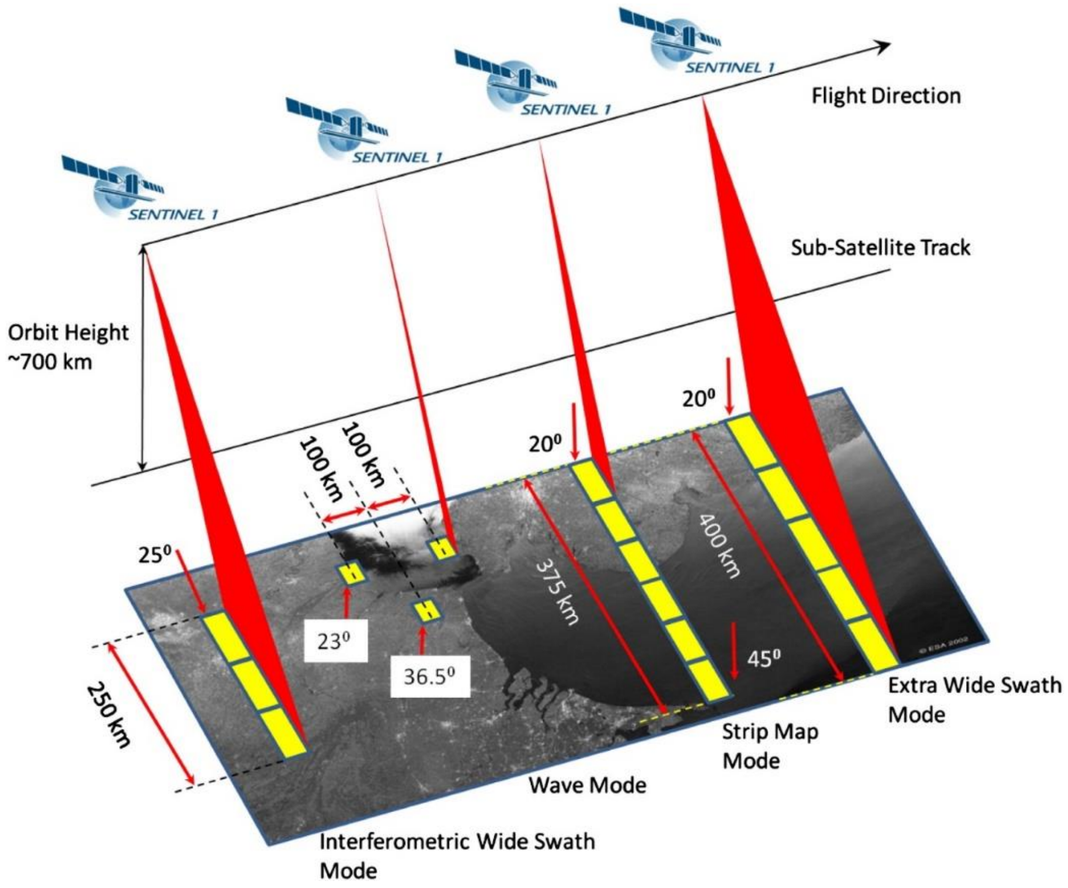


Figure 23. SAR Instrument working modes *[20]*

- **Interferometric Wide Swath Mode:** this one is the mode usually used to cover land, because the lack of issues it gives. IW mode allows to cover a large swath, around 250km, with an okay spatial resolution, between 5 to 20 meters. In addition, it can be decomposed on three sub-swaths.

- **Wave Mode:** it is the mode most commonly used to cover open ocean. Its main feature is analyzing the wave of the oceans (height, direction, etc.). It allows to collect images with two different incident angles, every 100km. Therefore, images with the same incident angle will be obtained every 200km. The resolution of the images is really low, around 20km.

- **Strip Map Mode:** this mode purpose is to assure the continuity of the Envisat and ERS missions. The resolution of the images is really high, around 5 meters. The sub-swaths can be addressed by selecting different incident angles. In total there are 6 sub-swaths.

- **Extra Wide Swath Mode:** the aim of this mode is giving valuable information to operational applications in the maritime and ice domain, due its ability of covering large areas with a low revisit time. Its working principle is similar to the IW mode, but with 5 sub-swaths and a lower resolution, between 20 and 40 meters.

Satellite	**Sentinel 2**
Instrument	MultiSpectral Instrument (MSI)
Objective	Copernicus Land Monitoring studies, including the monitoring of vegetation, soil and water cover, as well as observation of inland waterways and coastal areas
Physical Principle	Reflectance/ intensity
Measured Variable	-
Products	Vegetation parameters: 1.Fraction of absorbed photosynthetically active radiation (FAPAR) 2.Leaf Area Index (LAI) 3. Fractional Vegetation Cover 4. Leaf Chlorophyll Content (LCC) 5. Leaf Water Content (LWC)

Table 14. Sentinel 2, MSI characteristics

The MSI is a multifrequency radar, which means, that is a radar able to transmit pulses in a huge variety of frequency and wavelengths.

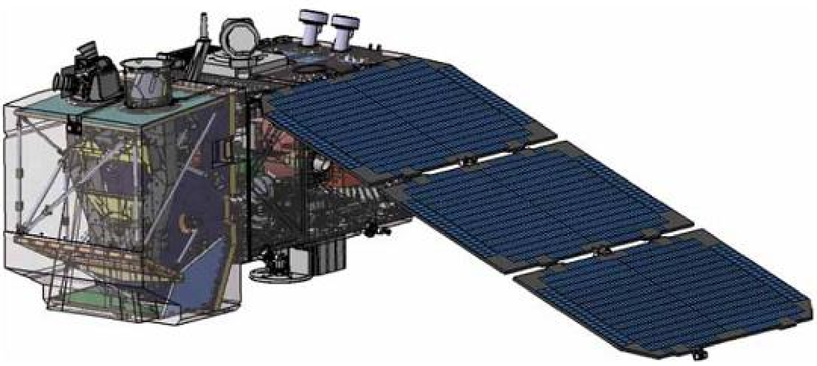


Figure 24. Sentinel 2 Satellite with MSI on-board instrument *[20]*

	S2A		S2B		
Band Number	**Central wavelength (nm)**	**Bandwidth (nm)**	**Central wavelength (nm)**	**Bandwidth (nm)**	**Spatial resolution (m)**
1	442.7	21	442.3	21	60
2	492.4	66	492.1	66	10
3	559.8	36	559.0	36	10
4	664.6	31	665.0	31	10
5	704.1	15	703.8	16	20
6	740.5	15	739.1	15	20
7	782.8	20	779.7	20	20
8	832.8	106	833.0	106	10
8a	864.7	21	864.0	22	20
9	945.1	20	943.2	21	60
10	1373.5	31	1376.9	30	60
11	1613.7	91	1610.4	94	20
12	2202.4	175	2185.7	185	20

Table 15. Sentinel 2, MSI bands characteristics *[20]*

Satellite	**Sentinel 3**			
Instrument	Ocean and Land Color Instrument (OLCI)	Sea and Land Surface Temperature Radiometer (SLSTR)	SYNERGY	ALTIMETRY
Objective	Screening the ocean and land surface to harvest information related to biology. Providing information on the atmosphere and contributes to climate study	Providing global and regional Sea and Land Surface Temperature (SST, LST)	Monitoring of the land use	Studying the ocean topography, mainly, Sea Surface Height (SSH), Significant Wave Height (SWH), Wind Speed over ocean surface
Physical Principle	Solar radiation reflected by the Earth	Infra-red radiation	Combine data of OLCI + SLSTR in order to obtain specific data	Reflation
Measured Variable	1. Water color 2. Biological and atmosphere parameters	Radiance and brightness of each pixel		Time for the wave form to go back to the satellite from the earth
Products	1. Density of sediments/species on the water 2. Atm. Composition (water vapor and aerosols) and vegetation parameters	Temperature parameters: 1. Sea Surface Temperature (SST) 2. Fire Radioactive Power (FRP) 3. Land Surface Temperature (LST) 4. Aerosol Optical Depth (AOD)	1. Surface reflectance and aerosol parameters 2. Vegetation information	1. Sea Surface Height (SSH) 2. Significant Wave Height (SWH) 3. Wind Speed over ocean surface

Table 16. Sentinel 3, OLCI, SLSTR, SYNERGY and ALTIMETRY characteristics

As it can be seen on the table 16, Sentinel 3 has several instruments on board *[20]*, each of them contributes differently to the mission of the satellite.

- **OLCI:** it is a spectrometer radar working in 21 spectral band. Its design is based on the opto-mechanical design of the MERIS sensor.

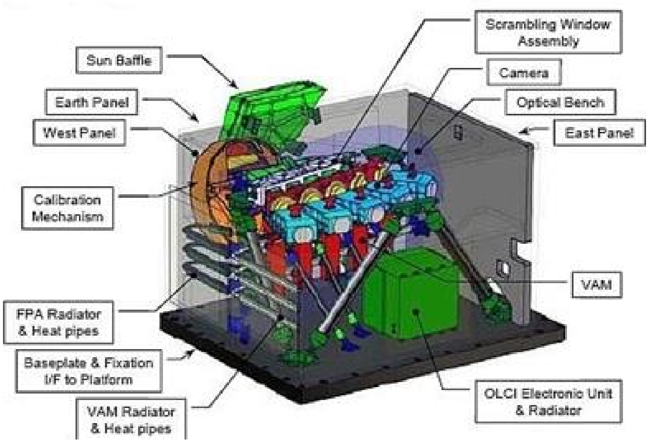


Figure 25. OLCI graphical representation *[20]*

Figure 26. OLCI Instrument *[20]*

- **SLSTR:** It is a dual scan temperature radiometer, working on the infrared spectrum. It is an enhancement of the of AATSR, which was one of the instruments on board of the Envisat.

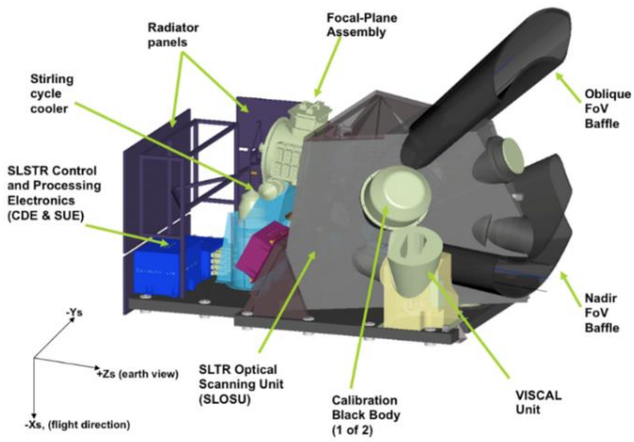


Figure 27. SLSTR Instrument graphical representation *[20]*

Figure 28. SLSTR Instrument *[20]*

- **SYNERGY:** the products of this instrument are obtained by combining OLCI and SLSTR measurements. Its objective is to continue the SPOT Vegetation program. It is a program created by several European countries, with the objective of monitoring, on daily basis, terrestrial and vegetation coverage.

- **ALTIMETRY:** it is composed of several instruments, which are able to measure the distance between the satellite and the Earth surface.

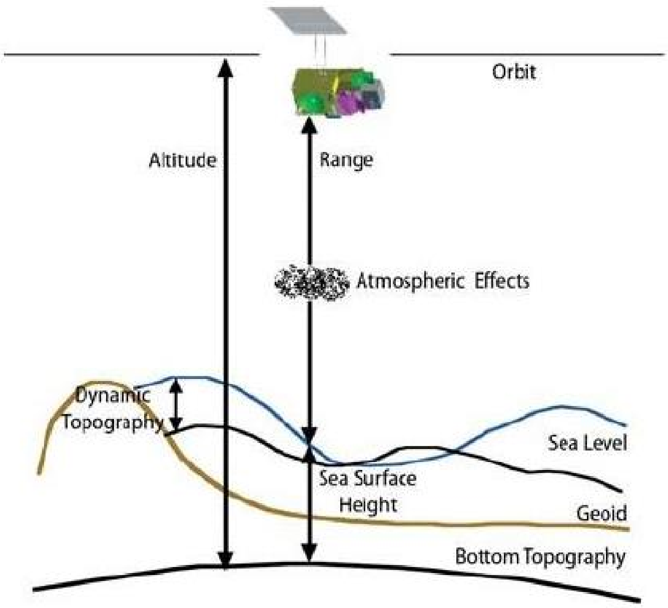


Figure 29. ALTIMETRY working principle *[20]*

It can work on two modes:

- **High Resolution Mode:** it is known as well as SAR, and is used when the analyzed surface is flat.

- **Low Resolution Mode:** this technology uses conventional pulse-limited altimeter operation, and is used when SAR technology cannot be applied.

The instruments that composed this technology are the followings:

1. Altimetry (SRAL)

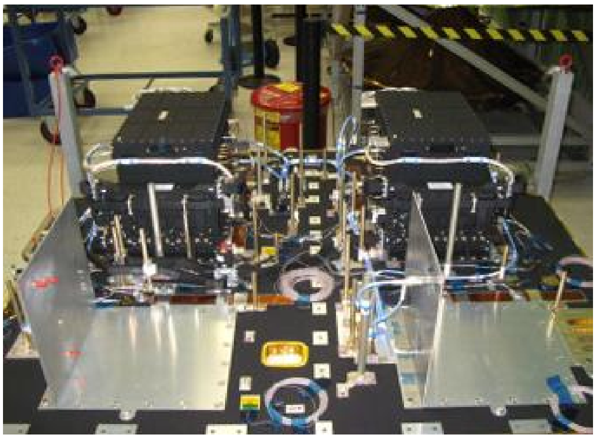


Figure 30. SRAL Instrument *[20]*

2. Microwave Radiometer (MWR)

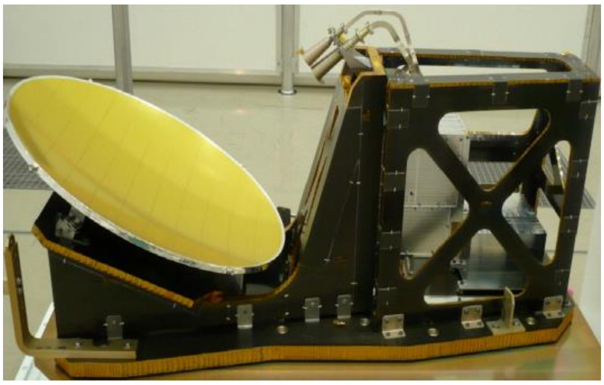


Figure 31. MWR Instrument *[20]*

3. Precise Orbit Determination (POD), including:

    a. Global Navigation Sat. System receiver (GNSS)

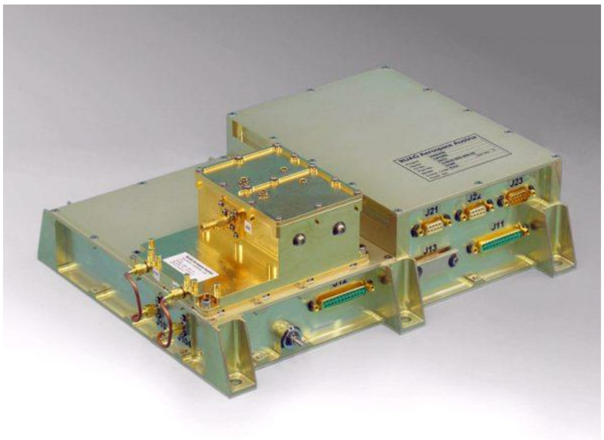


Figure 32. GNSS Instrument *[20]*

b. Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS)

Figure 33. DORIS Instrument *[20]*

c. Laser Retro reflector (LRR)

Figure 34. LRR Instrument *[20]*

Satellite	**Sentinel 5P**
Instrument	TROPOMY
Objective	Environmental themes like: air quality, stratospheric ozone layer and climate change monitoring and forecasting
Physical Principle	Solar radiation reflected and radiated form the earth
Measured Variable	-
Products	Parameters of: 1. Air Quality 2. Stratospheric Ozone Monitoring

Table 17. Sentinel 5P, TROPOMY characteristics

The TROPOMY sensor is a spectrometer radar. It can cover wavelengths from the ultraviolet to the shortwave infrared. It is a passive radar and measures the solar radiation reflected and radiated from the Earth from the Top of Atmosphere (TOA).

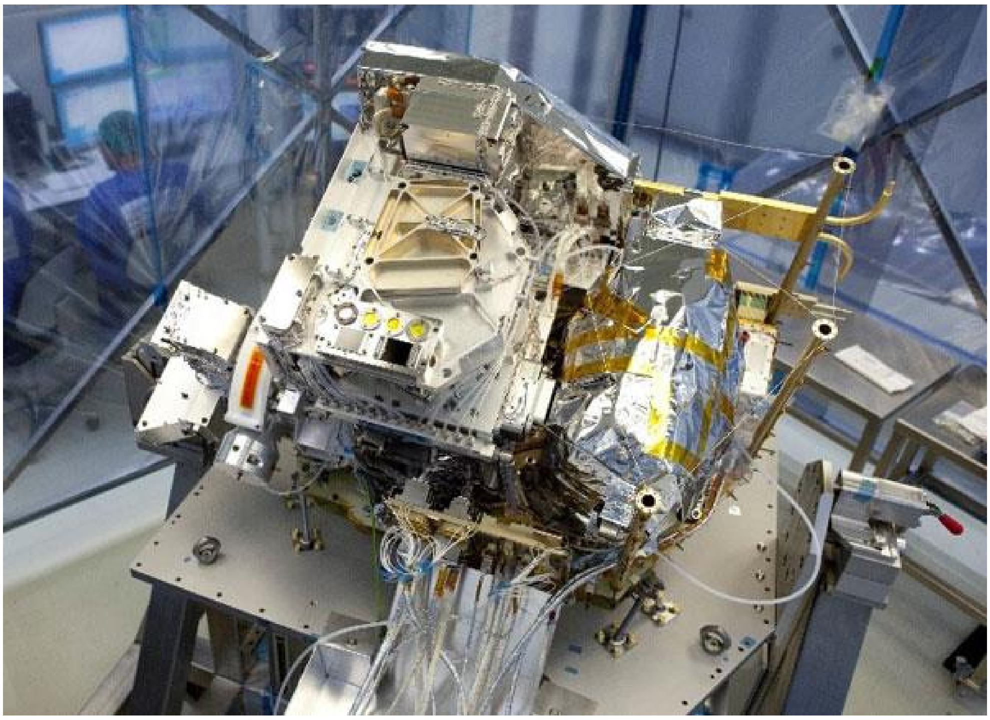


Figure 35. Sentinel 5P, TROPOMY *[20]*

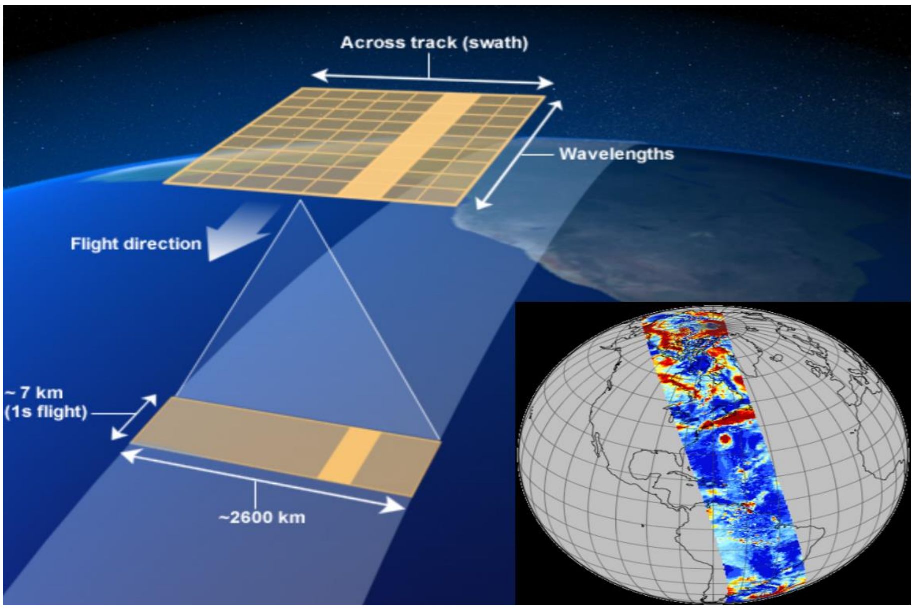


Figure 36. TROPOMY working principle *[20]*

2.2.5.2. Cloud Engine

Due to the large number of satellites, the Sentinel group offers different products covering many areas. However, there is no specific soil moisture products that gives the estimation of this variable. In order to obtain it, various algorithms can be applied, like change detection methods. In the context of remote sensing, change detection refers to the process of identifying differences in the state of land features by observing them at different times *(Shunlin Liang, 2012) [12]*. The data used is the one coming from Sentinel 1 and 2. To achieve better resolution, Sentinel 3 data can be applied as well.

An application, called SNAP, is available in the public domain, to work with the data of these satellites in an easy way. The application allows to process all the images obtained by the satellites, through different of algorithms, methods and tools, to obtain water-related data.

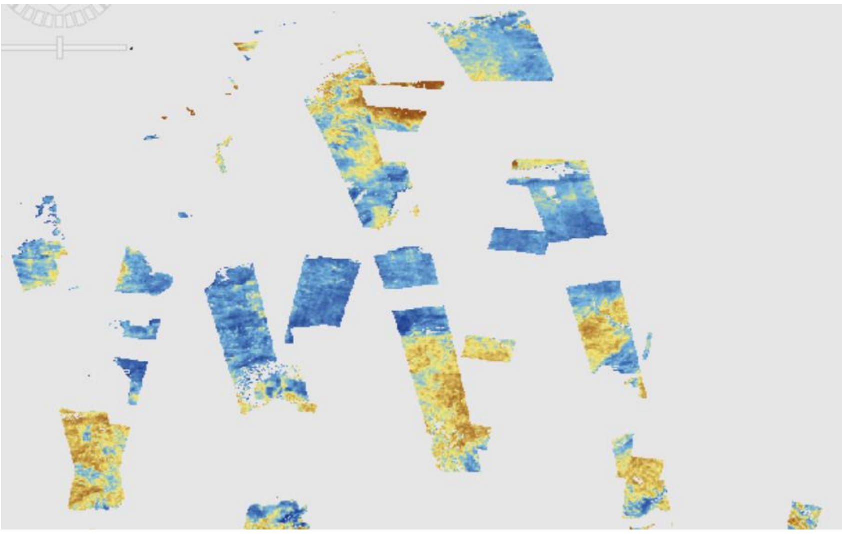


Figure 37. Soil Moisture estimations obtained with SNAP application. Credit: Copernicus Global Land Service

The SNAP application is a software that can be installed in any computer desktop, but cannot be used online. Among its numerous features, stand out *(ESA, 2018) [21]*:

- Very fast image display and navigation even of giga-pixel images
- Rich region-of-interest definitions for statistics and various plots
- Easy bitmask definition and overlay
- Flexible band arithmetic using arbitrary mathematical expressions
- Geo-coding and rectification using ground control points

On the following page a schema of the information flux of the ESA in relation with soil moisture products can be seen. It includes all the satellites which data can be processed to obtain water-related data, as well as the Engine Cloud and the Data Platform of the ESA.

The ESA has its own Engine Cloud, that is a Virtual Machine, were many toolboxes allowing to process the images of their satellites are already installed. All the images can be used directly on this Virtual Machine without having to download them on the computer. Furthermore, once a code for an application has been developed it can be uploaded to the MEP Platform, after having it validated, in order to create a real application.

The MEP Platform is an operational Exploitation Platform, created by the ESA in order to complement the PROBA-V mission. The aim of this mission is to map land cover and vegetation growth across the entire planet every two days. The platform was created to allow users to work and create products that could be globally used, in order to expand the data of this mission.

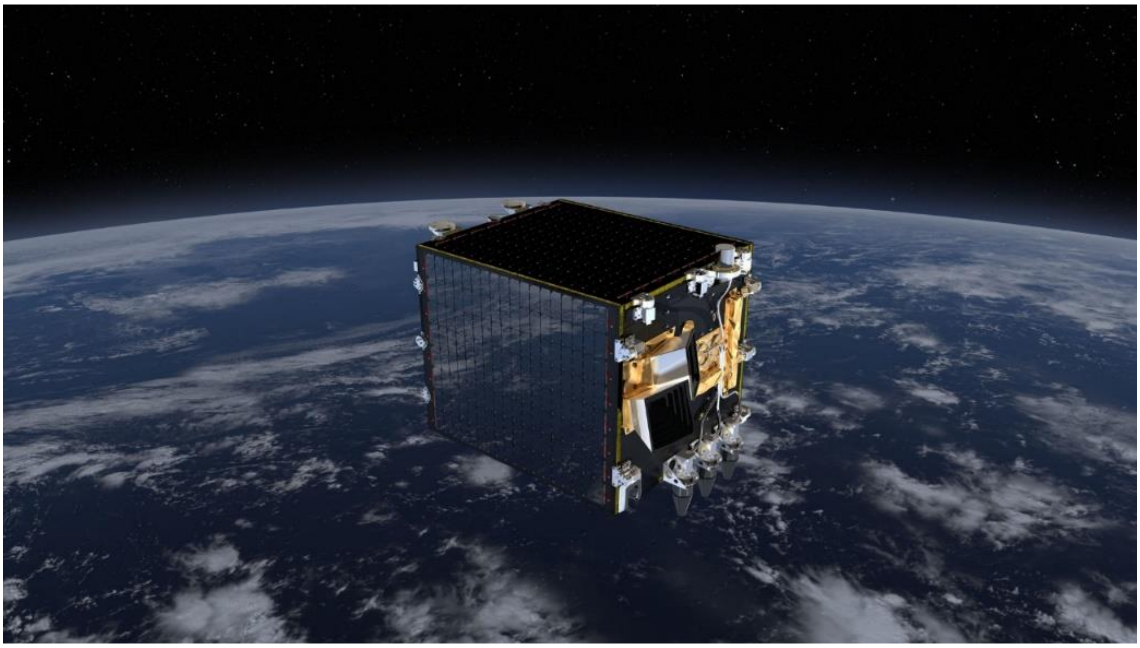


Figure 38. Probe-V Satellite *[22]*

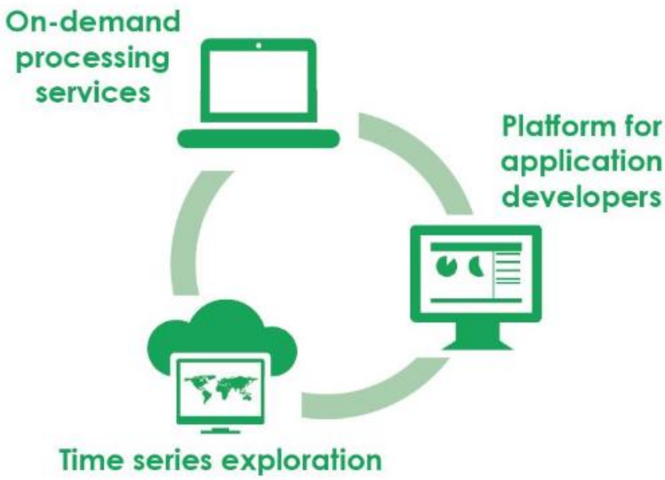


Figure 39. Proba-V MEP [23]

The great advantage of this platform, comparing it with the NASA Cloud Engine (Open NASA), is its capability to mix data from different satellites. Due to this characteristic, the resolution of the products obtained can be higher, and therefore they will be more useful for applications that need to meet high spatial resolution requirements, like in this case.

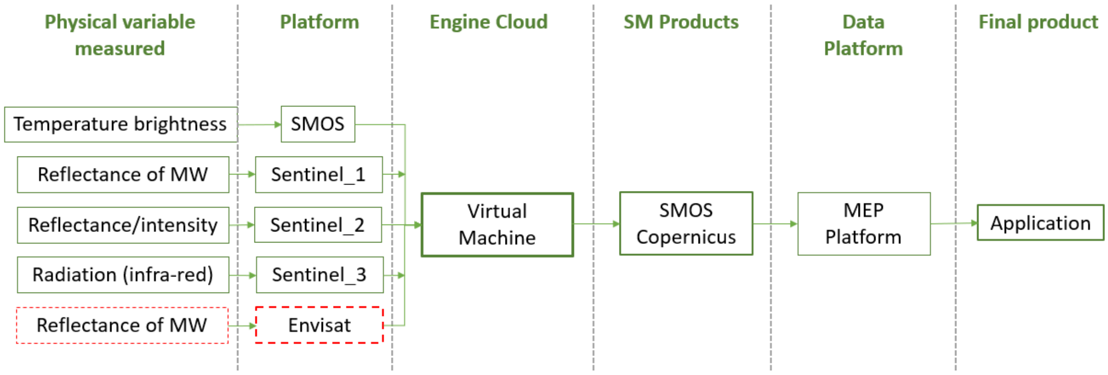


Plate 3. Data Flow for European Space Agency: from detection to final processing for soil moisture estimations. Platforms marked in red correspond to ended missions

2.3. Copernicus Program

The Copernicus Program is a project directed between the European Space Agency and the European Union (EU) through the European Environment Agency, created in 2014. Its aim is to achieve a complete, autonomous and continuous terrestrial observation capacity, obtaining high quality information that can be free-accessed by the scientific community, or by any other interested part. The objective of obtaining this exact and continuous information is to improve the management and conservation of the environment. Furthermore, to better understand and mitigate the effect of the climate change. Finally, it seeks to ensure the civil security.

This program, initially named Global Monitoring for Environment and Security (GMES), is looking to merge together different information sources, coming from both satellites and ground measurements, in order to give valuable information about the Earth.

The estimated cost of the program between 1998 and 2020 was 6700 million of euros. The estimated benefits for 2030 are 30.000 million of euros *(Copernicus Program) [24]*.

2.3.1. Treatment of the information

Copernicus program transformed all the measurements from the satellites and in-situ observations into value-added information. These transformations depend on the initial information measured and the final product desired.

The value-added information created is saved for years. Therefore, layers of information that can be compared and searched are available. These datasets have several objectives, the main ones are forecasting and monitoring changes of different Earth areas.

Finally, from these datasets several maps are created, using different imagery techniques. The maps are really useful in order to identify anomalies and features of the terrains and to obtain statistical information.

2.3.2. Infrastructure

Copernicus program obtained the information from two main sources: satellites and in-situ observations.

The space segment can be divided in two main categories:

1. **Sentinel:** they are a family of satellites created to support the program. The aim of the program is to create six different satellites, each of them with a particular mission. The program will develop two satellites of each type, with different orbits, in order to increase the temporal resolution of the data obtained. These satellites have already been explained on the previously.

2. **Contributing missions:** they are operated by National, European or International organizations and their objective is to provide data for Copernicus services. There is a total of 30 contributing missions.

The responsible of operating the satellites are the European Space Agency and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). ESA operates Sentinel-1, Sentinel-2 and Sentinel-5P satellites and the land mission from Sentinal-3. Meanwhile, EUMETSAT operates Sentinel-4, Sentinel-5 and Sentinel-6 satellites and the marine mission for Sentinal-3. Furthermore, both agencies coordinate the delivery of the data coming from the contributing missions.

Regarding to the ground segment, the in-situ observations are carried out on ground stations. The objective of these stations is double. Firstly, they give support to the space segment, managing the data pick-up, and transforming the raw data into the final products. Secondly, the ground measurements taken there are used to calibrate and validate the different methodologies implemented to create the mentioned final products.

The ground segment is based on infrastructure delivered by both public and private facilities and international agencies. It is located all around the Earth.

Some examples of these stations are: ground-based weather stations, ocean buoys and air quality monitoring networks.

2.3.3. Copernicus Working Areas

The Copernicus program was created under the framework of providing services to a huge range of Earth sectors, which is the reason of the developing of so many different satellites. The different services in which Copernicus contributes are going to be shown grouped depending on the Earth theme they affect. The information of the working areas was taken from *[25]*.

2.3.3.1. Atmosphere

The Copernicus Atmosphere Monitoring Service (CAMS) provides continuous data about the composition of the atmosphere. These data give daily information of the atmosphere situation. In addition, it can be used to forecast changes on this situation up to four days. Moreover, CAMS is well known for studying information of previous years, in order to find anomalies or patrons.

This service has several applications in in different domains such as health, environmental monitoring, renewable energies, meteorology and climatology.

CAMS are used in five main areas:

- Air quality and atmospheric composition
- Ozone layer and ultra-violet radiation
- Emissions and surface fluxes
- Solar radiation
- Climate forcing

Figure 40. CAMS Logo *[25]*

2.3.3.2. Marine

The Copernicus Marine Environment Monitoring Service (CMEMS) objective is provide information about the global oceans, as well as, the Europeans seas, analyzing their dynamics and variability. In addition, it studies the marine ecosystems, giving information about their physical and biogeochemical state.

CMEMS is used to obtain daily information about the mentioned topics, as well as forecast. It is applied on several areas, such as:

- Marine safety
- Marine resources
- Coastal and marine environment
- Weather, seasonal forecasting and climate

Figure 41. CMEMS Logo *[25]*

2.3.3.3. Land

The Copernicus Land Monitoring Service (CLMS) provides information about the geography and the territories, in particular, the different uses of the land, its main changes and the state of the vegetation. Moreover, this service covers the information of the water cycle, and themes related with the earth surface energy.

This service supports a lot of applications in different domains, for example: urban planning and rural development, forest and water management, agriculture and food security, nature conservation and restoration.

CLMS consists of five main areas of application:

- The systematic monitoring of biophysical parameters
- Land cover and land use mapping
- Thematic hot-spot mapping
- Imagery and reference data

Figure 42. CLMS Logo *[25]*

2.3.3.4. Climate Change

The Copernicus Climate Change Service (C3S) objective is to provide reliable information about the climate all around the world. In order to carried out this task, this service analyzed present and past data. By forecasting, this service aim is to help to elaborate climate change policies.

This service provides as well an online platform, in order to let the user work with Copernicus products or raw data to obtain their desired output. This platform will be further analyzed on chapter 4.

Figure 43. C3S Logo *[25]*

2.3.3.5. Security

The Copernicus service for Security objective is to support EU policies, by giving information in relation with the European security challenges. These data are used to improve the prevention, preparation and answer while facing a crisis in one of the following areas:

- Border surveillance
- Maritime surveillance
- Support to EU External Action

Figure 44. Emergency Logo *[25]*

2.3.3.6. Emergency

The Copernicus Emergency Management Service (CEMS) gives precise spatial and geographical information of different type, to face an emergency. This information varies depending on the different actors involve in managing the emergency. These emergencies can be: caused by human, natural disasters and humanitarian crisis

In order to achieve its objective, the CEMS has two components:

- Mapping component
- Early warning component

Figure 45. CEMS Logo *[25]*

2.3.4. Copernicus Impact Areas

Apart from providing reliable and daily space information on several areas, Copernicus program has a huge number of non-spatial applications that contributes in different quotidian activities and operations. All the information about the impacts of Copernicus Program came from *Copernicus Impacts [30]*.

2.3.4.1. Agriculture

Agriculture is the main area of support of the Copernicus program. The data is provided by the land and Climate Change services.

The program allows to measure and evaluate the state and types of crops in each region. Furthermore, it can give valuable information for irrigation and water management. This information can be used by both, farmers and governmental authorities.

Figure 46. Agricultural fields image taken from satellite [26]

2.3.4.2. Blue Economy

The contributions to this area come by the hand of the Maritime and Climate Change Copernicus Services.

Copernicus data is used, among other tasks, to measure the quality of the water, to map fishing areas, to analyze the development of harmful algae, to keep track of coastal erosion or to protect marine diversity. All these applications are developed by monitoring the physical, chemical and biological characteristics of the sea and oceans captured by the satellites.

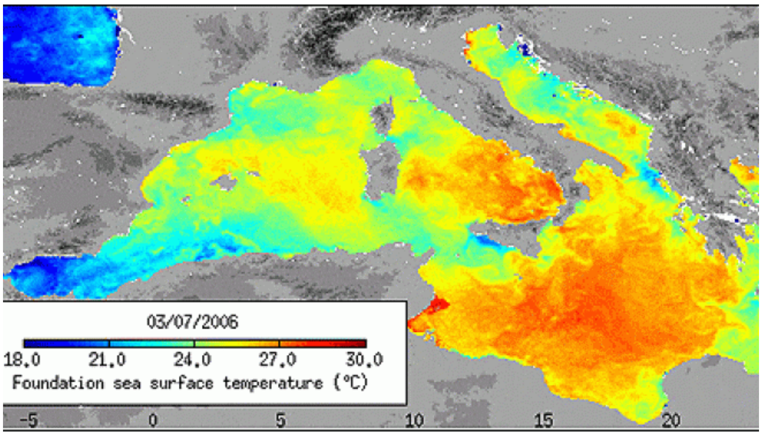


Figure 47. Mediterranean temperatures of the 3rd of July 2006 [27]

2.3.4.3. Climate Change and Environment

Atmosphere, Maritime, Land and Climate Change Services support this area of application.

Copernicus data provides a huge number of key rates, link with climate change. Therefore, it helps supporting European adaptation and mitigation policies. Some of the data provided is the level of carbon dioxide, glacier melting, the raise of the water levels, temperature differences between each year, etc.

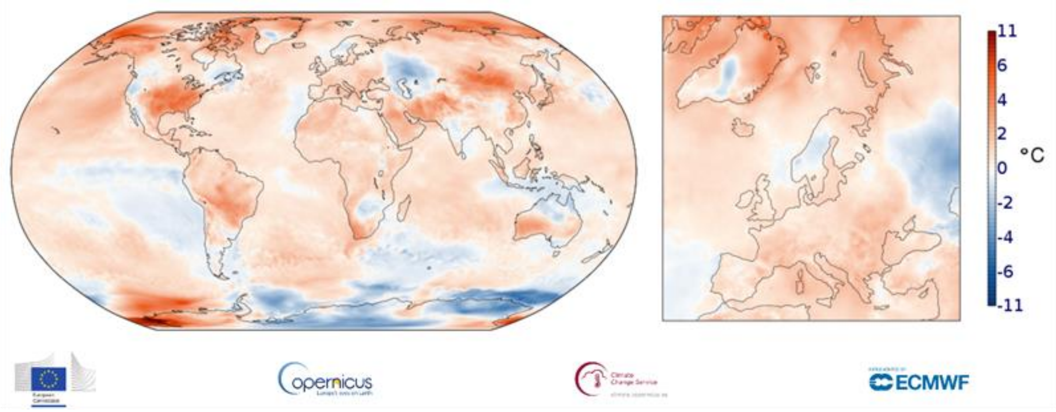


Figure 48. Surface air temperature for September 2019 relative to 1981-2010. ***Data source: ERA5. Credit: ECMWF-Copernicus Climate Change Service (C3S)***

2.3.4.4. Development and Cooperation

The data to support this theme come from several Copernicus Services: Atmospheric, Maritime, Land, Climate Change and Emergency.

Copernicus supports European Union international relationships by exchanging satellites data with the space agencies of other countries. In addition, it helps adapting to non-European countries the products and data obtained by the program.

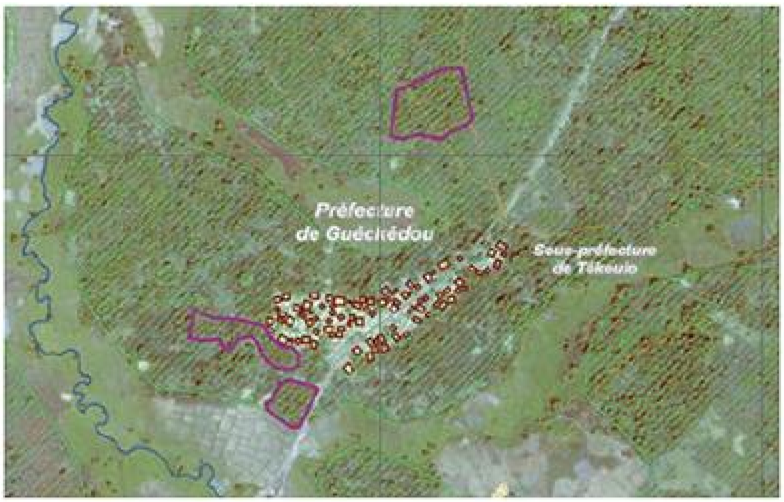


Figure 49. Map of Meliandú (Guinea). Original area of Ebola virus crisis 2014. Credit: Copernicus EMS

2.3.4.5. Energy and Natural Resources

Atmospheric, Marine and Land Copernicus Services are the main sources of information on this area.

Renewable energies are a clear priority to the European governments. It has been settled that the use of these energies should be up to the 20% of the total energy consume by 2020, and up to 27% in 2030. Among this type of energy, the main ones are, wind and sun energy, biomass and hydroelectric centrals.

Copernicus data about sun and wind predictions in different zones is widely used at the moment of deciding where to locate the correspondent installations. Moreover, it is very useful to analyze water levels and biomass.

Finally, Copernicus data about marine pollution, coasts analysis and water flows can be extremely helpful in non-renewable energies applications.

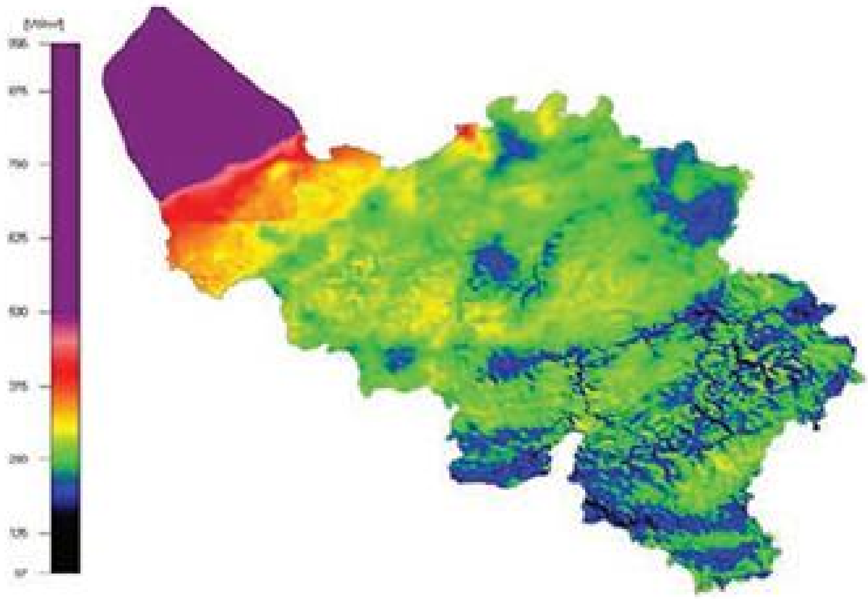


Figure 50. Wind Power Density (W/m2) over the surface of Belgium (100m above ground). Credits: 3E

2.3.4.6. Forestry

This sector is monitored by the Land and Climate Change Services from Copernicus.

The data obtained from these services is used to map forests all around the word. In addition, important information can be collected from these data, such as the changes of the forests and the main species it is composed of.

Finally, the data is used to identified and analyze fires and illegal logging.

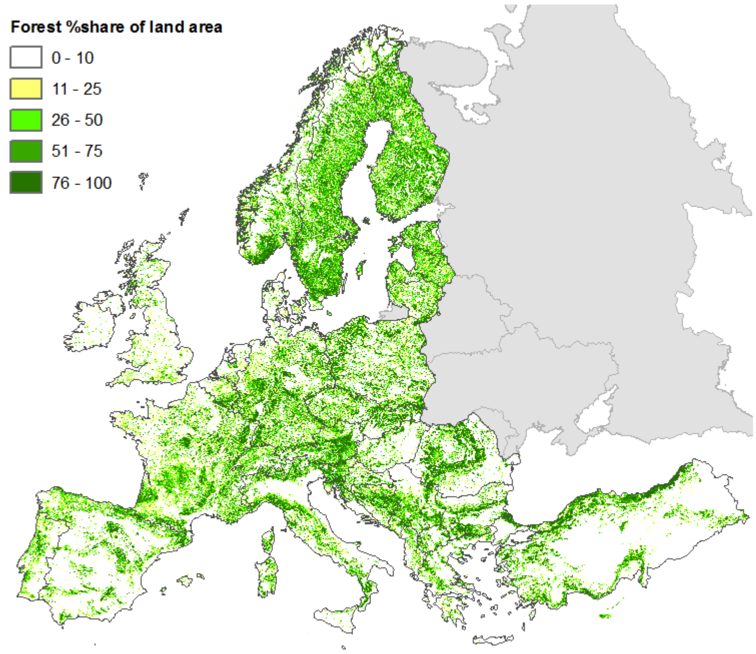


Figure 51. **Forest map of Europe** *[28]*

2.3.4.7. Health

The applications on the health area are developed between several Copernicus services, such as Land, Marine, Emergency and Atmosphere.

The program monitors different environmental phenomena that are related with human health, and provides this information to the health authorities. Two of the main health public issues come by the hand of atmospheric pollution and ultraviolet radiation. Copernicus fight against these problems by providing accurate forecast of these critical factors.

In addition, by analyzing data from different environmental aspects, such as water, air and vegetation quality, Copernicus can help to identify potential areas of apparition and propagation of epidemics.

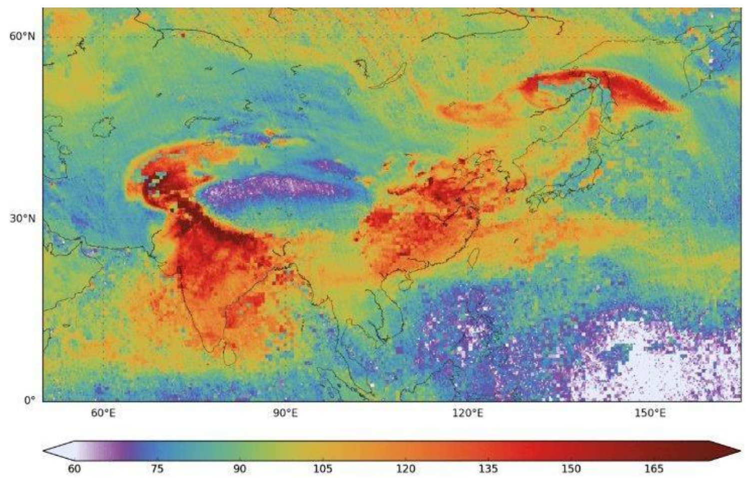


Figure 52. Data on air pollutants maps, July 2018. Credits: Copernicus Sentinel 5P

2.3.4.8. Insurance and Disaster Management

The applications on this area are under the framework of the Security and Defense services of Copernicus program.

The insurance sector is supported by this program by the validation, calibration and update on risk models that it can provide. Moreover, Copernicus is useful to analyze the loss after a catastrophe and therefore evaluate the compensations that needed to be paid.

Catastrophes, from natural disasters to industrial accidents, affected millions of persons every year. Copernicus program is used to prepare and prevent the risks, due to information that can be provided. Furthermore, it is very useful to interpret the scope of the damages. Finally, it analyzes the long-term repercussions and impacts in all the fields affected by the catastrophe, such as security, economy, environment, etc.

Figure 53. Flood extent map of the area of Lazarevac, Serbia. Credits: CEMS

2.3.4.9. Security and Defense

The applications on this area are related with the Security and Emergency services. The program supports EU challenges on these topics. By improving the surveillance of the European barrier, the program looks for reduce the illegal immigration and to save lives on the sea. Furthermore, it gives geographical information to difficult access areas which are under any type of emergency.

Regarding to maritime surveillance, Copernicus information can be applied to assure navigation security, to control fishing activities and to guarantee law enforcement. Finally, the program fight against water pollution.

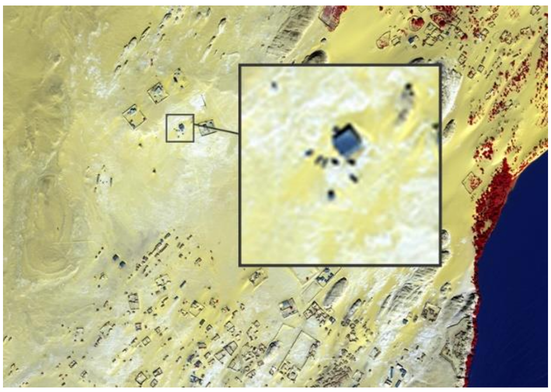


Figure 54.Activity report. Credit: Copernicus Service in Support to EU External Action

2.3.4.10. Tourism

Land, Marine and Atmospheric Services are the responsible of providing the data for tourism analyses.

Copernicus supports tourism by analyzing environmental aspects that could affect negatively to it. For example, it can forecast the presence of jellyfishes and algae on the beaches. In general, the data can be used to measure the quality of the water on the coast to assure a better protection of the bathing areas.

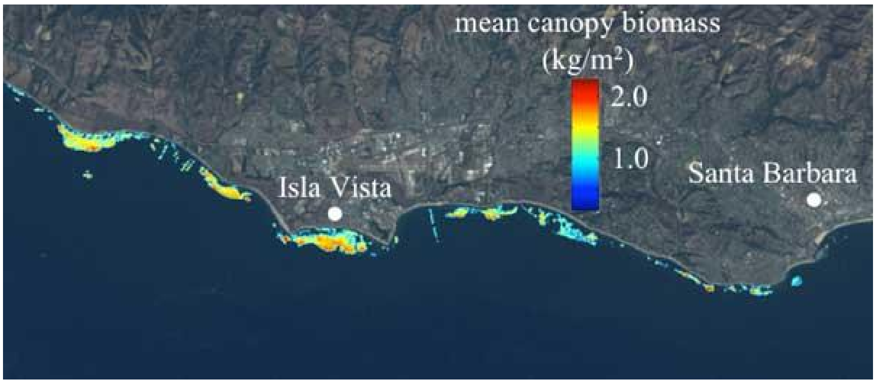


Figure 55. Satellites images of the subaquatic forests of gigantic algae *[29]*

2.3.4.11. Transport

This sector has support from the Atmospheric, Marine, Land and Security Copernicus Services.

Transport is a key factor of the European economy, in which passenger's safety plays a crucial role. Copernicus data can be used to analyzed water flows or the presence of ice while speaking about maritime transport. Regarding to flying, the presence of volcanic eruptions can be a huge source of problems.

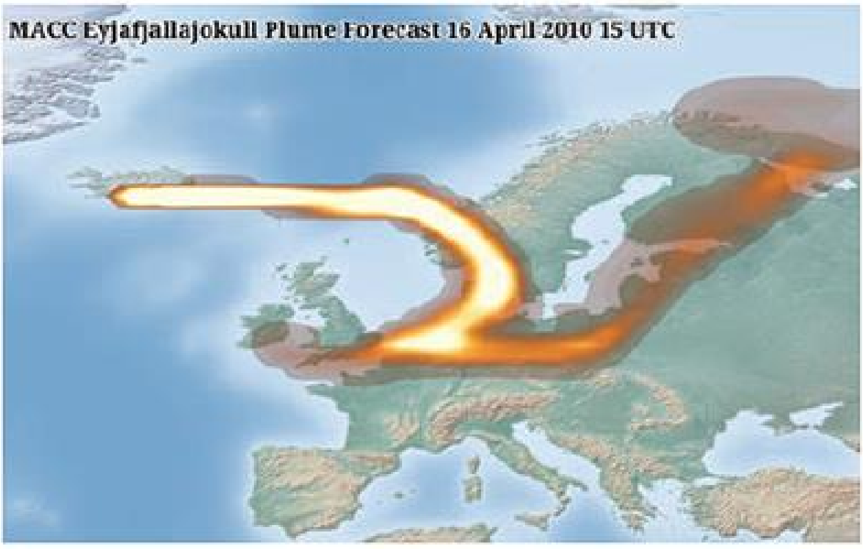


Figure 56. Following of the volcano Eyjafjallajökull ash cloud. Credits: CAMS

2.3.4.12. Urban Planning

The last application of the Copernicus program is urban planning. The data that support this application come from the Land and Atmospheric Services.

Copernicus gives valuable information about the use and occupation of the land, as well as the physical properties of the soil, such as the impermeability. This information is used by the authorities related with the management of urban areas in order to succeed in the implementation of all kinds of needed infrastructures.

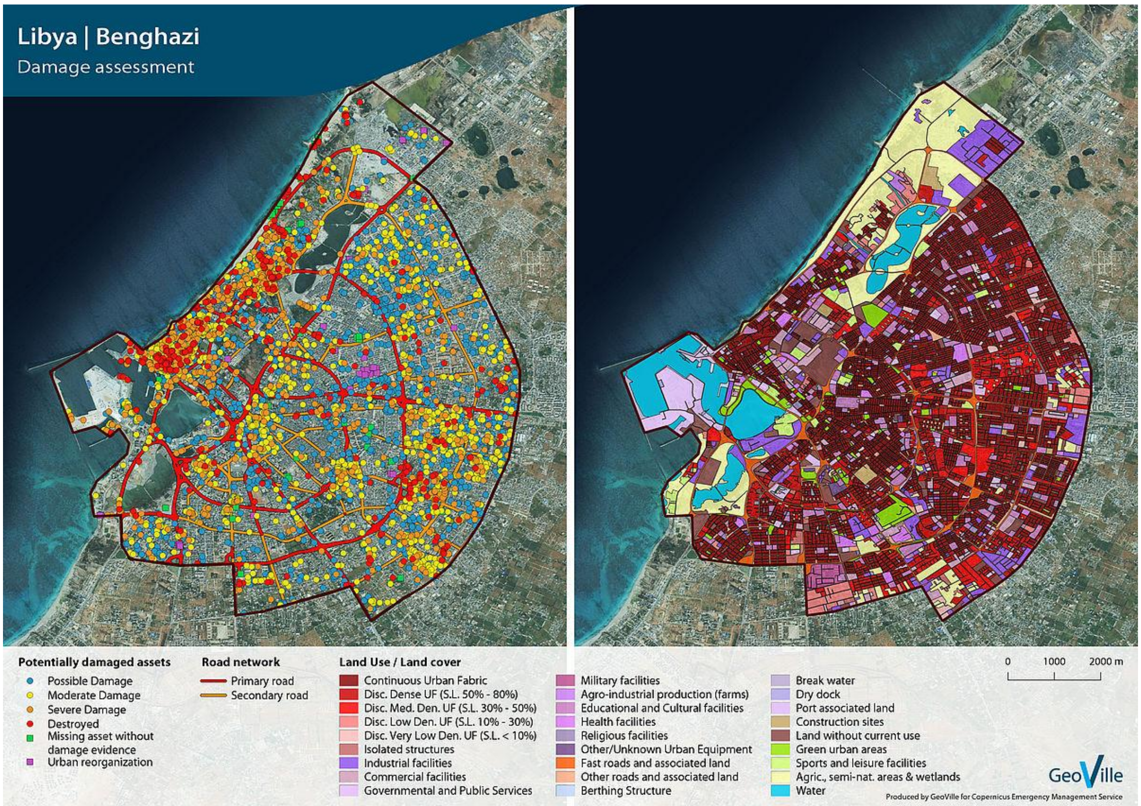


Figure 57. Damage assessment in Libya. Credits: Produced by GeoVille for CEMS

3. State of Art in Remote Sensing Applications

In this chapter some already developed projects and products using Copernicus satellites to estimate soil moisture will be analyzed. The aim of this chapter is to highlight the importance of Copernicus Program in the developing of new methodologies in several areas, but particularly on the agriculture sector.

3.1. Case 1. Improving Irrigation Management in Austria

The project aim was to improve irrigation management techniques on one region of Austria, called Marchfeld, where there is a shortage of rainfall. The techniques implemented to develop this task were GIS and remote sensing, specifically, satellites from the Sentinel constellation.

The research was carried out by The Institute of Surveying, Remote Sensing and Land Information from the University of Natural Resources and Life Sciences of Vienna. The analyzed area had a surface of approximately 60,000 hectares. The research was carried out during the months of May to September of 2013, as a demonstration campaign.

The innovation of this project, in comparison with similar ones that has been carried out all around the world, was that it was addressed to farmers, instead of being addressed to agricultural organizations.

The methodology applied to develop this project was the following: Firstly, stakeholders analyzed the remote sensing estimations of irrigation water volumes. Secondly, they compared these estimations with the actual volumes of water being used, supplied by the farmers. This way, the efficiency of the use of water was estimated. The satellites used during the project were Sentinel 2 and Landsat-8.

This research delivered four main products that could be used by the farmers to improve their irrigation systems. The products were the followings:

1. Crop development maps, with a spatial resolution between 10 to 20 meters. They were available every 7 to 10 days.

2. Evapotranspiration's maps.

3. Weather data and forecasts., which were delivered daily.

4. Specific irrigation requirements for each crop type present on the region.

Furthermore, 54% out of the 300 farmers that took part on the research, assure they will pay for having access to this type of remote sensing services. This service can help them low their irrigation cost, which is between EUR 8 million to 20 million for a year, depending on the size of the region own.

The use of the Sentinel satellites on this project means reducing the cost of remote sensing images. This cost reduction is up to 23% using Copernicus data instead of commercial missions.

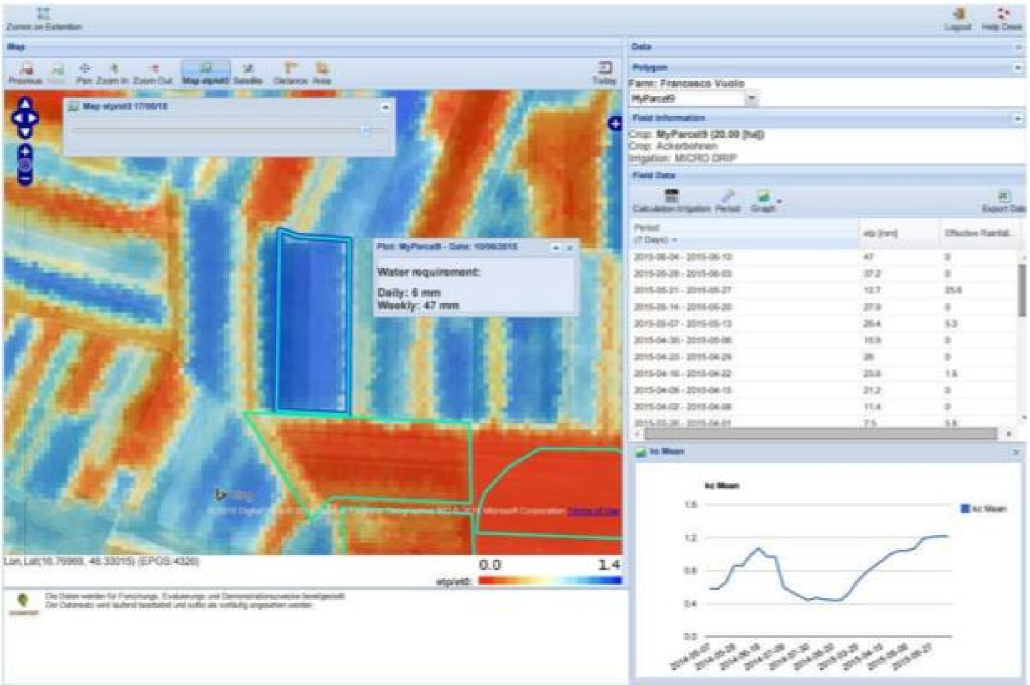


Figure 58. Extract of the webGIS information used to deliver information to farmers. Source: Institute of surveying, Remote Sensing and Land Information

For more information of these project see *(Improving irrigation in Austria) [31]*.

3.2. Case 2. The Challenge of irrigation Management in Cyprus using Copernicus

One of the biggest challenges of the Mediterranean regions is leading with the lack of water. This problem, has been even increased due to the Climate Change. According to the European Environment Agency, the problem of irrigation in Europe is mostly concentrated along the region of the Mediterranean where some countries use more than 80% of the fresh water for this purpose.

The aim of this project was facing this "water problem" by applying different tools and techniques to achieve a more efficient water management on the irrigation framework.

To achieve their objective the researches developed a new method for estimating crop evapotranspiration (ETc). Evapotranspiration is understood as the loss of moisture due to direct evaporation and to the transpirations of the vegetation. It is measured in mm per time unit.

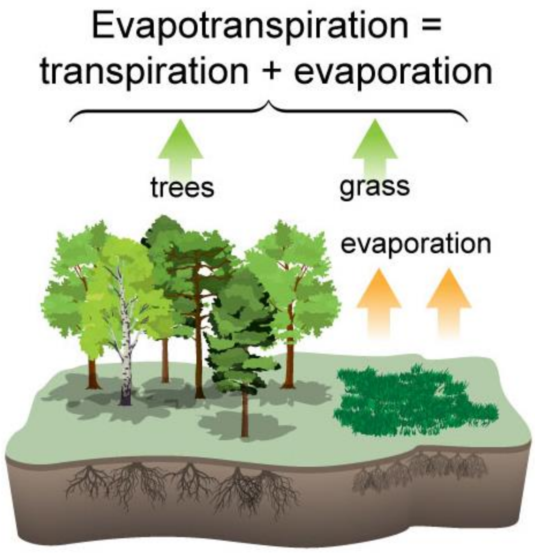


Figure 59. Evapotranspiration graphical definition *[32]*

Applying this new method, ETc estimations were obtained systematically using remote sensing techniques. It was established by the ERATOSTHENES Research Centre (ERC). The output of this project was the obtention of semi-empirical models, which were developed regarding canopy factors of each crop. In order to do this, several balance energy algorithms, soil data coming from both, in-situ measurements and remote sensing images and modeling techniques were used. Furthermore, under the framework of this project, some Vegetation Indices were created, i.e. Leaf Area Index (LAI) and Crop Height (CH). These indices were created to better define and describe some crop canopy factors *[5]*.

The information achieved during this research can be used by farmers, agricultural organizations and water management authorities, between others, to reduce farming costs Several data products were created during this research, seeking to provide visual mapping and time series information which will give the users useful data of water requirements and crops states.

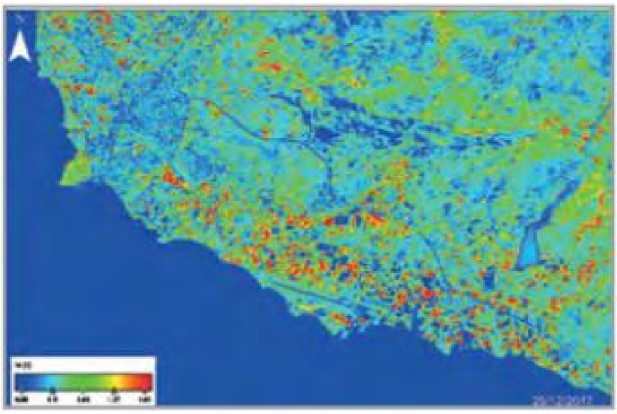


Figure 60. LAI map using Sentinel 2 in Pafos, Cyprus. Credit: Contains Modified Sentinel 2 data (2018) *[5]*

For more information of these project see *VV.AA. (2018) [5]*.

3.3. Case 3. Earth Observation Data to Detect Irrigated Areas. An application in Sothern Italy.

In Southern Mediterranean areas irrigation is a critical factor to assure the correct development of crops during the late spring and summer season, due to the high temperatures and the lack of rain. Therefore, the improvement of water management has become a crucial task in order to guarantee the best possible used of water.

The aim of the project was analyzing the irrigation of several agricultural fields in two land Reclamation Consortia located in the Campania Region (Italy), in order to detect non-authorized water abstractions.

In order to understand the development of the crops, remote sensing imagery technologies can be applied. In this research, Sentinel 2 satellite was used to calculated the Normalized Differentiate Vegetation Index (NDVI). Sentinel 2 was chosen in this project due to its high spatial resolution and medium temporal resolution, which was enough for the scope of the research.

This Vegetation Index gives useful information of the grade of development of the crops, its quality and its quantity. It is calculated using two of the spectra bands of the Sentinel 2 satellite. This term will be further analyzed on chapter 5.

The information obtained through the NDVI was compared with the water used for irrigation. This way, it was simple to find those areas that have been using water without permission, as well as that ones that have used more water volume than the amount they were authorized to use.

Figure 61.Cadastral parcels with (green parcels) and without (red and orange parcels) necessary water authorizations *[5]*

For more information of these project see *VV.AA. (2018) [5]*.

3.4. Case 4. High-precision satellite-based Soil Moisture data from VanderSat

VanderSat is a Netherlands company that provides global products and services coming from satellites observations. Most of the products of this company are center on the agricultural sector, analyzing importance variables of this fields, such as water, temperature and vegetation. They also provide products of the insurance industry and water management related. VanderSat has been chosen by the European Commission as one of the most innovative companies in the space domain in Europe.

VanderSat has created a global product that provides soil moisture estimations daily within a resolution of 100x100 meters. The characteristics of the product are the followings:

- Near-Real Time data. The data is available six hours after the satellites have passed over the desired region. Furthermore, it is cloud and dark proof.
- The data is available at high resolution since June 2002, and with low resolution since 1978.
- High resolution data: 100x100 meters.
- There is data available for different root zones depths.
- Dynamic open water bodies are taken into account.

VanderSat Soil Moisture Monitoring	
Unit	Moisture content in m^3/m^3
Sensing depth	0-5 cm
Rootzone Options	10 cm // 20 cm // 40 cm
Pixel resolution	100x100 meter // 25x25 km
Temporal resolution	Daily
Data availability 100m product	June 2002 - present
Data availability ¼ degree product	October 1978 - present
File format	GeoTiff (images), csv (time series)
Data delivery	VanderSat API
Data viewer	VanderSat Viewer

Figure 62. VanderSat Soil Moisture product characteristics [33]

4. Cloud Engine Tools

In this chapter the two main cloud engines are going to be analyzed. Under the framework of this project, a cloud engine is understood as an online platform where both, raw data and already developed products, can be obtained. Moreover, one of the main characteristics of these tools is the possibility of working online with the raw data in order to create a specific product, that fulfill all the requirements proposed.

In this project, the final product must be soil moisture data with a really high spatial resolution, and the best possible temporal resolution.

There are several advantages to work with this type of technology. Firstly, it enables the user not to download the data from the satellites, which normally, are quite big and heavy files, filling lots of memory, and taking a lot of time to be downloaded. Secondly, the possibility of working with raw data allows to obtain products which characteristics can be defined by the user. Finally, treating the images online means an application, that can be used worldwide, can be created.

The two main cloud engines that are going to be analyzed are the Copernicus Climate Change Service and the Google Earth Engine. These two tools have several similitudes and differences between each other, as well as limitations. All these main aspects are going to be explained in order to understand the reasons of selecting Google Earth Engine Tool to design and develop the soil moisture estimation product of this project.

Firstly, an introduction to each of the clouds will be done, analyzing the satellites they have at their disposal, as well as the already existing products. Secondly, their main features will be developed. Finally, the conclusion for selecting one of the Cloud Engines will be developed.

4.1. Copernicus Climate Change Service

4.1.1. General Overview

Copernicus Climate Change Service (C3S) is one of the six services that the Copernicus program offers to the users. This service is of extremely importance because it provides an online platform to the public. On this online platform the user is able to visualize and analyze the datasets coming from the satellites. Furthermore, the user can benefit from already developed applications and products, or create new ones.

C3S has been implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), which is an independent intergovernmental organization conformed by 21 European member states and 13 associated states. It was created in 1975 and their headquarters are in Reading, England. It is a research institute and an operational service that seeks to provide weather predictions to its members. This organization is specialized in numerical weather prediction for up to two weeks.

The purposes of C3S are link with the Copernicus program objectives, and can be grouped on three big categories: economic benefit, social benefit and environmental benefit.

1. **Economic benefit.** It seeks to achieve this objective through three main actions.

    a. Developing policies related with climate, i.e. flood prevention, to protect citizens and minimize material damage.

    b. Supporting the creation of more services based on social development.

    c. Analyzing and improving mitigation plans for some human activities.

2. **Social benefit.** It is center on two main aspects, security and emergencies. In the first one it seeks to monitor the borders of the country members. Regarding to emergencies, the program supports catastrophes and other type of emergencies by providing action plans and visualization of affected areas of difficult access.

3. **Environmental benefit.** The program provides valuable information and forecasting of climate. Furthermore, it analyzes key climate change parameters.

This service has a huge variety of products in its portfolio. The products are created using past, present and future forecast information based in all the data store in its file. The types of products that can be obtained are listed hereunder:

1. Global and regional reanalysis. One of the most important ones is the ERA5 data segment, that will be explained later.

2. Products based on observations, none forecast or models are applied while developing these products.

3. Climate forecast and projections at global and regional scales.

4. Important information regarding to the economic or social areas, as it is said in the program purposes.

5. Forecast on a wide range of variable and factors. This forecast can be done daily, weekly or seasonal.

6. Estimation of various Essential Climate Variables (ECV). The ECVs are biological, physical or chemical variables, which contribution is crucial to characterize the Earth climate, i.e. snow, soil moisture, surface temperature, etc.

7. Near real time climate monitoring facility.

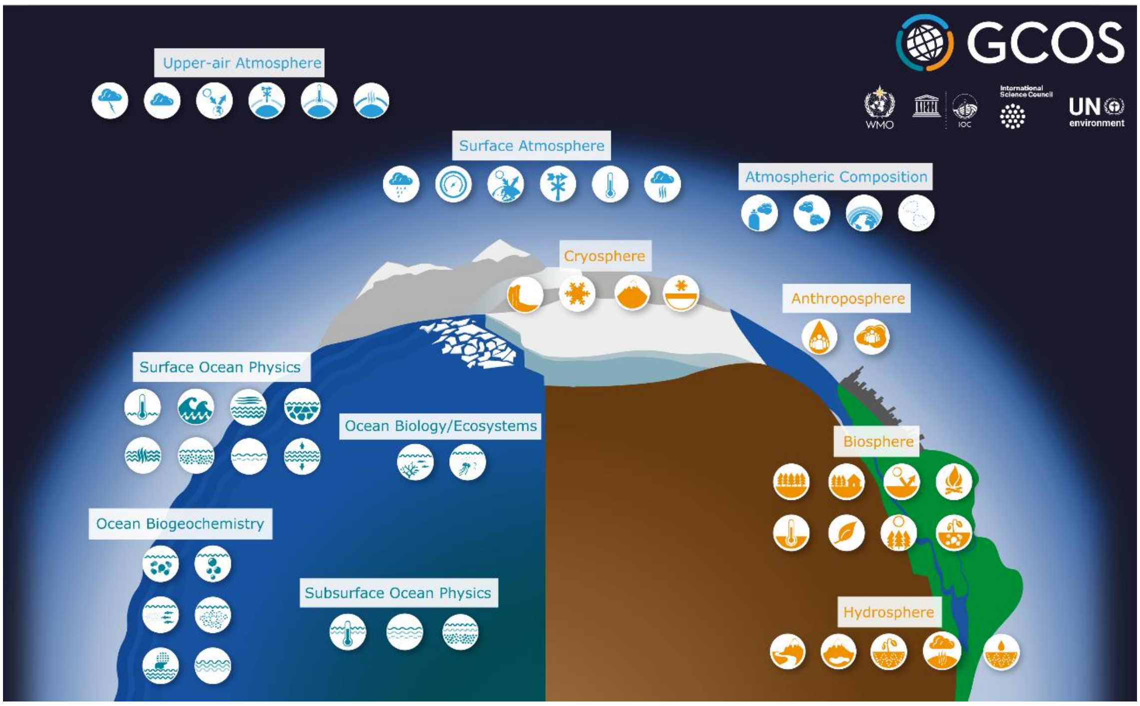


Figure 63. Essential Climate Variable *[34]*

Among all the above-mentioned type of products, several soil moisture products can be found on the C3S catalog. Unfortunately, any of them have a high enough space resolution for the requirements of the project. Therefore, they could not be used. The products and their main characteristics can be seen on the table 18 to table 25. All the information come from *C3S Data Catalog [35]*.

Soil moisture gridded data from 1978 to present	**Horizontal coverage**	Global
	Horizontal resolution	0.25°x0.25°
	Temporal coverage	1978 to present
	Temporal resolution	Day, 10-day and month
	Update frequency	Depends on the product:
	File format	NetCDF
	Data type	Grid

Table 18. Copernicus Climate Change Services Products characteristics

River discharge and related historical data from the European Flood Awareness System	**Horizontal coverage**	Europe. The domain spans from northern Africa beyond the northern tip of Scandinavia. In the west it ranges far into the Atlantic Ocean and in the east as far as to the Caspian Sea.
	Horizontal resolution	5km x 5km
	Temporal coverage	1991-01-01 to near real time (30-day delay) for the most recent version.
	Temporal resolution	Daily data.
	Update frequency	-
	File format	GRIB and NetCDF
	Data type	Grid

Table 19. Copernicus Climate Change Services Products characteristics 2

River discharge and related forecasted data by the European Flood Awareness System	**Horizontal coverage**	Europe. The domain spans from northern Africa beyond the northern tip of Scandinavia. In the west it ranges far into the Atlantic Ocean and in the east as far as to the Caspian Sea.
	Horizontal resolution	5km x 5km
	Temporal coverage	2018-10-10 to near real-time
	Temporal resolution	Forecasts are issued daily at 00 and 12 UTC.
	Update frequency	The EFAs forecasts are published on CDS at regular intervals with a minimum of 1-month lag with respect to the actual date.
	File format	GRIB and NetCDF
	Data type	Grid

Table 20. Copernicus Climate Change Services Products characteristics 3

Essential climate variables for assessment of climate variability from 1979 to present	**Horizontal coverage**	Global
	Horizontal resolution	0.25°x0.25°
	Temporal coverage	1979 to present.
	Temporal resolution	Monthly
	Update frequency	Monthly
	File format	GRIB
	Data type	Grid

Table 21. Copernicus Climate Change Services Products characteristics 4

UERRA regional reanalysis for Europe on soil levels from 1961 to present	**Horizontal coverage**	Europe. The domain spans from northern Africa beyond the northern tip of Scandinavia. In the west it ranges far into the Atlantic Ocean and in the east, it reaches to the Ural.
	Horizontal resolution	11km x 11km for the UERRA-HARMONIE system. 5.5km x 5.5km for the MESCAN-SURFEX system.
	Temporal coverage	January 1961 to present.
	Temporal resolution	Analysis are available each day at 00, 06, 12 and 18 UTC.
	Update frequency	Month with a delay of about four months relatively to actual date.
	File format	GRIB2.
	Data type	Grid

Table 22. Copernicus Climate Change Services Products characteristics 5

CMIP5 monthly data on single levels	**Horizontal coverage**	Global
	Horizontal resolution	From 0.125°x0.125° to 5°x5° depending on the model
	Temporal coverage	1850-2300 (shorter for some experiments)
	Temporal resolution	Month
	Update frequency	-
	File format	NetCDF
	Data type	Grid

Table 23. Copernicus Climate Change Services Products characteristics 6

Era5 Land hourly data from 2001 to present	**Horizontal coverage**	Global
	Horizontal resolution	0.1°x0.1°
	Temporal coverage	January 2001 to present
	Temporal resolution	Hourly
	Update frequency	Monthly with a delay of a few months relatively to actual date.
	File format	GRIB

Table 24. Copernicus Climate Change Services Products characteristics 7

Era5 Land monthly data from 2001 to present	**Horizontal coverage**	Global
	Horizontal resolution	0.1°x0.1°
	Temporal coverage	January 2001 to present
	Temporal resolution	Monthly
	Update frequency	Monthly with a delay of a few months relatively to actual date.
	File format	GRIB
	Data type	Grid

Table 25. Copernicus Climate Change Services Products characteristics 8

The schema of the figure 64 helps to better understand the parts involve in the organization of Copernicus Climate Change Service.

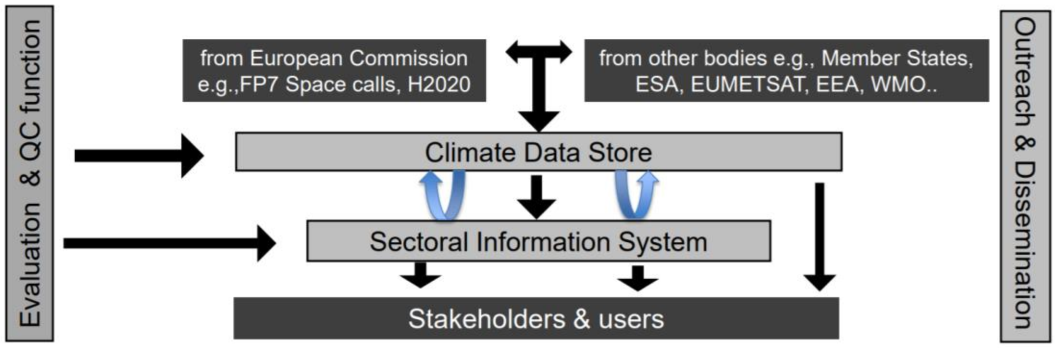


Figure 64. C3S in a nutshell *[36]*

Finally, the following figure shows the C3S data flow, from the detection phase by the satellites to the final products.

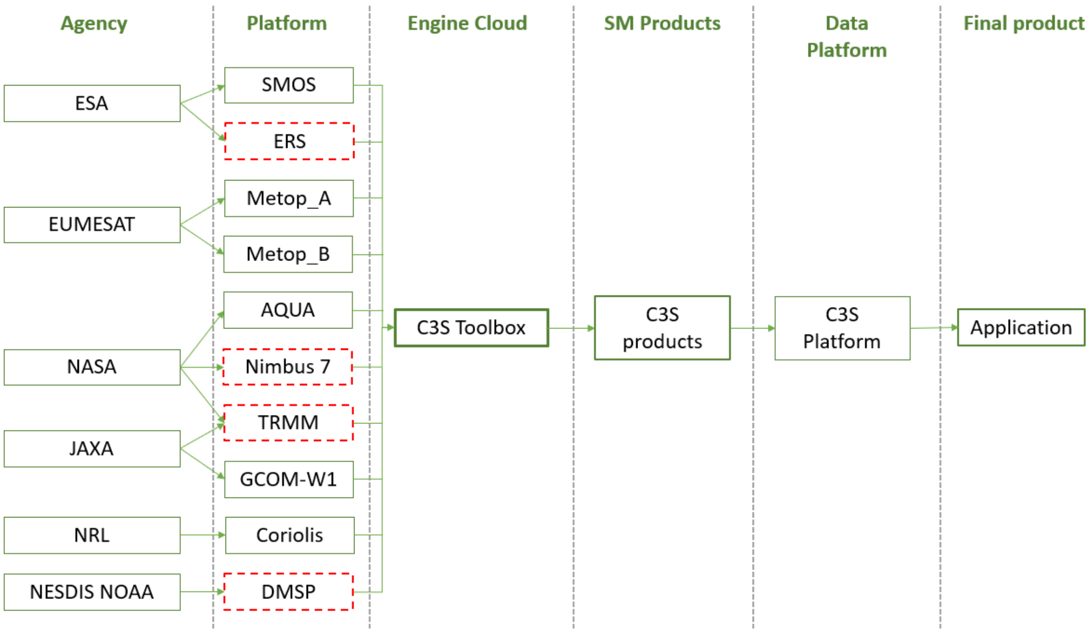


Figure 65. Data Flow for C3S: from detection to final processing for soil moisture estimations. Platforms marked in red correspond to ended missions

4.1.2. Main Components

C3S main components are the datastore, the applications and the datasets.

The datastore is composed of two main elements, the APIs and the Toolbox.

The toolbox interface can be seen in the figure 66. As it can be seen on the left panel, the available applications and datasets can directly be accessed from the toolbox. The applications area has some computational examples that can be used as guidelines for getting starting on the toolbox. The dataset is the C3S catalogue, both the raw data and the already developed products are found here. The last button of the left panel is the documentation. This area explains how to use some C3S specific functions.

On the center panel there are several parts. The first one is the script area, in which the codes are developed in order to transform and analyze the desire data. This area has a run and a save button, in order to execute and save the scripts.

In the console the computed outputs of the script will appeared. The history button shows the latest actions developed on the toolbox. Finally, in the "your queue" sector the actions taking place appeared, i.e. the exportation of data.

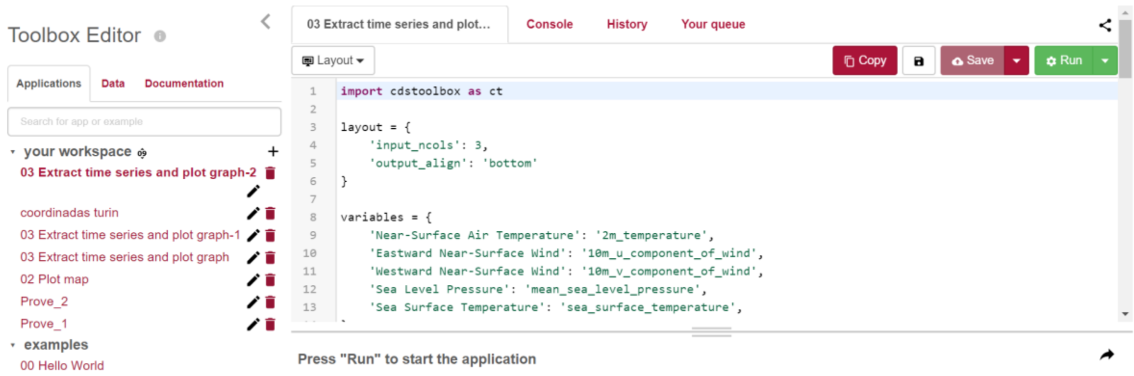


Figure 66. C3S Toolbox Editor interface

4.1.3. ERA5

ERA5 is the newest climate reanalysis product provided by C3S and ECMWF. A climate reanalysis product uses past data combine with models in order to create time series for the desired variables. The data is provided every hour since 1979, with a high precision, 0.25°x0.25°. The data may be amplify using meteorological information from 1950. ERA5 provides atmospheric, land-surface and sea-state parameters, some of them are listed hereunder.

- **Atmospheric parameters:** air temperature, wind at different altitudes and pressure.
- **Land Surface parameters:** rainfall or soil moisture.
- **Sea-State parameters:** height of the waves.

ERA5 is substituting ERA-Interim climate reanalysis product, providing a higher resolution regarding to both, space and time, and being able to compute bigger data groups.

Figure 67 is an example of a comparison between ERA5 and ERA-Interim products spatial and temporal resolution.

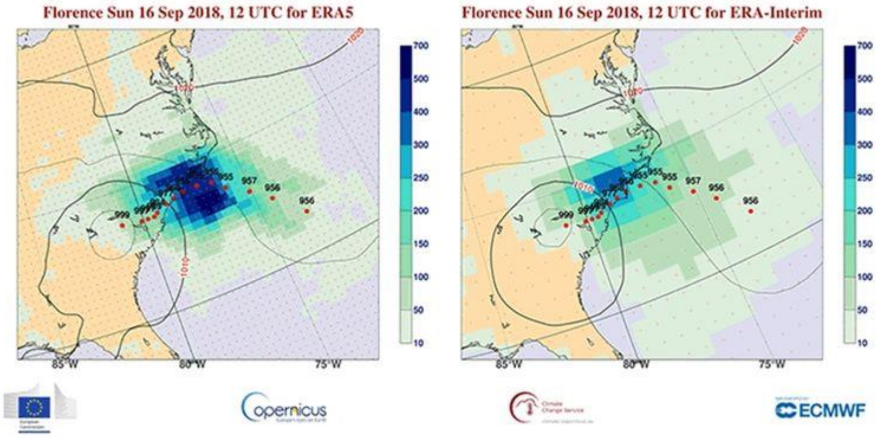


Figure 67. Comparison between ERA5 and ERA-Interim products from 16th September 2018. Credits: ERA5 and ERA-Interim.

4.1.4. Existent Applications

C3S datasets has been largely used on a wide range of areas and fields. The products have different characteristics, i.e. temporal and spatial resolution, temporal and horizontal coverage, etc. Down below, some products with different characteristics between each other will be shown in order to demonstrate the huge possibilities of this platform.

4.1.4.1. Glaciers elevation and mass change data from 1850 to present from the Fluctuations of Glaciers Database

The objective of this product is analyzing the transformation of the glaciers. This studio is used to help understanding the impact of the climate change *[37]*. Table 26 shows the characteristics of this product.

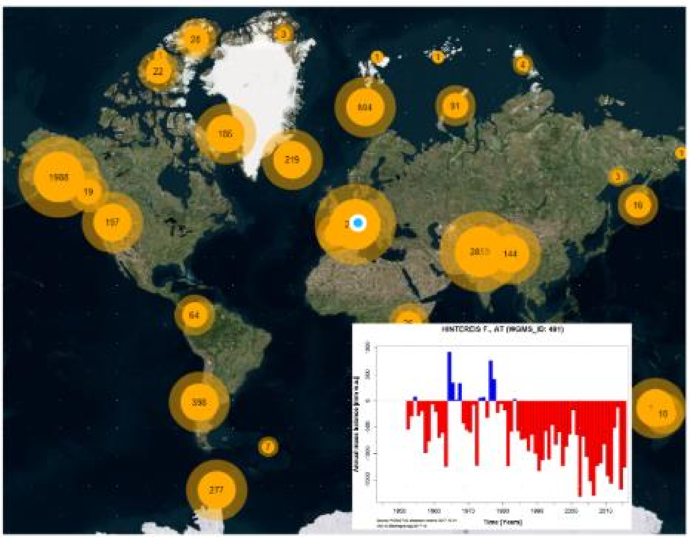


Figure 68. Worldwide distribution of glaciological series. The blue dot refers to the location of the Hintereis glacier in Austria. Its glaciological series is shown in the graph *[37]*

Data type	Point shape file and text attribute file linked through common identifier
Horizontal coverage	Global
Horizontal resolution	Individual glaciers
Vertical coverage	Surface
Vertical resolution	Single level
Temporal coverage	1850 to 2017
Temporal resolution	Annual to decadal
File format	ESRI shape files (Shape files can be read by a number of software programs such as ArcGIS and QGIS) and comma-separated value (CSV) text files
Update frequency	Annual

Table 26. Glacier elevation and mass change data product *[37]*

4.1.4.2. Aerosol properties gridded data from 1995 to present derived from satellite observations

This product studies the properties and presence of the aerosols on the atmosphere. These particles are in a really low proportion on the atmosphere, but their impact is crucial on the climate, because they influenced directly in the global radiation by scattering or absorbing it. Furthermore, they have an indirect impact influencing cloud reflectivity, lifetime and cover *[38]*.

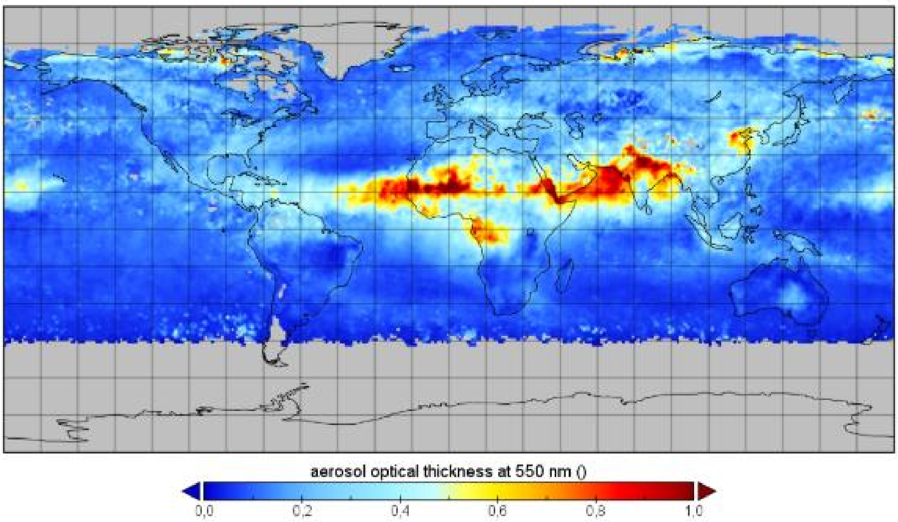


Figure 69. Aerosol optical thickness global product *[38]*

Data type	Gridded
Horizontal coverage	Global
Horizontal resolution	2.5° x 2.5° for aerosol extinction coefficient 1° x 1° for all other variables
Temporal coverage	June 1995 to present with 5-month delay
Temporal resolution	5-daily composite for the aerosol extinction coefficient Daily and monthly for all other variables
File format	NetCDF
Conventions	Climate and Forecast (CF) Metadata Convention v1.6 Attribute Convention for Dataset Discovery (ACDD) v1.3
Update frequency	6 months Full mission reprocessing every 2-3 years

Table 27. Aerosols properties gridded data product *[38]*

4.1.4.3. Fire burned area from 2001 to present derived from satellite observations

This product provides global information of the total burned area by identifying the first day of fire detection. This detection was carried out analyzing the reflectance variations measured by Sentinel 3. Additionally, the size of the burned area is given as well. These surfaces were obtained working with Copernicus Climate Change Service land cover dataset *[39]*.

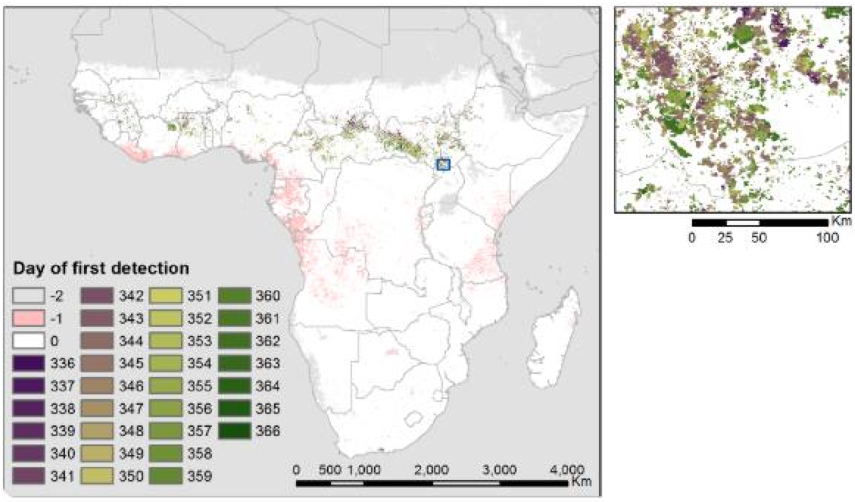


Figure 70. Burned Area for Africa, December 2016 *[39]*

Data type	Grid and pixel
Horizontal coverage	Grid product: Global Pixel product: Continents
Horizontal resolution	Grid product: 0.25 x 0.25 Pixel product: 250m (v5.0cds and v5.1cds)
Vertical coverage	Surface
Vertical resolution	Single level
Temporal coverage	From 2001 to 2016 for version 5.0cds From 2001 to 2017 for version 5.1cds
Temporal resolution	Grid product: 15 days (v5.0cds); 1 month (v5.1cds) Pixel product: Month
File format	NetCDF4
Conventions	Climate and Forecast (CF) Metadata Convention v1.6 and ESA CCI Data Standards [DSWG 2015]
Versions	Version 5.0cds and 5.1cds provide data from the European Space Agency Climate Change Initiative from 2001 until 2017 All versions are produced with the same processing chain.
Update frequency	Yearly

Table 28. Fire burned area product *[39]*

4.2. Google Earth Engine

4.2.1. General Overview

Google Earth Engine (GEE) is one of the newest applications created by Google. This platform was designed to analyze and download cartography information coming from Digital Terrain Models and satellites images, being able to process and work with this information without any costs. Therefore, GEE was created with scientific analyses purposes, being able to process global information at a petabyte scale. Furthermore, it allows the visualization of geospatial data for all types of users, such as commercial, public, etc.

The purposes of this platform are a lot, and cover a huge range of different areas, the main ones are:

1. Contribute to the progress of global challenges, such as climate change or humanitarian crisis, by the use of remote sensing datasets.

2. Provide new applications, methods, models and algorithms which can be developed and used at global scale.

3. Contribute to the development of data-driven science by creating strong-impact products based on this technology.

4. Create new opportunities to apply large datasheets in the remote sensing scope.

This platform must not be confused with Google Earth. Google Earth allows to see maps, satellites images, terrains, building in 3D and much more, but it is not an analysis tool. The user cannot work and transform the data coming from Google Earth into a real application product. Meanwhile, GEE allows several actions to be carried out on the data provided. Some of its most interesting functions are:

1. Satellite data visualization, both historical ad near real time data.

2. Download of huge amounts of information. The data downloaded can be selected from the satellite images by bands, in order to allow the user downloading only the needed data.

3. Create time laps.

4. Satellite data management by the application of complete mosaics.

5. Compose territorial index, with analytical purposes.

6. Work and transform data coming from satellites and Digital Terrain Models. The data can be processed by the creation of scripts with the development of different kind of algorithms.

The last function explained is very important in order to have an overall view of the scope of the platform, because it allows to better understand and classify the different types of analysis that the platform can performed, based on the sort of the algorithm produced. *(GEE information) [40].*

1. **Machine Learning:** develop supervised and unsupervised classifications.

2. **Images:** visualization, mathematical operations, metadata, gradient calculations, etc.

3. **Images Collections:** visualizations, metadata, filtering, etc.

4. **Geometries, geometrical objects and collections of geometrical objects:** geometric operations, filtering, etc.

5. **Reductions:** statics parameters and operations of a region of an image, linear regressions, etc.

6. **Unions:** simple unions, special unions, intern unions, etc.

7. **Graphics:** temporal evolutions in image regions, histograms, etc.

8. **Matrix:** matrix transformation.

9. **Specialized Algorithms:** for Landsat or Sentinel 1.

10. **Active management**: import and export of different types of files.

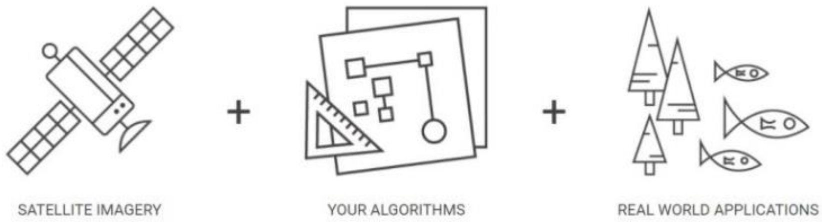


Figure 71. GEE working principle *[41]*

4.2.2. Main Components

Google Earth Engine main components are the datasets, the compute power, the APIs and the Code Editor Platform.

4.2.2.1. Datasets

The platform has a peta-byte scale archive, with data from more than 40 years old to the present. The data is essentially remote sensing images, but it has as well some already developed products, such as the Canada Annual Crop Inventory. All the datasets are available to the users at the Google Earth Engine Catalog.

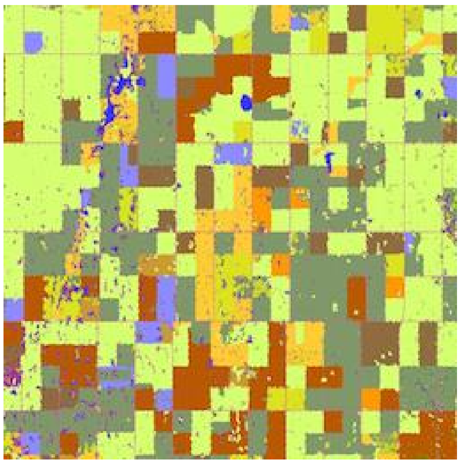


Figure 72. Canada AAFC Annual Crop Inventory *[42]*

4.2.2.2. Compute Power

The platform has a really high computational power. The infrastructure is optimized for parallel processing of the data.

4.2.2.3. APIs

API, application programming interface, is a set of subroutines, functions and procedures, which are offer by a certain library, to be used by the user on a particular software.

The platform offers several APIs. There are available for both JavaScript and Python, being more direct accessible the ones for Java because it is the programming language predetermined on the server. While analyzing the satellite data these APIs can be accessed from the Code Editor.

4.2.2.4. Code Editor

It is an Integrated Development Environment for complex analysis and visualization. It was in this component of the GEE platform, where the code to estimate soil moisture was developed.

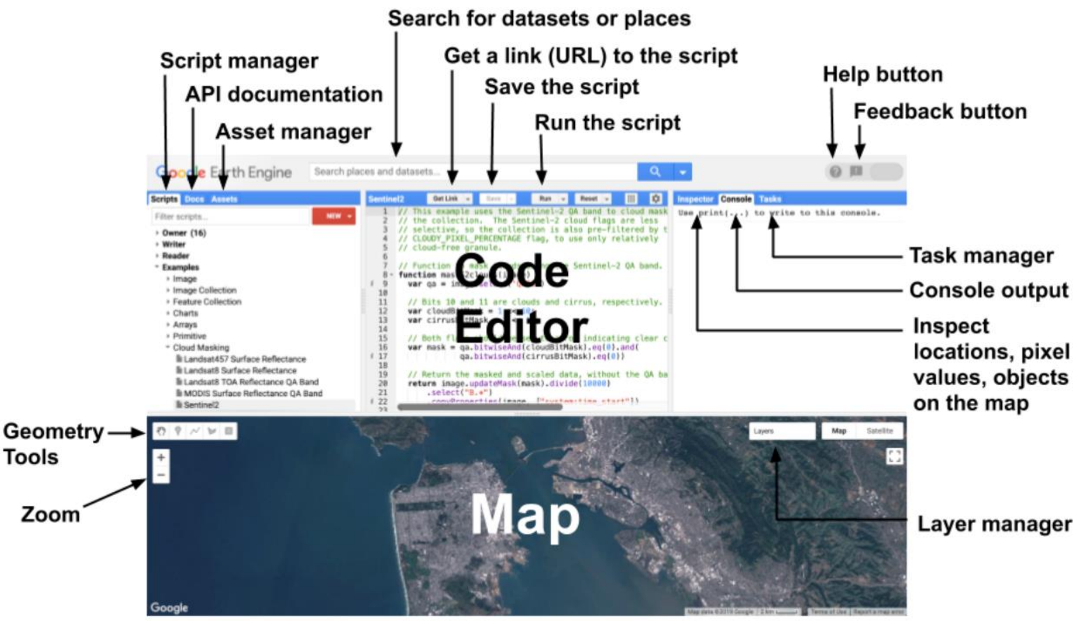


Figure 73. GEE Code Editor interface *[43]*

- The central panel of the screen is the proper Code Editor. Its programing language is Java.
- On the top part of the editor there are several buttons. They can be used to erased the map, run and save the script.
- The "Get Link" button provides a unique URL for the script being developed at the moment.

- The map on the inferior panel contains all the aggregated layers for the script results. At the left corner of the map several geometries tools can be found. There are usually used to draw the study areas directly on the map. Some tools to navigate through the map are available as well. At the right corner a view selector is available. In addition, the layer button allows to select the layers visualization characteristics, among the output layers computed in the script.

- On the superior part of the screen a search bar can be seen. It can provide groups of data and places.

- The left panel has three different buttons. The first one has code examples already developed. The second one has a reference for API searches. The third one is a manager for data privacy.

- The right panel has, as well, three buttons. The first one is an inspector. It is used to check the values obtained in the map. The second one is an output console. The outputs created on the script will appear on this area. The third button is a task administrator. This area is the responsible of managing large duration task, for example, data exportation.

- The help button on the top right corner has links to the Google Earth Engine official guidelines, as well as some other resources in which solutions to possible problems can be found.

4.2.3. Advantages

The use of this tool has several advantages while developing an application, some of them are going to be listed hereunder:

1. The data catalogue is public and available online

2. This tool provides a high computation engine power

3. It is an interactive development platform

4. It is very useful to save and share projects between users

5. It is possible to export and import data on the platform

6. The results obtain can be shown in several platforms, such as Matlab, arcGIS or QGIS

7. Google Erath Engine is free of charge for education, investigation and non-profit body users

4.2.4. Existent Applications

Google Earth Engine has already been used on several real case studies in different parts of the world. Some of them are going to be listed and briefly explained down below. It is important to highlight that it was not possible to find soil moisture products with the desired space resolution. Therefore, a script was created in order to obtained the results wanted.

4.2.4.1. Global Forest Change

It is a studio carried out by the Maryland University. It seeks to analyses the extension, loss and gain of the global forest cover, by using Google Erath Engine data. The research was published on the Science magazine. It succeeds in analyzing almost all the global surface, missing the Antarctic and soma artic islands. The analyzed area had an extension of 128,8 million of km2, which meant 143 billion of pixel data from Landsat satellite with a resolution of 30 meters *[43]*.

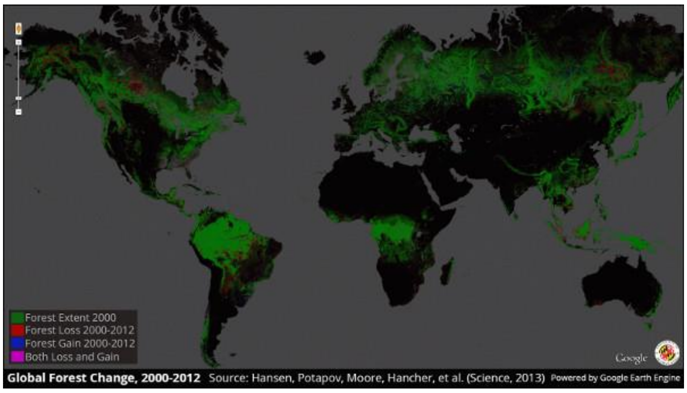


Figure 74. Global Forest Change, from 2000 to 2012 *[43]*

4.2.4.2. Australian SRTM Hydrologically Enforced Digital Elevation Model

The Hydrologically Enforced Digital Elevation Model (DEM-H) was derived from the SRTM data acquired by NASA in February 2000. The DEM-H captures flow paths based on SRTM elevations and mapped stream lines. This product provides a DEM suitable for use in hydrological analysis such as catchment definition and flow routing *[44]*.

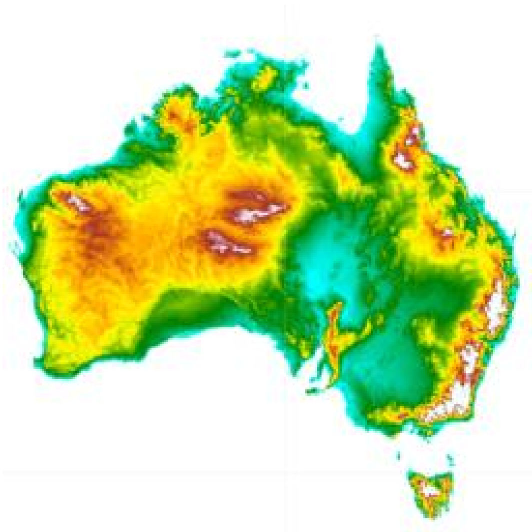


Figure 75. Australian SRTM Hydrologically Enforced Digital Elevation Model *[44]*

4.2.4.3. Land Area (Gridded Population of the World Version 4.11)

The Gridded Population of World Version 4 models the distribution of global human population for the years 2000, 2005, 2010, 2015, and 2020 on, approximately, 1km grid cells. Population is distributed to cells using proportional allocation of population from census and administrative units. The input data are extrapolated to produce population estimates for each modeled year *[45]*.

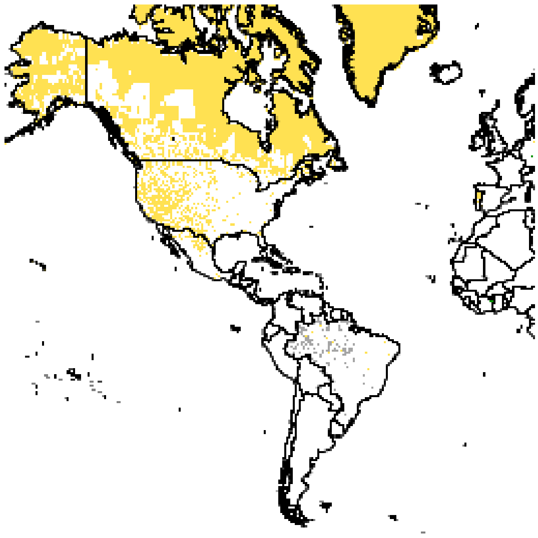


Figure 76. Land Area (Gridded Population of the World Version 4.11) *[45]*

4.3. Cloud Engine Toolbox Selection

A briefly comparison between the two toolboxes is going to be done in order to select which one is going to be used to develop the desire product in this project.

Both of them are really similar regarding to the data and products available. The two cloud engines have already developed soil moisture products but any of them have high enough space resolution to be applied on this project. The space resolution needed was between 10 to 15 meters, while all the products surrounded the dozens of kilometers. Therefore, creating and developing a script will be necessary no matter what toolbox was chosen.

Due to this reason, the selected toolbox was Google Earth Engine. GEE programing language is Java, meanwhile, C3S has its own programing language. Due to my programing knowledges, implementing a Java code would be easier than learning a new language for scratch. Moreover, the guidelines found for GEE were more, speaking of number of resources available. In addition, they were more complete, with more examples and detail explanations of the possible functions that could be implemented.

Despite all of this, both platforms are barely new, which implicate a lot of restrictions on the possible applications that can be created. According to their future evolution, more complex and accurate methodologies will be able to be developed, designing this way better quality final products.

5. Methods and Models to estimate Soil Moisture values through Remote Sensing

In this chapter the existing methods to estimate soil moisture values through remote sensing will be analyzed.

As it has been explained on the previous chapters, soil moisture estimations have been carried out from remote sensing traditional instruments due to its importance and applications on different areas. Among these instruments, it is important to highlight the Envisat and SMOS satellites of the European Space Agency, and the SMAP satellite of the NASA. The huge limitation all these satellites have in common is its low spatial resolution (around 40km), which made the soil moisture estimations insufficient for being applied to the agricultural sector.

Nowadays, in order to solve the spatial resolution issue, soil moisture estimations can be achieved by using the Sentinel 1 satellite, which allows to obtain images within 10 meters spatial resolution. It is true though, that temporal resolution will be lowered to 6 days (while using both Sentinel 1 A and B) from the 2-3 days temporal resolution that was obtained with the traditional satellites.

Satellites	**Sensor**	**Spatial Resolution**	**Temporal Resolution**
Envisat	ASAR	1km	1-3days
SMOS	MIRAS	30-50km	3 days
SMAP	Radiometer	40km	2-3 days
Sentinel 1	SAR	10m	6 days

Table 29. Satellites sensors spatial and temporal resolution characteristics

On chapter number 2, Sentinel 1 C-SAR instrument working principle has been explained. SAR imaging has been long used to estimate soil moisture using L, C and X bands. C-SAR band has been proved to be able to estimate soil moisture under different vegetations covers. There are three principle methods to retrieve these values using the C-SAR instrument which are: Neural Networks (NN) approach, Water Cloud Model (WCM) and Change Detection (CD) methods

5.1. Theoretical concepts

Synthetics Aperture Radar (SAR) has shown to have a huge potential to retrieve soil moisture due to its sensitivity. Nonetheless, it has several sources of errors owing to the huge amount of factors backscatter is influenced by, specially: dielectric properties of the soil (and therefore, surface roughness and soil moisture), sensor radiometric parameters (in particular, the incident angle) and the vegetation cover.

In order to fully understand the soil moisture retrieval methods some theoretical concepts are going to be introduced.

SAR instrument has already been explained, but not the bands it uses. C-Band is the type of band that is going to be used in all the following soil moisture estimation methods. It works with a frequency between 4 to 8GHz within the microwave of the electromagnetic spectrum, which lead to microwaves with a wavelength around 5.6cm. One of its greatest advantages is its capacity of not being affect by atmosphere phenomenon, and being able to "see" through dense clouds and rainfall. Finally, it can detect vegetation cover and "see" until the first layers of the soil. This band allows to collect data in dual polarization (HH+HV, VV+VH), which is very useful to land cover classification and sea-ice applications.

Meanwhile, X-Band operates with a frequency between 8 to 12.5GHz within the microwave of the electromagnetic spectrum, which lead to microwaves with a wavelength around 3cm. Its greatest advantage is the high resolution of the images taken. It is widely applied on the military sector in surveillance tasks, due to its great features for mapping.

Finally, the L-Band operates with a frequency between 1 to 2GHz within the microwave of the electromagnetic spectrum, which lead to microwaves with a wavelength around 22cm. It can penetrate rain, vegetation, etc. Therefore, its main application is satellite navigation.

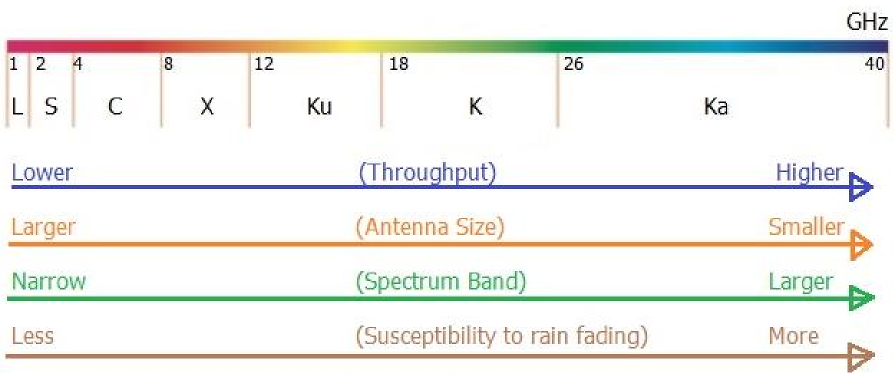


Figure 77. Frequency Bands *[46]*

The radar polarizations modes are named with two capital letters. The first letter corresponds to the transmitted signal and the second one to the received signal. For example, having a VV polarization means both the transmitted and received signal are oriented on the vertical plane by means of the radar antenna.

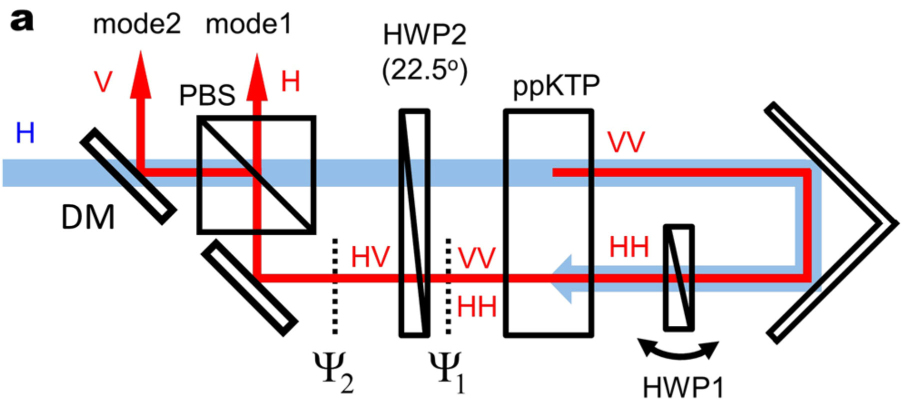


Figure 78. Polarization types *[47]*

Wavelength can be explained as the distant between two points on a signal wave. These two points must be within the same phase and in consecutive periods.

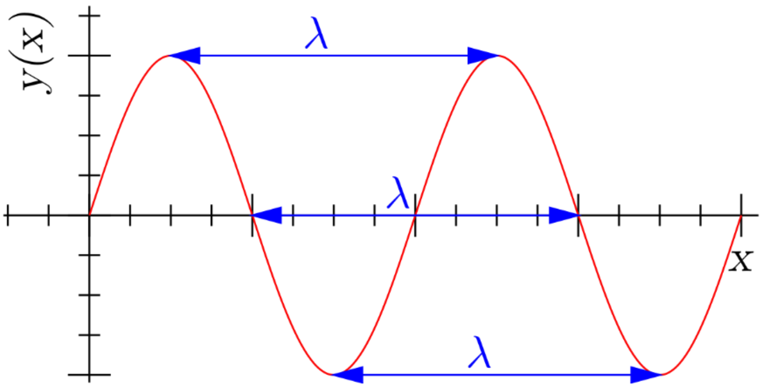


Figure 79. Wavelength *[48]*

From the physics point of view, backscatter is understood as the reflection of a signal back on the direction it came from at first place.

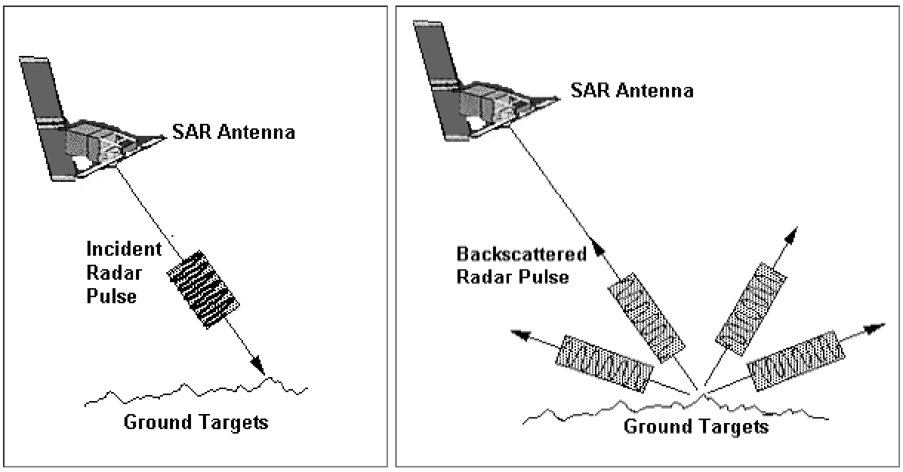


Figure 80. Backscattering definition demonstration *[49]*

The dielectric constant is a quantity measuring the ability of a substance to store electrical energy in an electric field *(Oxford dictionary) [50]*. This constant is around 80 for water, and between 3 and 5 for dry soil. Soil moisture can be estimated by inverting backscattering values measured by the satellite via scattering models.

Surface roughness is the measure of the finely spaced micro-irregularities on the surface texture which is composed of three components, namely roughness, waviness, and form *(Roughness) [51]*.

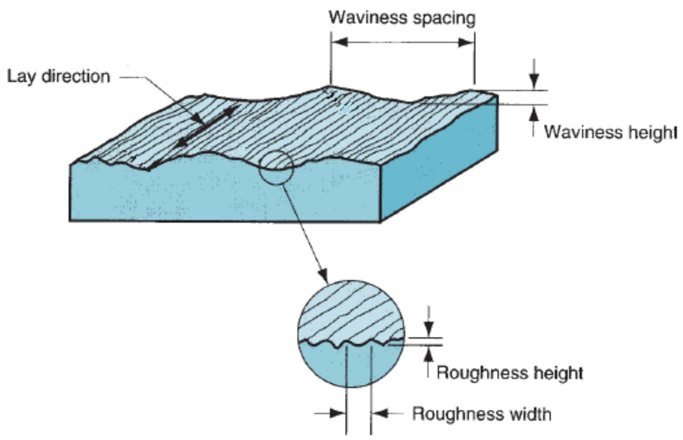


Figure 81. Roughness graphical explanation *[52]*

The incident angle is the angle between the incident ray to a surface and the perpendicular line to the surface (surface normal) at the point of incidence.

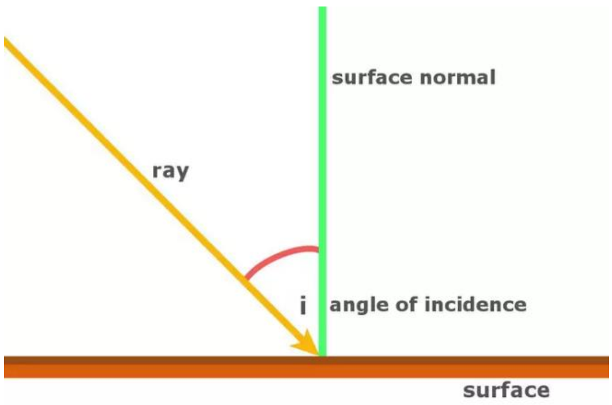


Figure 82. Incident angle graphical explanation *[53]*

Depending on the model applied backscattering can be considered as a dependable or undependable variable of the explained above parameters. In case of being an undependable variable, the parameters are seen as static arguments.

5.2. Neural Network Approach

Neural Networks represents on a simple way how the human neural system works. It is composed of "neurons", which are the basic units of the model, which are arranged in layers. Normally, there are three types of layers: input layer, hidden layer and output layer.

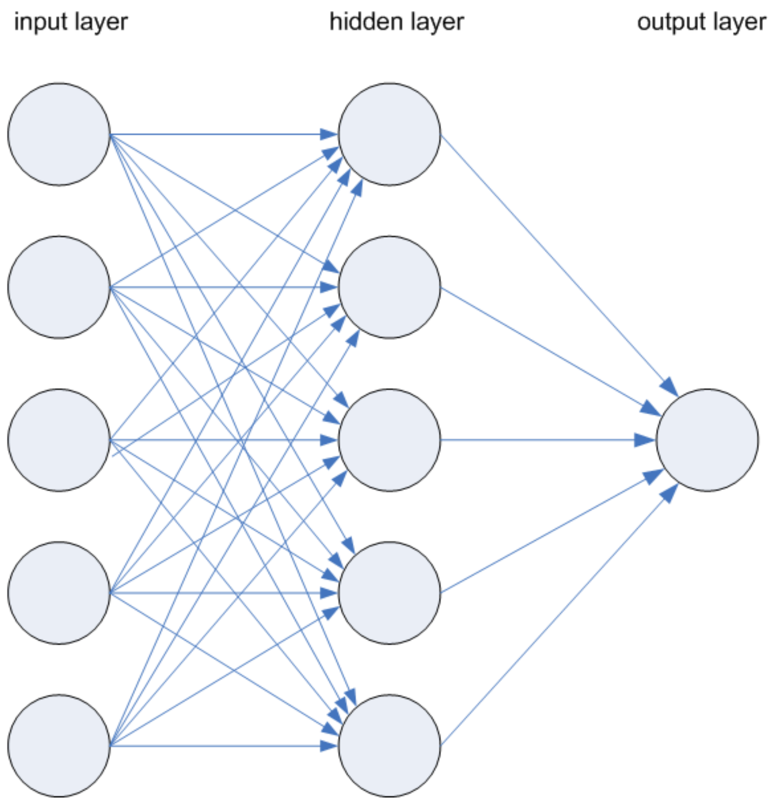


Figure 83. Neural Network schema *[54]*

They are simple elements operating in parallel. The unions between the different neurons and layers are carried out with variable connection strengths or weights.

At the beginning, the weights are random and therefore the firsts outputs are nonsense. In order to achieve a correct output, the network must be trained. This learning is conducted by given inputs to the network and comparing its outputs to known outcomes. The information of this comparison is passed thought the neural network again, which progressively will adjust the weights. While the training advanced the results will become more accurate. Once the training is finished, the neural network can be applied to cases with an unknown outcome *[54]*.

On the one hand, these methods are extremely accurate. On the other hand, in order to trained the model, sufficient information of the studied area is needed in advanced. For this case, soil moisture values from a certain period must be acquired in order to train the network. These values could come from in-situ measurements or from another method to estimate soil moisture. Clearly, the network would be more precise if the data come from ground measurements rather than having being retrieved with another model which might probably have errors.

5.3. Water Cloud Model

The Water Cloud Model developed by: *(Ulaby, 1978) [55]*, relates soil moisture with backscattering. This model describes the total backscattering coefficient as a contribution of the soil backscattering coefficient and the vegetation backscattering coefficient *[55]*.

$$\sigma_{tot} = \sigma_{veg} + T^2 * \sigma_{soil}$$ Equation 1

$$\sigma_{veg} = A * V_1 * cos\theta * (1 - T^2)$$ Equation 2

$$T^2 = e^{-2*B*V_2*sec\theta}$$ Equation 3

$T^2 \rightarrow attenuation\ parameter\ due\ to\ vegetation\ cover$

$\theta \rightarrow incident\ angle$

$V_1\ and\ V_2 \rightarrow vegetation\ descriptors$

$A\ and\ B\ are\ fitted\ parameters\ of\ the\ model$

The contribution of the soil backscattering coefficient can be obtained applying different approaches. The most common one is the Integral Equation Model (IEM): *(A.K. Fung, 1992) [56]*, calibrated by *(N. Baghdadi, 2007) [57]* and *(Nicolas Baghdadi J. A., 2011) [58]*. These papers present an empirical calibration of the IEM in order to enhance attainment of soil backscattering values for agricultural uncovered fields. Another approach to obtain the soil backscattering coefficient can be seen on the figure 84, where *(Borham, 2017) [59]* uses absolute difference between like and cross polarized signals (ADLC) Cumulative Distribution Function (CDF) of the like polarized signal.

WCM must be parametrized to estimate and simulate the parameters and variables. This parametrization is carried out with in-situ measurements data of soil moisture and surface roughness. Once the parametrization is finished the total backscatter value can be obtained. After that, investing the model, using the backscatter as an input, soil moisture values can be retrieved *(Nicolas Baghdadi M. E., 2017) [60]*.

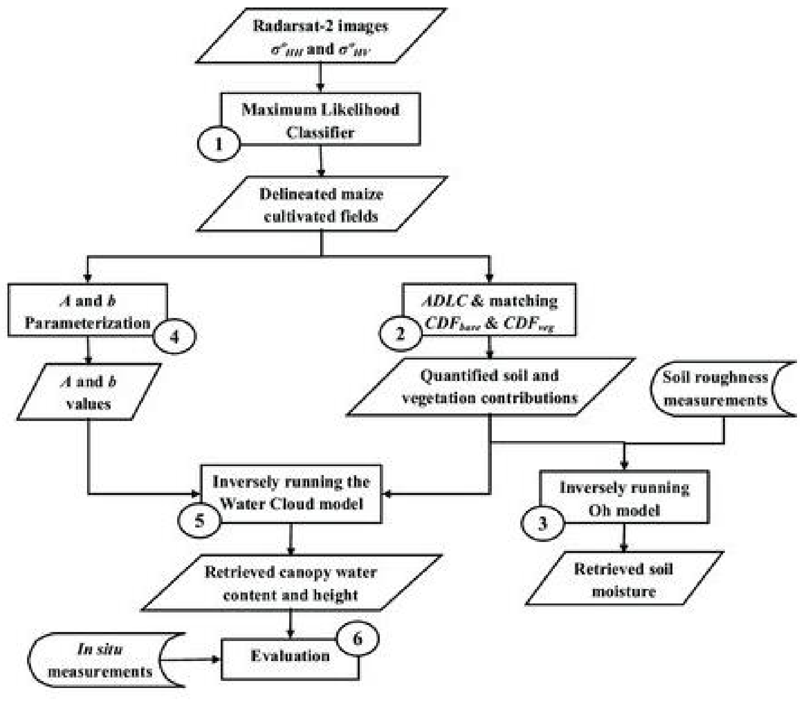


Figure 84. Example of WCM application to Randarsat 2 images *[59]*

5.4. Change Detection Methods

These methods are based on analyzing the difference of the variable observed by the satellite at varying times. CD Methods are really useful when no prior information of the study region is available.

In this case, the variable measured will be the backscatter (or backscattering), as it was formerly introduced on the theoretical approach.

Depending of the observation moments when the backscattering is measured and the used of extra information coming from another satellite, several CD methods can be applied. On this study, the most useful ones for the aim of the project are analyzed for its future implementation.

5.4.1. Copernicus Global Land Service Method

This method is applied by the Copernicus Global Land Service. As it has been explained, the outcome of this service are products with 1 km spatial resolution, which is way too wide for the purpose of this project. Therefore, this method will be directly applied to raw data coming from Sentinel 1, in order to obtain soil moisture values within a resolution of 10m.

The estimations calculated by this method depend on the incident angle, while the vegetation cover and surface roughness are interpreted as static parameters.

The equations to obtain soil moisture values from backscattering ones are the followings *(Hassan Bazzi, 2019) [61]*:

$$\boldsymbol{SSM_{\alpha}(t) = SMM(t) * (SSM_{max} - SSM_{min}) + SSM_{min}}\ [\boldsymbol{vol.}\%] \qquad \text{Equation 4}$$

$SSM_{\alpha}(t) \rightarrow final\ soil\ moisture\ value\ that\ wants\ to\ be\ obtain\ for\ every\ day$

SSM_{max} and $SSM_{min} \rightarrow constant\ values\ of\ SM$: $0.32\ and\ 0.05\ respectively\ (m^3/m^3)$

These constant values are obtained from *(Qi Gao, 2017) [62]*, due to some technological limitations of the satellites while measuring the variable that has to be analyzed. A linear relation can be found between the backscattering values and the soil moisture ones while analyzing data form the SMOS satellite, see figure 85. This relation can be obtained until soil moisture values get bigger than 0.32m3/m3 an lower than 0.05m3/m3.

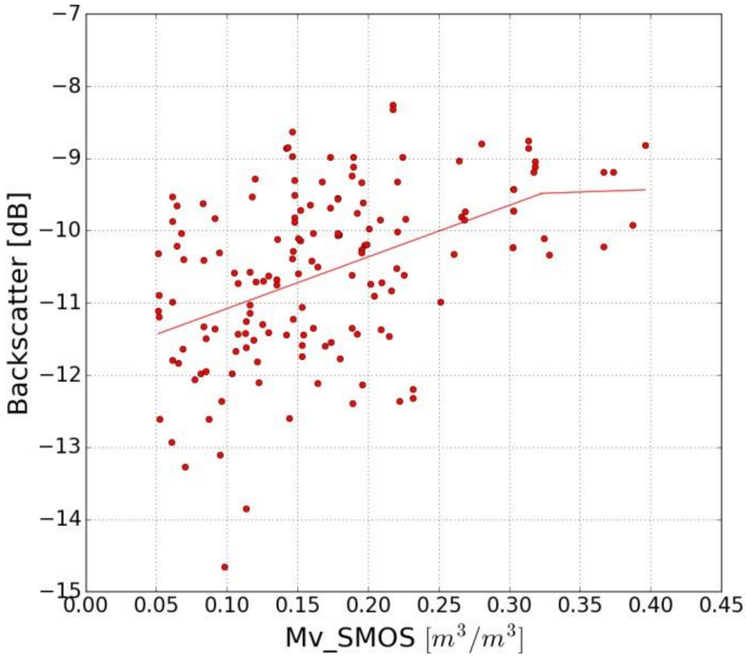


Figure 85. Soil Moisture and Backscattering relation *[62]*

$SMM(t) \rightarrow$ *relative surface soil moisture at day t and depend on the incident angle*

$$\boldsymbol{SSM(t)} = \frac{\Delta\boldsymbol{\sigma^o(\theta,t)}}{\boldsymbol{S(\theta)}}[\%] \qquad \text{Equation 5}$$

$\Delta\sigma^o(\theta,t) \rightarrow$ *change in the normalized backscatter (relative to dry conditions)*

$$\Delta\boldsymbol{\sigma^o(\theta,t)} = \boldsymbol{\sigma^o(\theta,t)} - \boldsymbol{\sigma^o_{dry}(\theta)}[\boldsymbol{dB}] \qquad \text{Equation 6}$$

$\sigma^o(\theta,t) \rightarrow$ *backscatter value obtain by the satellite for each day*

$\sigma^o_{dry}(\theta) \rightarrow$ *lowest value of backscatter obtained during the analyzed period*

$S(\theta) \rightarrow$ *the sensitivity to the SSM changes at reference angle* $\Theta = 40°$

$$\boldsymbol{S(\theta)} = \boldsymbol{\sigma^o_{wet}(\theta)} - \boldsymbol{\sigma^o_{dry}(\theta)}[\boldsymbol{dB}] \qquad \text{Equation 7}$$

$\sigma^o_{wet}(\theta) \rightarrow$ *biggest value of backscatter obtained during the analyzed period*

In conclusion, this approach to estimate soil moisture is based on the normalized backscattering difference relative to the driest condition over the analyzed period, depending on the incident angle.

5.4.2. 1st Method using NDVI

The following method, from *[62]*, is based as well on the normalized backscattering difference relative to the driest condition over the analyzed period, but also applying the Normalized Difference vegetation Index (NDVI), which is a vegetation index that gives information of the quality, quantity and development of the vegetation on the studied area.

It is obtained by applying a mathematical equation to two of the bands that Sentinel 2 satellite measurements:

$$\boldsymbol{NDVI} = \frac{\boldsymbol{NIR-RED}}{\boldsymbol{NIR+RED}} \qquad \text{Equation 8}$$

Where NIR (Near Infrared band) represent the band number 8, and RED the band 4. Its value varies between -1 and 1. An agricultural area is found between the 0.1 and 0.8.

$$\boldsymbol{SSM_{\alpha}(t)} = \frac{\Delta\sigma^{NDVI}}{f(NDVI)} * (\boldsymbol{SSM_{max}} - \boldsymbol{SSM_{min}}) + \boldsymbol{SSM_{min}(t)}\ [\boldsymbol{vol.}\%] \qquad \text{Equation 9}$$

$SSM_{\alpha}(t) \rightarrow final\ soil\ moisture\ value\ that\ wants\ to\ be\ obtain\ for\ every\ day$

SSM_{max} and $SSM_{min} \rightarrow constant\ values\ of\ SM$: 0.32 and 0.05 $respectively$ (m^3/m^3)

See figure 85, for theoretical explanation of these values.

$\Delta\sigma^{NDVI} \rightarrow change\ in\ the\ normalized\ backscatter\ (relative\ to\ dry\ conditions)$

The difference with the previous method is that this value is calculated only between cells with the same NDVI values.

$$\Delta\boldsymbol{\sigma}^{NDVI} = \boldsymbol{\sigma}^{NDVI}(\boldsymbol{t}) - \boldsymbol{\sigma}^{NDVI}_{dry}[\boldsymbol{dB}] \qquad \text{Equation 10}$$

$\sigma^{NDVI}(t) \rightarrow backscatter\ value\ obtain\ by\ the\ satellite\ for\ each\ day$

$\sigma^{NDVI}_{dry} \rightarrow lowest\ value\ of\ backscatter\ obtained\ during\ the\ analyzed\ period$

$$\boldsymbol{f(NDVI)} = \Delta\boldsymbol{\sigma}^{NDVI}_{max}[\boldsymbol{dB}] \qquad \text{Equation 11}$$

$f(NDVI) \rightarrow maximum\ difference\ of\ bacscatter\ values\ over\ the\ analyzed\ period$

This method was validated with ground measurements, obtaining a Root Mean Square (RMS) error in volumetric soil moisture of 0.087 m^3/m^3.

As it was previously introduced, the mathematical equations of this method are the same as the previous one, but in this case the result depends on the NDVI instead of depending on the incident angle.

5.4.3. 2nd Method using NDVI

The method from *[62]* uses as well de NDVI, but it is based on analyzing the difference between two consecutives acquisition days in order to estimate the soil moisture values.

$$\boldsymbol{SSM_{\alpha}(t_2)} = \boldsymbol{H(\delta\sigma(t_1, t_2))} + \boldsymbol{SSM_{\alpha}(t_1)}\ [\boldsymbol{vol.}\%] \qquad \text{Equation 12}$$

$SSM_{\alpha}(t) \rightarrow final\ soil\ moisture\ value\ that\ wants\ to\ be\ obtain\ for\ every\ day$

$SSM_{\alpha}(t-1) \rightarrow SM\ value\ for\ the\ previous\ day\ to\ the\ one\ that\ wants\ to\ be\ calculated$

It is important to outline, that in order to applied this method, the value of soil moisture for the first day must be given, either from in-situ measurements or from a previous analysis.

$$H\big(\delta\sigma(t_1,t_2)\big) = \frac{\delta\sigma_{NDVI}}{g(NDVI)} * \delta M_{vmax}\ [vol.\%] \qquad \text{Equation 13}$$

$\delta\sigma_{NDVI} \rightarrow backscatter\ difference\ between\ two\ consecutives\ acquisition\ dates$

$g(NDVI) \rightarrow maximum\ difference\ of\ bacscatter\ values\ over\ the\ analyzed\ period$

$$g(NDVI) = \delta\sigma_{max}^{NDVI}\ [dB] \qquad \text{Equation 14}$$

$\delta M_{vmax} \rightarrow maximum\ difference\ of\ SM\ between\ two\ consecutives\ acquisition\ dates$

This value is obtained from in-situ measurements statics.

$$\delta M_{vmax} = 0.15\ [m^3/m^3] \qquad \text{Equation 15}$$

To sum up, this method used a new approach, based on analyzing the changes between two consecutive acquisition days depending on the NDVI. The main problem of these method is the need of previous information for its first step.

This method was validated with ground measurements, obtaining a Root Mean Square error in volumetric soil moisture of 0.059 m^3/m^3.

5.4.4. General recommendations to apply the Change Detection Methods

For all these CD methods, several aspects must be taken into account:

1. All the computations must be carried out for each cell of the image for each day.

2. The images of backscattering values coming from Sentinel 1 must be pre-processed before applying any of the mathematical operations:

    a. Thermal noise removal

    b. Radiometric calibration

    c. Terrain correction using SRTM DEM at 30 m

    Normally, on the online platforms, the data from Sentinel 1 available has already been through all this processes. For applying them on a personal computer the SNAP application is recommended. It has a special toolbox for this satellite that carry out these tasks autonomously.

3. Only VV polarization values from Sentinel 1 is taken into account, because of its better efficiency *[62]*.

4. While using the NDVI:

    a. Band QA60 (bit mask with could info) must be applied in order to eliminate areas covered by clouds.

b. Only the areas with a vegetation index between 0.1 and 0.8 must be taken into account. Values bigger than 0.8 are sociated with forest areas, while an index lower than 0.1 represents water surfaces.

5.5. Comparison of the methods

First of all, the NN and WCM methods are more precise and can be implemented together *[61]*. The only disadvantage they have is the need of ground measurements and previous information on soil moisture and surface roughness. Therefore, these two methods cannot be implemented under the framework of this project.

Meanwhile, the CD methods can be divided in two different groups: those that analyze the backscatter in relation with the NDVI and those that do not. Evidently, the ones taken into account the vegetation index will be more precise, but their computational implementation will be harder. It carries a larger number of images to obtained by the satellites as well as complex analysis between backscattering and NDVI values. On the other hand, methods that do not taken any vegetation index into consideration might have a lower accuracy, especially when the vegetation of the agricultural fields is dense.

Finally, it is important to point out, that even though backscatter values have been proven to be influenced by surface roughness, change detention methods do not take this variable into consideration on daily basis. This aspect is because other parameters, such as the vegetation index or the incident angle, have more influence on agricultural fields than surface roughness, and therefore, this variable is normally treated as a static parameter.

5.6. Porosity Analysis

An analysis of the porosities of different types of soil was carried out in order to see if the maximum and minimum soil moisture values fixed previously were corrected and coherent.

Porosity is understood as a measurement of the empty holes of a material. It is a relation between the volume of these holes and the total volume of the body. It is usually expressed in percentage.

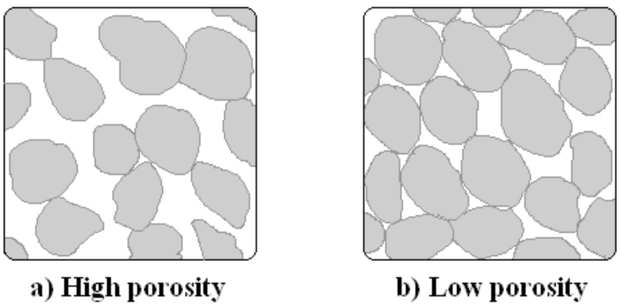


Figure 86. Porosity *[63]*

The effective porosity is a delimitation of the porosity. It is calculated on the same way, but just taken into account the holes connected between each other, which means, the ones where water can flow. Evidently, effective porosity is always lower than porosity.

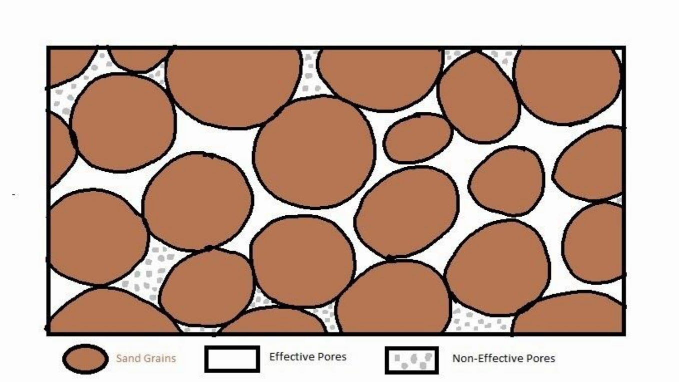


Figure 87. Effective porosity *[63]*

In the table 30, several types of soil with their correspondent porosity and effective porosity are shown.

Soil	Porosity	Effective Porosity
Thick Gravel	28	23
Media Gravel	32	24
Thin Gravel	34	25
Thick Sand	39	27
Media Sand	39	28
Thin Sand	43	23
Limo	46	8
Sandstone of fine grain	33	21
Clay	42	3
Sandstone of median grain	37	27
Limestone	30	14
Dolostone	26	-
Dune Sand	45	38
Loess	49	18

Peat	92	44
Schist	38	26
Siltstone	35	12
Mudstone	43	-
Shale	6	-
Till Sand	31	16
Till Silty	34	6
Tuff	41	21
Basalt	17	-
Manipulated Gabbro	43	-
Manipulated Graphite	45	-

Table 30. Porosity and effective porosity values for different types of soil *[64]*

Analyzing the table, it can be said that the soil moisture values chosen are corrected. These values were 5%vol and 32%vol. Almost all the soils have their effective porosity in within this range. The only exceptions are the sand dune and the peat. Soils of sand dune are not appropriate for agriculture purposes and therefore they do not have to be taken into account on this research. Regarding to the peat, it has different applications on the agriculture sector. Mainly, it is use as compost, but it is not a "typical soil" for agriculture. Therefore, the data selected as maximum and minimum for the soil moisture estimation methods are considered as valid.

6. First approach for Soil Moisture Estimations. Test Case: Rome Area

6.1. Introduction

The method selected to estimate soil moisture, between the three ones explained in the chapter 5, is the Copernicus Global Land Service Change Detection method.

In this chapter the reasons of choosing this method will be explained by analyzing the limitations of all the technologies involve in the process of developing the soil moisture estimations product, such as the satellites and cloud engines characteristics.

Additionally, images and results of applying the method on a random area, on this case, nearby the city of Rome, will be seen in order to prove that the method can be applied to whatever region, having into account always that the precision of the results will be the highest working on agricultural fields (zones cover by a medium vegetation).

In the following chapters the method will be validated and applied to the study region.

6.2. Initial Method Application

The method selected to develop this soil moisture estimation product is the Copernicus Global Land Service Method.

As a summary from the previous chapter, the main difference between the Copernicus method and the other two CD methods, is that the last two takes into account the NDVI for analyzing soil moisture. The use of this parameter makes these methods have a higher accuracy, and the ability of distinguishing between agricultural and not agricultural areas. Therefore, on the following sections, the reasons of choosing the Copernicus method, that do not use the NDVI, and consequently, has a worse accuracy, are going to be explained.

6.2.1. Reasons for selecting the Copernicus Soil Moisture Estimation Method

The main reason of selecting the Copernicus method are the programming limitations that Google Earth Engine platform has while working with raw data online. Basic functions and math bands are easily implemented, but when the degree of complexity increases the platform does not support it, and gives several problems. This is the motive of choosing the Copernicus method, which is the "simplest" to program.

6.2.1.1. Platform Limitations

All the methods explained are designed for working pixel by pixel. Which means, all the equations are applied to each cell or pixel of the image in order to estimate the soil moisture for each point of the region selected. While working with Google Earth Engine, the problem found was that it treats the images as a whole. Consequently, it was not possible to apply the methods that uses the NDVI.

As a summary of the last chapter, these methods indicate different calculations for the backscatter of each cell (measured with Sentinel 1 satellite) depending on the value of the NDVI calculated for each cell (measured with Sentinel 2 satellite). This distinction between cells was not able to be achieved with the platform due to its way of treating the images. Therefore, it was not possible to apply any of the methods that use the vegetation index.

The following pictures shown the area analyzed as an example of application of the method without data (figure 88), with the backscatter values (figure 989) and with the NDVI calculated (figure 90). It can be highlighted the difference land cover between the Sentinel 1 and Sentinel 2 images for the same day on the same region. This is because the different orbits the satellites had, which was as well a difficulty while trying to develop the methods that take into account the vegetation index.

Figure 88. Area analyzed as a first approach for SM estimations calculations

The area analyzed as an example in order to achieve the correct development of the method was around the city of Rome. The coordinates can be seen on the following table.

Region Characteristics

A	Latitude: 42,39° Longitude: 11,634°
B	Latitude: 41,48° Longitude: 11,634°
C	Latitude: 41,48° Longitude: 13,61°
D	Latitude: 42,39° Longitude: 13,61°
Area	16687km2

Table 31. Coordinates of the region

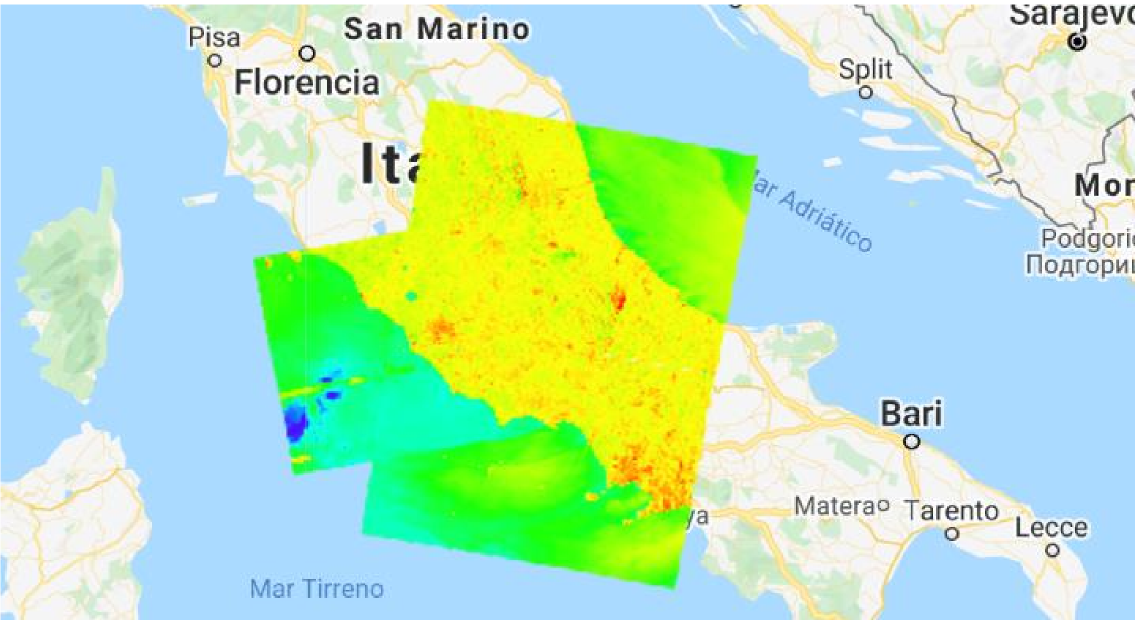


Figure 89. Backscatter values for the analyzed area on the 11/09/2019

The backscatter values are obtained directly from the satellite. The only filter add to the raw data was the selection of the type of polarization needed. As it was explained on the previous chapter soil moisture estimations calculus are usually implemented using the VV polarization.

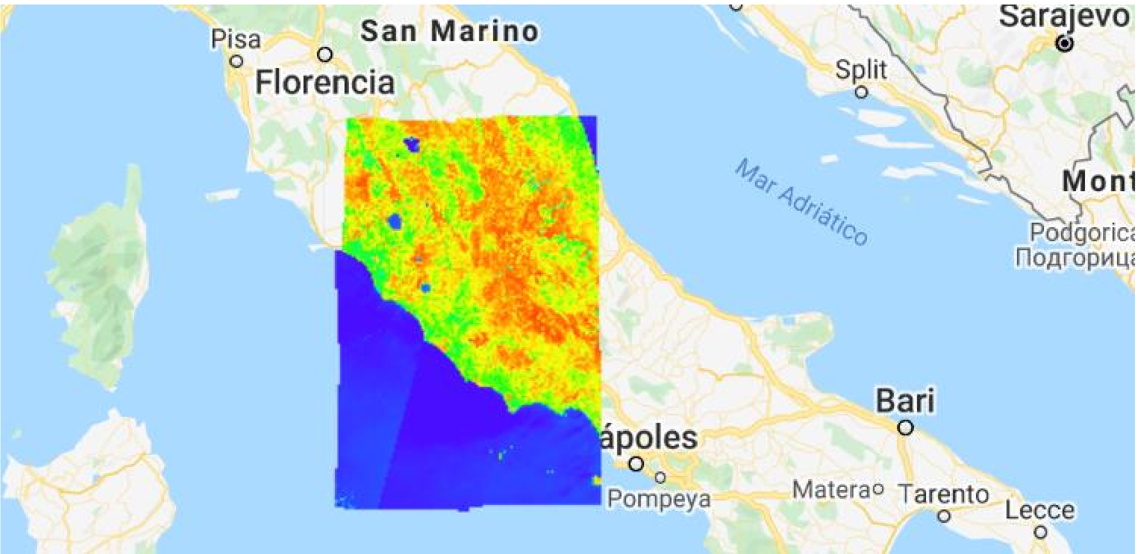


Figure 90. NDVI values for the analyzed area on the 11/09/2019

The NDVI values are obtained to each pixel by applying the band-math, explained in the last chapter, to the data measured by Sentinel 2. In order to have good quality data a cloud filter has been applied to the measured data. This filtering objective is to select only those images with low cloud coverage, assuring this way, the best possible data quality.

6.2.2. Temporal Resolution issues

Once the method was selected, another big problem was faced while trying to develop it. This issue was the temporal resolution of the Sentinel 1 satellite. As it has already been explained, the temporal resolution is the time between two consecutive acquisitions of data in a specific area. This temporal resolution varies depending on the location of the area and its size. The wider is the area, the lower the temporal resolution is. Several photos and explanations of this aspect will be carried out on the following chapters while explaining all the analyzed regions characteristics.

The following table shows the acquisition days of the region of the figure 88, during the month of October of 2019. The meaning of the colors is explained on the table 33. In addition, one example of each type of "data day" is shown.

October 2019						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
29	30	1	2	3	**4**	**5**
6	7	8	9	**10**	**11**	**12**
13	14	15	**16**	**17**	**18**	19
20	21	**22**	**23**	**24**	25	26
27	**28**	**29**	**30**	31	1	2

Table 32. Acquisition dates for Sentinel 1 satellite on the analyzed area

Acquisition dates table key

Yellow	Days with complete data
Blue	Days with partial data (left part of the region)
Orange	Days with partial data (right part of the region)

Table 33. Acquisition dates table key

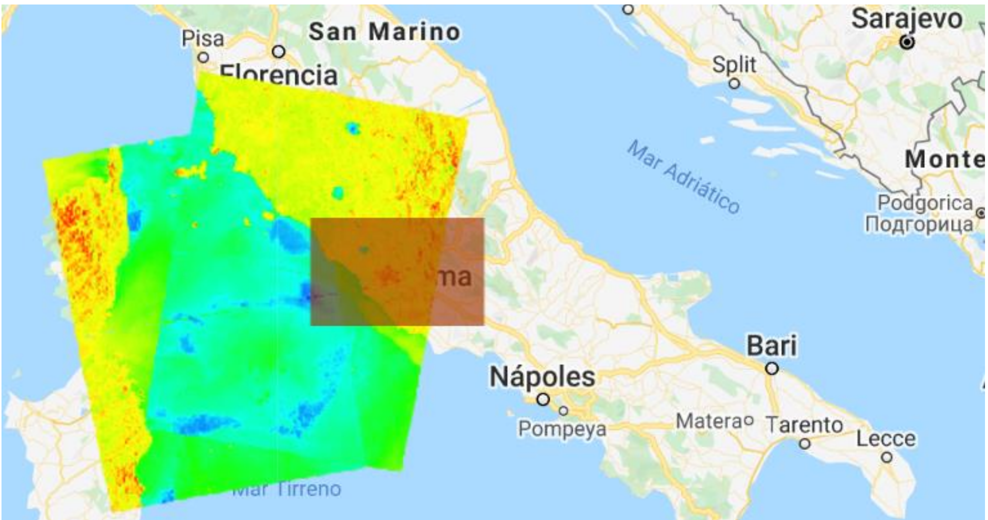


Figure 91. Backscatter values for the analyzed area on the 10/09/2019

Figure 91, shows an example of a "blue day". There is not data available for all the region on the 10th of October. If the soil moisture of the right side of the location wants to be estimated data infilling techniques should be applied.

Figure 89, is a clear example of a "yellow day". All the region is covered by the satellite, and therefore all the data is available without any extra computations.

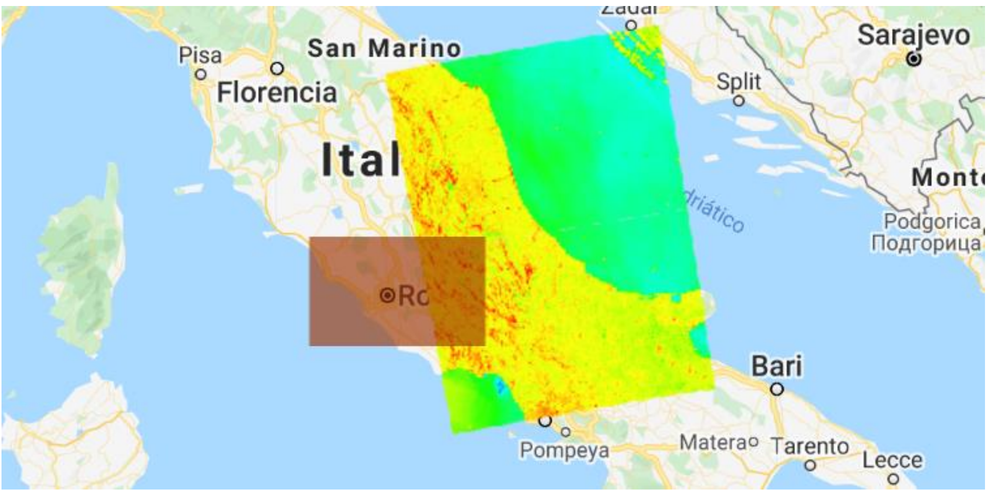
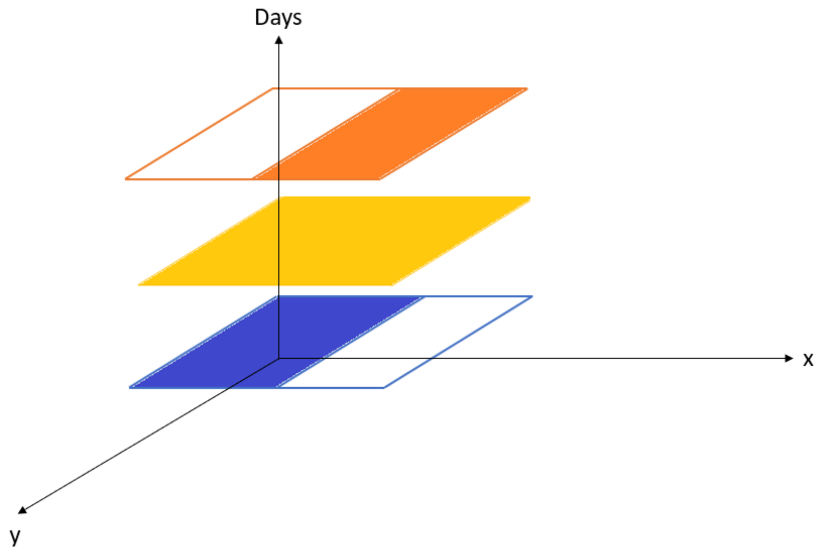


Figure 92. Backscatter values for the analyzed area on the 12/09/2019

Finally, figure 92, shows an example of an "orange day". Only a small right area of the total location is covered by the satellite. As in the case of the "blue days", data infilling techniques must be carried out in case of needing soil moisture values of the uncovered area.

Graphic 1, is an example of the "layers" of data that would be obtained for every group of days. For infilling the data missing, interpolation/extrapolation and statics could be used. For example, for estimating the area of the "blue day" the first approach will be extrapolating the data of the "yellow and orange days". Moreover, to minimize the error an analysis of the data available of the "blue day" and its differences with the "yellow day" will be carried out, applying to the initial "blue estimation" the corrections obtained for the previous statics' analysis.



Graphic 1. Graphical representation of the "types of days"

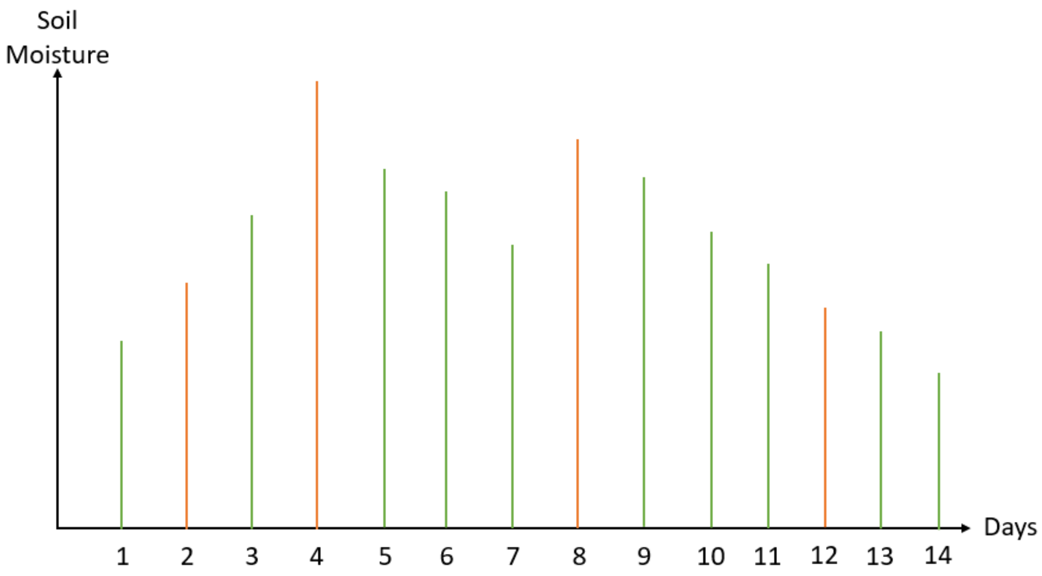
The initial idea for the product was estimating soil moisture values for every day, but with the Sentinel 1 temporal resolution it was not possible to have backscatter values daily. The initial approach was to interpolate/extrapolate between days with and without data. This task became extremely complex due to the programming limitations of the platform and the presence of external factors, such as rainfall or irrigation. These factors are extremely related with soil moisture, and in case of occurring in a day without data they would not be taken into account and therefore the interpolation error would be really high. It is for these reasons that at the end, soil moisture will only be estimated for the days that have satellite data.

The following graphic is an example in order to better understand the complexity of the infilling data techniques needed to estimate soil moisture. Green lines represent the days in which data is fully available, while orange lines represent those days without complete information.

On the one hand, infilling the values for day 2 and 12 can be easily implemented by a simple interpolation. The error will not be very high because the slope that links the days 1, 2 and 3, and the days 11, 12 and 13 respectively does not vary sharply between the points.

On the other hand, estimating the value of day 4 can be more difficult. The slope between the points varies a lot between days 3 and 4, and days 4 and 5, surely because of the rainfall or irrigation. Therefore, interpolation will generate a big error on this case.

The last, and most complex estimation will be for day number 8. On this case, further information will be needed in order to understand the volume of water that has arrived to the soil by rainfall or irrigation. Without this extra data the error of this estimation will be extremely high.



Graphic 2. Representation of possible infilling data days

6.2.3. Development of the method

The method was developed and implemented taken into account all the considerations previously mentioned.

Following the equations of the Copernicus Global Land Service Method the steps followed to apply to method were the followings:

1. Analyzing the desired region, in order to know the days which, have data and those ones which do not.

2. Obtaining the backscatter data from Sentinel 1 for the days selected.

3. Calculating the media for each day. Normally, satellites take more than one picture for each day. Consequently, the media of every day was calculated in order to be able to obtain daily soil moisture estimations.

4. The maximum and minimum values of backscatter over the analyzed period were calculated, in order to have the most wet and driest days.

5. The final formula was applied and the soil moisture estimations were obtained.

It is important to highlight, that all the estimations were done monthly, for all the days with data available of the month being analyzed.

The following photo shows the result of the method application.

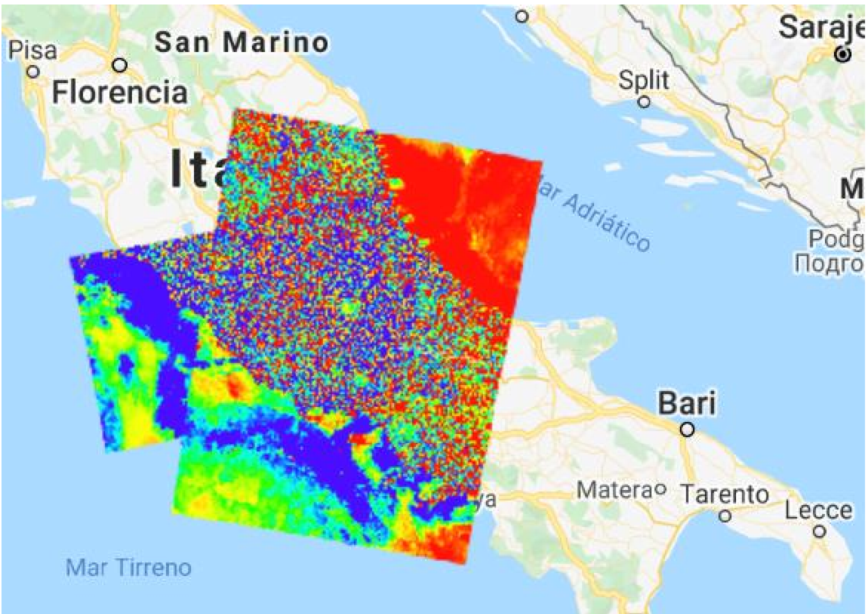


Figure 93. Soil Moisture estimations for the 11th of October.

7. Validation of the Soil Moisture Estimation Method. Test Case: South of France

7.1. Introduction

In this chapter the validation process of the Copernicus Global Land Service (C-SM) method for estimating soil moisture is going to be described. Firstly, the data used to do the comparison will be explained. Secondly, the soil moisture estimations for the desired region will be shown. Finally, both the approach taken to validate the output of the project as well as the results of the validation will be explained.

7.2. Validation Data

The data that is going to be used to validate the implementation of the soil moisture estimation method comes from the project *[62]*, from now on it will be referred as validation-project. The data of this research was chosen because the region analyzed; Occitanie region in the southeast of France, is covered essentially by agricultural fields, just like the Piedmont region that is going to be studied in this project.

7.2.1. Project used to Validate de method

The aim of the validation-project is to compare two different soil moisture products with in-situ measurements. The first one is the Copernicus soil moisture product, with a spatial resolution of 1kmx1km. The second product, combines Sentinel 1 and Sentinel 2 measurements, applying an inverted WCM and a NN approach, with a resolution of 12 meters. From now on, this product will be referred as 2C-SM.

The RMSD error of the Copernicus product comparison with the in-situ measurements was 6%vol, regarding to 2C-SM, the error was 4%vol. Finally, comparing both products among each other the error obtain was between 6%vol and 8%vol, depending on the areas of the region.

7.2.2. Theia Data

The validation-project is part of the Theia program. This program, created in 2012 by nine French institutions, seeks to provide products, methods, images, scales, etc. for continental observations, specifically from space. Nowadays the program is supported by 11 French institutions.

They develop products for several Earth fields, such as, vegetation, land cover, moisture or continental hydrology. All their products are available online and for free. Furthermore, they can easily be downloaded in order to work with them.

7.2.3. Analyzed Region

Theia data covers different regions on Europe. As it was explained before, the Occitanie region in Southern France was chosen because of its land use similarities with the Piedmont region that is going to be analyzed in this project. As it can be seen on the figure 94, there is also data available on the Northern region of Italy. This area was not chosen to validate the soil moisture estimations because the data base was not available at the beginning of the project, it was created on December 2019.

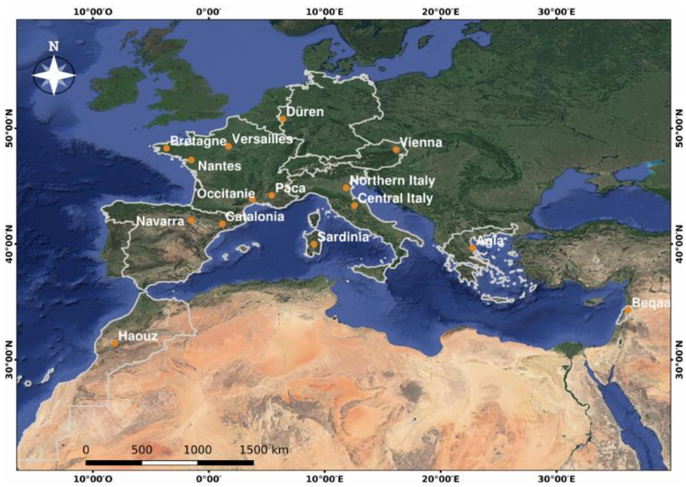


Figure 94. Locations of the soil moisture products of the Theia Program *[66]*

The figures 95, 96 and 97, show the area analyzed.

Figure 95. Occitanie region in Southern France

In the tables 34 and 35, the coordinates and surface of the region can be seen.

Coordinates	**A**	**B**	**C**	**D**
Latitude	45.076º	43.2703º	43.2703º	45.076º
Longitude	4.287º	4.287º	6.78º	6.78º

Table 34. Occitanie region in Southern France coordinates

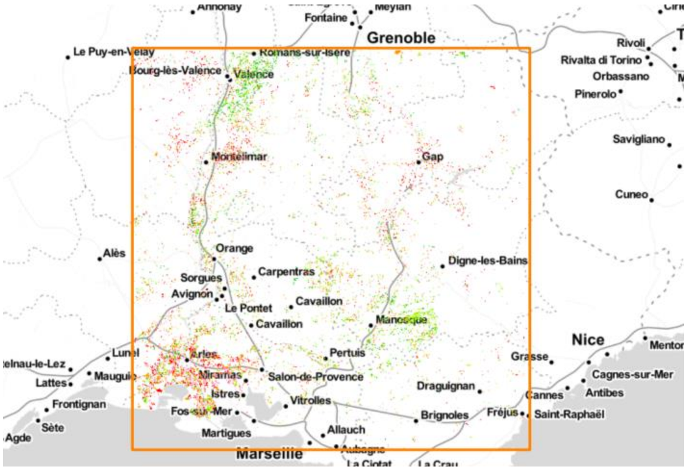


Figure 96. Occitanie region in Southern France with SM estimations

Length	***Width***	***Surface***
201.12km	195.94km	39.407km2

Table 35. Occitanie region in Southern France surface

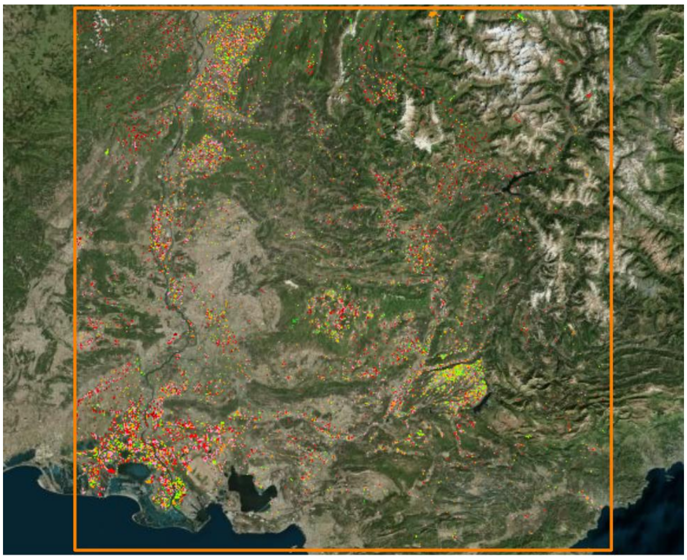


Figure 97. Occitanie region in Southern France with SM estimations. Satellite view

7.2.4. Data Treatment

Soil moisture estimation methods should only be applied on lands cover with a medium vegetation, in order to achieve an acceptable degree of accuracy. Therefore, the Theia program only gives soil moisture products on these types of areas. Consequently, they gave a zero value to all the cells where the land has a different use, i.e. tree aggrupation areas, hills, roads, urban areas, etc. Furthermore, they have created a system to identify and isolate the agriculture fields between each other, homogenizing the data of the cells that are located on a same field. Due to this system, it is possible to analyze, as a whole, the state of the crops of an agricultural field, which is more effective that having separate information of each of the cells that composed the total agricultural field.

Figure 98. Agricultural field (on the left). Theia SM estimations for that field (on the right)

7.3. Soil Moisture Estimation on the Validation Area

7.3.1. Date acquisition

In the table 36, the acquisition dates for Sentinel 1 satellite of the validation region can be seen. Like in the previous chapter, three types of days can be differentiated. On the one hand, "blue days" indicate only partial data on the left side of the region. On the other hand, "orange days" indicate partial data covering the right side of the region. Finally, "yellow days" indicate total data covering of the region.

October 2019						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
29	30	**1**	**2**	**3**	4	5
6	**7**	**8**	**9**	10	11	**12**
13	**14**	**15**	16	17	**18**	**19**
20	**21**	22	23	**24**	**25**	**26**
27	28	29	**30**	31	1	2

Table 36.Acquisition days for the Occitanie area for Sentinel 1 Satellite

Acquisition dates table key

Yellow	Days with complete data
Blue	Days with partial data (left part of the region)
Orange	Days with partial data (right part of the region)

Table 37. Acquisition days for the Occitanie area for Sentinel 1 Satellite key

The following images show examples of these "types" of days. These images were obtained applying the soil moisture estimation method on Google Earth Engine.

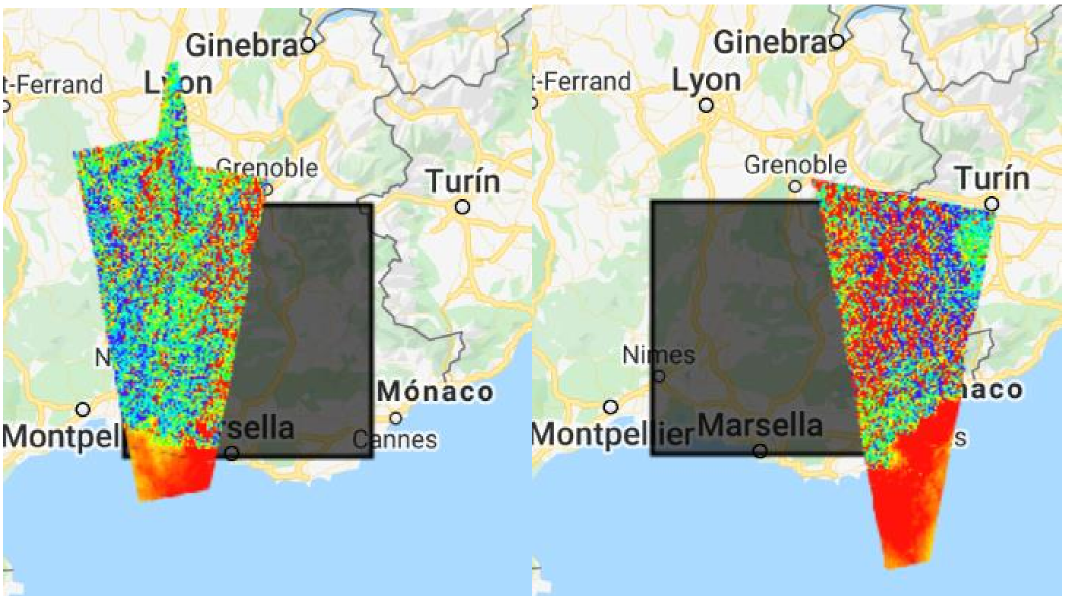


Figure 99. SM estimations. On the left: 6th October 2019, on the right: 9th October 2019

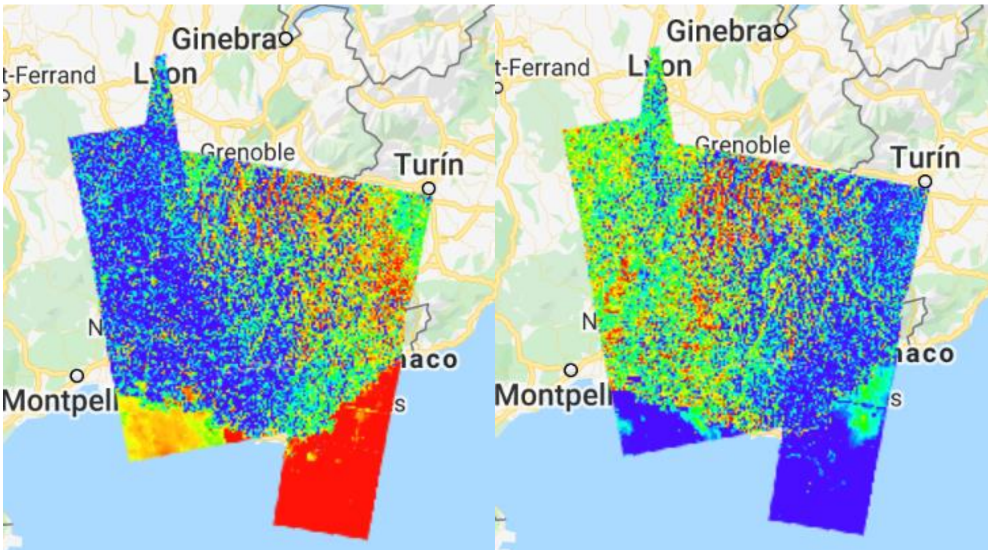


Figure 100. SM estimations. On the left: 7th October 2019, on the right 8th October 2019

Theia program uploads soil moisture maps products every six days, in order to assure working with days in which all the region is covered by the satellite orbit.

7.3.2. Soil Moisture Estimation

The Copernicus soil moisture estimation method was applied using the available data of all the "yellow days" of the month of October 2019, in order to obtain the best possible accuracy. The final soil moisture product was only compiled for the 2nd, 14th and 26th of August.

These three dates were chosen in order to have a more complete validation process. Validating three days of different periods of the month, beginning, middle and final, would give a better indication of the accuracy of the data worked out.

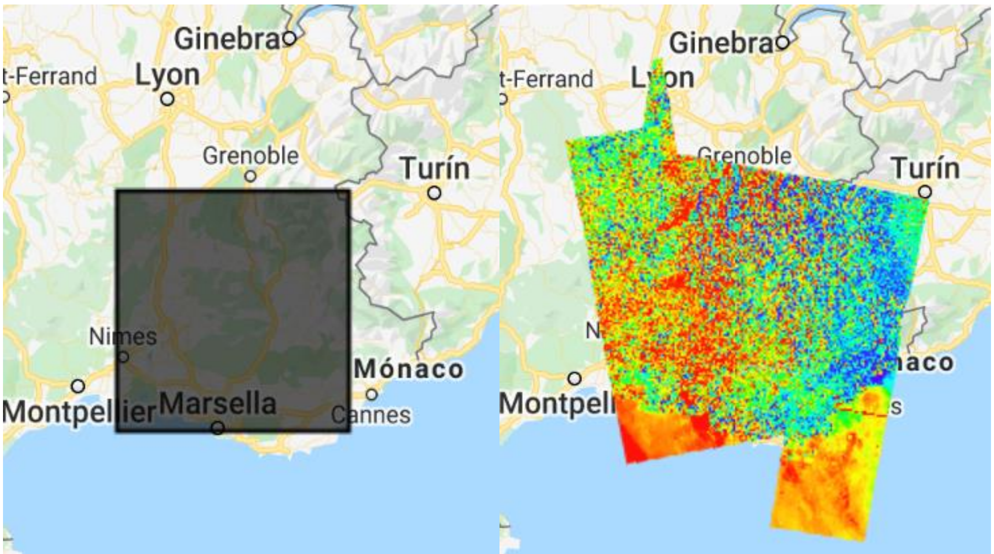


Figure 101. Occitanie area on the left. SM estimated the 2nd of October 2019 on the right

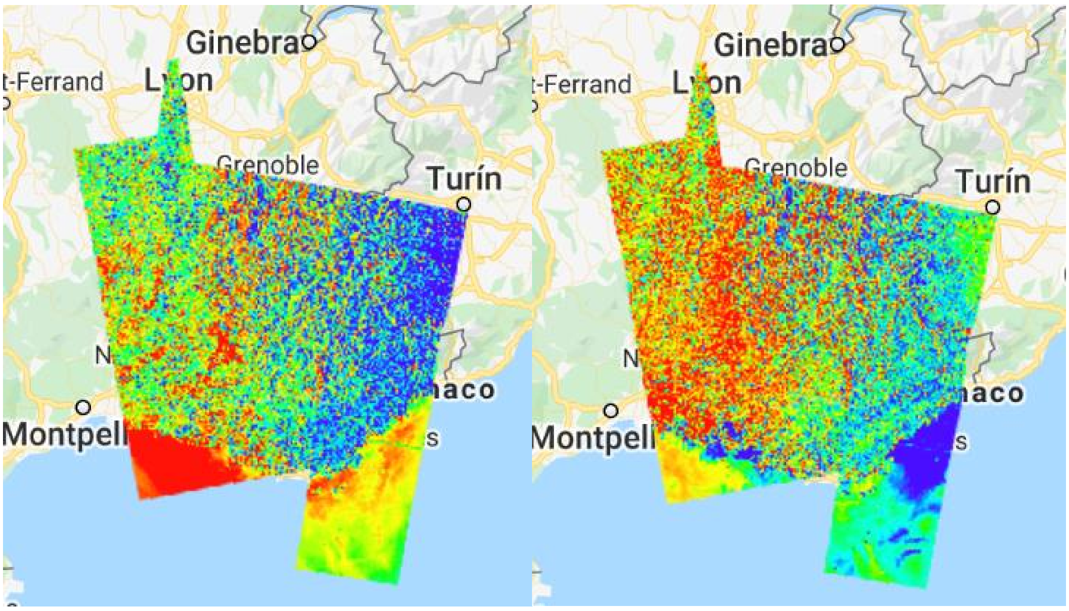


Figure 102. SM estimated the 14th of October 2019 on the left and the 26th of October 2019 on the right

7.4. Validation Method

The validation method was carried out using Matlab. Both soil moisture products, the one computed in GEE (C-SM) and the one from the Theia program (2C-SM), were downloaded and compared in order to calculate different errors and statics measurements, such as the root-mean-square-deviation error (RMSD), and the unbiased root mean square difference (ubRMSD).

Before calculating the errors, some transformations to the matrixes were carried out in order to be able to compare them. Firstly, both products were transformed into the same units, %vol. In case of C-SM the data was multiply by 100, and the 2C-SM product was divided by 5, as it was specified on the guidelines of the Theia web page.

Secondly, a homogenization was carried out in the C-SM product. It consisted on giving each cell a new value that was obtained pondering the value of the cell each-self and the ones around it with different "weights" depending on their positions. This task was done in order to "smooth" the results, and therefore, cells locate on same agricultural fields will have similar soil moisture values. As it was explained on the data treatment section, some similar homogenization process was carried out by the Theia program on the 2C-SM product.

Moreover, a comparison cell by cell between C-SM and 2C-SM products was performed. This comparison objective was to find the non-agricultural areas on the C-SM product, in order to give the correspondent cells a zero value, as it has already been done by the Theia program to the 2C-SM products.

Finally, after doing the above operations, the already mentioned errors were calculated separately for the three days previously pointed out.

7.5. Validation Results

The following equations were implemented to calculate the errors in order to validate the C-SM product obtained.

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \qquad \text{Equation 16}$$

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(O_i - P_i) \qquad \text{Equation 17}$$

$$ubRMSD = \sqrt{RMSD^2 - BIAS^2} \qquad \text{Equation 18}$$

Where O_i is the 2C-SM product for each cell i and, P_i is the C-SM product for each cell i, and n is the total number of cells different from zero. Only the non-zero cells are taken into account because are the "real" locations in which soil moisture is being estimate. Taking the zero cells would mean lower not-real-errors.

In the table 38, the results of the validation process can be seen.

Days	**RMSD (%vol)**	**BIAS (%vol)**	**ubRMSD (%vol)**
02/10/2019	8,65	-2,77	8,19
14/10/2019	8,59	-2,29	8,28
26/10/2019	8,49	-2,69	8,05

Table 38. Validation results: RMSD, BIAS and ubRMSD errors

In order to accept these results as valid they were compared with the ones obtained by the Theia program. In this program, the RMSD values varies between 6%vol and 8%vol depending on the area of the region being analyzed. Therefore, the results obtained on this project are going to be considered accurate enough to apply the soil moisture estimation method to the desire studio region on the following chapter.

8. Test Case in Piedmont

8.1. Introduction

In this chapter the already developed and validated soil moisture estimation method will be applied to the desired study region on the North of Italy.

8.2. Study Region

The area analyzed is about 1km2 surface. It is mostly composed of agricultural fields. Before analyzing the characteristics of this area, a more general scope of the region in which it is located is going to be given, in order to understand the rainfall and irrigation data that were used to analyze the time evolution of the soil moisture estimations calculated.

8.2.1. General Location

The study area is located nearby the municipality of Rivarolo Canavese. This municipality is part of the province of Turin, in the Piedmont region.

In the figure 103 the region location in the map can be seen. Moreover, in the figure 104 an exact view of the size and form of Rivarolo can be found.

Figure 103. Location of the Rivarolo Canavese region. Obtained through GEE

Figure 104. Rivarolo Canavese region

This region was chosen because of the great number of agricultural fields that surround it. In addition, both rainfall and irrigation data nearby the area are available.

8.2.2. Specific Area

The area chosen, of all the Rivarolo region, is about 1km2 surface composed essentially of agricultural fields. In the table 39, the coordinates of the vertexes of the area can be found.

Figure 105. Coordinates of the specific area analyzed from the Rivarolo region

Coordinates	A	B	C	D
Latitude	45.3257353°	45.3257353°	45.3167453°	45.3167453°
Longitude	7.7135720°	7.7007843°	7.7007843°	7.7135720°

Table 39. Coordinates of the specific area analyzed from the Rivarolo region

The location of the area was chosen from point A (a house), in order to have a reference on the map to find it easily. From point A all the other coordinates were calculated applying the following formulas *[67]*:

$$lat_B = \text{asin}\left(\sin(lat_A) * \cos\left(\frac{d}{R}\right) + \cos(lat_A) * \sin\left(\frac{d}{R}\right) * \cos(\theta)\right) \quad \text{Equation 19}$$

$$lon_B = lon_A + atan2\left(sin(\theta) * sin\left(\frac{d}{R}\right) * cos(lat_A), cos\left(\frac{d}{R}\right) - sin(lat_A) * sin(lat_B)\right) \quad \text{Equation 20}$$

Where d and θ are known, and represent the distance between point A and B and the direction angle respectively. All the angles must be in radians. Atan2(x,y) is the Excel formula expression to calculate the desire result.

The following figure shows the three coordinated calculated from A point.

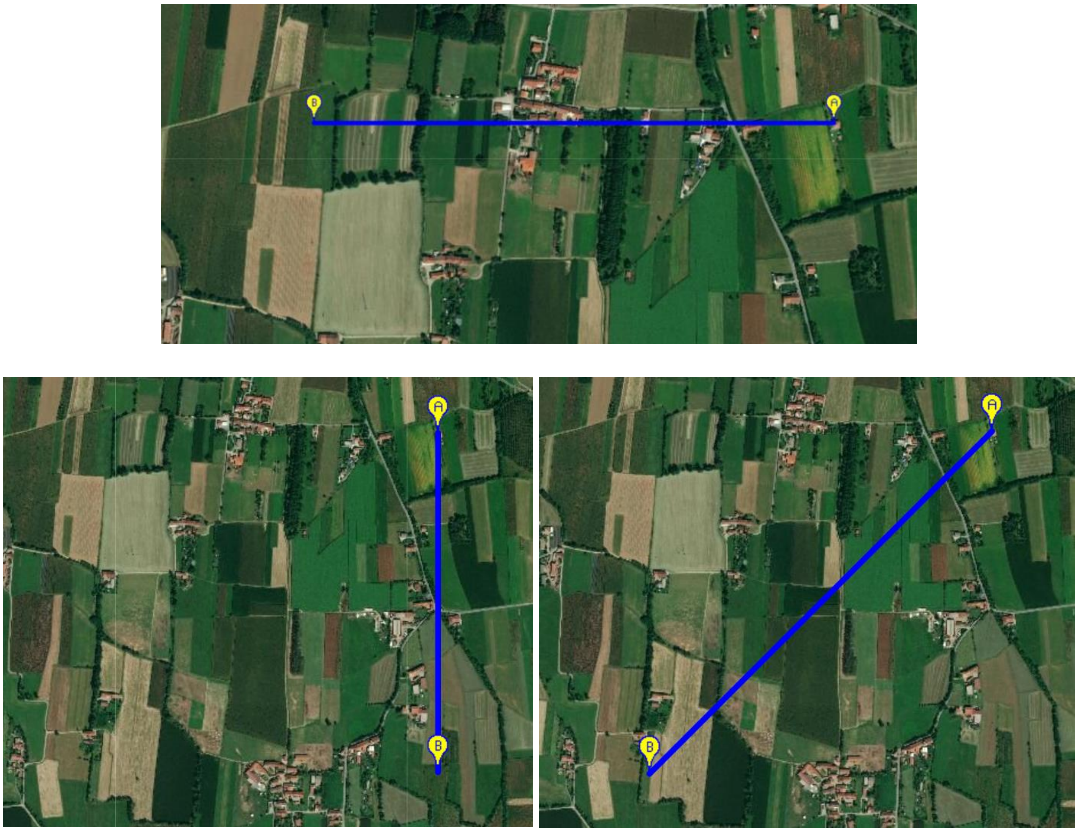


Figure 106. Points A and B (top image). Points A and D (bottom image at the left). Points A and C (bottom image at the right).

As it can be seen on the figure 107, some houses, trees, roads and paths can be found as well in this area.

Figure 107. Satellite view of the specific area analyzed from the Rivarolo region

The area was analyzed with a 12 meters resolution, having a total number of cells of 9996, which are the number of soil moisture estimations calculated per day.

8.3. Product Limitations

8.3.1. Temporal Acquisition

The aim of this project was to calculate the soil moisture estimations during the year 2018, because there is available both, rainfall and irrigation data for this period, to perform the desire analysis of the region.

It was not possible, like in all the other analyzed areas, to obtain data satellite for every day of the year because of the temporal resolution of the Sentinel 1. In order to know the days with available data a temporal annual studio was carried out monthly. Tables 40 to 51 show the data availability.

January 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
31	1	2	**3**	**4**	**5**	6
7	8	**9**	**10**	**11**	12	13
14	**15**	**16**	**17**	18	19	20
21	**22**	**23**	24	25	26	**27**
28	**29**	30	31	1	2	3

Table 40. Acquisition dates for Sentinel 1. January 2018

February 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
28	29	30	31	1	**2**	**3**
4	5	6	7	**8**	**9**	**10**
11	12	13	**14**	**15**	**16**	17
18	19	**20**	**21**	**22**	23	24
25	**26**	**27**	**28**	1	2	3

Table 41. Acquisition dates for Sentinel 1. February 2018

March 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
25	26	27	28	1	2	3
4	**5**	**6**	7	8	9	**10**
11	**12**	13	14	15	16	**17**
18	19	20	21	**22**	**23**	**24**
25	26	27	**28**	**29**	**30**	31

Table 42. Acquisition dates for Sentinel 1. March 2018

April 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	2	**3**	**4**	**5**	6	7
8	**9**	**10**	**11**	12	13	14
15	**16**	**17**	18	19	20	**21**
22	**23**	24	25	26	**27**	**28**
29	30	1	2	3	4	5

Table 43. Acquisition dates for Sentinel 1. April 2018

May 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
29	30	1	2	**3**	**4**	**5**
6	7	8	**9**	**10**	**11**	12
13	14	**15**	**16**	**17**	18	19
20	**21**	**22**	**23**	24	25	26
27	**28**	**29**	30	31	1	2

Table 44. Acquisition dates for Sentinel 1. May 2018

June 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
27	28	29	30	31	1	**2**
3	**4**	5	6	7	**8**	**9**
10	11	12	13	**14**	**15**	**16**
17	18	19	**20**	**21**	22	23
24	25	**26**	**27**	**28**	29	30

Table 45. Acquisition dates for Sentinel 1. June 2018

July 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	**2**	**3**	4	5	6	7
8	**9**	**10**	11	12	13	**14**
15	**16**	17	18	19	**20**	**21**
22	23	24	25	**26**	**27**	**28**
29	30	31	1	2	3	4

Table 46. Acquisition dates for Sentinel 1. July 2018

August 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
29	30	31	**1**	**2**	**3**	4
5	6	**7**	**8**	**9**	10	11
12	**13**	**14**	**15**	16	17	18
19	**20**	**21**	22	23	24	**25**
26	**27**	28	29	30	**31**	1

Table 47. Acquisition dates for Sentinel 1. August 2018

September 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
26	27	28	29	30	31	**1**
2	3	4	5	**6**	**7**	**8**
9	10	11	**12**	**13**	**14**	15
16	17	**18**	**19**	**20**	21	22
23	**24**	**25**	**26**	27	28	29
30	1	2	3	4	5	6

Table 48. Acquisition dates for Sentinel 1. September 2018

October 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
30	**1**	**2**	3	4	5	**6**
7	**8**	9	10	11	**12**	**13**
14	15	16	17	**18**	**19**	**20**
21	22	23	**24**	**25**	**26**	27
28	29	**30**	**31**	1	2	3

Table 49. Acquisition dates for Sentinel 1. October 2018

November 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
28	29	30	31	**1**	2	3
4	**5**	**6**	**7**	8	9	10
11	**12**	**13**	14	15	16	**17**
18	**19**	20	21	22	**23**	**24**
25	26	27	28	**29**	**30**	1

Table 50. Acquisition dates for Sentinel 1. November 2018

December 2018						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
25	26	27	28	29	30	**1**
2	3	4	**5**	**6**	**7**	8
9	10	**11**	**12**	**13**	14	15
16	**17**	**18**	**19**	20	21	22
23	**24**	**25**	26	27	28	**29**
30	**31**	2	3	4	5	6

Table 51. Acquisition dates for Sentinel 1. December 2018

Yellow days indicate days in which data was available for all the area extension, and therefore the days for which the soil moisture was estimated. Meanwhile, white days represent days with no satellite data at all. Due to the small size of the area, and its location, the satellite swaths covered completely the area for three days in a row, allowing to calculate soil moisture estimations for a huge amount of days.

8.3.2. Non-agricultural areas identification

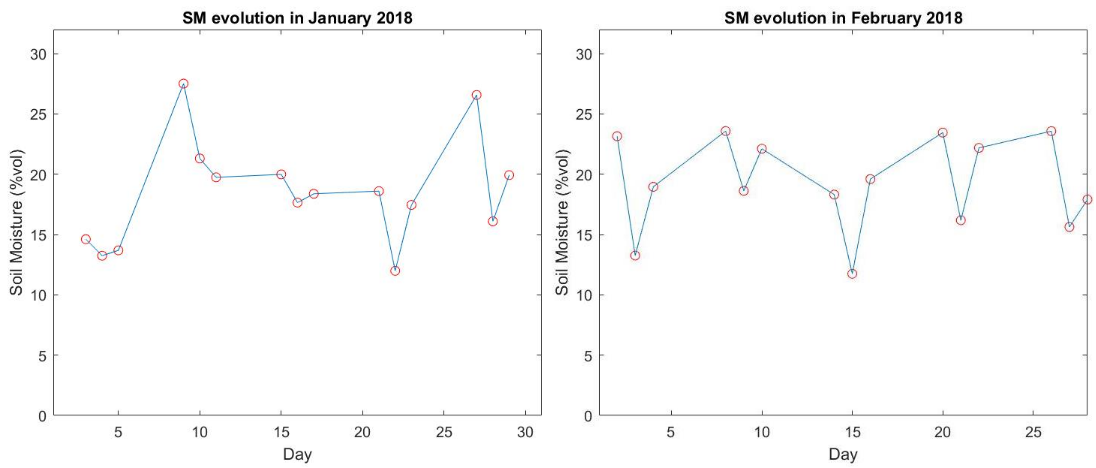
Another limitation of the soil moisture estimations calculated was the impossibility of identifying automatically the non-agricultural areas. Therefore, a cell analysis was carried out in order see if it was possible to do this identification depending on the soil moisture estimations values. This analysis was really helpful in order to prove the accuracy of the method developed to calculate soil moisture.

8.4. Temporal Analysis Studios

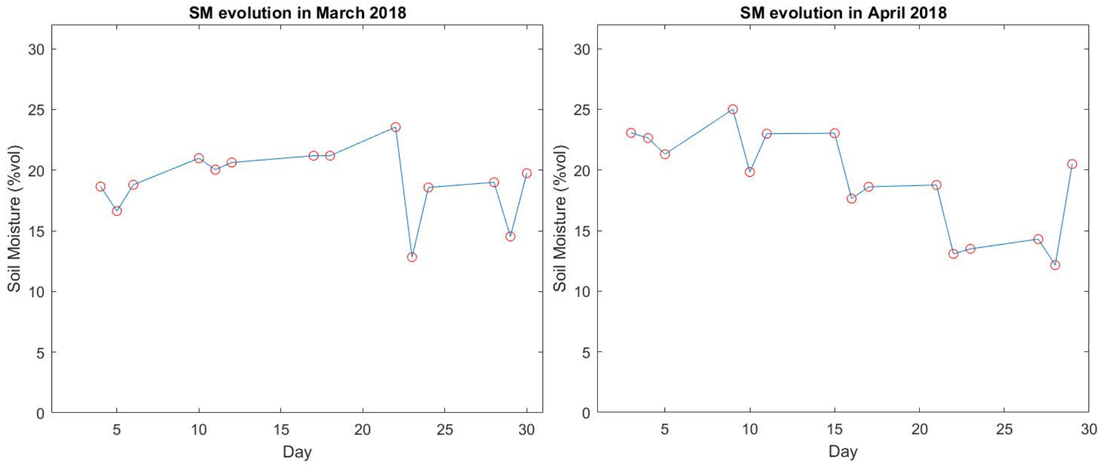
Several analyses have been carried out once the estimations of soil moisture were calculated. The analyses have been done monthly or/and annually, depending on their usefulness. The aim of these researches was to understand the effect of rainfall and irrigation in the evolution of the soil moisture, as well as trying to differentiate between agricultural and non-agricultural areas. All these methodologies were carried out on Matlab or Excel.

8.4.1. Monthly Soil Moisture Estimation Evolution

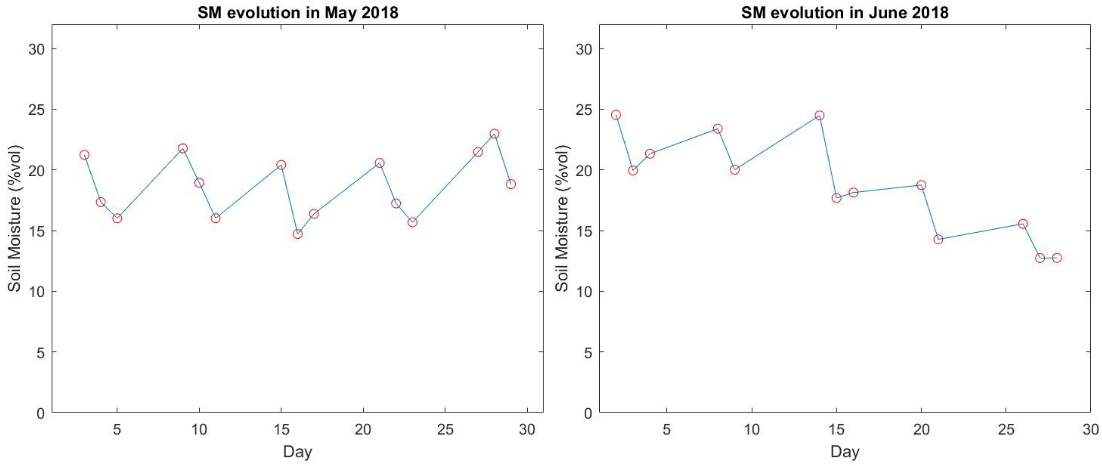
The aim of this evaluation was to see the changes on the average between the different days of the month. The graphics 3 to 8, represent the media of the whole area for the days in which soil moisture was estimated.



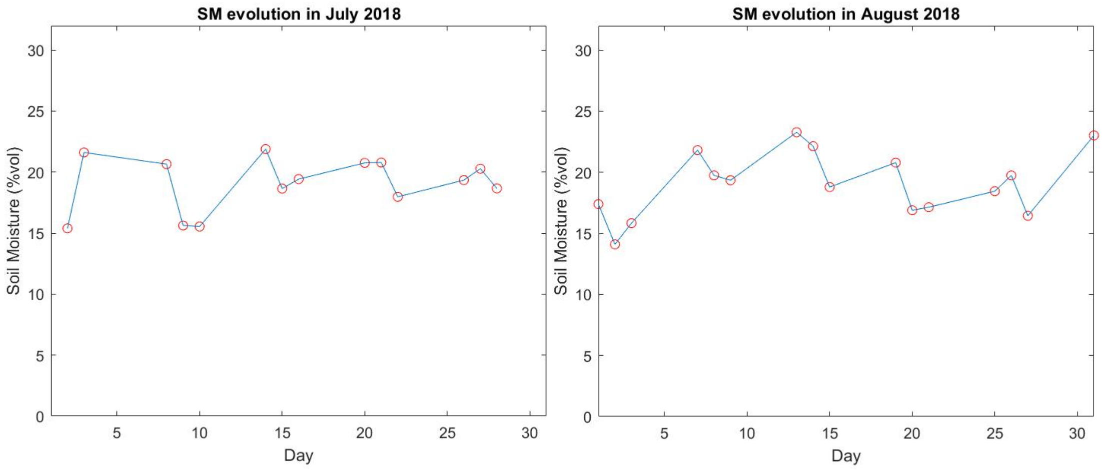
Graphic 3. SM evolution in January (left) and February (right)



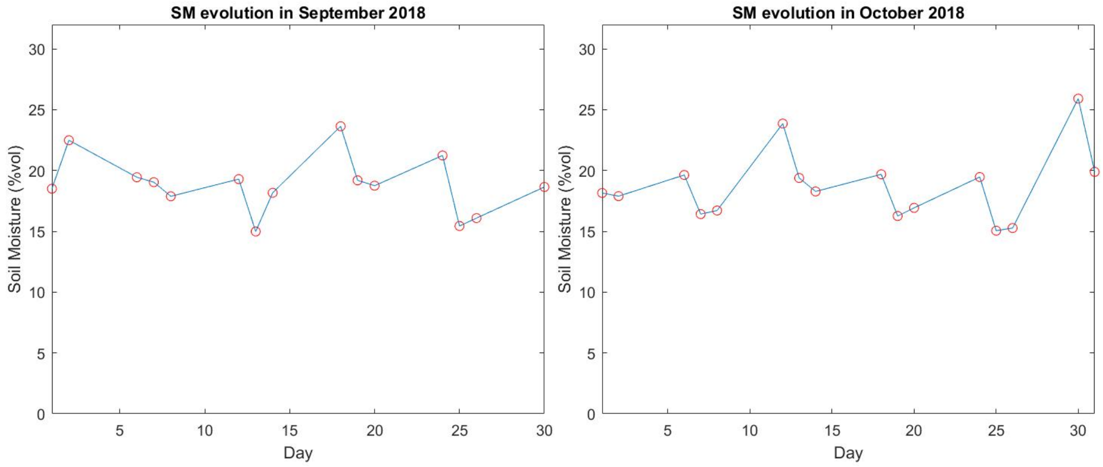
Graphic 4. SM evolution in March (left) and April (right)



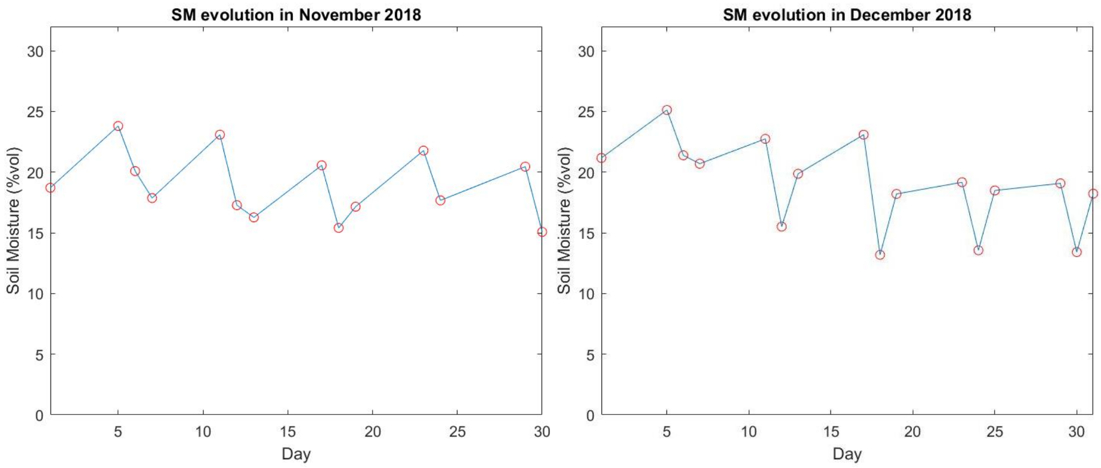
Graphic 5. SM evolution in May (left) and June (right)



Graphic 6. SM evolution in July (left) and August (right)



Graphic 7. SM evolution in September (left) and October (right)

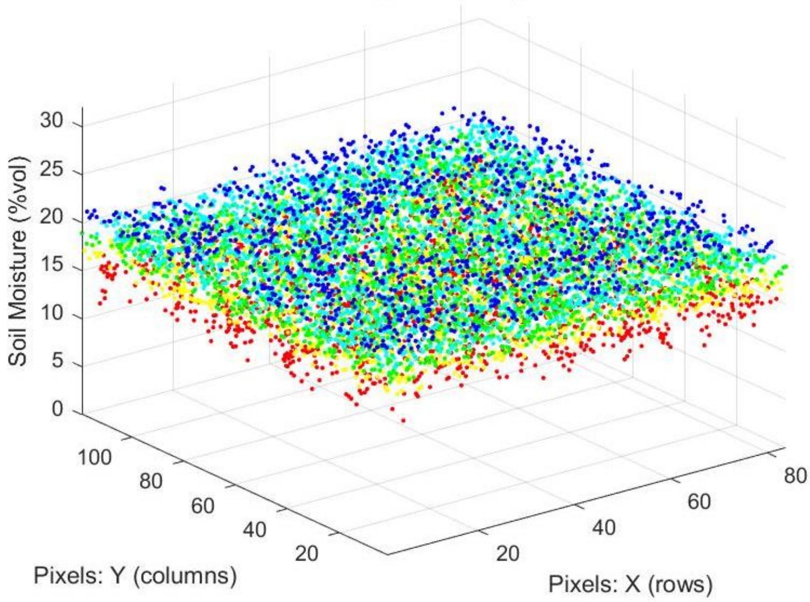


Graphic 8. SM evolution in November (left) and December (right)

From these graphics it can be seen that the values of soil moisture are inside the expected range, between the minimum and maximum stablished. In order to further understand the variations of soil moisture between the different days, comparisons using rainfall and irrigation data from the region are going to be carried out.

8.4.2. Cell Analysis

The aim of this analysis was having an overview of the soil moisture estimations of each cell of the region studied. The total number of cells, as it was explained previously, is 9996. In order to understand the evolution of the soil moisture values per cell the average value of each cell was calculated, both monthly and annually. Graphic 9, shows a 3D representation of the soil moisture average data per cell for the month of January.



Graphic 9. Soil Moisture estimations average value per cell for January 2018

Soil Moisture Graphic Key (%vol)	
	> 21.6447
	18.9111-20.2779
	17.5443-18.9111
	16,1776-17.5443
	<16,1776

Table 52. Key table for graphic 9

The graphics for the rest of the months can be seen in the annex 3.

The annual analysis is especially important because it has been proven to be very useful to identify on the map the non-agricultural zones. Figures 108 and 109, are the soil moisture annual average estimations per cell and the study area respectively. Several zones can be studied in these images.

Firstly, it is important to highlight the red cells that have been circled on red. These cells are the lowest average soil moisture values for all the year and perfectly correspond with the zones where there are houses built. The areas circled in orange correspond to houses that can be identified in the soil moisture map as well, but less clear. Finally, the two houses that cannot be appreciated in the soil moisture map in the ones circled in green. These anomalies can be caused by several factors, for example, the houses are new constructed and therefore did not exist on the analyzed period, or they are partially cover by trees making them more difficult to be detect with the method.

Moreover, another important zone is the one circled in purple. It corresponds to a dense wooden area. The soil moisture values of the correspondent cells show a low values patron that can be easily identified as well.

Finally, it was not possible to identify the roads of the area in the soil moisture map. This can be due to their small width, or because they are not roads but paths, and therefore the method cannot differentiate between the soil path and the agriculture fields due to their similar soil moisture values.

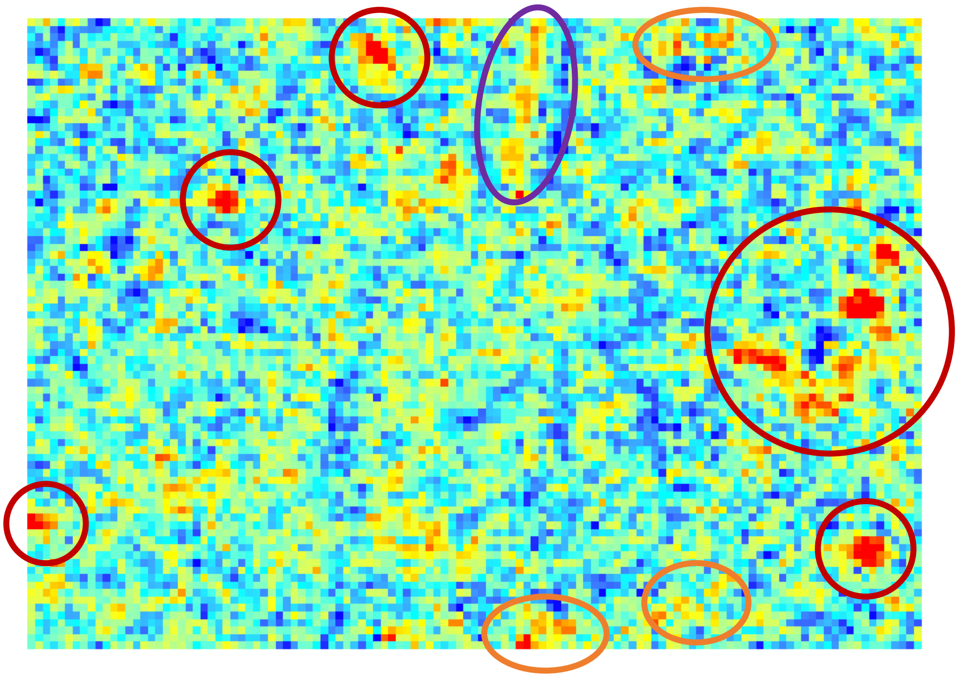


Figure 108. SM estimations for the analyzed area. Average value per cell for the whole year 2018

Figure 109. Satellite view of the analyzed region

From this analysis it can be concluded that the method applied to develop the soil moisture estimations is correct as an initial approach, but its accuracy can be improved doing some modifications. For example, including in the analysis a vegetation index could be crucial to perfectly identify agricultural fields from non-agricultural areas.

The following figure shows an overlap of the figures 108 and 109, in order to give a better comprehension of the analysis carried out.

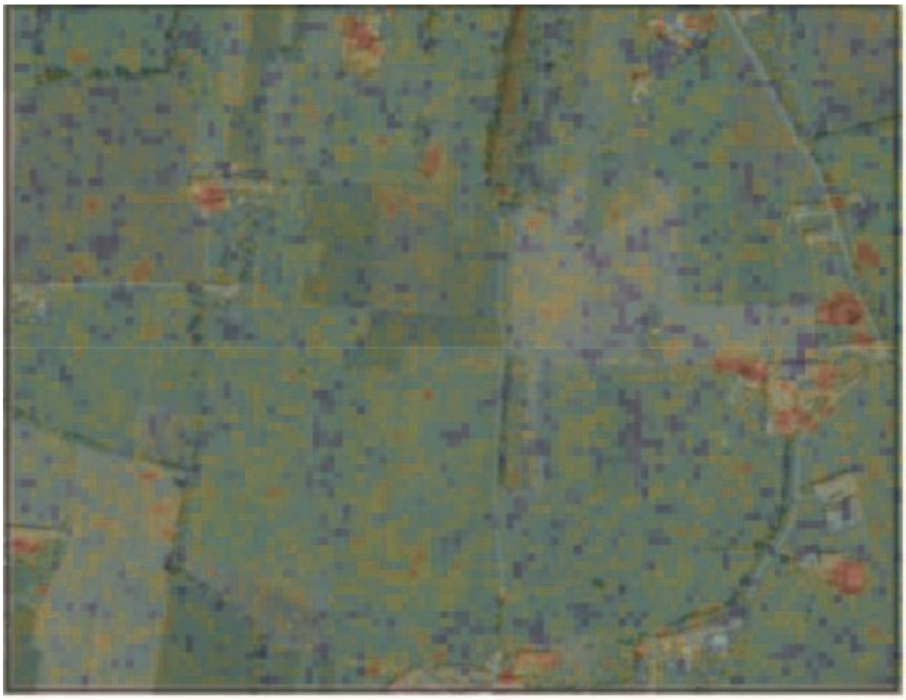


Figure 110. Overlap of figure 108 and 109

8.4.3. Rainfall, Irrigation and Soil Moisture comparison

The aim of this comparison is analyzing the changes in soil moisture in relation with irrigation and rainfall, in order to better understand the contribution these two factors have in soil moisture. Furthermore, this analysis can be used to see how accurate the method applied to estimate soil moisture is. The more coherent the data is between each other, the better the method has been developed.

Before starting the comparison some aspects, that may have affected negatively to this analysis must be taken into account. First of all, soil moisture data is not continuous over the time, the normally proportion of data in this study is three consecutive days with estimations followed by other three consecutive days without them. Moreover, regarding to the rainfall data, it must be taken into account that the data available is from a nearby region, but not from the analyzed region. Therefore, even though similar values of rainfall are expected between the regions some incoherencies or anomalies can appear while facing soil moisture evolution with the rainfall data. The rainfall data is from the Vialfre locality, and it was obtained through the "ARPA Piemonte meteo network". Finally, speaking about the irrigation data, it must be taken into account that the available data is for all the agricultural area of Rivarolo, and not just for the small region selected to work with. This implies that not all the water flow from the data obtained has been applied in the zone studied, which may cause some errors as well.

Due to all the mentioned limitations, these comparisons will be qualitative and not quantitative. First, the rainfall comparison will be done, in order to see if the days with heavy rainfall are reflected on the soil moisture estimations. Once the heavy rain days have been analyzed the comparison will continue with the irrigation data, in order to explain the variations of soil moisture in days without or with little rainfall.

The comparison in both cases will be shown in three different graphics. The first one will compare soil moisture with total rainfall or flow irrigation, respectively, for every day of the year 2018. The other two, will compare the cumulative rainfall or flow irrigation with the percentile difference of soil moisture. These graphics were carried out in order to assure the correct interpretation of the data. Furthermore, two graphics comparing the three variables at the same time have been developed to be able to analyze the impacts on soil moisture estimations of rainfall and irrigation together.

8.4.3.1. Rainfall analysis

From the graphics 10 to 12 the days analyzed were those ones with heavy rainfall, precipitation values over 30mm, or days with strong soil moisture incrementations. Table 53 shows the most relevant chosen days along with an explanation of the conclusions taken from the graphics observation. Furthermore, the analyzed days are marked with different colors on the graphic 10 corresponding with the colors of the table, to achieve a better comprehension of the analysis.

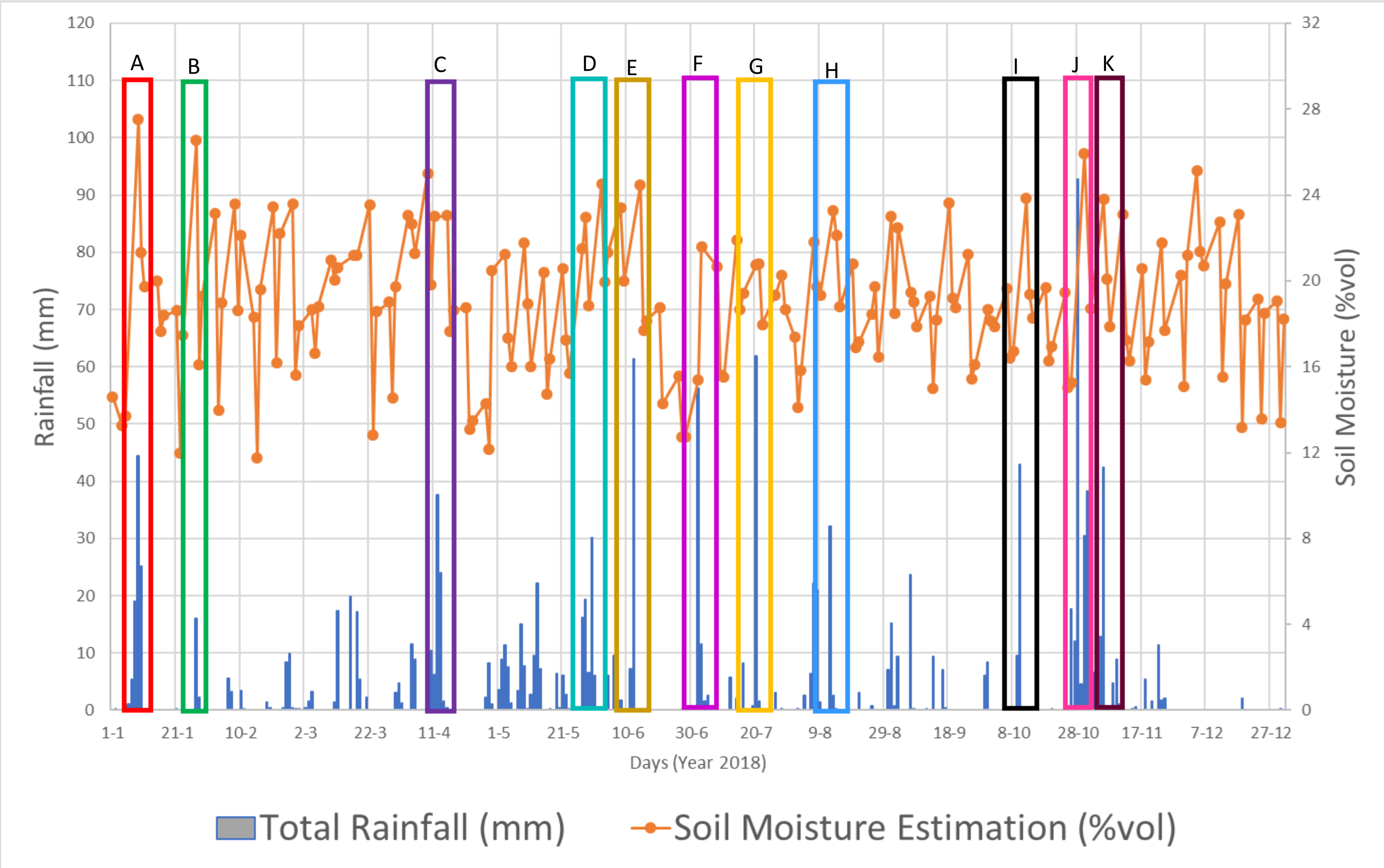
Days	**Data**	**Observations**	**Key**
9-January	R: 44,4mm SM: 27,52%vol	Rainy day which causes huge SM incrementation (from 13,69 to 27,52%vol)	**A**
27-January	R: 16mm SM: 26,57%vol	Strong SM incrementation in comparison with a medium-low rainfall day. Moreover, there was no rainfall on the previous days. Irrigation data should be analyzed in order to find a valid conclusion.	**B**
12-April	R: 37,6mm SM: 22,99-23,03%vol	Medium to high rainfall with a correspondent increment on the SM values around that day.	**C**
30-May	R: 30,2mm SM:18,83-24,53%vol	Medium rainfall with a correspondent increment on the SM values around that day. Irrigation may have occurred in order to achieve so high SM values the 2-June.	**D**

12-June	R: 61,4mm SM: 20,01-24,48%vol	High rainfall with a correspondent increment on the SM values around that day. Irrigation may have occurred in order to explain the continuous SM increment after the rainy day.	**E**
2-July	R: 56,2mm SM: 15,39%vol	Rainy day with a coherent incrementation in SM values.	**F**
20-July	R: 61,8mm SM: 20,76%vol	Rainy day which an incrementation in SM values. The growth is not as high as expected from the previous data, surely because of the high temperatures of the month of July.	**G**
12-August	R: 32,2mm SM: 19,35-23,28%vol	Medium rainfall with a high SM growth. Surely, irrigation occurred during these days because the high increase in SM does not completely fit with the rainfall data.	**H**
10-October	R: 43mm SM: 16,71-23,86%vol	Heavy rainfall with a high SM increment.	**I**
28-October	R: 92,8mm SM: 15,27-25,91%vol	Really strong rainfall with a coherent high SM incrementation.	**J**
5-November	R: 42,4mm SM: 21,38%vol	Rainy day with a coherent incrementation in SM values.	**K**

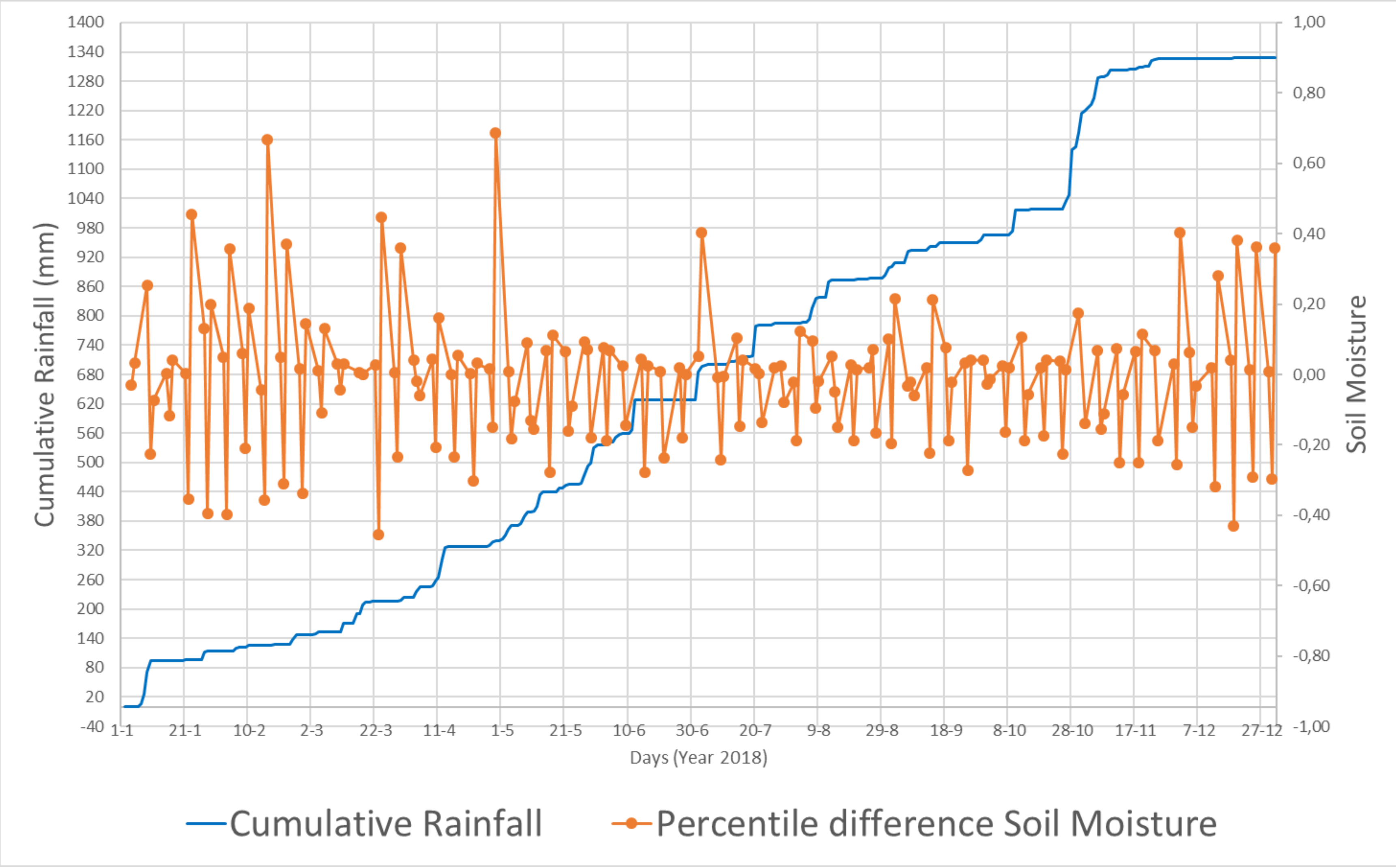
Table 53. Rainfall analysis

R: Rainfall in millimeters.

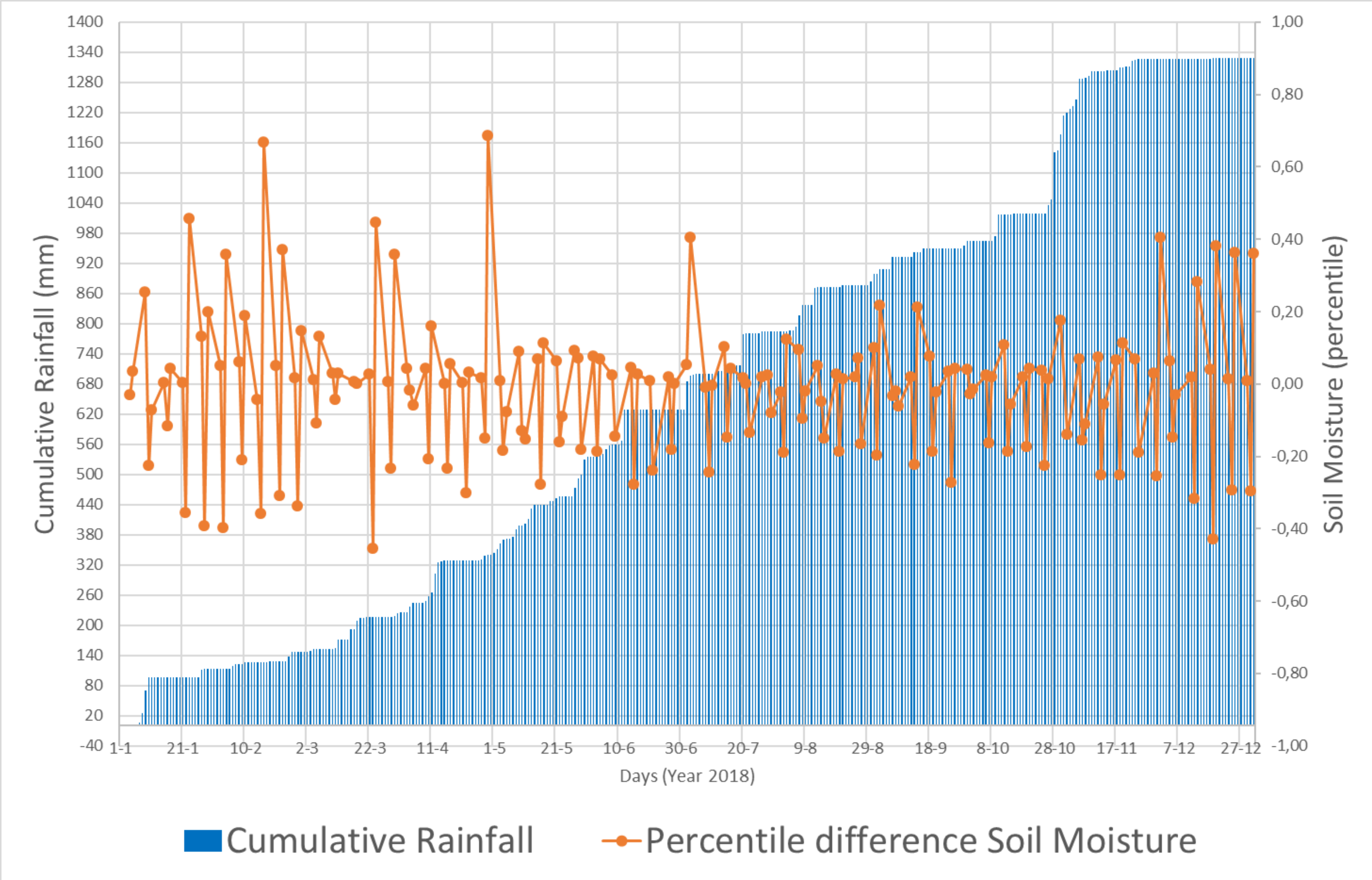
SM: Soil Moisture estimations (%vol). If the value for this variable is a range of data it means a soil moisture estimation was not available for that day. The values given correspond to the immediately previous and following days.



Graphic 10. Soil Moisture (%vol) versus Rainfall (mm)



Graphic 11. Percentile difference of Soil Moisture versus Cumulative Rainfall



Graphic 12. Percentile difference of Soil Moisture versus Cumulative Rainfall (histogram)

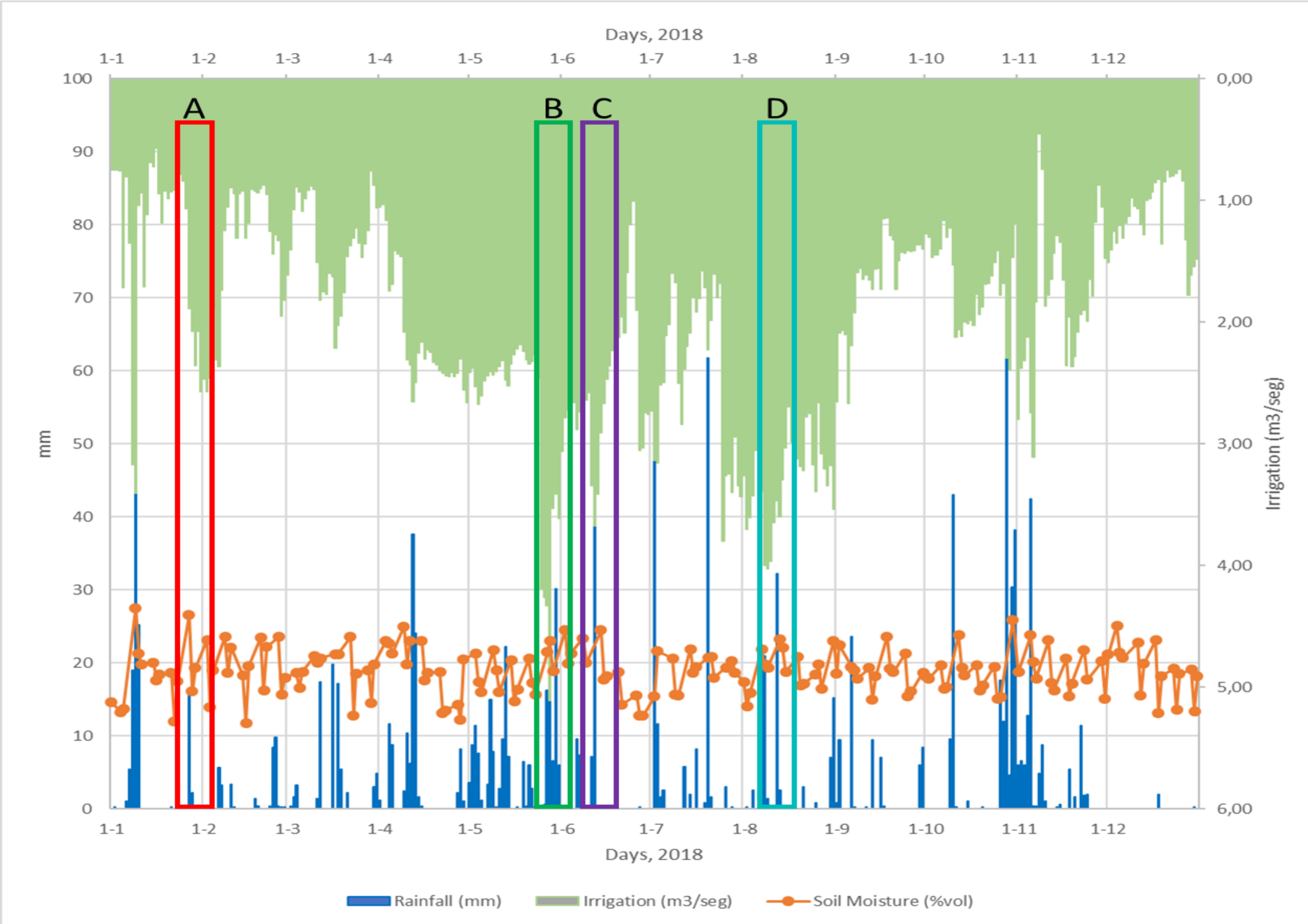
8.4.3.2. Irrigation analysis

This analysis was carried out to understand soil moisture estimations variations when there was a lack of rainfall. The data available is considered to not take into account rainfall water, just water used for irrigation. Due to the lack of knowledge of the exact days in which the water flow available was applied to the study area the comparison will be qualitative. Furthermore, instead of only analyzing individual days, the comparison will be carried out for periods of days in which soil moisture estimations variations were continuous and cannot be explained with rainfall.

The first table, table 54, correspond to the four days analyzed on the rainfall comparison that needed irrigation information for being completely coherent. The second table, table 55, shows the days and ranges of days found of interested to be compared with the irrigation data. Furthermore, the analyzed days are marked with different colors on the graphic 13 and 14 corresponding with the colors of the tables 54 and 55 respectively.

Days	**Data**	**Observations**	**Key**
27-January	R: 16mm SM: 26,57%vol I: 1,89m3/seg	The irrigation flow is lower than it was expected in order to understand the SM incrementation as a combine effect of rainfall and irrigation. It is quite probable that the error is due to inaccuracies in the rainfall data or in the SM estimations.	**A**
30-May	R: 30,2mm SM:18,83-24,53%vol I: 3,41mm	The irrigation flow is high enough to explain the high SM values obtained this day and the following ones.	**B**
12-June	R: 61,4mm SM: 20,01-24,48%vol I: 3,68m3/seg	The irrigation flow is high enough to explain the big SM increment as a combine effect of rainfall and irrigation.	**C**
12-August	R: 32,2mm SM: 19,35-23,28%vol I: 3,47m3/seg	The irrigation flow is high enough to explain the big SM increment as a combine effect of rainfall and irrigation.	**D**

Table 54. Irrigation analysis 1



Graphic 13.Rainfall, Irrigation and Soil Moisture global comparison 1

Days	Data	Observations	Key
9-January	R: 44,4mm SM: 27,52%vol I: 3,41m3/seg	The high SM values are coherent with the high irrigation and rainfall data.	**A**
22-January	R: 0mm SM: 11,99%vol I: 0,92 m3/seg	Really low SM values corresponding with a no rainy day with really low irrigation flow.	**B**
28-Jan to 15-Feb	SM: 16,1 to 11,75%vol ▪ Max: 23,58 ▪ Min: 11,75 I: 2,07 to 1,31 m3/seg ▪ Max: 2,57 ▪ Min:0,89	Up and down SM variations in accordance with the changes in the irrigation flow. In the last days of the period huge SM drop which fits with the lowering of the irrigation flow on that days.	**C**
17-March to 4-April	SM: 21,19 to25%vol ▪ Max: 25 ▪ Min:12,83 I: 2,21 to 2,08m3/seg ▪ Max:2,21 ▪ Min:0,75	Up and down SM variations in accordance with the changes in the irrigation flow. In the last days of the period there is an incrementation in SM values which fits with increment of the irrigation flow on that days.	**D**
12-April	R: 37,6mm SM: 22,99%vol I:2,65m3/seg	High constant values for SM during a couple of days due to the joint action of water from irrigation and rainfall.	**E**

Table 55. Irrigation analysis 2

21-April to 29-April	SM: 18,76 to 20,49%vol ▪ Max: 20,49 ▪ Min: 12,15 I: 2,40 to 2,55m3/seg ▪ Max: 2,55 ▪ Min: 2,30	No correlation between SM and irrigation data. Probably the high flow of water for irrigation for these days was not use in the study area, which will explain why there was not an increment on the SM values.	**F**
29-April to 27-May	SM: 20,49 to 21,48%vol ▪ Max: 21,77 ▪ Min: 14,72 I: 2,55 to 4,33m3/seg ▪ Max: 4,33 ▪ Min: 2,18	Up and down SM variations in accordance with the changes in the irrigation flow.	**G**
28-May	SM: 22,98%vol I: 5,11m3/seg	Too much water flow for irrigation. Probably, not all the water was used on the study region.	**H**
14-June to 27-June	R: 0 to 0,2mm ▪ Max: 0,2 ▪ Min: 0 SM:24,48 to 12,74%vol ▪ Max: 24,48 ▪ Min: 12,74 I: 2,91 to 3,06m3/seg ▪ Max: 3,06 ▪ Min: 1	Coherent results, which show a drop in SM values due to the lack of water coming from both, irrigation and rainfall.	**I**

Table 56. Irrigation analysis 2 (continued)

27-June to 26-July	R: 0,2 to 3mm ▪ Max: 61,8 ▪ Min: 0 SM: 12,74 to 19,34%vol ▪ Max: 21,89 ▪ Min: 12,74 I: 3,06 to 3,26m3/seg ▪ Max: 3,80 ▪ Min: 1,58	Concordance between the medium to high SM values with low irrigation flow but high rainfall data.	**J**
2-August	R: 0,2mm SM: 14,1%vol I: 3,70m3/seg	None coherent SM data with irrigation flow. Probably the irrigation water of this day was not used in the study area.	**K**
6-Aug to 13-Sept	SM: ≈21,82 to 14,99%vol ▪ Max: 23,28 ▪ Min: 14,99 I: 3,15 to 1,73m3/seg ▪ Max: 4,02 ▪ Min:1,55	Up and down SM variations in accordance with the changes in the irrigation flow.	**L**

Table 57. Irrigation analysis 2 (continued)

13-Sept t 8-Oct	R: 9,4 to 0mm ▪ Max: 9,4 ▪ Min: 0 SM: 14,99 to 16,71%vol ▪ Max: 21,24 ▪ Min:14,99 I: 1,73 to 1,30m3/seg ▪ Max: 1,73 ▪ Min: 1,14	Small variations of SM. Low SM values that fit with the low water data coming from both irrigation and rainfall.	**M**
8-Oct to 31-Dec	SM: 16,71 to 18,23%vol ▪ Max: 25,91 ▪ Min: 13,18 I: 1,30 to 1,48m3/seg ▪ Max: 3,11 ▪ Min: 0,45	Up and down SM variations in accordance with the changes in the irrigation flow. In the last days of the period remarkable SM drop which fits with the lowering of the irrigation flow on that days, as well with the low rainfall data.	**N**

Table 58. Irrigation analysis 2 (continued)

R: Rainfall in millimeters.

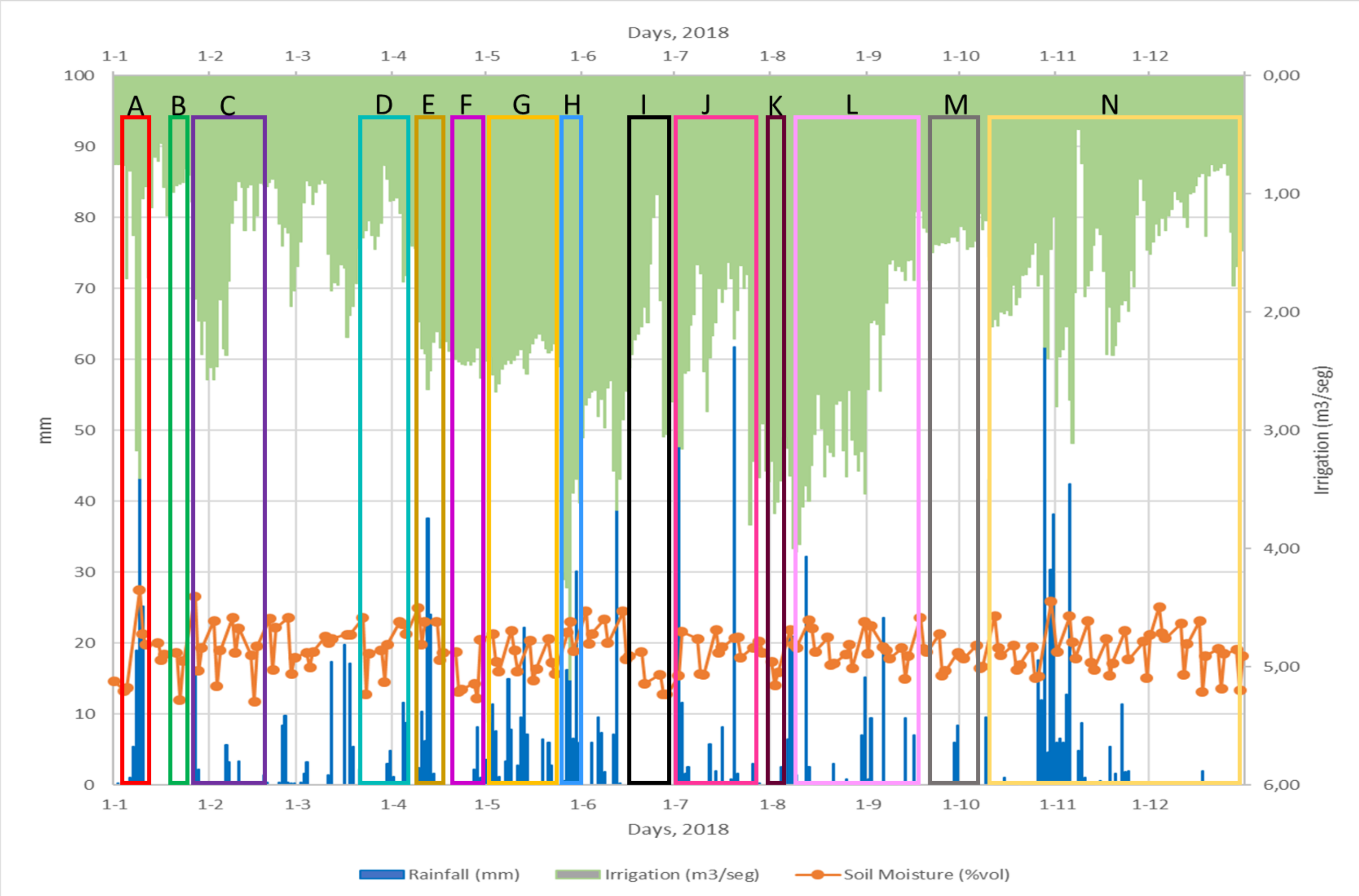
SM: Soil Moisture estimations (%vol). If the value for this variable is a range of data it means a soil moisture estimation was not available for that day. The values given correspond to the immediately previous and following days.

- The symbol ≈ before a soil moisture value indicates that the estimation was not available for that day, and therefore, the data given is for the immediate consecutive day with value available.

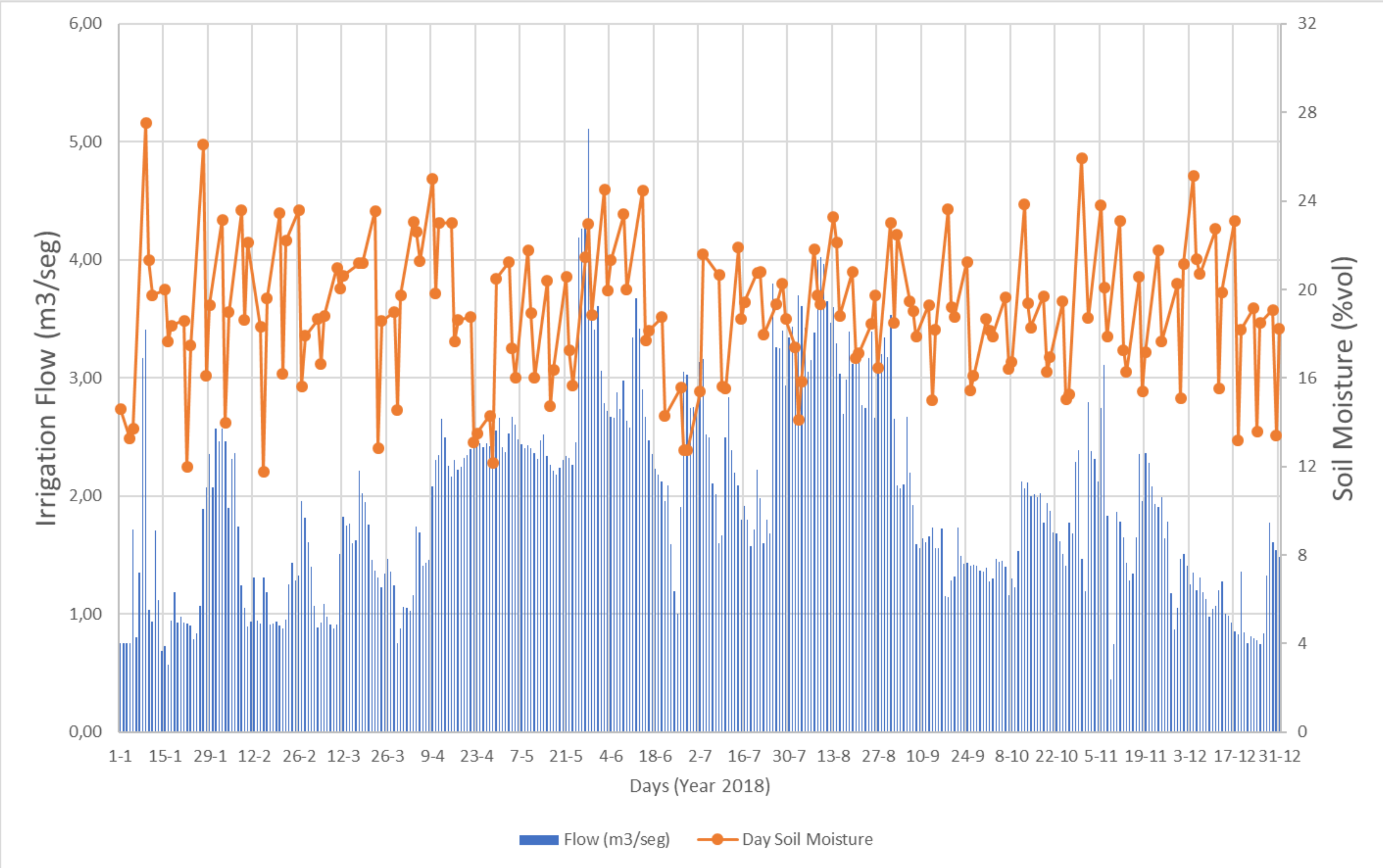
I: Irrigation Flow in m3/seg.

While analyzing groups of days the data is given following successive schema:

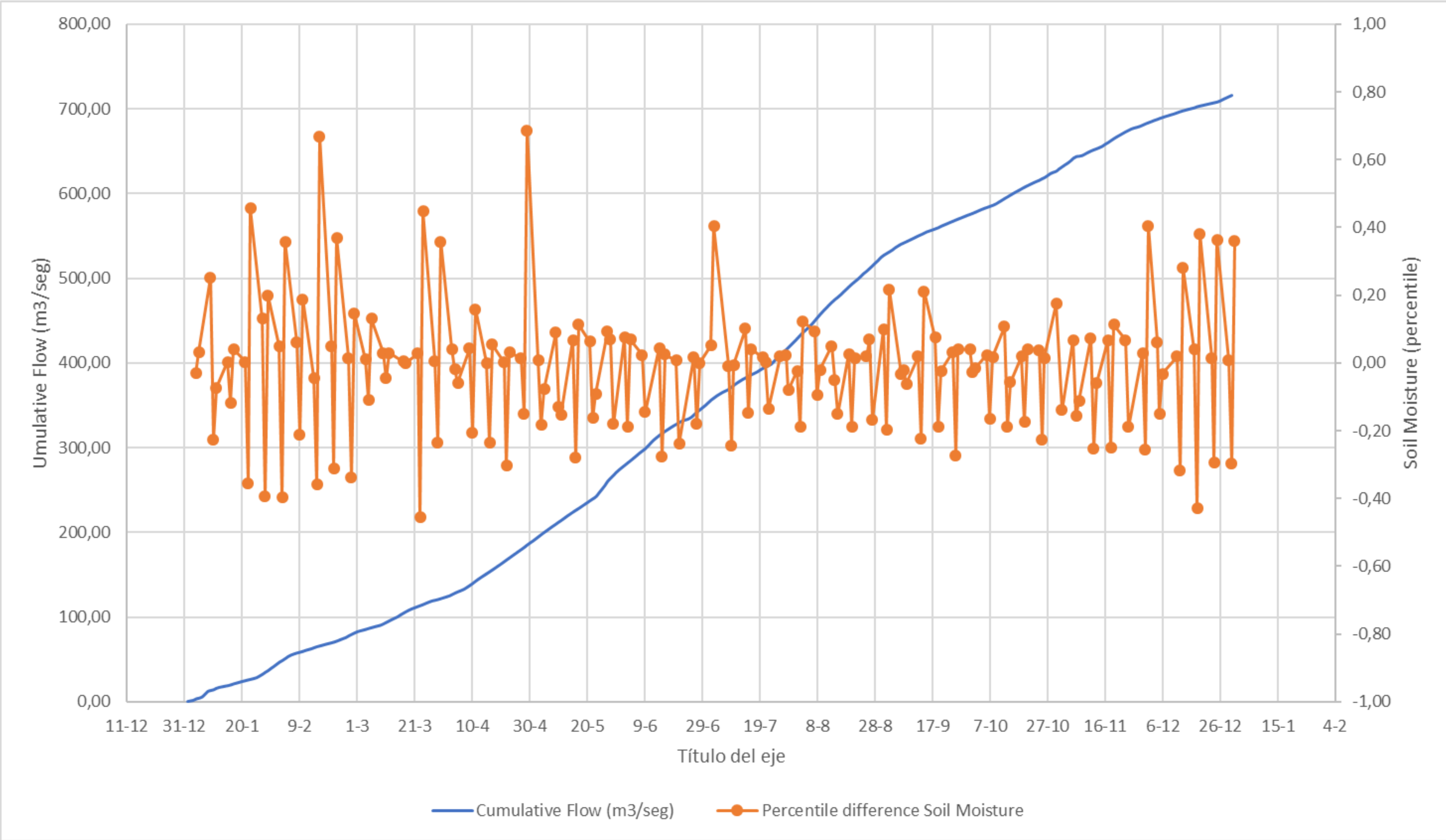
- The data shown is for the days at the extremes of the analyzed period, for all the variables used on the conclusions of the graphical observations. Maximum and minimum values of the variables on the analyzed period are given as well.



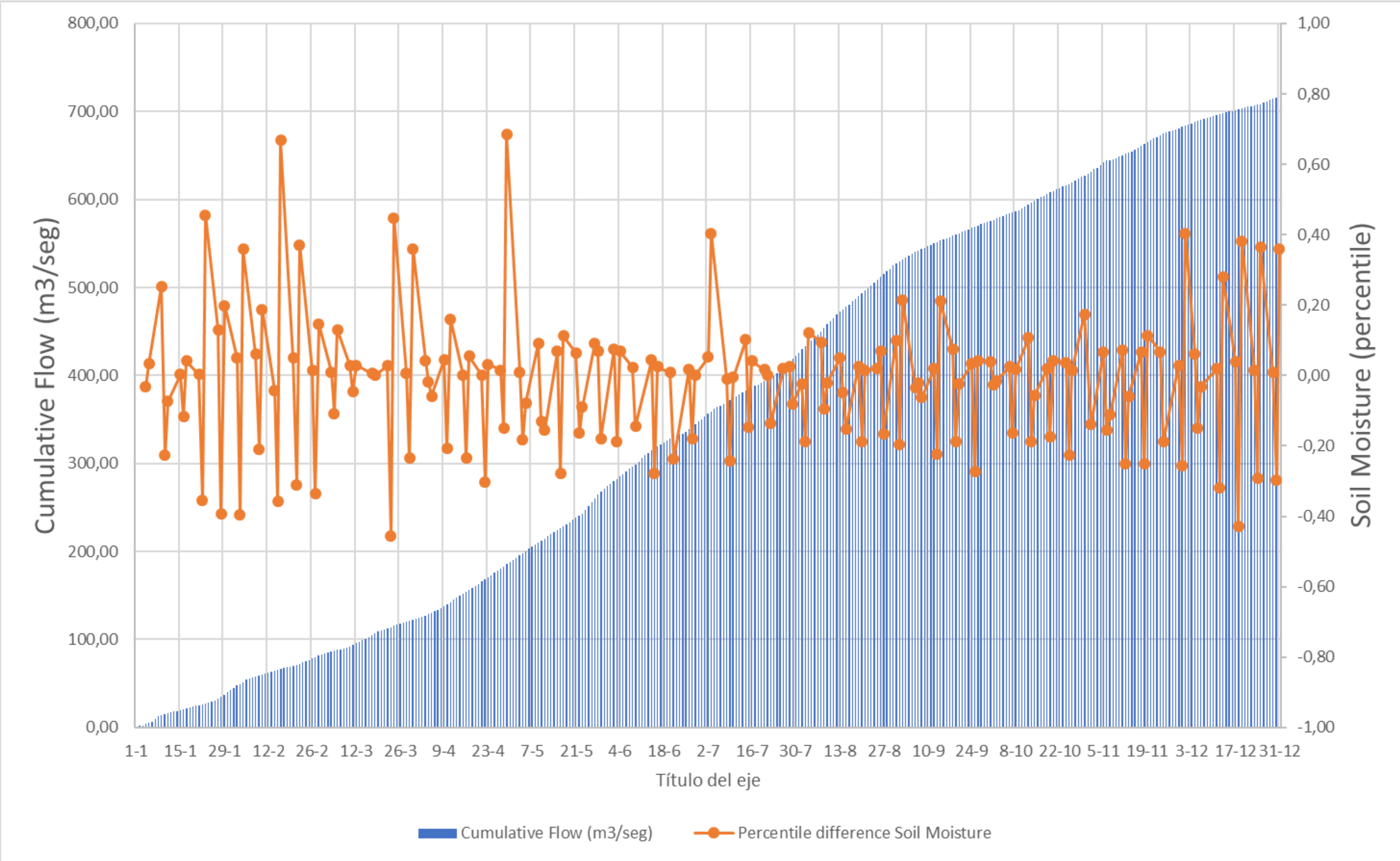
Graphic 14. Rainfall, Irrigation and Soil Moisture global comparison 2



Graphic 15. Soil Moisture (%vol) versus Irrigation Flow (m3/seg)



Graphic 16. Percentile difference of Soil Moisture versus Cumulative Irrigation Flow



Graphic 17. Percentile difference of Soil Moisture versus Cumulative Irrigation Flow (histogram)

8.4.3.3. Final Remarks

The high coherence between the soil moisture estimations and the water data coming from irrigation and rainfall shows that the method developed to calculate the soil moisture estimations is quite accurate. The anomalies found during the analysis can be easily explained due to the limitations of the data available of both irrigation and rainfall, which were mentioned above.

9. Conclusions and Future Development

In this chapter a summary of the conclusions of the project will be shown. Moreover, the limitations of the product developed will be explained, as well as the future lines of development for the project in order to solve the previous limitations.

9.1. Conclusions

This thesis, in which a Change Detection method to estimate soil moisture from satellite observations was applied, has had a correct execution, because not only the soil moisture estimations have been achieved, but the data calculated has been proven to have a high accuracy.

In the validation process, the average of all the RMSD error obtained was of 8,57%vol, which has been considered as a correct result because of the three following reasons:

1. The validation data comes from a French project with a RMSD error between 6%vol to 8%vol.

2. Moreover, the French project had at their disposal in-situ measurements, which allowed them to applied Neural Network and Water Cloud Models, that are more accurate than CD methods.

3. Finally, CD methods can be divided in two groups: those ones who applied NDVI and those ones who does not. Using NDVI in the method will suppose an increase on the accuracy of the method. Due to programing limitations of the Google Earth Engine platform, it was not possible to apply this vegetation index.

Taking into account all these considerations, the validation errors obtained in this project are considered low enough to perform different analysis on the soil moisture estimations in order to prove the level of accuracy of the method applied.

The output of the analysis carried out allows to conclude that the results obtained are very accurate. Two main analysis were implemented:

1. **Cell analysis.** Its aim was to be able to distinguish between agricultural and non-agricultural areas. In general, it was possible to identify almost all the houses and large tree areas from the agricultural fields.

2. **Irrigation, rainfall and soil moisture comparison.** The aim of this analysis was to understand the variations of soil moisture caused by the irrigation and rainfall water volumes. In overall, the water volumes of both, irrigation and rainfall, were coherent with the soil moisture changes.

As a summary, from the validation process it can be concluded that the RMSD error was inside the limits permitted. In addition, due to the great results of the analysis carried out to these estimations, it can be concluded that applying the selected method to obtained the estimations has led to quite high accuracy soil moisture results.

9.2. Future Development

The project can be continued by improving the features of the soil moisture estimations obtained. These improvements can be developed on two main areas: the method applied to obtain the soil moisture estimations and the number of days with soil moisture.

Speaking about the method applied, it could be improved by introducing the NDVI. Applying this vegetation index has been proven to increase the accuracy of the results obtained. Furthermore, it will give the possibility of distinguishing automatically between agricultural and none agricultural areas.

Finally, the number of days with soil moisture estimations could be increased by developing an accurate infilling data process. This will be reflected on having a better daily knowledge of the variations of soil moisture. Therefore, a better comprehension of the relation between irrigation and rainfall water volume with soil moisture estimations will be achieved.

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