# 03 - DROUGHT MONITORING, PRECIPITATION STATISTICS, AND WATER BALANCE WITH FREELY AVAILABLE REMOTE SENSING DATA: EXAMPLES, ADVANCES, AND LIMITATIONS

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**Abstract**

Ireland is facing dryer conditions in recent years, when compared to past decades. The study of drought and precipitation parameters, in addition to water balance, has become increasingly necessary. New technologies, such as remote sensing and satellite imagery, big data handling, visualised within geospatial software could serve as highly valuable tools to assess various hydro-meteorological parameters. The aim of this study is to showcase and discuss these new technologies for hydro-meteorological studies. Six of NASA's web-repositories that can be used to freely download and visualise such spatial and/or time-series factors are listed and explained with examples for Ireland: ways to access hydrological, meteorological, soil, vegetation and socio-economic data are shown, and estimations of various precipitations statistics, anomalies, and water balance are presented for monthly and seasonal analyses. The advantages, disadvantages and limitations of the satellite datasets are discussed to provide useful recommendations about their proper use, based on purpose, scale, precision, time requirement, and modelling-expansion criteria. Overall, the added value and novelty of this contribution is the guidance through resources and examples, using freely accessible tools. Thus, it can be a basis for several applications, data explorations, assessments, exercises etc. by a wide range of professionals, including practitioners, academics, students, educational material, etc.

**KEYWORDS:** Remote Sensing; Satellite imagery; GIS; Hydrological balance; Drought monitoring; Precipitation anomaly; Precipitation statistics; Vegetation indices.

## 1. INTRODUCTION

Ireland is increasingly facing dryer conditions in recent years, when compared to past decades (Alamanos et al., 2021a). According to the National Water Resources Plan (NWRP), Met Éireann and Central Statistics Office (CSO) data, 11 cities might have difficulties meeting their water needs due to a combination of decreased seasonal precipitation, increasing population, and water consumption per person above the country's average (Irish Water, 2021; DHPLG, 2017; Met Éireann, 2021). Thus, the study of drought, precipitation parameters, and water balance, becomes increasingly necessary. The most common impediments for the application and development of hydrological-water management models are often their complexity, data requirements and the time needed. However, new technologies, such as remote sensing and satellite imagery, big data handling, and geospatial software could serve as highly valuable tools to assess various hydro-meteorological parameters (Alamanos and Linnane, 2021). Ireland has been slow to examine the potential of all of these advances for possible use in such applications. From our experience in many instances where even simple hydrological modelling or extreme climate analyses considering drought conditions could provide answers to many issues, poor awareness and understanding, data limitations and model complexity restrict their understanding and application (Antwi et al., 2022; Alamanos et al., 2021b). The aim of this study is to showcase and discuss some new technologies that could be helpful for hydro-meteorological studies, overcoming complex, data-hungry, and time-consuming ways. The use and potential of remote sensing and satellite imagery, and the visualisation of several parameters through geospatial software is analysed focusing on access to freely available datasets, examples and demonstration on their use and potential analyses.

## 2. MATERIALS AND METHODS

All droughts originate from precipitation that is "below normal". According to the international drought categorisation (Wilhite, 2000), we have Meteorological, Agricultural, Ecological, Hydrological, and Socio-economic Drought. These are region-specific, can have high spatial variability, and are directly connected to factors such as precipitation shortage, meteorological parameters, evapotranspiration, vegetation growth, soil moisture, runoff, supply and demand rates and socio-economics. NASA's satellites are observing these factors and can provide useful insights in the case of absence of earth-based and locally measured data. Six of NASA's web-repositories are listed and explained, where spatial and/or time-series data relevant to the above datasets can be freely downloaded or visualised. These resources cover most countries globally, however, in this work, their potential is demonstrated with examples for Ireland (listed in Table 1 – and explained below).

***Table 1:*** *The examples presented in this work, with available satellites and data sources.*

| Examples | Satellites/ Algorithm | Data sources |
|---|---|---|
| ***Example 1:*** Monthly precipitation analysis<br>***Example 2:*** Seasonal precipitation analysis | GPM satellite – IMERG algorithm[1] | https://giovanni.gsfc.nasa.gov/giovanni/ |
| ***Example 3:*** Hydrological Balance | Shuttle Radar Topography Mission (SRTM)[2] | https://photojournal.jpl.nasa.gov/catalog/PIA06672<br>https://www2.jpl.nasa.gov/srtm/ireland.html#PIA06672<br>https://www.hydrosheds.org/<br>https://giovanni.gsfc.nasa.gov/giovanni/ |
| ***Additional examples and resources:*** | | |
| Vegetation Index<br>Soil Moisture | MOD 13 – A1,<br>SMAP | https://www.cpc.ncep.noaa.gov/products/Soilmst_Monitoring/gl_Soil-Moisture-Monthly.php<br>https://search.earthdata.nasa.gov/search<br>https://worldview.earthdata.nasa.gov/ |
| EvapoTranspiration (ET) | SMAP,<br>GRACE | http://eeflux-level1.appspot.com/ |
| Socio-economic Data | Multiple | https://sedac.ciesin.columbia.edu/data/sets/browse |

The software Q-GIS has been used for the visualization and analysis of the above parameters, as it is a freely available resource for geo-spatial analysis. The next sections describe the available resources and their use per example.

### NASA satellite data

It is well recognised that long-term precipitation measurements are necessary for understanding and monitoring regional precipitation characteristics, study droughts, and other related parameters. NASA has several satellites for observing various parameters, listed in Table 2.

[1] Precipitation timeseries
[2] Digital Elevation Models (DEM), Basins, Meteorological parameters

***Table 2:*** *NASA Remote Sensing data available for drought and hydrological monitoring.*

| Type of Drought / hydrological factors | Parameters | Satellites: years active |
|---|---|---|
| Meteorological Drought | Precipitation | • Tropical Rainfall Measuring Mission (TRMM): 11/1997 – 04/2015<br>• Global Precipitation Measurements (GPM): 02/2014 – present |
| Agricultural Drought | NDVI, EVI, ET | • Landsat 07/1972 – present<br>• Terra: 12/1999 – present<br>• Aqua: 05/2002 – present |
| Hydrological Drought | Soil Moisture, Groundwater | • Soil Moisture Active Passive (SMAP): 01/2015 – present<br>• Gravity Recovery and Climate Experiment (GRACE): 03/2002 – present |

## Precipitation

TRMM was the first NASA mission dedicated to that purpose. It operated from November 1997 to April 2015. The Global Precipitation Measurement (GPM) Mission launched in February 2014 as a follow-on to TRMM. Both TRMM and GPM satellites, with additional national and international satellites, were used to produce multi-satellite products such as TMPA and IMERG. Until recently, these two separate products covered different time periods, so there was a lack of long-term, continuous, precipitation time series data (Huffman et al., 2007). More recently, GPM-IMERG retrospectively analysed TRMM-TMPA data to produce a consistent, combined precipitation time series from 2000-present. Multi-satellite algorithms allow improved spatial and temporal coverage of precipitation data and are widely used for applications on droughts, regional and global drought indices, precipitation statistics, and several researchers have successfully used them. Their main characteristics are shown below (NASA, 2019):

- TRMM Multi-satellite Precipitation Analysis (TMPA) – 01/1998-present: Spatial resolution 0.25°x0.25°; Global spatial coverage (50°S-50°N); 3-hour temporal resolution.
- Integrated Multi-satellitE Retrievals for GPM (IMERG) – 01/2014-present: Spatial resolution 0.1°x0.1°; Global spatial coverage (60°S-60°N – will be extended from pole to pole); 30-minutes temporal resolution.

In the examples below, data from GPM (IMERG) were used because of its higher spatial and temporal coverage and resolution.

## Vegetation Indices

The first vegetation index mentioned in Table 2, NDVI (Normalized Difference Vegetation Index), is based on how 'green' or 'red' the leaves colour which indicates the dryness of the vegetation (Pettorelli, 2013). Its values range from -1 to 1 (low to high density of green leaves). The second one, the EVI (Enhanced Vegetation Index) is similar to NDVI and can be used to quantify vegetation greenness. It corrects for some atmospheric conditions, canopy background noise, and is more sensitive in areas with dense vegetation. Multiple products can be used (Landsat, Terra, Aqua). MODIS (2000–present) has a spatial resolution of 250-1000m. Its temporal resolution can be daily, 8-day, 16-day, monthly, quarterly, yearly. MOD 13 it the MODIS type that observes Vegetation Indices. It produces 16-day, 250-meter spatial resolution (gridded) results. Their anomalies can be used to identify drought.

## Other parameters

There are multiple available options for the rest of the parameters of Table 2. In particular, for Evapotranspiration (ET), there are Landsat-based ET images available online at 30m resolution

(METRIC EEFLUX[3]). These maps provide information about changing ET, indicative of agricultural and hydrological drought conditions. Soil Moisture is available from various databases, e.g. (NOAA, National Weather Service[4]) which provides the anomalies of soil moisture, or GRACE[5]-based on water storage anomalies for drought monitoring, and also a variety of other parameters. Moreover, the platform Giovanni[6] provides various meteorological datasets form different satellites depending on the location, and the desirable spatial and temporal resolution. Finally, several socio-economic data are freely available through NASA's SEDAC[7] repository.

## 3. EXAMPLES: ACCESSING, ANALYSING, AND VISUALISING DATA

### 3.1 Example 1: Monthly precipitation analysis

The platform Giovanni is a great resource for meteorological parameters. It requires only an account, which can be the same as the user's account for NASA's Earthdata platform. In order to download precipitation data for Ireland, the GPM satellite (IMERG algorithm) was used, as mentioned above. In this example, monthly precipitation data for 10 years were used, in order to avoid the computational power needed for e.g. an hourly time step for multiple years. However, the procedure is the same. In the platform's options, the user can select the parameter of interest (precipitation, runoff, ET, etc.), define the type of the map (time-averaged, accumulated, etc.), the Start and End time, and the location by selecting a list of countries, or drawing it in the global map, or by entering its coordinates (Figure 1). In our case, we can select a time-averaged map of monthly precipitation of GPM (IMERG) from 2010-01-01 to 2019-12-31 for Ireland. The result includes the monthly precipitation maps for the averages of the period 2010-2019. The files are available in multiple formats (e.g. geotiff, NC, etc.) and it is up to the user's geospatial software to choose which one works best. The downloaded data have a certain name format which is recommended to be changed to facilitate the user (e.g. "*GPM_IMERG_month number_coordinates*"). Having downloaded monthly precipitation maps for the averages of the period 2010-2019, an interesting analysis is the precipitation anomalies. It is used for examining drought conditions, as it shows the difference for each month's precipitation from the "usual conditions" (Janowiak et al., 1986). In this example, each month of the year 2018 was used to compare its precipitation with the 10-year average. Operations with maps (raster files) can be done within the QGIS software through the raster calculator routine. These can be simple operations (addition, subtraction, multiplication, division) or even simple statistics. Thus, in order to estimate the anomalies per month, we can subtract the precipitation of 2018 (mm/month) from the 10-year averages (mm/month) (Figure 2). The user can execute various analyses with such datasets and explore further drought phenomena, for example, the Standard Deviation of anomalies can be estimated, and it can be a very useful step for the estimation of SPI (Standarised Precipitation Index), or for 'playing' with many different time-steps. The year 2018 was used in this example as it was characterised as a dry year for Ireland (Antwi et al., 2022), and the results of Figure 2 are in line with that. More specifically, all months of 2018 had lower precipitation than the 10-year averages. The spatial distribution varies, as for some months the southern part of the country was drier (January, February, June) while for others the north or west part (March, May, July, September, November, December), which has in general higher

[3] http://eeflux-level1.appspot.com/
[4] https://www.cpc.ncep.noaa.gov/products/Soilmst_Monitoring/gl_Soil-Moisture-Monthly.php
[5] http://geoid.colorado.edu/grace/dataportal.html
[6] https://giovanni.gsfc.nasa.gov/giovanni/
[7] https://sedac.ciesin.columbia.edu/data/sets/browse

precipitation (according to the 10-year averages). Thoughts and findings like the above prove the usefulness of such simple analyses with freely available resources.

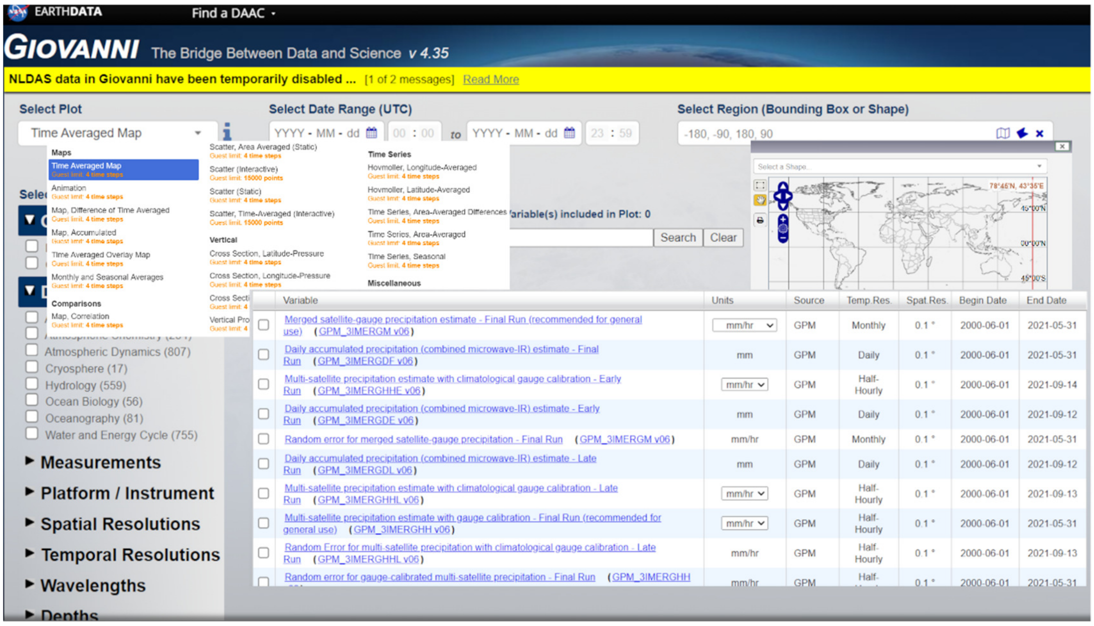


***Figure 1:*** *Accessing dataset from the Giovanni platform: in the left column the user selects the desirable parameter (e.g. precipitation), and the pop-up windows refer to the map type, dates, location. The results show units, satellite source, dates, temporal and spatial resolution, so that the user can download the dataset(s).*

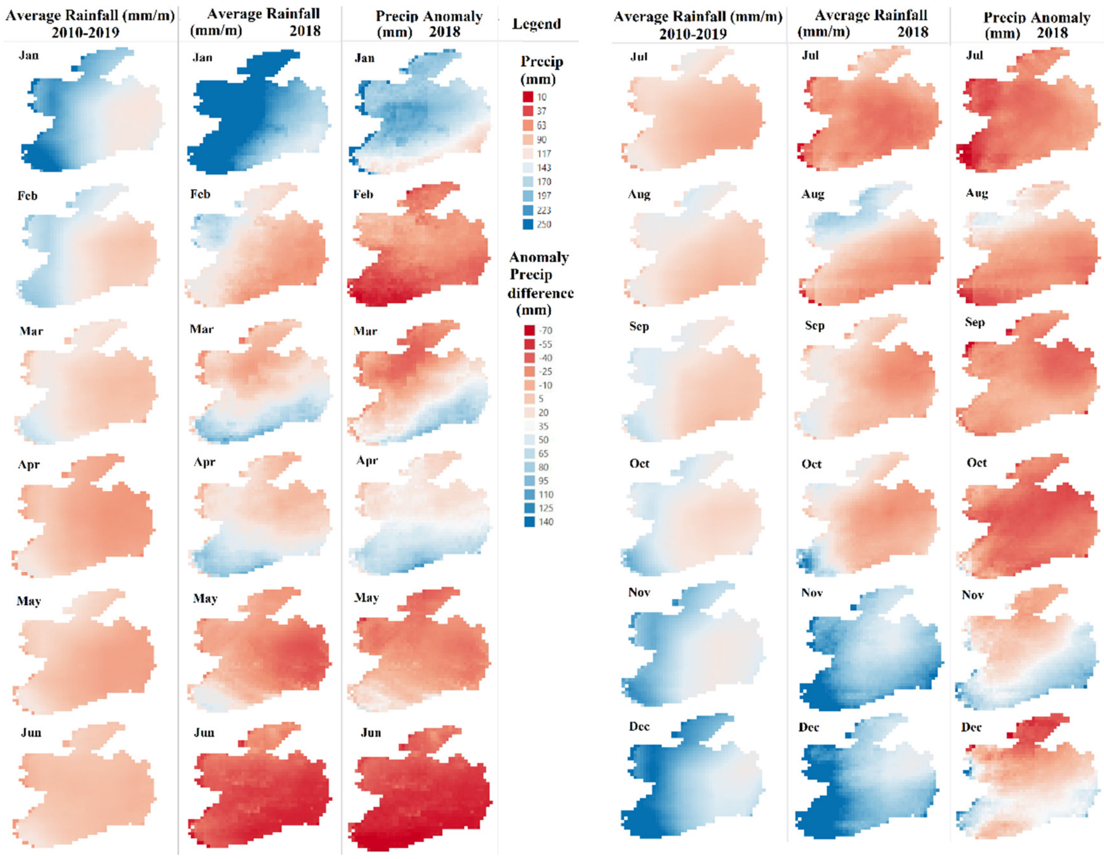


***Figure 2:*** *Average 10-year precipitation (left column) and monthly 2018 precipitation (middle column). Their difference (right column) expresses the anomaly per month of 2018.*

### 3.2 Example 2: Seasonal precipitation analysis

Following the same procedure, seasonal data from Giovanni was downloaded, again using the GPM (IMERG). As shown in Figure 3, seasonal (and monthly) averages, (DJF stands for December-January-February, MAM for March-April-May, JJA for June-July-August, and SON for September-October-November), can be accessed. These data can be in a time-series form (seasonal) or the user can select a season (e.g. only JJA) and examine the averages for a series of years. In this example, time-series for each season are presented for the last 20 years (Figure 3). Again, several statistical measures can be easily estimated within the r-series routine of QGIS, as shown in Figure 3 for example, the standard deviation for JJA of each year to the overall 20-year average.

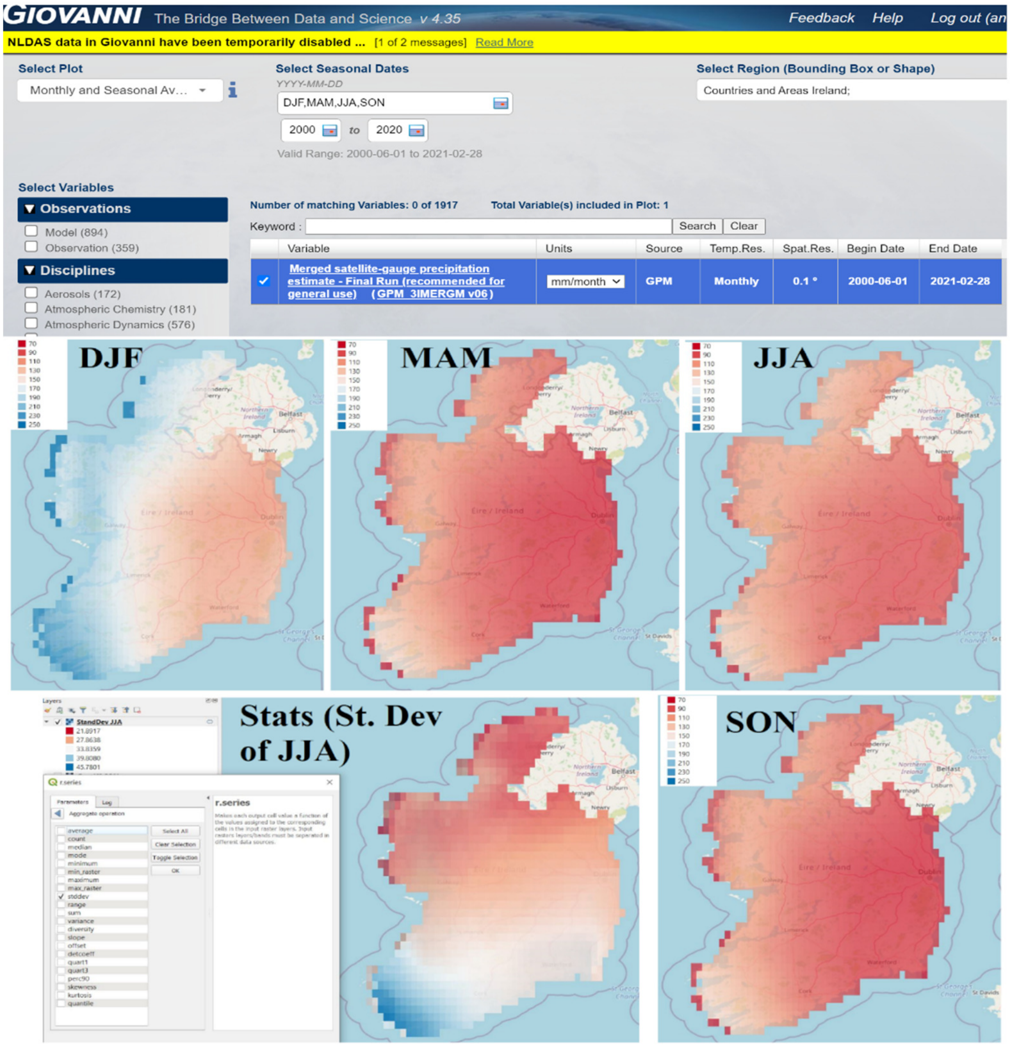


***Figure 3:*** *In the upper part: accessing seasonal data from Giovanni. In the lower part: Plotting the seasonal precipitation time-series and estimating simple statistics in QGIS.*

There are numerous possibilities that can be explored, both in terms of different datasets and spatial and/or statistical analyses. Like the previous example, anomalies can also be estimated, and an interesting map is the comparison of JJA of 2018 to the averages of 2000-2020 (Figure 4a). This shows how dry the summer of 2018 was compared to the past 20 years, resulting in only negative values (anomalies). Finally, an important feature of the Giovanni platform is that all these data are extractable to be further edited in spreadsheets (Figure 4b).

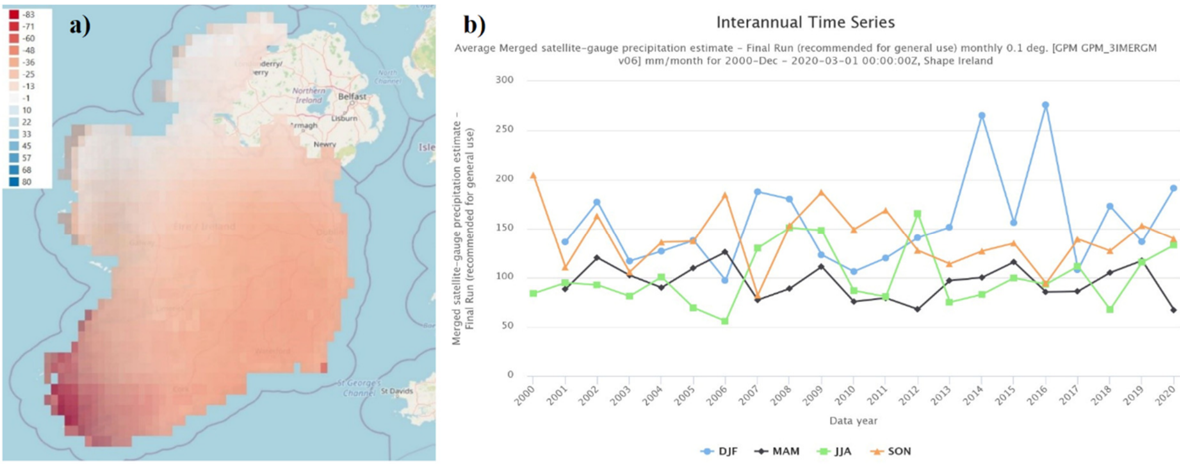


***Figure 4:*** *a) Anomaly of the summer of 2018, b) Plotting seasonal time-series.*

### 3.3 Example 3: Hydrological Balance

This example is presented for two reasons: Firstly, hydrological balances are essential for most hydrological studies, not only droughts. Secondly, it requires many datasets, so it is a good opportunity to demonstrate ways to access them and make operations with raster files. There are many sources and repositories for downloading DEMs (Digital Elevation Models): NASA's PhotoJournal[8] , NASA's SRTM[9], or HydroSheds[10] with its HydroBasins repository. The Giovanni platform can be used for the other datasets needed. These are: Precipitation (P), ET, Sub-surface flow (Qsubsurface), and runoff (storm runoff). At this stage it is important to have the same coordinates, spatial resolution, and units for the analysis. The DEM was used from the HydroBasins repository, and its coordinates are EPSG:4326-WGS 84-Geographic. Thus, this was the coordinate system (or converted into it within QGIS) for P, ET, Qsubsurface (Qsub), and StormRunoff (SR). All datasets (area averaged maps) were downloaded in a spatial resolution of 0.1x0.1. Regarding the units, most parameters were in kg/m²/year, so these units were chosen for the analysis. A few parameters that were in kg/m²/second were converted into annual values by using simple multiplication operations within QGIS (raster calculator). It is possible to edit this spatial information in QGIS, for example through *Symbology* conversions, changing property styles in different colours (e.g. using Equal Interval of 9 classes, as in Figure 5). Having these time-series (raster files) of the above in annual kg/m² of 0.1 degrees of resolution, allows making operations in the Raster calculator routine. This means that the classic equation of water balance can be applied (where ΔS is the difference of water storage). The inputs and results in Figure 5):

$$\Delta S = P - ET - Qsub - SR \quad (1)$$

[8] https://photojournal.jpl.nasa.gov/catalog/PIA06672
[9] Shuttle Radar Topography Mission (SRTM) https://www2.jpl.nasa.gov/srtm/ireland.html#PIA06672
[10] https://www.hydrosheds.org/

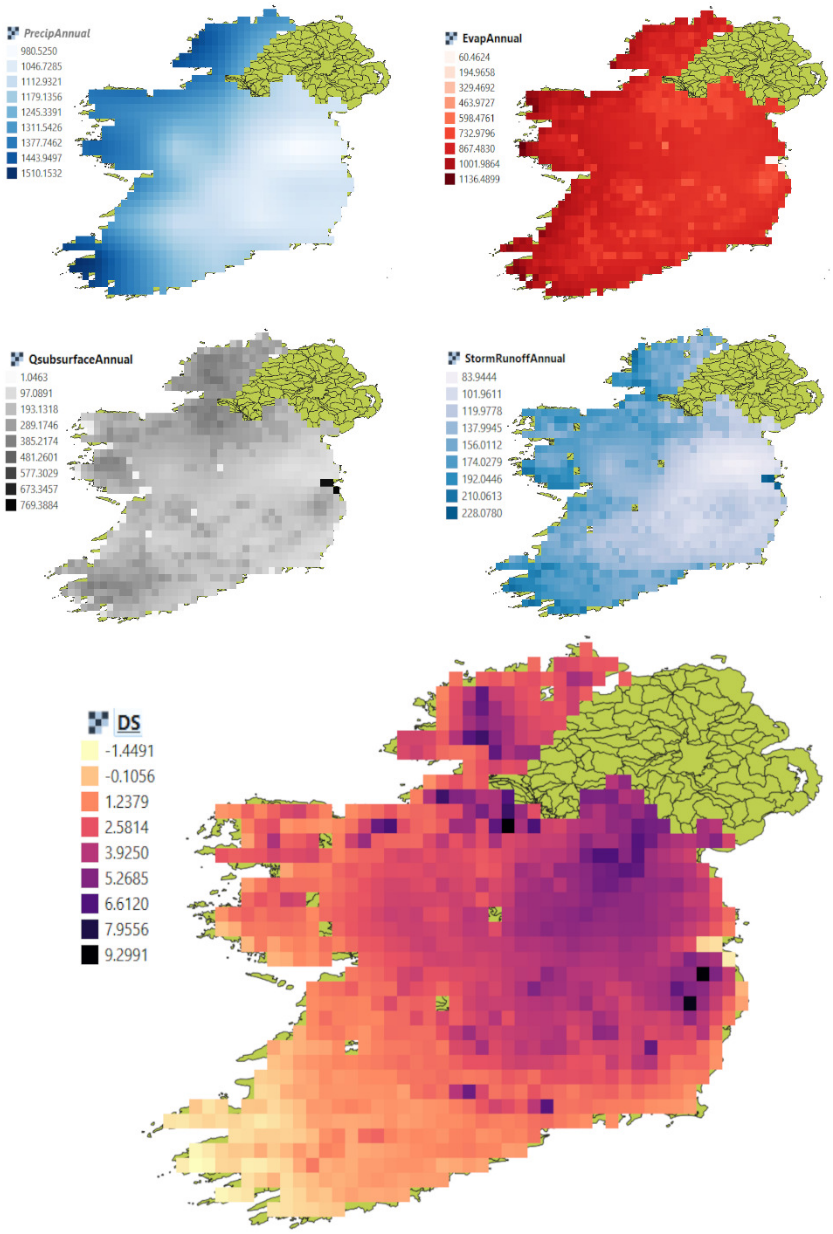


***Figure 5:*** *An indicative water balance considering P, ET, Qsub, SR and ΔS (in kg/m²/year).*

## 3.4 Additional examples and resources: Vegetation Index, Soil Moisture, ET, Socio-Economic data.

NASA's Earthdata is a freely available resource for deriving vegetation index observations. In the website, there is a search bar where the user can input different keywords. Another resource, perhaps even more user-friendly is the Worldview of NASA's Earthdata[11]. There, the user can search for vegetation index, soil moisture and other parameters, mainly from MODIS satellites, as mentioned (Figure 6). Since early 2015, the SMAP mission provides global soil moisture observations that can be used to monitor its variability from day-to-day and month-to-month. Therefore, daily and monthly soil moisture data can be visualised using NASA Worldview, which provides the option to see the changes as a video. Figure 6 shows a sample with varying soil moisture over different months of 2017-2018.

[11] https://worldview.earthdata.nasa.gov/

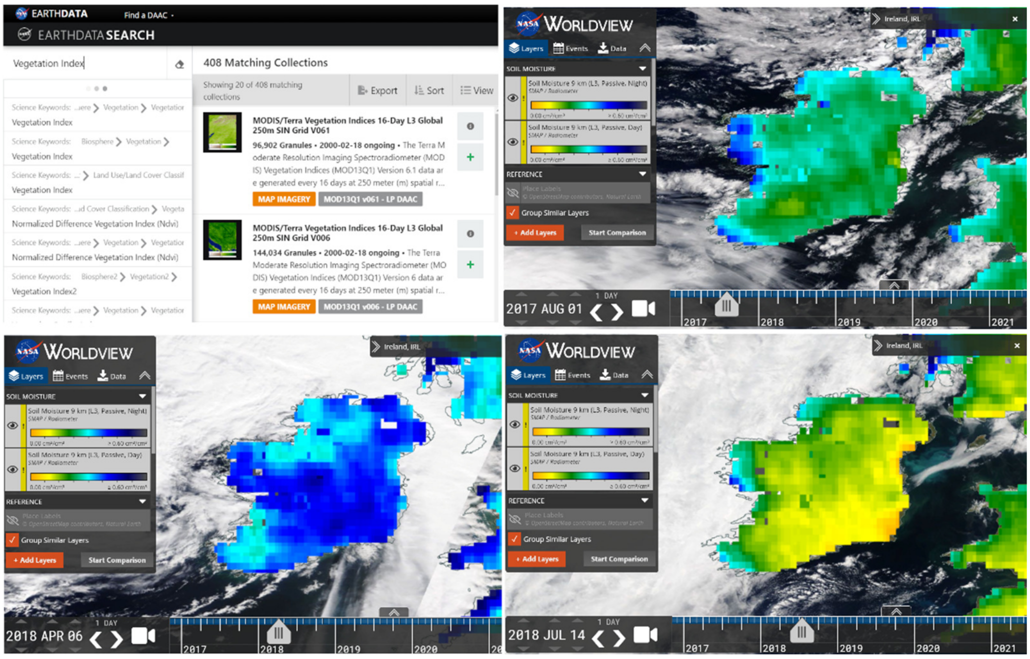


***Figure 6:*** *NASA Earthdata: searching for parameters to visualise. NASA World view: a demo video of Ireland's soil moisture (starting 2017). The visualisation is direct within both websites, no geo-spatial software is needed.*

In relation to additional resources for these parameters, NOAA Climate Prediction Center (from the US National Weather Centre)[12] provides calculated monthly soil moisture climatology (1971-2000) and anomalies for present-day and the past 12 months. These maps visually provide indications of soil moisture deficit and drought conditions. ET for Drought Monitoring are freely accessible through the EEFLUX website[13]. It provides Landsat-based ET images available online at 30m resolution. The user can extract maps with information about changing ET, a parameter indicative of agricultural and hydrological drought conditions. In the search menu, the user selects Dates, Location, and can then see the available image(s) with the percentage of clouds for each. Figure 7 shows an indicative result-list for an area around Dublin. As can be seen, it is worth noting that the results also provide various other parameters such as albedo, NDVI, different ET metrics, land cover, DEM, temperature, etc.
Another website with useful information for drought monitoring is GRACE from the University of Colorado[14]. It provides global or large-scale maps of different parameters, Water Storage Anomalies being the most relevant one regarding drought studies.

[12] http://www.cpc.ncep.noaa.gov/products/Soilmst_Monitoring/gl_Soil-Moisture-Monthly.php
[13] http://eeflux-level1.appspot.com/
[14] http://geoid.colorado.edu/grace/dataportal.html

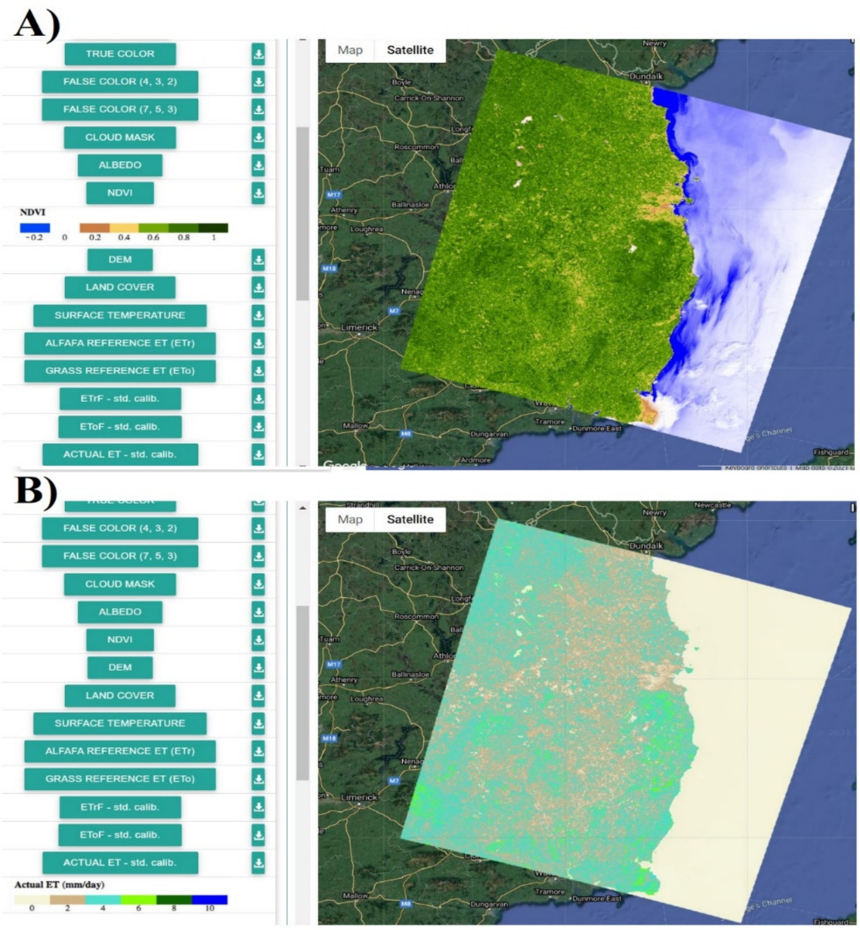


***Figure 7:*** *Viewing search results in EEFLUX website, for Dublin area. The menu in the left has the available parameters: A) NDVI, B) Actual ET.*

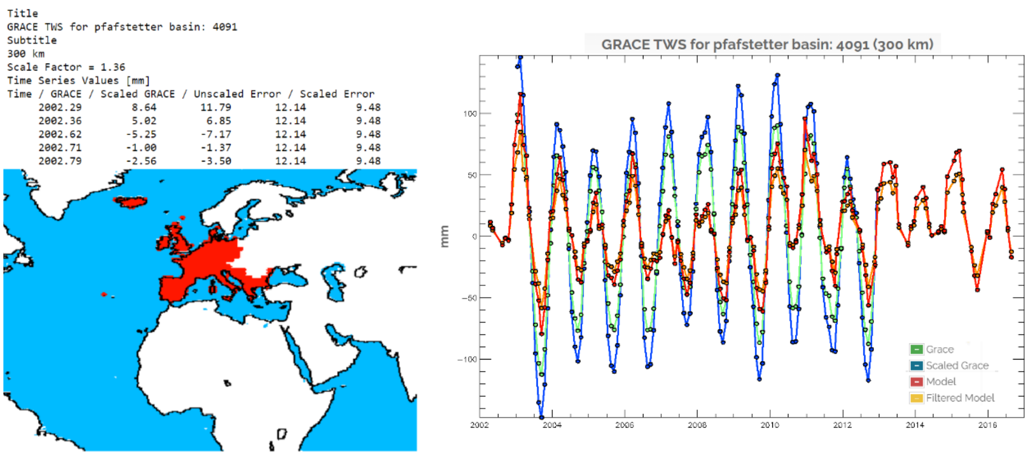


***Figure 8:*** *GRACE indicative results for Total Water Storage (TWS) and statistics.*

The website provides an interactive map, a time-series option, and the visualisation and statistical tool similar to Figure 8. As can be seen, these results are better suited to preliminary estimations, or for getting a high-level picture. Finally, social and economic data are also important factors to be studied as drivers or for the consequences of drought conditions. NASA's SocioEconomic Data and

Applications Center (SEDAC)[15] includes various datasets that can be freely downloaded and analysed comparatively to other parameters. For example, data on crops, agriculture, population density, economic losses from disasters, drought or flood risk mortality, etc. can be found here in various formats (e.g. for editing in spreadsheets, or for visualising and analysing them in a Geographic Information System). The main usefulness of this repository for drought (or other) studies is the ability to analyse and edit the downloaded data either as statistics or spatial information, combined with physical parameters and analyses. Figure 9 is an example of such combinative approaches, comparing indicatively the population density with the seasonal precipitation Standard Deviation of JJA of 2018, as estimated above. Such combinative approaches are useful for detecting vulnerable or other sites of interest, in a very easy and fast way.

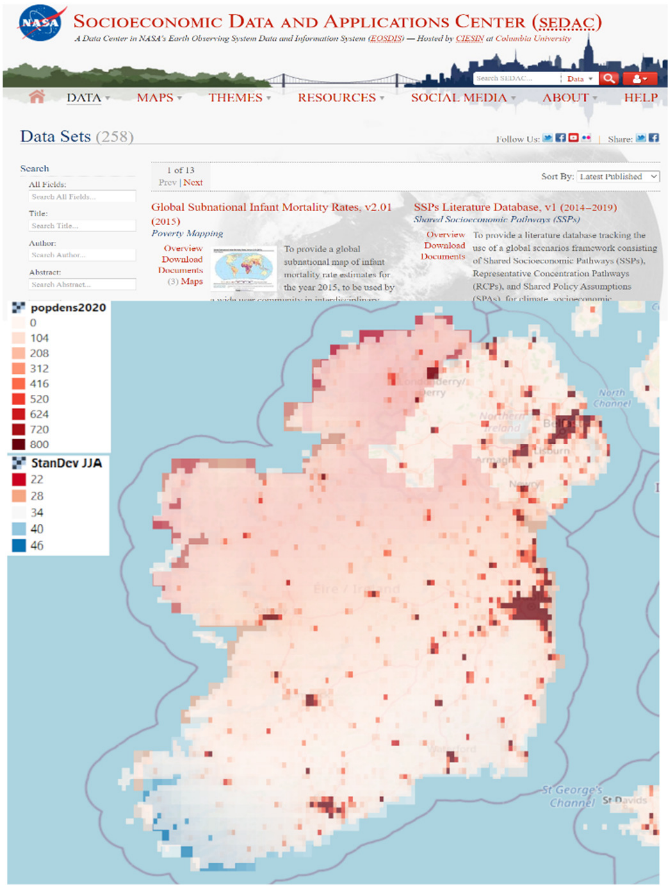


***Figure 9:*** *Searching in SEDAC repository and combining such data with other parameters, e.g. precipitation.*

## 4. CONCLUSIONS

In this article, several free resources for monitoring droughts and relevant parameters (precipitation, ET, meteorological, hydrological, vegetation indices, soil moisture, etc.) were presented, and examples were demonstrated in order to support any future effort of accessing and downloading data, and performing similar analyses. It is very important that the user understands the physical processes and the theoretical background of the analyses and their meaning, what data are necessary, in which format, which is the most appropriate source each time, correctly combining spatial and temporal resolutions and units, and evaluating the strong and weak points of each analysis. New technologies provide many opportunities and solutions, especially helpful in data-scarce problems (Alamanos and Linnane, 2021).

[15] https://sedac.ciesin.columbia.edu/data/sets/browse

The main limitation was the large scale (pixel) and approximations or measurement errors that can affect the results, and the absence of earth-based factors that were not monitored from the satellite data and affect hydrological processes (e.g. terrain). Such applications are not yet recommended for small areas, and they cannot replace catchment modelling fed with earth-observed data, in terms of accuracy, calibration-validation, and testing under various scenarios. However, remote sensing technologies can be combined with local-data to refine any analysis and perform simple or more complex operations, with respect to hydrological, water quality (e.g. colour-based analyses), or other parameters. The advantage of such combinative analyses is the provision of a near real-time monitoring for processes that demand a data-hungry and longer simulation and modelling effort. However, both approaches must be used together in a complementary way. A great and unique advantage of using freely available resources for drought monitoring is the ability to get an idea of the behaviour and distribution of many parameters, in a very easy and fast way. Furthermore, the results are satisfactory for large areas and can give a high-level understanding of the drought, hydrological, water balance estimates and their components. Thus, their use can be very beneficial for education, raising awareness, and understanding of the natural processes and the magnitudes of the various parameters, their different spatial and temporal scales, performing some analyses when there are no data available, and when one seeks a fast, preliminary picture of a situation without needing to develop and solve a model. Even those simple and preliminary estimations can majorly assist and provide guidance for more detailed research (e.g. identifying years, months or seasons and areas with specific hydrological characteristics). In any case, this work encourages the study of droughts, hydrological processes, and similar analyses, in order to enhance their understanding and communication.

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