Monitoring of soil moisture for irrigation water management in Catalonia

by Antonio Reppucci*

WATER MANAGEMENT FOR IRRIGATION IS AN ESSENTIAL ACTIVITY IN GENERAL BUT ESPECIALLY IN AREAS WHERE WATER IS SCARCE AND IN HIGHLY AGRICULTURAL AREAS. BY DEFINITION, WATER MANAGEMENT REPRESENTS THE USE OF THE APPROPRIATE QUANTITY OF WATER AT THE PROPER TIME AND IT IS USUALLY PURSUED BY COMBINING MEASUREMENTS OF SOIL MOISTURE WITH AN OPTIMISED IRRIGATION PLAN. WHILE THE SECOND ELEMENT IS EASY TO DESIGN IF WATER IS AVAILABLE, HAVING DETAILED SPATIAL INFORMATION ON SOIL MOISTURE IS STILL A CHALLENGE. *IN SITU* MEASUREMENT USING PROBES IS COSTLY AND DOES NOT ALLOW A DENSE ENOUGH SAMPLING OF THE SPATIAL BEHAVIOUR OF A WHOLE REGION. IN THIS CONTEXT, MICROWAVE (RADAR) REMOTE SENSING DATA FROM ACTIVE SENSORS ON EARTH OBSERVATION (EO) SATELLITES HAVE DEMONSTRATED THEIR POTENTIAL TO MEASURE SOIL MOISTURE QUANTITATIVELY ON BARE AND SHORT-VEGETATED SURFACES. THANKS TO THEIR ABILITY TO OPERATE IN ALL WEATHER CONDITIONS AND WIDE COVERAGE, DATA FROM SYNTHETIC APERTURE RADAR (SAR) OFFER THE OPPORTUNITY TO MONITOR LARGE AREAS WITH HIGH SPATIAL RESOLUTION. THE ADVANCED SAR ON THE EUROPEAN SPACE AGENCY'S (ESA) ENVISAT SATELLITE AND OTHER FOLLOW-UP GMES MISSIONS WILL HELP COMMUNITIES THAT SUFFER WATER SCARCITY TO IMPROVE THE MANAGEMENT OF WATER RESOURCES THROUGH THE CONTINUOUS MONITORING OF SOIL MOISTURE FOR MULTIPLE APPLICATIONS. THIS ARTICLE WILL FOCUS ON SOIL MOISTURE MONITORING WITH EO DATA FOR IRRIGATION WATER MANAGEMENT.

Many activities rely on the ability to measuring soil moisture over relatively large areas: crop yield expectation, flood forecast, prediction of local meteorological events, erosion and slope failure forecasting, water reservoir management, etc. Sectors such as agriculture, biological and environmental monitoring, local meteorology, geology and hydrology demand reliable soil moisture information to properly carry out their activities.
Before the development of remote sensing / Earth Observation (EO) techniques, soil moisture was mainly measured by means of ground surveys using specially designed sensors. However, the use of *in situ* point measurements might not be appropriate to represent the spatial and temporal behaviour of soil moisture. It can also be costly in terms of deployment and maintenance, hence reducing the range of applications that can benefit from such important geophysical information.

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EO data have been demonstrated to be a useful source of information. The choice of the type of sensor depends on the application. In the case of water management for irrigation, the most suitable types of instruments record microwave (Radar) radiation and are presented by Synthetic Aperture Radars (SARs), which give high spatial resolution, large area coverage and night/day/all weather acquisition capabilities.

The results presented hereafter have been achieved in the framework of the *AGORA* project, partially funded by the regional government of Catalonia, which aims to study the benefits of assimilating EO data into a hydrological model for water predictions. One of the objectives of this project is to study the viability of producing maps of surface soil moisture for the Catalonia area. During its two-year duration, the partners involved in the project have worked on different issues concerning the operational retrieval of soil moisture information using SAR images.

The soil moisture maps generated from SAR data can be used by governmental agencies that manage water distribution or by the every farmer to schedule the irrigation of their fields in a more efficient way. The information contained in these maps could be an input for intelligent irrigation algorithms in the field of smart agriculture.

How Earth Observation data can help monitoring soil moisture

Scientific investigation on the analysis of soil moisture using satellite sensors has a long history: it began with the availability of the first satellite images. Research has been done using different sensors, spanning different parts of the measured electromagnetic spectrum, leading to several methodologies to estimate soil moisture content. All the algorithms developed are based on the inversion of models, of analytical or empirical nature, that relate variables measurable by satellite sensors to near-surface soil moisture. Depending on the sensor employed to image the Earth's surface, different spatial and temporal resolutions can be achieved, thus the selection of the appropriate sensor will

Improving Water Management

The monitoring of soil moisture variability is of utmost importance, especially in areas where water resources are scarce. Soil moisture is important as a prime parameter for the surface hydrological cycle. Water storage in soil, either in the surface layer or in deeper levels, affects not only the vapour transpiration, but also the heat storage capability of the soil, its thermal conductivity, and the partitioning of energy between latent and sensible heat fluxes. In addition, surface layer volumetric soil moisture direct evaporation determines the possibility of surface run-off after rainfalls.

The degree of soil moisture is an important factor to move towards sustainable agriculture, it affects, for instance, the run-off of water and fertilisers.

be related to the type of monitoring that is being pursued.

> **"Soil Moisture maps can be used by governmental agencies managing water distribution or by farmers"**

Optical sensors are remote sensing instruments that can acquire data in several bands of the optical and near infrared part of the spectrum. The variable that is possible to measure with this type of instrument is the spectral reflectance, i.e. the ratio of reflected energy to incident energy as a function of wavelength. This quantity can be directly related to surface soil moisture, although soil reflectance is influenced also by other variables, such as soil roughness, texture and plant cover, which can lead to a wide variation in the measurements for a constant value of soil moisture. A more robust methodology makes use of combined information from the optical and infrared part of the spectrum. A major drawback of optical instruments is the impact of atmospheric conditions and the need for the sun as a source of illumination.

Microwave sensors acquire measurements in the frequency range from 0.3GHz to 300GHZ (i.e. a wavelength that spans from 1m to 1mm). There are two main types of such instruments: passive and active. Passive microwave sensors or radiometers measure the radiation emitted by the Earth's surface in the field of view of the instrument. Active microwave sensors or radars send out pulses of electromagnetic radiation and measure the amount that is backscattered in the direction of the sensor. Over land, the emitted radiation is mainly dependent on soil temperature and its dielectric properties, the latter being directly influenced by soil moisture. Although radiometers do not require solar illumination and the atmosphere has a small impact on the measured signal, the resolution of such instruments is in the order of several kilometres making them useful only for studies on the global scale, and therefore not suitable for irrigation water management applications.

The backscatter data recorded by microwave radars (Scatterometer, SAR) are also sensitive to changes in soil moisture among other parameters. Having their own source of illumination, such sensors can acquire data at night and day and in presence of cloud coverage. Scatterometers, with a spatial resolution of several kilometres, have been used with success for studies on the global scale, while SARs, with a spatial resolution that can be as small as a few meters, is suitable for studies on the local scale.

The methodologies developed for the estimation of soil moisture from active microwave sensors are based on the following idea: the microwave radiation backscattered from sparsely vegetated surfaces is related to dielectric [1]properties of the illuminated area, surface characteristics (roughness, topographic conditions) and instrument characteristics. The soil's dielectric constant is highly dependent on soil moisture; typical dielectric constant of dry soil is around three while the one of water is eighty. Theoretical models (e.g. small perturbation model, geometric optics model) are able to represent the backscattering variations due to changes in

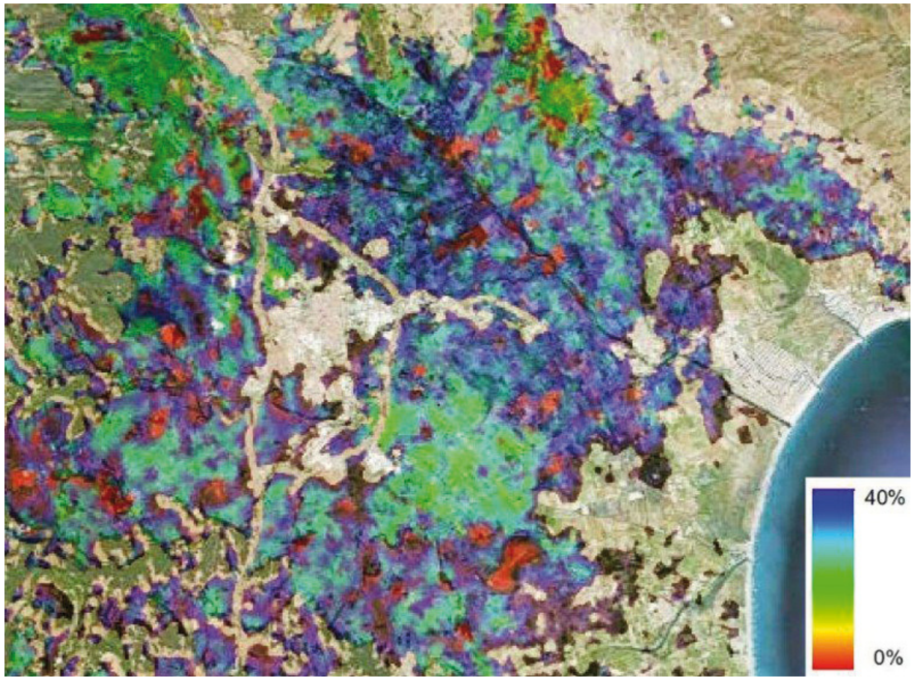
[1] A dielectric material is a substance that is a poor conductor of electricity, but an efficient supporter of electrostatic fields.

The area used for the calibration of the algorithm, which extends for about 20 km x 20 km, is located in the North-East of Catalonia (Alt Empordà); red dots represent the field sampled during the surveys (Credits: Google Earth).

soil moisture content, surface roughness and vegetation attenuation. However, from an operational point of view, these models cannot be employed due to the restrictive assumptions made when building them. Therefore, empirical models may be more useful and robust to estimate soil moisture operationally from SAR data.

The approach chosen for the measurement of soil moisture in the Mediterranean area of Catalonia is based on the calibration of a semi-empirical algorithm [1]. The calibration attempts to optimise the model to take into account the specificities of the vegetation cover in the area of interest. The soil moisture retrieval method is a two-step process. First the conversion of the measured backscattered signal to dielectric constant is accomplished. This is done using a semi-empirically derived relationship between the measured backscattered signal and the dielectric constant.

In a second step, the conversion from dielectric constant to soil moisture is performed. For this purpose a dielectric mixing model is used. The employed algorithm was originally developed and validated over an area located in central Europe where the main vegetation types were fields planted with cereals, grassland, root crops or covered by bare soil. As soil and vegetation characteristics vary when moving between different regions, a calibration of the algorithm was needed to take into account the vegetation type specific of the area of study. For this purpose a series of ground campaigns were planned in the framework of the project. Ground data were also used to validate the developed algorithm.



Soil moisture map generated from an image taken with the ASAR sensor on ESA's satellite ENVISAT acquired on September 3rd, 2011 over the area of study. Values are given according to the volume percentage of water (Credits: Starlab).

The area selected for the soil moisture survey is located at the most north-eastern corner of the Iberian Peninsula. Its natural boundaries are the Pyrenees, the Mediterranean Sea, and the plains of the Empordà that joins it with the Baix Empordà and the area of Alta Garrotxa. The landscape consists of a great alluvial plain furrowed by the Muga and the Fluvià rivers. The campaigns were carried out on 24 fields distributed throughout an area of about 20 km x 20 km.
The most common crops present in Catalonia (wheat, oat, alfalfa, ray-grass, root crops, olive groves) were chosen as a reference. Soil and plant samples were taken by triplicate at each site. The EO-based soil moisture measurements relate to the first few centimetres of the ground (about 5 cm using the C-band SAR data from ESA satellites).

In Fig. 2, an example of a soil moisture map generated using an image acquired by the ESA satellite ENVISAT with the ASAR sensor is shown.

The results have been compared to ground measurements acquired during several *in situ* campaigns, showing that SAR data are able to estimate surface soil moisture with a root mean square error that can vary between 5% and 10% (volumetric units), depending on the type of vegetation cover. Once the algorithm has been calibrated for the area of interest, maps of soil moisture with a resolution of 150 m x 150 m can be produced with a repetition time of some days, depending on the latitude. When the planned GMES Sentinel constellation is operational, the frequency of data acquisition will be between one and three days over Europe and Canada.

Soil moisture maps generated from SAR data can be used to monitor the evolution of soil moisture conditions at a regional scale with high spatial resolution. This is particularly interesting for an application such as water management for irrigation where the knowledge of the fine scale distribution of the soil water content would allow detecting sensitive areas precisely. Moreover, such a product could bring improvements in the accuracy of numerical model forecasting, through assimilation.

The results obtained in the first phase of the project have paved the way to study the development of an innovative forecasting model based on computational intelligence techniques and the retrieval of soil moisture from Earth Observation, *in situ* measurements, and weather prediction data, which will provide forecasting irrigation assessments to the final service users.

Conclusions

The results of this study have confirmed that retrieval of soil moisture using C-band SAR data is feasible over surfaces with sparse vegetation and having highlighted the importance of correctly accounting for the local vegetation type and characteristics. High spatial resolution maps of surface soil moisture could be of great interest to monitor droughts and to control vegetation growth especially in areas that suffer from water scarcity.
To further improve the results and the robustness of the approach employed, the potential of combining SAR measurements with a limited number of *in situ* measurements is being studied. This could allow a dynamic calibration of the retrieval algorithm in real-time to continuously produce more and more accurate results. The outputs from such a combined approach could be of great interest for many applications where continuous knowledge of soil moisture is a key parameter.

Reference

Loew, A., Ludwig, R.; Mauser, W. (2006). *Derivation of surface soil moisture from ENVISAT ASAR Wide Swath and Image Mode data in agricultural areas.* IEEE Trans. Geosci. Remote Sens., vol. 44, pp. 889-899.

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