

EARTH OBSERVATION-ENABLED DECISION SUPPORT FOR TERRITORIAL- SCALE IRRIGATION WATER MANAGEMENT

AIDE À LA DÉCISION ACTIVÉE PAR L'OBSERVATION DE LA TERRE POUR LA GESTION DE L'EAU D'IRRIGATION À L'ÉCHELLE TERRITORIALE

Guido D'urso¹, Carlo De Michele², Oscar Rosario Belfiore³, Salvatore Falanga Bolognesi⁴

ABSTRACT

Free availability of high spatial and temporal resolution multispectral data from Sentinel-2 satellites of European Copernicus Program has opened new opportunities for supporting irrigation water management, by providing Earth Observation (EO) products for routine estimation of irrigation water requirements and construction of multi-level information portfolios - from irrigated area inventories to basic and advanced water use products - explicitly designed for multi scale decision making (plot, irrigation unit, district, aquifer and basin). Near real time delivery through web-GIS and Information and Communication Technologies (ICTs) of data, i.e. crop maps, growth time series and recommended irrigation depths, closes the gap between information production and actionable decisions by farmers, irrigation consortia and public authorities, embracing concerted approaches for scaling up from the farm to district/basin scale.

This multi-level approach to irrigation management improves decisions by: a) supporting agronomic scheduling that accounts for actual canopy development and within field heterogeneity, reducing yield losses associated with under and over irrigation; b) enabling more equitable and efficient allocation rules and cost recovery, including a shift from area based water fees (which can incentivize over irrigation) toward needs or performance based management linked to EO informed crop water requirements; c) strengthening environmental stewardship via spatial water use accounting, identification of inefficiencies and “critical zones”, and performance evaluation even where metering is incomplete; d) providing objective, repeatable monitoring of irrigated areas and irrigation volumes that supports compliance with water governance frameworks where lack of consistent observations is often the limiting factor.

This paper evidence the application of above concepts in different operational contexts, to show the relevance and usefulness of Earth Observation data in support for irrigation water management.

Keywords: spatial and temporal resolution; spatial and temporal resolution; performance evaluation; multi-level approach; irrigation water management.

RESUME

La disponibilité gratuite de données multispectrales à haute résolution spatiale et temporelle provenant des satellites Sentinel-2 du programme européen Copernicus a ouvert de nouvelles possibilités pour soutenir la gestion de l'eau d'irrigation, en fournissant des produits d'observation de la Terre (EO) destinés à l'estimation de routine des besoins en eau d'irrigation et la construction de portefeuilles d'informations à niveaux multiples - des inventaires des superficies irriguées aux produits de base et avancés d'utilisation de l'eau – explicitement conçus pour la prise de décision à échelles multiples (parcelle, unité d'irrigation, périmètre, aquifère et bassin). La fourniture de données en temps quasi réel

¹ University of Naples Federico II, Dept. Agricultural Sci., Italy, URSO@unina.it

² Ariespace srl, Naples, Italy, carlo.demichela@ariespace.com

³ University of Naples Federico II, Dept. Agricultural Sci., Italy, oscarrosario.belfiore@unina.it

⁴ Ariespace srl, Naples, Italy, salvatore.falanga@ariespace.com

par le biais du Web-SIG et des technologies de l'information et de la communication (TIC), c'est-à-dire les cartes des cultures, les séries chronologiques de croissance et les profondeurs d'irrigation recommandées, comble l'écart entre la production d'informations et les décisions pratiques prises par les agriculteurs, les associations d'irrigants et les autorités publiques, en adoptant des approches concertées pour passer de l'échelle de l'exploitation à celle du périmètre ou du bassin.

Cette approche à niveaux multiples de la gestion de l'irrigation améliore les décisions en : a) soutenant une programmation agronomique qui tient compte du développement réel du couvert végétal et de l'hétérogénéité au sein du champ, réduisant ainsi les pertes de rendement associées à une irrigation insuffisante et excédentaire; b) permettant des règles d'allocation et de recouvrement des coûts plus équitables et efficaces, notamment en passant d'une tarification d'eau basée sur la superficie (ce qui peut inciter à l'irrigation excédentaire) vers la gestion basée sur les besoins ou la performance liée aux exigences en eau des cultures informées par l'observation de la Terre (EO); c) renforçant la gestion responsable de l'environnement grâce à une comptabilité spatiale de l'utilisation de l'eau, à l'identification des inefficacités et des «zones critiques», et à l'évaluation des performances, même dans l'absence de systèmes de comptage complets; d) fournissant une surveillance objective et reproductible des zones irriguées et des volumes d'irrigation qui favorise la conformité avec les cadres de gouvernance de l'eau où l'absence d'observations cohérentes est souvent le facteur limitant.

Cet article met en évidence l'application des concepts ci-dessus dans différents contextes opérationnels, afin de montrer la pertinence et l'utilité des données d'observation de la Terre pour soutenir la gestion de l'eau d'irrigation.

Mots-clés : Résolution spatiale et temporelle; Evaluation des performances; Approche à niveau multiple; Gestion de l'eau d'irrigation.

INTRODUCTION

During the last two decades, the volume and types of Earth Observation (EO) data has increased enormously, entering in the everyday life of billions of people using digital devices such as smartphones and portable computers. The development of advanced Information and Communication Technologies (ICT) such as cloud storage and processing, together with open data policies, have deeply transformed the Earth Observation (EO) industry. In meantime, research has developed models and algorithms coupled with environmental data for interpreting the physical processes underlying the crop production systems. These models, now more and more integrated with Artificial Intelligence algorithms, transform data into information, allowing an increased awareness of the system and the application of good practices for farmers. Timely information can support the agri-business and the decision-making processes at different levels, from local farmers to rural communities and nations.

An ongoing challenge for the scientific community is how to support farmers in transitioning towards climate-smart agriculture, to better cope with precursors effects of climate change already being experienced in Mediterranean regions and affecting agricultural production and water resources management. Prolonged droughts during recent years have evidenced the vital importance of continuously monitoring water demand and the corresponding availability of resources.

On the practitioners' side, farmers lack access to data and information for adjusting their water demand in relation to the actual crop needs and the actual availability of water resources; as a consequence, they often tend to over-irrigate being afraid of possible reductions of their production levels (and profit). Mature technologies based on EO data and ICTs have already been developed by the European industry sector, i.e. IRRISAT, AGRISAT, FARMSTAR, to support farmers in the management of water in real-time, with geospatial data. EO-based services provide the necessary data and information for an integrated management of irrigation water from the level of subplot to that of the irrigation scheme or river basin (Calera et al., 2017).

The advantages in adopting such technologies are tangible both for the farmers' business and for the water resources managers and environmental agencies. To cite a first important operative application, in most countries the actual extent of irrigated areas and the corresponding irrigation volumes remain difficult to quantify. In the European Union, data acquired through periodical surveys (e.g. Eurostat, ISTAT Agricultural Census) are designed to give a picture at national scale, but they lack the precision needed at regional and local scales, which are the most relevant for the management of water resources in hydrographic basins.

This lack of reliable and up-to-date data has hindered the full implementation of the EU Water Framework Directive (WFD), especially in Mediterranean regions. Communications from the EU Commission to the European Parliament (e.g. Com.673/2012) led to additional conditionalities for the use of EU funds in the agricultural sector.

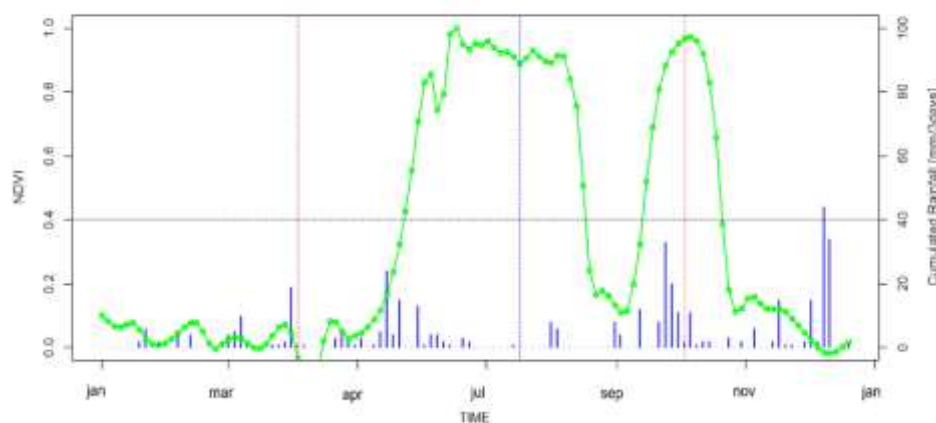
Furthermore, frequent EO observations allows to monitor irrigation water requirements in time and space, thus allowing an effective water accounting strategy from farm to district/basin level.

The potentiality of crossing different scales enables different kinds of users such as farmers and water authorities to share the same information supporting the respective decision processes. EO-services have evolved from prototype level to complete and qualified systems (TRL 9) enabled by new data available i.e. those from the Copernicus Sentinel missions. The Copernicus program builds on these premises a new perspective for EO services that can contribute to shaping a more profitable and sustainable agriculture, thanks to the free availability of data.

MAPPING OF IRRIGATED AREAS

Often accurate information about the location and extension of actually irrigated areas is not available to water managers, who have also to deal with unauthorized water withdrawals for irrigation. Several studies have shown how classification algorithms applied to time series of EO data are able to identify not only crop types but also if they are actually irrigated or not. These methods are based on the analysis of crop growth and phenology (by using temporal series of spectral indexes from Normalized Difference Vegetation Index NDVI to EO-based Leaf Area Index LAI), integrated by soil moisture indexes (shortwave or microwave based) and precipitation data.

In more detail, the assumption is that, in conditions of hydrological deficit, typical of the summer period in arid and semi-arid environments (like the Mediterranean regions), crop growth is possible only with irrigation. In other words, high trends of vegetation indicate irrigated crops when the precipitation and/or the rise from groundwater are not sufficient to provide the water supplies required for their growth, in reverse for the rainfed crops (Figure 1) (Ozdogan et al., 2010).



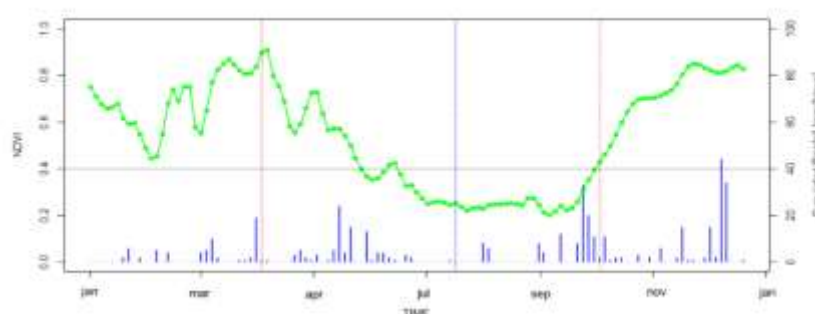


Figure 1. Examples of the NDVI temporal pattern labelled as irrigated crop (a) and rainfed crop (b) (adapted from Belfiore et al., 2022). The vertical red lines delimit the irrigation season, while the blue line indicates the date of the field survey.

For the purpose of the detection of irrigated areas different data sources and approaches are needed depending on the characteristics of the study area.

As an example, in two Irrigation Consortia in Southern Italy, Sardegna Centrale and Basso Volturno, time-series of NDVI maps and rainfall data were used as input data in a supervised classification process (Falanga Bolognesi S. et al., 2020).

Pre-processing included atmospheric correction of Sentinel-2 data (S2), cloud masking and gap-filling process. Three-day cumulated rainfall data were derived from Persiann dataset² and added to the input dataset for supervised classification, carried out by means of different Machine Learning Algorithms (MLA) i.e. Random Forest (RF), Support Vector Machine (SVM), Boosted Decision Tree (BDT), Single Decision Tree (SDT), Artificial Neural Network (ANN), k-Neighbour Neighbour (k-NN).

In the Sardegna Centrale Consortium (Sardegna region, 12,000 ha irrigated area, served by means a pressurized distribution system), main crops are meadows, pastures, alfalfa, maize, sorghum, vegetables, and tree crops such as vineyards, olives, and, citrus. In this case, the VIS-NIR-Rainfall assumption is not sufficient, given that many pastures and tree crops such as olives and vineyards are irrigated occasionally during the dry periods i.e. pastures during winter-spring and autumn and tree crops in the summer.

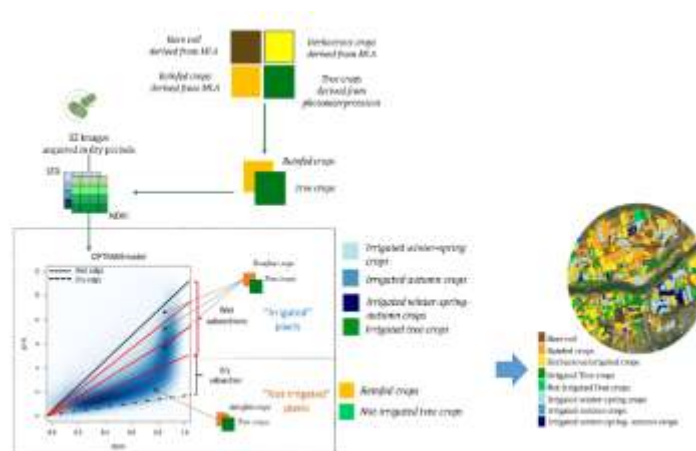


Figure 2. Model adaptation for the detection of irrigated areas and detail of the output for “Sardegna Centrale” consortium area in 2020 (adapted from Belfiore et al., 2022).

² CHRS Data Portal, <https://chrsdata.eng.uci.edu/>

To this end, the VIS-NIR-SWIR-Rainfall domain is tested by using the OPTical TRapezoid Model (OPTRAM) (Sadeghi et al., 2017), properly adapted by Belfiore et al. (2020). The OPTRAM model is based on the pixel distribution within the Shortwave Infrared Transformed Reflectance (STR)-NDVI space, where the STR index is computed from S2 SWIR band 12- 2190 nm), is linearly related to the water content of the soil-canopy ensemble. As shown in Fig. 2 in the STR-NDVI space, the upper limit represents the position of pixels corresponding to wet conditions in the soil-plant ensemble (“wet edge”), and the lower the drier (“dry edge”). Dividing the region between the two extreme edges in four sub-sections, and selecting S2 images acquired in dry periods without significant rainfall, the pixels previously detected as rainfed and tree crops located in the upper wet regions of the scatterplot are considered as irrigated. In reverse, those pixels included in the dry subsection are labeled as not irrigated (Fig. 2).



Figure 3. Compliance assessment of water rights and abstracted volumes (adapted from De Michele et al., 2018)

When combined with ancillary data such as cadastral-based water rights or farmers' declarations, it is possible to detect unauthorized water abstractions for irrigation, from distribution networks either from groundwater.

In the Sannio Alifano Consortium (northern part of Campania Region) irrigated plot without water rights were identified by cross-checking the maps of actually irrigated plots with the authorization database, allowing to better identify missing compliance in terms of authorization and irrigation water volumes. This

information, rendered in the form of “red light” (Fig.3) has greatly reduced conflicts between users and water managers, with benefits in terms of water allocation and losses.

In the lower Volturno basin (Campania region, about 68,000 ha) the RF-based classification of NDVI time series for the 2021 irrigation season achieved an overall accuracy of 87% in identifying irrigated areas, with producer accuracy (PA) of 93.2% and user accuracy (UA) of 95.4% for herbaceous crops (Belfiore et al., 2024) (Fig. 4).

By overlaying the irrigated-area map with the cadastral database of authorized irrigation wells, it was possible to identify outside the perimeters of the consortium irrigation districts, areas that were irrigated but not located within 150 m of any registered well.

The analysis revealed 1,505 polygons potentially served by unregistered wells, for a total area of 3,020.9 ha. The corresponding water volume drawn from the aquifer was estimated at 12.39 Mm³ for the May-September 2021 period, equal to 10.3% of the total irrigation water needs of the study area, with significant exploitation of the groundwater aquifer in the area.

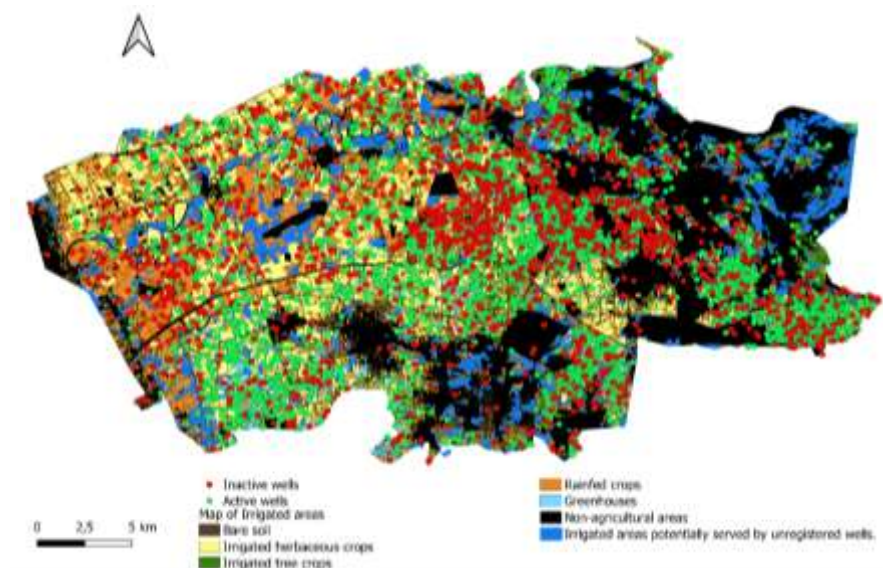


Figure 4. Map of the Volturno basin study area with the classified irrigated areas and the location of active, inactive and irrigated areas potentially served by unregistered wells (adapted from Belfiore et al., 2024).

WATER ACCOUNTING: MEASUREMENTS vs ESTIMATES

The crop evapotranspiration (ET) is computed by using the Penman-Monteith (PM) equation based on the “one-step approach” implemented in the IRRISAT© methodology [4]. The ET modeling is carried out by deriving canopy parameters, hemispherical albedo (α) (D’Urso et al., 2006), and Leaf Area Index (LAI) (Weiss et al., 2022) by using S2 data (Pasqualotto et al., 2019). The agro-meteorological input data (solar radiation, wind speed, air temperature, dew point temperature, atmospheric pressure, and precipitation) were derived from the reanalysis data provided by the Copernicus ERA5 single level dataset (horizontal resolution: 0.25° x 0.25°). This dataset, along with the ERA5-Land dataset, represents a valid data source for the estimation of ET in irrigation water management applications (Vanella et al., 2022), especially when the availability of ground-based stations is limited (Pelosi et al., 2020; 2022). The crop irrigation water requirements (IWR) were computed on a daily basis (mm day⁻¹) by subtracting from the ET the effective precipitation (Pe), derived by using a semi-empirical model of interception of total precipitation (P) (Braden H., 1985). In conclusion, the gross irrigation water requirements (GIWR) were derived by dividing the IWR by irrigation method efficiency, assuming the following values: i) 45% for surface irrigation, ii) 75% for sprinkler, and iii) 85% for drip irrigation.

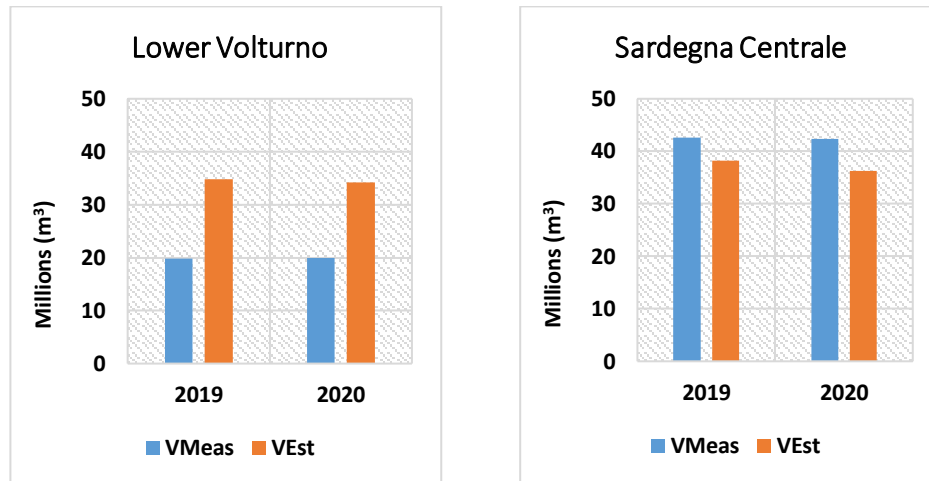


Figure 5. Comparison of measured irrigation volumes (V_{Meas}) against Earth-Observation-derived seasonal estimates (V_{Est}) for the 2019 and 2020 irrigation season in the Lower Volturno and Sardinia Centrale consortia (adapted from Belfiore et al., 2022).

The validation of the satellite-derived products is performed at two levels: (a) comparison of satellite-estimated LAI against field measurements obtained with portable instruments (LI-COR LAI-2200); and (b) comparison of estimated irrigation volumes against actually delivered water volumes at both farm and district level. In the Campania Region the comparison between applied and estimated water volumes for farms with tree crops equipped with drip irrigation showed good agreement (Figure 6).

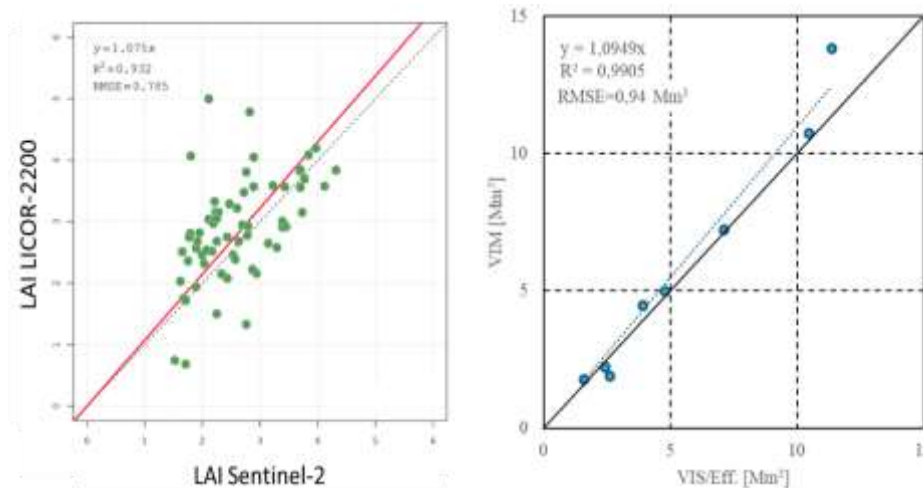
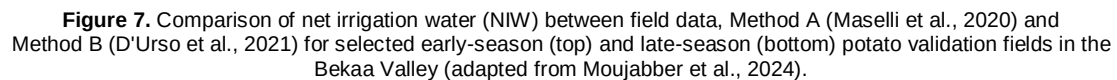


Figure 6. Validation of IRRISAT® products: satellite-derived LAI vs. field-measured LAI for tomato, tobacco and maize fields in the Campania region, July-September 2023 (left); satellite-estimated vs. measured seasonal irrigation volumes for the Sannio Alifano and Volturno Inferiore Consortia, 2023 irrigation season (right).

The estimation of irrigation water requirements using different methodologies based on EO data was also tested in arid and semi-arid contexts. In the Bekaa Valley (Lebanon), two EO-based approaches for estimating net irrigation water requirements (NIW) were compared on irrigated potato crops: the first based on a water stress scalar (Maselli et al., 2020) applied to reference evapotranspiration, and the second based on the Penman-Monteith equation with Sentinel-2-derived canopy parameters (D'Urso et al., 2021). The comparison with field-measured irrigation volumes showed that the two approaches have different strengths depending on the growing season, providing useful indications for irrigation water accounting in data-scarce regions (Moujabber et al., 2024) (Fig.7).



MULTI-SCALE INFORMATION PRODUCTS AND DELIVERY

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³ <https://www.coalaproject.eu/tag/earth-observation-from-space-roadmap/>

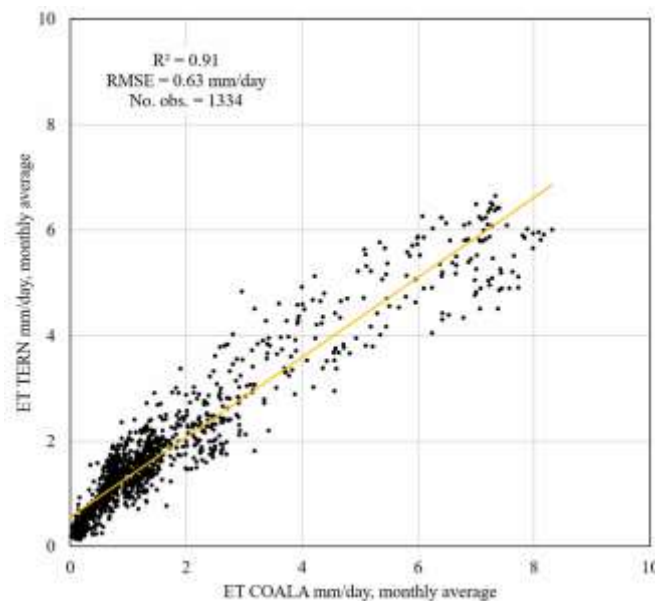


Figure 8. Location of the 329 validation sites in the irrigated districts of South-Eastern Australia (left) and scatter plot of COALA monthly ET vs. TERN CMRSET AET (right).

The IRRISAT® platform (www.irisat.com), developed by Ariespace s.r.l. and operational in Italy since 2007, provides farm-level irrigation advice and consortium-level water-use monitoring through a web and smartphone interface (Map Time Explorer, MTE). The methodology underlying IRRISAT® was developed in support of the EU Water Framework Directive and is compliant with the Italian MIPAAF Decree of 31 July 2015, which established a national framework for the measurement and estimation of irrigated areas and irrigation water volumes. IRRISAT® is explicitly cited in the national methodology document approved by the Conferenza Stato-Regioni (3 August 2016) as a reference tool for satellite-based estimation of crop water requirements (Vuolo et al., 2015).

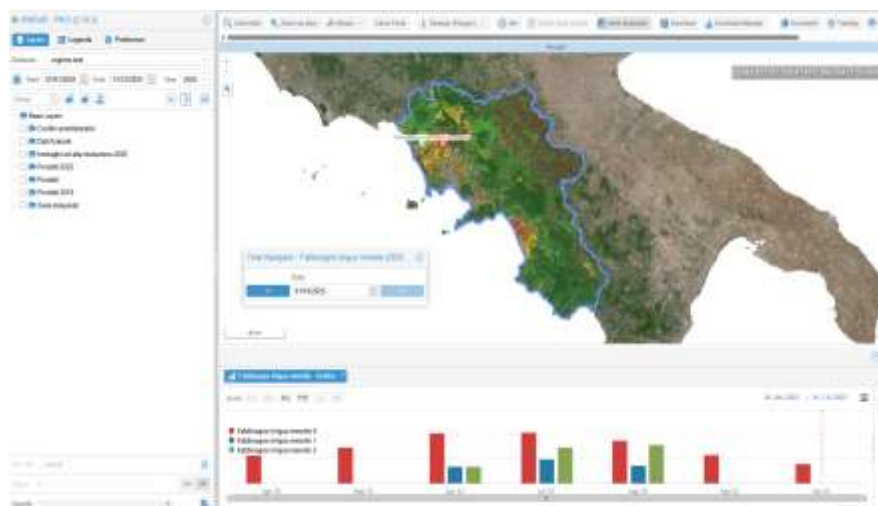


Figure 9. IRRISAT® WebGIS interface (MTE - Map Time Explorer): irrigated area map for the Campania region overlaid on a Sentinel-2 image (top), and monthly irrigation water requirements for three selected pixels (bottom).

A parallel WebGIS interface developed for the irrigation consortia and water user associations allows the aggregation of crop water requirements at district level, supporting the management of distribution networks and the verification of water allocation (Fig.9).

DISCUSSION

The experiences presented in this paper show that EO-based tools can address different components of the irrigation water management problem at territorial scale. The benefits can be grouped into four areas.

From an agronomic point of view, the estimation of crop water requirements based on satellite-derived biophysical parameters (LAI, albedo, fractional cover) takes into account the actual spatial variability of crop development within each field. This is a clear improvement over approaches based on tabulated crop coefficients, where a single K_c value is assumed for each crop type regardless of local soil conditions, planting density or agronomic practices.

From an economic point of view, spatially detailed information on crop water requirements makes it possible to move from water pricing based on the irrigated area toward pricing based on estimated or measured water use. This can improve the equity and efficiency of water allocation within irrigation consortia and reduce the incentive for over-irrigation.

From an environmental point of view, spatially distributed water-use maps allow the identification of areas with excessive water consumption or low distribution efficiency. The comparison between EO-estimated water requirements and the volumes actually delivered by the distribution network gives an indication of the overall performance of the irrigation system, even in districts where metering infrastructure is not complete.

From a regulatory point of view, the repeatable and objective nature of satellite-based monitoring supports the implementation of water governance frameworks. The case of the Volturno basin illustrates how EO products, combined with well census databases, can support the identification of potentially unauthorized groundwater abstractions on a territorial scale, directing field inspections where they are most needed.

The fact that the same methodological framework was applied in Southern Italy, Lebanon and Australia, with consistently good results, shows that the approach is transferable across different agroclimatic contexts, although local calibration remains necessary, for example for the parameterisation of the OPTRAM model edges and the soil-canopy resistance functions in the Penman-Monteith equation.

CONCLUSIONS

This paper presented an EO-based decision-support framework for irrigation water management at territorial scale. The framework uses Sentinel-2 multispectral data to derive biophysical indicators of crop water demand, irrigation water use and distribution efficiency, organised at multiple spatial scales from plot to basin level.

The approach was tested in three operational contexts: (i) irrigation advisory services in Southern Italy (IRRISAT® platform, operational since 2007 and recognised at national level for compliance with the MIPAAF Decree of 31 July 2015); (ii) detection of unauthorised groundwater abstractions in the Volturno basin; and (iii) irrigation water accounting in the Bekaa Valley (Lebanon) and in South-Eastern Australia (COALA platform), where satellite-derived evapotranspiration showed good agreement with independent reference data ($R^2 = 0.91$).

Near-real-time delivery of information through WebGIS platforms enables the coordination between farm-level and district-level management. Future work will focus on the integration of weather forecast data for short-term irrigation scheduling, the improvement of crop-type classifications, and the application of the framework in additional geographical contexts where the lack of consistent observations remains a bottleneck for water governance.

Although the market of EO-services for the agricultural sector has significantly expanded in the context of European and Mediterranean agriculture, the penetration of EO-services among farmers is still rather low in comparison to the potentialities, mainly because of three reasons: i) a low perception of potential business improvements by farmers; ii) the economic dimension of agricultural enterprises, especially in the driest area of Southern Europe and Mediterranean Countries; iii) the difficulties in adjusting everyday operations according to the information received, which is seen as a complication and/or a waste of time.

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