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Public irrigation decision support systems (IDSS) in Italy: Description, evaluation and national context overview

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ABSTRACT

This survey comprehensively examines the public irrigation decision support systems (IDSS) in Italy, offering a detailed description, analysis and evaluation of their features. The study investigates the agrometeorological networks and infrastructures that support Italian IDSS, providing a clearer understanding of the national context. The evaluation criteria include relevant factors such as soil moisture monitoring, crop water requirements (CWR) estimation models, biophysical parameters along with their spatial and temporal resolutions, irrigation planning and decision support visualization. Additionally, the assessment covers accessibility, scalability and interoperability of these systems. The survey also highlights the strengths and weaknesses of various IDSS, such as IRRIFRAME, IRRISIAS and IRTO, discussing their operational methodologies, data integration and regional coverage. The aim is to provide insights that facilitate advancements in sustainable irrigation management practices and address key challenges for future developments at both regional and national levels. This comprehensive evaluation seeks to enhance the effectiveness of IDSS in promoting sustainable water management in agriculture across Italy.

1. Introduction

The Mediterranean basin, including southern Italy and islands, is experiencing an unprecedented crisis with high spring temperatures and persistent rainfall deficits. According to data from the European Drought Observatory, a 16.1% of Europe territory now faces severe drought conditions, with 1.2% already under alarm [1]. With record-breaking high temperatures and a lack of precipitation reported in 2023 and in 2024, Italy finds itself facing this challenge [1]. Sicily, in February 2024, declared a state of natural disaster as it is experiencing the driest season in a century. Similar concerns emerged in Sardinia, where reservoir levels are rapidly decreasing. These alarming conditions are prompting measures including irrigation restrictions within several municipalities. In addition, regions from central and northern Italy are also experiencing a shortage in water resources, thus urgent attention and customized solutions are crucial to address the actual water crisis.

Information and communication technologies (ICT) have demonstrated a significant impact in promoting sustainable water management in agriculture. The extensive monitoring of agricultural factors through Internet of Things (IoT) technologies, cloud computing and wireless sensor networks generate datasets to advice for correct irrigation needs [2]. Nevertheless, the advancement of irrigation systems requires continuous efforts with the integration of evolving sensors for environmental monitoring [3]. Traditionally, most sensors are embedded in weather stations, which work alongside soil volumetric water content sensors to estimate water availability for plants from factors like soil texture, structure, temperature, water salinity and the soil spatial variability [4,5]. In recent years, many of these sensors are being equipped with wireless connectivity for easier deployment [6]. However, irrigation management is complex due to additional variables from thermal and multispectral cameras, as well as factors related to productivity, fruit quality and deficit irrigation strategies [7] may affect the proper functioning of thresholds. Irrigation Decision Support Systems (IDSS) have been developed to support farmers with water management and to function as audit tools across different geographical scales. An IDSS integrates data from different sources and processes them to provide farmers with precise recommendations on irrigation volumes, timing, and scheduling. Typically, an IDSS is composed of a database for historical data purposes, a model for water requirements estimation and a user interface, facilitating effective decision-making in agricultural water management. Jha et al. [8] provided a detailed overview of various IDSS used in California and categorized by the type of data they

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monitor, including soil-based, canopy-based and imagery-based parameters. Soil-based devices primarily measure soil properties like volumetric water content and soil water potential. Canopy-based devices focus on parameters related to plant conditions, such as evapotranspiration (ET) and canopy temperature. Imagery-based systems, utilize satellite or aerial imagery from unmanned aerial vehicles (UAVs) to assess water stress and vegetation indices. These devices are integrated with telemetry service providers or platforms that offer web and mobile applications, enabling real-time data analysis and informed decision-making for optimal irrigation management. The integration partners, including companies like Irrimax (Sentek, Stepney, Australia) and Irriwatch (Maurik, The Netherlands) and some open-source tools such as CIMIS[1] and OpenET[2] play a crucial role in processing and delivering insights to users. Research on IDSS is ongoing. For instance Simionesei et al. [9] developed IrrigaSys, an IDSS designed to optimize irrigation water management at the field plot level. This system, tested over five years in collaboration with the Sorraia Valley Water Board in Portugal, uses open-source tools and a soil water balance model (SWB) to provide farmers with weekly irrigation schedules, soil water balance data, weather forecasts and satellite imagery, proving overall effective. Similarly, Shi et al. [10] developed an IDSS to optimize water usage in agriculture by adapting irrigation to the specific needs of different fields. This system employs multi-spectral images from UAVs to calculate vegetation indices and determine ETc and crop water stress index (CWSI), producing a prescription map that was successfully tested in a water stress experiment. While much research has focused on the advantages of IDSS for agricultural water management, their utility extends beyond agriculture. IDSS have also demonstrated effectiveness in greenhouse irrigation management [11] and for urban areas [12].

IDSS undoubtedly provides advantages in irrigation management practices and Morrison [13] studied farmers perception regard this tool. Author state that farmers view IDSS as tools to optimize water resources, reduce pesticide usage and enhance crop monitoring. Furthermore, it is widely acknowledged that IDSS ease the decision-making process and decrease the information gap among stakeholders [14]. These advantages are particularly evident when IDSS are supplied to farmers at no cost and information is easily accessible. Conversely, the imposition of fees for the service or a required knowledge necessitate an evaluation of whether the service remains cost-effective for the intended users. Indeed, the adoption of precision farming in Italy has remained low mainly due to the small farms scale, the lack of awareness about precision agricultural practices and technologies, and the high initial investment costs [15]. These findings are corroborated by Ferrari et al. [16] that examined barriers and drivers influencing digitalization in rural areas. Authors identified major obstacles such as the lack of connectivity in rural contexts, apprehension toward the lack of a technological background knowledge and costs and challenges associated with ambiguous data governance. In Italy, precision farming finds its primary applications in vineyards, tomatoes and cereals crops [17]. Research and development on IDSS in Italy has been ongoing since 1998 [18] and this study aims to present, describe, and evaluate the various IDSS implemented across different Italian regions. The paper's objective is to identify and describe the currently active public Italian IDSS, offering a comprehensive analysis of their characteristics. IDSS identification involved a detailed examination of the National Information System for the management of water resources in agriculture (SIGRIAN) publications. This research investigates the capabilities, data source integrity and decision-making of the selected IDSS. Additionally, by evaluating its performance in terms of accessibility, scalability and interoperability, the study aims to support ongoing enhancements and propose recommendations for future advancements of Italian IDSS.

2. Politic context for sustainable water management

The European Union (EU) has enacted multiple directives and regulations to address water scarcity and promote effective agricultural water management. The Water Framework Directive (Directive 2000/60/EC) is a pivotal legal framework established by the EU with the primary objective of ensuring sustainable management and protection of water resources across the continent. Additionally, the 6th Environmental Action Programme (Directive 1600/2002/EC) prioritizes the protection of water resources and the mitigation of water stress. Furthermore, European Regulation n. 1303/2013 outlines the allocation of European Structural and Investment Funds (ESIF) for the 2014–2020 planning period. Concurrently, recent revisions introduced by European Regulation n. 2115/2021 focus on the utilization of ESIF and the European Agricultural Fund for Rural Development (EAFRD), with specific emphasis on enhancing irrigation systems and protecting water bodies. These measures align with the imperative to develop policies that ensure benefits for farmers and society at large, while balancing the need of food production and environmental preservation.

The Ministerial Decree July 31, 2015 addresses the standardization of guidelines and methods for irrigation water volumes quantification in Italian regions. In response to the necessity of a standardized evaluation framework, the Research Centre for Agricultural Policies and Bioeconomy (CREA-PB) has developed the SIGRIAN. This system serves as a centralized information system for managing water resources in agriculture. By providing comprehensive data, decision support tools and facilitating coordination among stakeholders, it contributes to efficient and transparent water management practices in the agricultural sector. The SIGRIAN aggregates technical and economic data related to agricultural water management for each region, storing the information within an open-source database. However, while some of the GIS data and reports are accessible for download, numerous resources are restricted to irrigation consortia and are not available to the public. Although SIGRIAN contributions are valuable at the national level, the implementation of WFD guidelines, including methodologies for quantifying irrigation water volumes, is decentralized to regional authorities. Each region adapts national guidelines to local conditions, ensuring that water management practices are effective within their specific territories. Between 2016 and 2017, every region provided regulations approvals for the WFD as is shown in Fig. 1.

The Directorate Decree December 6, 2018, (n. 574/STA), introduced the "Operational and Methodological Manual for the Implementation of Economic Analysis" outlining the necessity for analyzing various water services. Aligning with WFD principles, the manual emphasizes evaluating the costs of the multisectoral water service provider to quantify environmental costs already internalized by the operator. This operative manual represents the applicative tool of Ministerial Decree February 24, 2015, (n. 39), and provides a unified national methodology for economic analysis in the context of water resource management planning at the River Basin District level of the Water Management Plans. The Ministerial Decree September 30, 2022, (n. 485,148), which is the last Decree issued, establishes criteria to promote sustainable water use in agriculture and lends support to SIGRIAN for both collective and self-supply irrigation. The criteria defined in this document aim to enhance water resource management practices and align with broader national recovery goals.

The political framework set the basis for the widespread adoption of sustainable water management practices. However, it is crucial to understand how these policies translate into practical applications within agricultural systems. Indeed, EU-funded projects have played a significant role in advancing irrigation water management technologies, with 10 projects over the past decades (overall from 2006 to 2017) focusing on innovations like crop modeling, yield optimization and energy-efficient irrigation. However, these projects often struggle to transition from research to marketable products, with few developing business plans [19]. Numerous strategies and tools exist to enhance water use

[1] Available at: https://cimis.water.ca.gov
[2] Available at: https://etdata.org

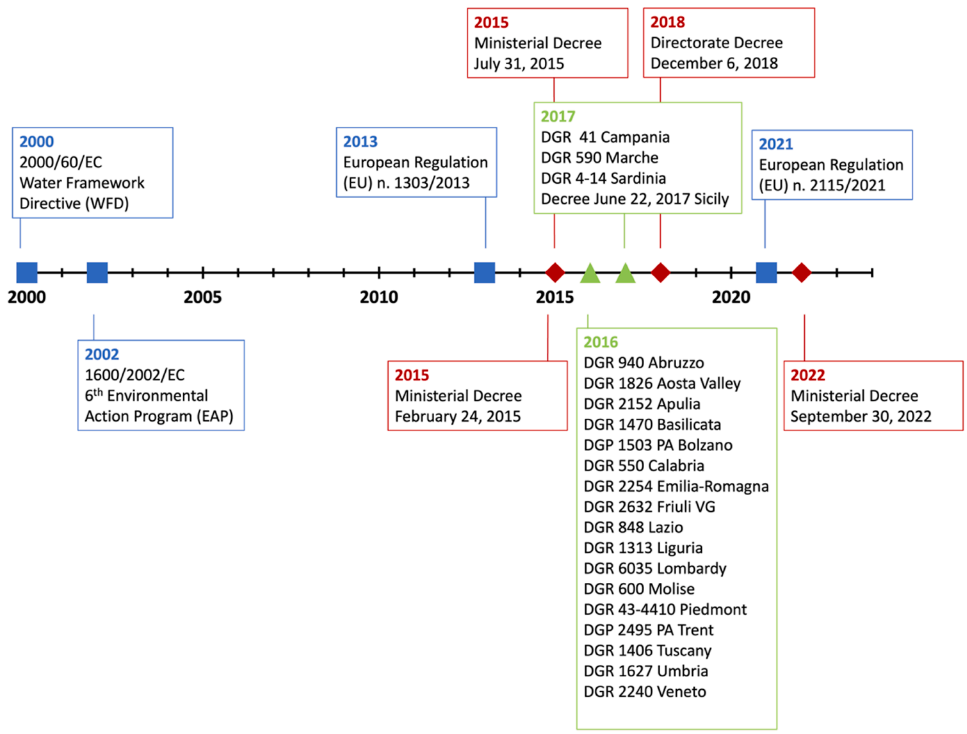

Fig. 1. European (Blue squares), National (Red diamonds) and Regional (Green triangles) water regulations and approval timeline from the Water Framework Directive.

efficiency (WUE) and promote water conservation in agriculture, each relying on agrohydrological models for accurate estimation of crop water needs. Since these models underpin the optimization of irrigation practices, the following section explores the technical aspects of water management in agriculture, including state function parameterization and the methodological background of crop water requirements (CWR).

3. Methodological background, agrohydrological framework and state function parameterization

According to the standard approach proposed by Allen et al. [20] CWR are computed as follows:

$$CWR = ET_c - P_n \tag{1}$$

where ETc (mm) represents potential crop ET and Pn (mm) is the net precipitation, which is the amount of rainwater available for crops after accounting run-off and foliage interception losses. Two widely used methods for water requirements estimation in agricultural practices are the soil mass water balance (SWB) and the surface energy balance (SEB) models.

The SWB model, also known as bucket model, represents a straightforward approach that uses a weather-based methodology for irrigation requirements estimation. Despite SWB models being less precise compared to more sophisticated models, they have shown to be efficient for yielding irrigation variables (i.e. irrigation timing and schedule) at both farm and field level. Changes in the amount of water available in the soil portion where crop roots are most actively absorbing water and nutrients, which can significantly impact plant growth and yield, are explained by means of a depletion function:

$$D_{r,i} = D_{r,i-1} - P_i - RO_i - I_i - CR_i + ET_{c,i} + DP_i \tag{2}$$

where $D_{r,i}$ represents the amount of depletion on the i^{th} day [mm], $D_{r,i-1}$ the amount of depletion of the previous day [mm], Pi the precipitation on the i^{th} day [mm], RO_i the run-off on the i^{th} day [mm], I_i the net irrigation on the i^{th} day [mm], CR_i the water supply for capillary rise from the underground aquifer on the i^{th} day [mm], $ET_{c,i}$ crop ET on the i^{th} day [mm] and DP_i the water losses due to deep percolation on the i^{th} day [mm].

While certain parameters (e.g., P or I) can be measured, some of them require specific hydrological models to be determined (e.g., RO, CR and DP). Among these components, ET is of particular importance. In the Mediterranean basin, rainfall during the irrigation season is generally scarce, characterized by short, intense thunderstorms [21]. These seasonal characteristics, exacerbated by climate change over the last century [22], make monitoring difficult [23]. Consequently, the rainfall contribution to overall CWR is generally negligible compared to crop potential evapotranspiration [24], making ET the most critical component over time. ETc depends on both crop-specific parameters (e.g., surface albedo and crop height) and weather variables (e.g., air temperature, solar radiation, humidity, wind speed, and air pressure). A conventional method for assessing ETc is the 'two-steps' procedure recommended by Allen et al. [20], where ETc is obtained by multiplying the reference evapotranspiration (ET0) by a crop coefficient (Kc). The FAO56 model [20] is a SWB model extensively used for CWR estimation and scheduling irrigation which employs the Penman-Monteith equation for ET0 assessment along with either an adjusted single crop coefficient (Kc) or dual crop coefficients. The FAO56 dual-component approach incorporates an evaporative (Ke) and transpirative (Kcb) coefficient to separate the evaporation and transpiration components and increase accuracy. Under field conditions, the potential ETc is adjusted to account for actual field conditions (ETc act) through the utilization of a stress coefficient (Ks) as follows:

$$ET_{c\ act} = (K_s \cdot K_c) \cdot ET_0 = (K_s \cdot K_{cb} + K_e) \cdot ET_0 \tag{3}$$

Ks ranges between 0 and 1, with 1 indicating optimal conditions. The FAO56 model employs a linear crop water stress function for simplicity, however, this approach does not take into account the large variety of crop responses to stress. This aspect is crucial for precision irrigation strategies development since a specific water stress degree results beneficial for certain trees and vine crops. In these water stress conditions crops can optimize yield and quality. This beneficial stress known as eustress, should be incorporated when determining Ks and the stress state function. Additionally, over the past two decades several new cropping systems have emerged, thus necessitating updated Kc and Kcb values, some of which are available in recent literature [25,26]. IDSS employing the FAO56 model should incorporate the last recommendations and the updated coefficients.

The SEB model calculates irrigation needs by measuring the energy fluxes exchanged between the surface and the atmosphere. It determines evapotranspiration rates using the latent heat flux derived as the residual term in the surface energy balance equation:

$$\lambda ET = (R_n - G_0) - H \tag{4}$$

where R_n represents the net radiation [W m^{-2}], G_0 represents the ground heat [W m^{-2}] and H represents the sensible heat fluxes [W m^{-2}] at the acquisition time.

The SEBAL model [27] treats soil and vegetation as a unified resistance layer, calculating daily ET from instantaneous values and Λ (evaporative fraction) as an integration parameter. In arid climates, the adoption of this model relying on Λ requires assumptions that may lead to an underestimation of daily ET because of factors like afternoon advection or higher wind speeds. Remote sensing tools such as satellite-based radiometers, imaging spectrometers and thermal sensors exhibit considerable potential to perform surface energy balance assessments. These tools are widely applied [28] to enable the estimation of key variables determining sensible energy and heat flux.

Both models described exhibit strengths and weaknesses: the SWB model is easier to implement and requires fewer input parameters, whereas the SEB model provides a thorough assessment of irrigation needs across extensive areas, taking into account spatial variations in sparse crop systems.

4. IDSS perspective in Italian farming scenario

Italy is characterized by different climatic conditions and a wide variety of crops, crop systems reflecting the complexity of agricultural practices. Across the country, different regions adapt to their unique environmental and economic conditions by optimizing crop production and resource use through varying levels of investment in irrigation tools and digitalization, as shown in Fig. 2a.

Regions like Trentino-Alto Adige, Veneto, Emilia-Romagna, Apulia, Sicily, and Sardinia show high levels of investment, with more than 2000 farms making irrigation investments. Other regions, such as Aosta Valley, Umbria, Marche, and Molise, show less than 250 farms making irrigation investments. In Fig. 2b, the number of digitalized farms is shown [29]. The farms relying on digital technology vary significantly across regions, underlining the high variability of technological adoption within the agricultural sector. Regions, such as Lombardy, Veneto, Emilia-Romagna, Tuscany, and Apulia revealed a considerable proportion of farms that have embraced digitalization, with over 10,000 farms equipped with digital technologies. Smaller regions like Aosta Valley and Molise exhibit less than 2500 digitized farms. These distributions underscore the heterogeneous nature of agricultural investments and modernization efforts throughout Italy, influenced by factors such as regional agricultural priorities and access to resources and infrastructure.

Table 1 provides an overview of the spatial distribution of 3096 automatic weather stations designated for agrometeorological applications. The data reveal a high density of stations in northern regions, including Liguria, Emilia Romagna, and Friuli-VG, primarily resulting from their incorporation into additional meteorological networks that are not specifically designed for agrometeorological purposes.

[30] conducted a qualitative evaluation of the various regional agrometeorological networks. This evaluation was conducted in 2016 at the Italian National Coordination Table of agrometeorology in Italy, with the aim of bringing together national and regional services operators to systematize existing information. Through a closed-ended questions survey addressing key aspects of agrometeorological networks, data storage, processing and dissemination, information was collected and analyzed for [30]. The findings highlight regional variations in the adherence of weather stations to World Meteorological Organization (WMO) standards across Italy. While 14 regions exhibit high compliance rates (50% or more) others, five regions in Northern and Central Italy, show lower adherence levels (< 25%) to WMO standards. The distribution of meteorological stations across different altitude ranges in Italian regions is described in the following. In general, regions in northern Italy (i.e. Lombardy and Piedmont) show a predominant concentration of weather stations at altitudes exceeding 800 m above sea level, accounting for over 75% of weather stations installed in these areas. On the other hand, coastal regions like Campania and Apulia exhibit a significant concentration of stations below 400 m above sea level, with over 75% of stations located in these lower altitudes. Regions like Veneto, Friuli VG and Liguria have 51% to 75% of stations in different altitude categories, showing a balanced attention to both higher and lower altitude monitoring. Weather stations elevation and distance from the sea may affect data recording as highlighted by [31]. Authors investigated daily meteorological variables and ET0 prediction suitability from a database of NASA Prediction Of Worldwide Energy Resources (POWER- NASA Langley Research Center, Hampton, VA, USA). Predictions from the NASA dataset was compared with ground data from the Sicilian Agro-meteorological Information Service (SIAS) network. Evidence from this study revealed a correlation between data quality and elevations and distance from the sea. The authors concluded that weather stations located at higher elevations and higher distance from the sea lacked data because of a lower maintenance regime. Weather station maintenance in Italy is extraordinary for every region except for Piedmont, Liguria and Sicily (where it is provided only twice per year) and Umbria region which is only extraordinary. However, maintenance levels vary across the nation with regions like Veneto, Marche, Lazio, Basilicata and Calabria providing for more than two maintenance services per year, while Aosta Valley, Lombardy, Friuli VG and Emilia Romagna provide for annual maintenance. All the other regions provide for a default semestral maintenance and extraordinary.

Among the numerous methods and equations for ET estimation, FAO 56 Penman-Monteith is still the most used and considered very accurate to calculate ET daily [32]. It incorporates several variables such as: *Rn,* net radiation (MJ $m^{-2}d^{-1}$); *G,* soil heat flux (MJ $m^{-2}d^{-1}$); *ea*, actual vapor pressure (kPa); *es,* saturation vapor pressure (kPa); Δ, slope of saturation vapor pressure with air temperature (kPa $°C^{-1}$); γ, psychrometric constant (kPa $°C^{-1}$) and u_2, wind speed at 2 m height (m s^{-1}). For achieving consistent ET estimations across the nation, it is essential that regions utilize adequately equipped weather stations for the implementation of ET estimation models. Core equipment comprises temperature and precipitation sensors, with notable differences observed in the incorporation of air humidity, wind speed, solar radiation and soil temperature sensors (refer to Table 1).

Table 1 reveals a notable trend of uniformity in sensor deployment in Sardinia, Apulia, Sicily, Calabria, Molise, Tuscany, Lazio, and Piedmont. These regions showcase consistency for all monitored parameters and a comprehensive meteorological infrastructure, thus ensuring a robust monitoring of the local climate dynamics. Data shown in Table 1 should be interpreted with caution because it may not be up-to-date and could underestimate the capabilities of various Italian regions in terms of their agrometeorological station networks and sensor distribution. For instance, Emilia Romagna did not emerge among the best for number of sensors and uniformity, however, it is a region with one of the most robust and widespread agrometeorological services in Italy. Except for a few regions, almost all the national territory is provided with infrastructures to ensure precise and reliable ET estimation.

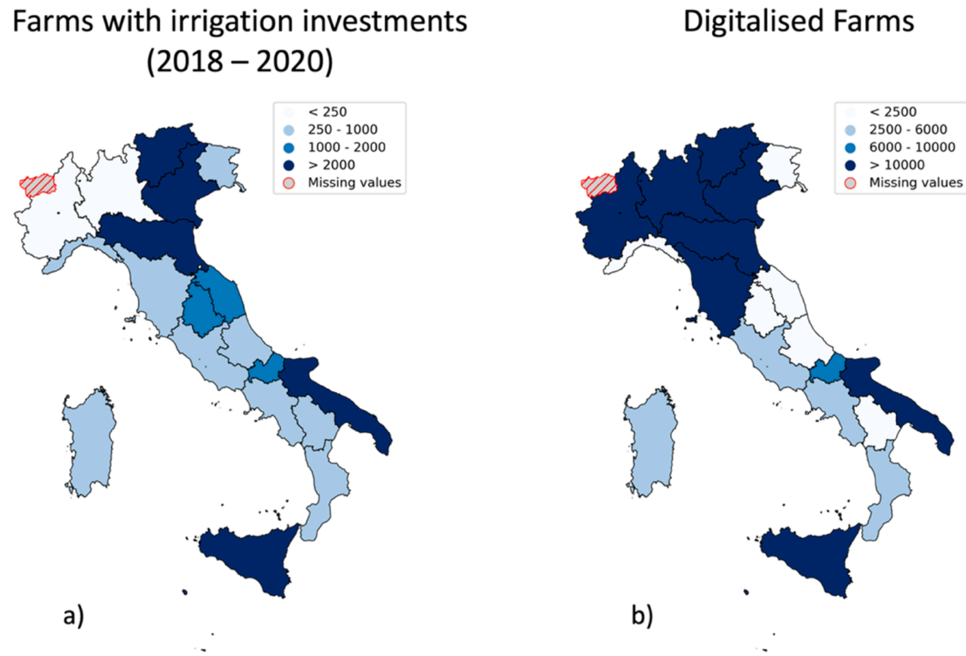

Fig. 2. a) Number of farms that invested in irrigation between 2018 and 2020 [29], b) Number of digitized farms across Italian regions.

Table 1
Agrometeorological stations distribution and key and principal sensors across Italian regions. Data in italic are retrieved from [30] because information was not reported in regional websites.

Region	# of Weather Station	# of Air Temperature sensors	# of Precipitation sensors	# of Relative Humidity sensors	# of Radiation sensors	# of Wind Speed sensors	# of Soil Temperature sensors
Piedmont	*140*	*140*	*140*	*140*	*30*	*45*	*15*
Aosta Valley	*12*	*12*	*12*	*12*	*10*	*12*	*0*
Lombardy	331	255	268	206	115	146	*15*
Liguria	345	184	200	85	29	57	*3*
Trentino - Alto Adige	285	188	153	188	*80*	176	*22*
Veneto	300	*171*	*167*	*142*	*114*	*131*	*33*
Friuli VG	*219*	*119*	*202*	*132*	*65*	*110*	*21*
Emilia Romagna	324	*200*	*300*	*100*	*30*	*20*	*0*
Tuscany	133	133	133	*96*	*73*	*76*	*0*
Umbria	128	*65*	*65*	*65*	*0*	*2*	*0*
Marche	81	*70*	*70*	*70*	34	*62*	25
Lazio	96	96	96	96	*77*	93	78
Abruzzo	49	49	49	*24*	*10*	*12*	*0*
Molise	24	24	24	24	7	24	13
Campania	37	37	37	37	19	35	24
Apulia	*94*	*94*	*94*	*94*	*59*	*94*	*59*
Basilicata	46	46	46	46	*5*	*40*	*3*
Calabria	*36*	*36*	*36*	*36*	*36*	*35*	*36*
Sicily	98	98	98	97	43	97	94
Sardinia	53	53	53	53	53	53	53

5. Current IDSS in Italy

A comprehensive examination of public IDSS at the regional level is proposed in the following section of the manuscript. Over the years, multiple regions have introduced irrigation advice services, each tailored to their unique agricultural landscape and water management needs. However, many of these regional services have either been integrated into larger IDSS frameworks or have been discontinued over time due to various factors. Consequently, the current evaluation focuses specifically on the IDSS utilized at the regional level and publicly available. Exception is made for a private system like IRRISAT because of its significance at regional level (for the Campania region). The described approach aimed to assess and understand the current landscape of IDSS employed across Italian regions, highlighting those that endured the test of time and policy shifts. Description and exploration of publicly available Italian IDSS is provided, building upon the work previously published by [33].

5.1. IRRIFRAME[3]

IRRIFRAME is a IDSS developed by Water Boards Italian Association (ANBI) in collaboration with the CER (Emiliano-Romagnolo Canal Irrigation Consortium) and has been validated through extensive local field experiments since 1984 [34]. The project started with the name of IRRINET only in Emilia-Romagna region and during the years this

[3] Available online at: https://www.irriframe.it/Irriframe

service has been extended in different regions [18,35,36] providing also technological innovation such as webGIS support and SMS interface [37]. This IDSS showed to be successful and in 2010 it was renamed IRRIFRAME and it was extended to the whole country [38–40]. To provide accurate estimations of irrigation requirements, the IRRIFRAME model integrates algorithms and combines three data categories: (i) Soil water dynamics; (ii) Crop growth phases; (iii) CWR.

(i) Soil water dynamics are simulated considering water interaction between three distinct layers: soil surface, root zone and bottom layer. The soil surface layer is principally described by the ground roughness as a result of tillage operation occurred. The root zone and the bottom layer are described by specific pedotransfer functions. These functions are used to estimate water storage capacity in the root zone (where active roots absorb water) and the bottom layer (beneath the root zone). Pedotransfer functions are empirical relationships based on soil properties. The water behavior between soil layers is computed by a systematic approach providing RO, dp and water movement between layers calculation. RO calculation is based on rainfall intensity, upper layer storage and soil infiltration rate. The movement of water between layers follows the approach proposed by Driessen [41], which considers each layer's storage capacity. DP refers to the deep drainage from the bottom layer and represents a total loss for the system. Moreover, the model accounts for the contribution of water table to CWR, determined as a percentage of ETc, with specific equations developed through extensive research [42–45].IRRIFRAME model allow users to choose up to 7 soil parameters and integrate data from local weather stations or phreatimeter.

(ii) Crop growth phases are estimated by the IRRIFRAME models starting from initial stages such as sowing, transplanting, or vegetative restart and considering factors like growing degree day (GDD) and root system growth. The model offers a choice between a total of 26 crops, with a wide range of tree, vegetable and arable crops selection (2 to 11 tree crops, 0 to 6 vegetables crops, 4 to 9 arable crops) according to the region or the specific irrigation scheme. In addition to choosing crop types, operators have the option to adjust 8 additional settings within the model. These settings are designed to fine-tune the model's parameters and calculations further, allowing operators to customize the simulation to better reflect local agricultural conditions, management practices, and specific crop requirements.

(iii) To compute CWR, IRRIFRAME estimates ETc under different conditions (both standard and non-standard). The model estimates ET under standard conditions using daily ET0 as a result of the Hargreaves-Samani equation [46]. For non-standard conditions, actual crop evapotranspiration (ET act) is estimated. This calculation requires knowledge of the crop-specific Kc, which adjusts ET0 to account for crop type, growth stage, and environmental factors affecting water demand. IRRIFRAME generates output including the optimal irrigation time, the precise amount of water and the number of hours the irrigation system needs to operate. IRRIFRAME model offers a large selection of water delivery systems (WDS) such as drip (2), rain/sprinklers (32) and basin/furrow irrigation to ensures a tailored alignment to the farm scenarios and the specific WDS efficiency.

This IDSS is a well-established and widely used tool in Italy, applied in 16 regions from the north to the south. [47] and has been validated over 30 years through field trials [48]. To improve data accuracy and relevance, each Italian region is subdivided into various irrigation schemes, with the number of schemes varying significantly among regions. For instance, regions such as Abruzzo have a single irrigation scheme, while regions like Veneto have up to ten. As of now, the IRRIFRAME model encompasses 69 of the 117 national irrigation schemes. However, IRRIFRAME service does not yet cover all the irrigation schemes within regions entirely. Partial service coverage is observed in regions including Friuli-Venezia-Giulia, Marche, Umbria, Abruzzo, Lazio and Calabria.

5.2. IRRISAT[4]

IRRISAT is a satellite-based irrigation advisory service developed in Italy and operative since 2007 in the Campania region [49]. The studies of this IDSS started within the framework of the DEMETER UE-RTD project [50]. Over the years, the initiative underwent successive enhancements and automation according to farmers' requirements. The service was able to provide personalized weekly irrigation advice at both field and regional scales through SMS technology [51] and later through webGIS platforms [52]. IRRISAT uses the "one-step" approach described by [20] and provides the maximum potential evapotranspiration (ET0) calculation using canopy variables such as surface albedo, canopy height and Leaf Area Index (LAI). IRRISAT model processes a time-series of high spatial resolution (10–30 m^2 pixel size) visible and near-infrared information included within Sentinel-2 satellite images to timely monitor the crop growth. These data are used in conjunction with weather forecast models spanning up to five days and the actual canopy development throughout the growing season to estimate crops water requirements. The efficacy of these methodologies has been validated through field experiment [50,52,53]. These investigations affirm the significant potential inherent in this IDSS. Furthermore, the incorporation of CWR into local management practices, coupled with user-friendly geo-spatial technologies, facilitate the information accessibility to end-users. The studies conducted have shown the potential economic advantages achievable through precise irrigation volumes usage. Notably, farmers express a positive interest in the information provided, particularly concerning crop ET and demonstrate a general willingness to pay for the advisory service [54]. However, it is important to acknowledge that the implementation of these models has some limitations due to the high amount of data and their complex processing.

5.3. IRRISIAS[5]

The IDSS was developed and launched in 2004 [55] to support Sicilian farmers with an innovative tool to make informed decisions about irrigation. IRRISIAS service addressed businesses and individual users' needs offering a comprehensive solution through a WEB-GIS water balance platform that integrates real-time information about (i) weather, (ii) crop growth phases and (iii) soil water dynamics.

(i) IRRISIAS weather data relies on a comprehensive and high-density weather stations network from the SIAS. The SIAS network consists of 68 weather stations that are strategically distributed to gather weather information across the whole region and are divided into two types of stations: primary and secondary. A total of 30 primary stations are equipped with advanced sensors for additional weather measures (i.e. wind speed, global radiation and atmospheric pressure). The remaining 38 secondary stations are equipped with basic sensors for temperature and humidity measurements.

(ii) IRRISIAS is provided with a detailed database concerning crop-specific data including crops species, cultivars, their growth stages and the respective percentage of soil surface covered by each crop. Users of IRRISIAS can select from a range of 46 crops, including 16 tree crops, 23 vegetable crops and 7 arable crops.

(iii) IRRISIAS requires soil texture and the depth of the useful soil portion for accurate functioning. The IDSS calculates water

[4] Available online at: www.irrisat.com

[5] Available online at: www.agroservizi.regione.sicilia.it

volume requirements using the FAO56 model. Satellite multispectral images are used to update and adjust Kc values to enhance plant stress estimation, resulting in more precise model simulations. By using high-resolution input parameters and data derived from high-density weather networks, IRRISIAS facilitates reliable predictions of meteorological phenomena. This IDSS identifies specific crop irrigation requirements and the remaining available water volume every week. Furthermore, the system suggests the optimal dates for irrigation, provides the exact volume of water required and calculates the operating hours required by the irrigation system.

5.4. IRTO[6]

This IDSS is designed to meet the specific needs of farmers based in Tuscany. IRTO operates on the basis of a SWB simulation, integrating the FAO56 model [20] and algorithms to assess water flows throughout the soil profile. The computation of water requirements relies on four key components: (i) crop and cropping system; (ii) soil; (iii) weather and (iv) location.

(i) Crops and cropping systems: this section of the model takes into account various crops growth phases and their root development. Users have the option to select from a total of 28 different crops, including 6 tree crops, 15 vegetables crops and 7 arable crops. The model considers different crops characteristics at a specific point of their growth cycle, such as sowing/transplanting or flowering that can be selected during the productive season. In addition, two primary management systems (tilled or no-till) along with two WDS (drip or rain) are integrated within the IRTO model resulting in a total of four cropping systems.
(ii) Soil characteristics: IRTO mainly relies on soil texture as it significantly influences the soil capacity for water retention and drainage. Estimation of water requirements also considers the initial soil wetness, providing insights into the current soil water content.
(iii) Weather data: ET estimation is computed using the Hargreaves-Samani equation and requires only temperature and rainfall as input. Data is obtained from the closest weather station within Tuscany's network of 103 stations distributed across the region.
(iv) Geographical coordinates: latitude provides insights on extraterrestrial radiation estimation for the ET calculation.

5.5. IrriNutri[7]

The Irri-Nutri DSS is tailored for advice framers in estimating water and nutrient needs, aligned with the integrated farming protocols of the Abruzzo Region [56,57]. The SWB model incorporates the FAO56 model [20] and algorithms for water flow assessment within the soil profile. The water balance exploited by this IrriNutri is similar to the IRTO IDSS described in the previous paragraph with four main components: (i) crop and cropping system; (ii) soil; (iii) weather and (iv) location.

(i) Crops and cropping systems: this IDSS offers users to select between a total of 32 different crops including 9 tree crops, 19 vegetables crops and 4 arable crops. Moreover, specific stages of their growth cycle together with different cropping and water delivery systems can be chosen and modified during the season. CWR have been retrieved from scientific studies conducted within the Abruzzo region [57–59].
(ii) Soil characteristics: Soil texture and initial soil wetness data are required.
(iii) Weather data: Rainfall and temperature data are controlled [60] and employed for ET calculation using the Hargreaves-Samani equation. Data is retrieved from the nearest of the 50 weather stations of Abruzzo region and accessible at https://agroambiente.regione.abruzzo.it/#/home (accessed on 26 June 2024).
(iv) Geographical coordinates: latitude is employed to estimate extraterrestrial radiation for the ET calculation.

5.6. iCOLT[8]

The iCOLT system (Classification of Cultivated Lands through Remote Sensing) is a climatic service that integrates satellite images, seasonal weather data and forecast for crop identifications and expected water requirement in the whole Emilia-Romagna region.

This tool utilizes the seasonal forecasts for Italian agriculture provided by ECMWF (European Centre for Medium-Range Weather Forecasts). This initiative was developed by ARPAE (Agency for Prevention Environment and Energy Emilia-Romagna) and operational since 2010 providing free accessible outcomes online. The iCOLT system gained official recognition between 2013 and 2014 from Emilia-Romagna authorities as a tool to cope with uncertainties in water availability for agriculture [61]. The primary beneficiaries of iCOLT are the Irrigation Boards in the Emilia-Romagna region to cope with adequate water resources allocation during high-demand season. The study area consists of the Emilia-Romagna plain with approximately 800,000 ha of agricultural land. The iCOLT system classifies crops in five distinct categories: winter, multi-annual, and spring-summer herbaceous crops, orchards and vineyards. Herbaceous crops are categorized through multi-temporal optical satellite image series analysis. Three distinct periods are identified for satellite images gathering:

(i) Late October to mid-November, checking the absence of vegetation in winter and summer crop fields, while the presence of vegetation in multi-annual crop fields.
(ii) Late January to the end of February, checking the absence of vegetation in summer crop fields and the presence of vegetation in both winter and multi-annual crop fields.
(iii) Late March to mid-April, checking the absence of vegetation in summer crop fields and the presence of vegetation in winter and multi-annual crop fields.

The classification process utilizes a static decision tree model, with three condition levels per node and generating three crop classes with similar phenological stages. The algorithm's accuracy, averaging around 95%, is assessed by comparing classification results to ground truths. To this crop map orchards and vineyard classes are incorporated and identified using local reference data sourced from the Emilia-Romagna Regional Agency. The final raster of crop classification is vectorized to serve as input for the SWB model. Indeed, during May, the crop map, the seasonal predictions and observed weather data are used as input for CRITERIA (Local Water Resource Monitoring to Reduce the Environmental Impact) SWB model to produce the estimated irrigation requirements for June–July–August period. Then, at the end of summer, observed daily weather data are used to validate the model predictions. iCOLT exhibited higher forecast skills compared to probabilistic climate predictions, attributed to its holistic computational approach that incorporates predictions and observed weather and water table data. Additionally, the system demonstrated the capability to capture spatial variability for irrigation amplitude through crop maps [62].

[6] Available online at: https://agroambiente.info.regione.toscana.it
[7] Available at: https://agroambiente.regione.abruzzo.it
[8] Available online at: https://sites.google.com/arpae.it/servizio-climatico-icolt

5.7. Fondazione Edmund Mach (FEM) irrigation service[9]

The FEM implements a SWAB (Soil Water Air Balance) model to compute the groundwater volume for the present year. The system relies on data from a network of 84 weather stations operated by FEM to provide integrated weather forecasts extending up to 10 days. The system provides users with graphical representations that estimate soil water content, specific for grapevine and apple crops in Trentino. This IDSS provides real time SPI (Standardized Precipitation Index) and SPEI (Standardized Precipitation-Evapotranspiration Index) for additional details. Moreover, only for some locations, the system also includes measurement campaigns and experiments with sensors installed in different areas, transmitting data every 15 min via LoRaWAN (still in an experimental phase). While the FEM network evaluates water balance based on specific soil data at each weather station, it does not factor in irrigation water. Therefore, the calculations reflect the water needs of crops in a rainfed scenario, offering insights into the shortfall of natural water sources for maintaining soil moisture in orchards or vineyards.

5.8. BiDriCo[10]

BIdriCO is the IDSS that serves the agricultural community in Friuli Venezia Giulia. This service operates exclusively during the months of June, July, and August, providing estimates of soil moisture and forecasting optimal irrigation timing based on specific input parameters such as location, soil type, crop details, and the date of the previous irrigation event [63]. BIdriCO incorporates data from only 19 weather stations covering the entire region and based on the location it is possible to select up to 10 soil classes. The system is designed for two crops (soybeans and corn) and generates precise recommendations for irrigation timing within a maximum interval of 7 days. However, comprehensive details regarding the specific methodologies employed by BIdriCO for estimating evapotranspiration and the parameters considered remain inadequate. Access to additional documentation and data, deeper insights into the system's operational mechanisms and models utilized for soil moisture predictions and irrigation advice are limited. Clarity on these technical aspects is essential for a thorough assessment of BIdriCO's effectiveness in providing irrigation recommendations.

A comprehensive overview of regional IDSS described in this section are presented and resumed in Table 2.

6. IDSS evaluation

The regional IDSS adoption level is illustrated in Fig. 3a. Except for the Aosta Valley, every Italian region adopts an IDSS to support irrigation. IRRIFRAME extends its coverage across almost the entirety of the country, encompassing 16 regions. Regions such as Tuscany, Abruzzo, Emilia-Romagna and Friuli VG rely on two IDSS at regional level, while Sicily rely on IRRISIAS, a single IDSS specific to the region. IRRISAT, which is the IDSS adopted for Campania region, is not a public IDSS, but has been reported to have a comprehensive map of the Italian IDSS. In Fig. 3b, an examination of various IDSS parameters is represented, delineating frameworks related to soil, irrigation, crop-specific parameters, and WDS. iCOLT, excels in soil and crop-related parameters, while IRRIFRAME showed a substantial count in parameters associated with irrigation, crop management and WDS.

Fig. 4, the number of crop categories available for each region is shown. Arable crops (e.g. wheat, corn, beet) reported in Fig. 4a, shows that most Italian regions have approximately six arable crops. No arable crops in Trentino-Alto Adige are reported up to a maximum of 11 or 12 crops in regions like Veneto, Emilia-Romagna, Piedmont, Lombardy, Umbria and Apulia. Tree crops (consisting of vineyards, apples, pears, apricots, almonds, olives, and various orchards) available in different Italian regions are depicted in Fig. 4b. Regions like Emilia-Romagna and Sicily exhibit a substantial focus on tree crops, with 13 and 16 crops recorded, respectively. North of Italy, Apulia and Sardinia region also showed a good tree crop representation ranging from 9 to 12 crops. Trentino-Alto Adige, Friuli VG, Abruzzo, Molise, Basilicata and Calabria are the regions with two to three crops represented. Insights on the vegetable crops number across various regions is provided in Fig. 4c. Veneto, Emilia-Romagna, Apulia, and Sicily stand out with higher counts of vegetable crops, ranging from 7 to 12. On the other hand, several regions, including, Trentino-Alto Adige, Lazio, Calabria and Molise have no vegetable crops recorded.

To gain comprehensive insights into the advancements and impact of the studied IDSS, a literature review has been carried out. The examination spanned from 2000 to 2024. The focus of this literature review considered articles, conference papers, and reviews that actively employed IDSS for CWR estimation in agricultural experimentation, as a comparative benchmark against proposed methodologies or leveraged them as a foundation for the deployment of more sophisticated systems. Evidence from literature reveals that IRRIFRAME (a total of 34 publications) and IRRISAT (a total of 29 publications) emerged as the predominant choices among academics for IDSS. Other IDSS were not included due to the absence or the low number of publications. Fig. 5 depicts the publications of the two IDSS over the years. Both IDSS maintained a consistent presence from 2013, and, despite occasional fluctuations, they continued to contribute to the literature. IRRISAT showed peaks in 2015 and 2020 (up to 5 publications), while IRRIFRAME showed peaks in 2022 and 2023 (up to 6 publications). Results reveal an overall increase in publications related to Italian IDSS in recent years. The higher number of publications, particularly evident after 2015, aligns with the adoption of the Ministerial Decree 31 July 2015 at regional level, suggesting a growing commitment at regional level towards agricultural technology for water resource management. Moreover, the increasing number of publications after the Decree adoption underscores policy influence on research priorities, thus emphasizing the crucial role of governmental initiatives.

Several among the studies depicted in Fig. 5 employed the two IDSS as a reference for irrigation management in various crops such as pear [64], apple [65], tomato [66], potatoes [67], soybean [68], millet [69] and table grape [70]. Research has also demonstrated the benefits of using IDSS in irrigation practices, particularly in improving WUE and reducing water volume application. Giannerini et al. [47] reported that IRRIFRAME could potentially save up to 120 million cubic meters of water annually, as it operates nationwide with no operational costs. Additionally, authors highlighted that irrigation scheduling computed by IRRIFRAME is integrated with economic considerations, comparing the cost of irrigation with the expected yield increase and the seasonal water allocation for the crop. Carucci et al. [66] tested various IDSS for tomato CWR and found that the IRRIFRAME-based IDSS achieved acceptable WUE while using the least amount of freshwater during the growing season. In [54], authors evaluated different IDSS and found that IRRISAT reduced irrigation water application by up to 15% in maize and alfalfa. Furthermore, in [53] authors demonstrated that IRRISAT provides advantages by offering different irrigation strategies throughout the orchard cultivation season, including the recommendation of deficit irrigation. Bonfante et al. [71] compared three different irrigation DSS for maize cultivation and concluded that IRRISAT, when coupled with various tools for ground data collection, delivered the best performance in terms of WUE.

The most recent Italian IDSS qualitative assessment was conducted by SIGRIAN in August 2016.[11] The report primarily investigated

[9] Available online at: https://meteo.fmach.it/meteo/irrigazione.php

[10] Available online at: https://www.meteo.fvg.it/bidrico.php

[11] Available online at: https://sigrian.crea.gov.it/wp-content/uploads/2020/11/PSRN_Allegato-9-Finale.pdf

Table 2
Overview of the regional Irrigation Decision Support System (IDSS) in Italy. (SWB: Soil Water Balance; SEB: Surface Energy Balance; SWAB: Soil Water Air Balance; HG: Hargreaves-Samani; PM: Penman-Monteith).

IDSS	Owner	Region	Public / Private	Model	ET0 estimation model	Kc source	Parameters			WDS	Crops	Forecast	Time series	Local data
							Soil	Irrigation	Crop					
IRRIFRAME	ANBI	Emilia-Romagna, Apulia, Veneto, Friuli VG, Calabria, Tuscany, Lazio, Lombardy, Basilicata, Abruzzo, Umbria, Liguria, Piedmont, Sardinia, Molise, Marche	Public	SWB	HG	FAO24	7	5	8	35	8 to 46	YES	–	YES
IRRISAT	Ariespace s.r.l.	Basilicata, Campania	Private	SEB	PM	FAO56 + Sentinel2	–	–	–	–	–	YES	YES	–
IRRISIAS	Regione Sicilia	Sicily	Public	SWB	PM	FAO56	3	1	5	4	46	YES	–	–
IRTO	Regione Toscana	Tuscany	Public	SWB	HG	FAO56	2	–	2	2	28	–	–	–
IrriNutri	Regione Abruzzo	Abruzzo	Public	SWB	HG	FAO56	2	–	2	2	32	–	–	–
iCOLT	ARPAE	Emilia-Romagna	Public	SWB	HG + PM	FAO56	23	1	4	–	5	YES	YES	YES
FEM	Fondazione Edmun Mach	Trentino Alto Adige	Private	SWB	SWAB	–	–	–	–	–	2	–	–	–
BiDriCo	Regione Friuli VG	Friuli VG	Public	–	–	–	1	–	–	–	2	YES	–	–

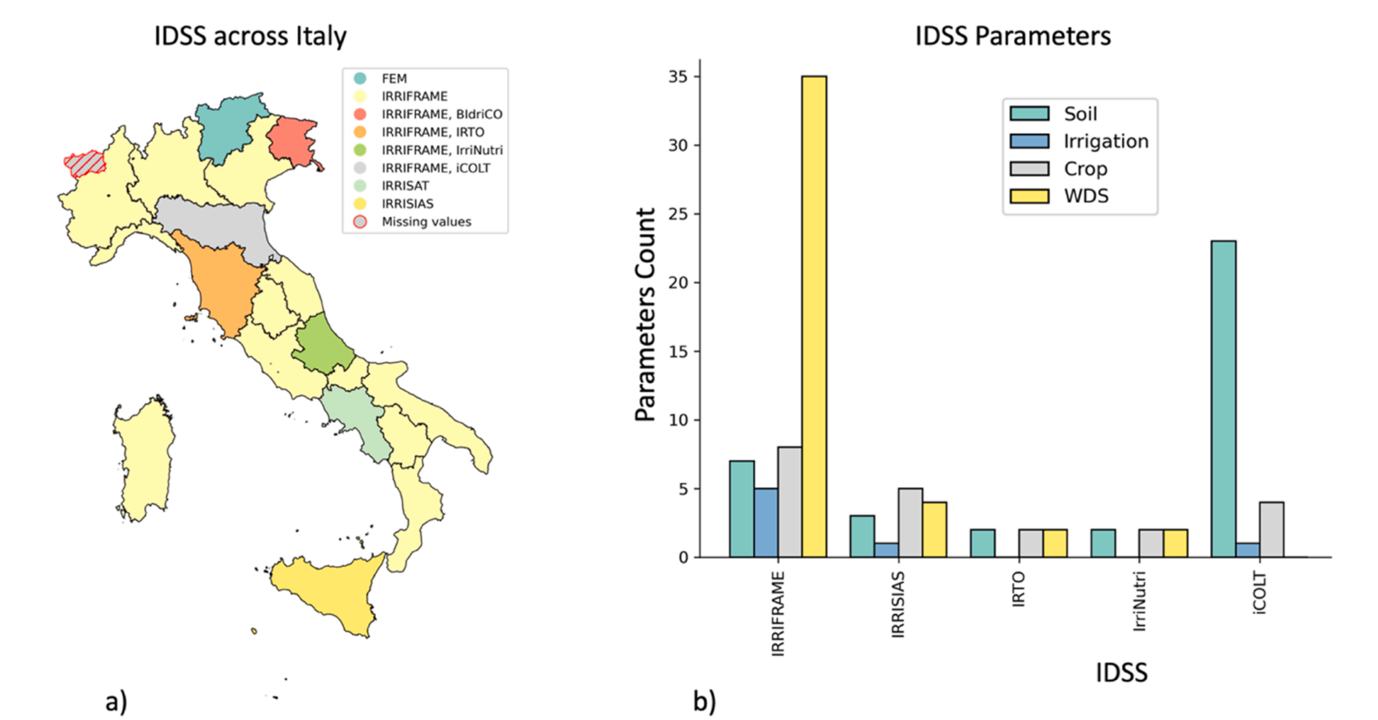

Fig. 3. Italy IDSS characterization. a) IDSS distribution across Italian regions. b) Number of parameters used by IDSS (FEM Irrigation Service and BIdriCO were not included in the figure due to their low parameters).

methodologies for estimating water volume among IDSS, assessing their usability levels and availability across Italian regions. The methodologies to estimate CWR were found to be coherent to SWB and SEB models. The IDSS usability was evaluated as "High", "Medium" and "Low" according to digital data format and the capability to generate accurate irrigation water requirement estimates for large areas, such as entire regions and for smaller, more specific irrigation schemes or projects. Furthermore, the availability of IDSS assessed whether these systems

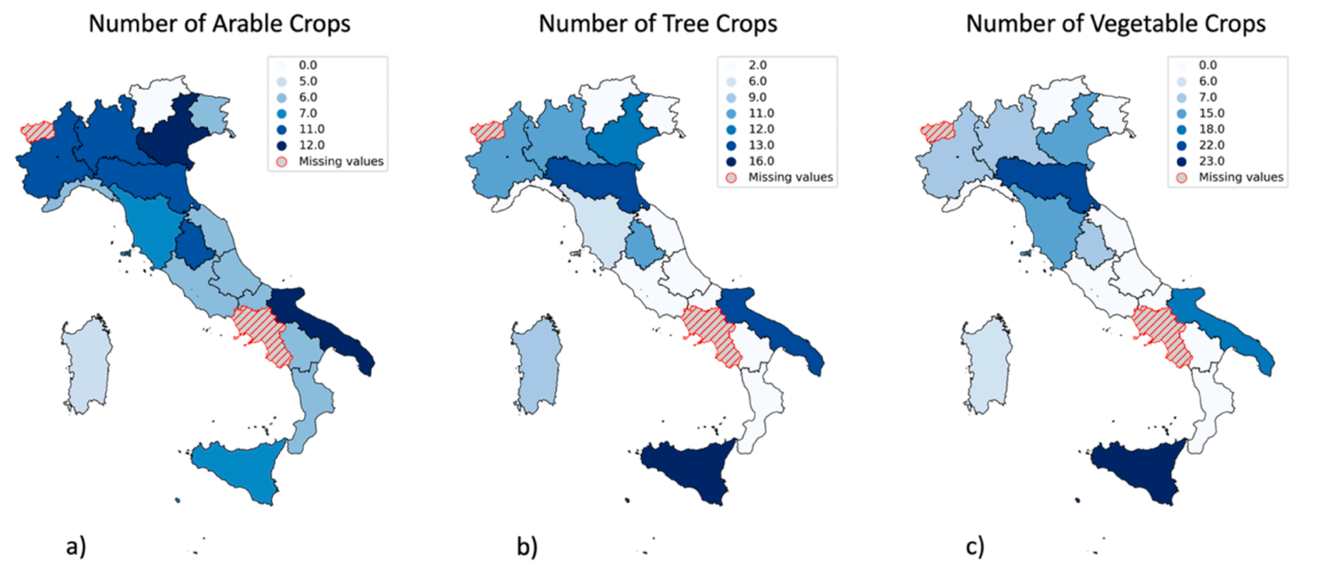

Fig. 4. Number of different crop categories publicly available in IDSS across Italian regions. a) Number of arable corps publicly available. b) Number of tree corps publicly available. c) Number of vegetable corps publicly available.

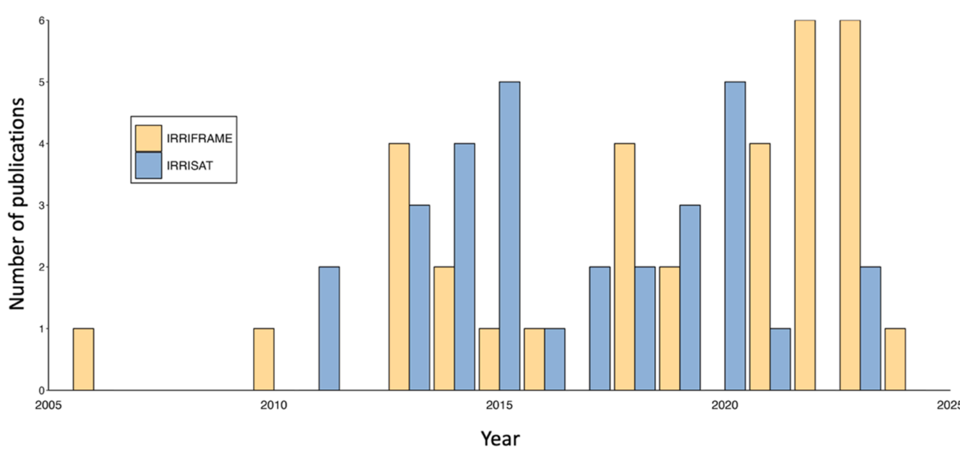

Fig. 5. Number of publications using IRRIFRAME and IRRISAT from 2000 to 2024.

were available for all irrigation schemes within different regions, checking if they offered complete or only partial coverage and the quality of their service. The following paragraph reports an evaluation of their accessibility, scalability and interoperability. The assessment of accessibility, interoperability, and scalability for the Italian IDSS has been conducted systematically in accordance with the Software Quality Requirements and Evaluation (SQuaRE) standard (ISO/IEC 25,010:2011, BSI Standards Publication[12]). The IDSS were evaluated based on accessibility, scalability and interoperability. The evaluation criteria and scores were established, with three stars indicating full consideration with technical details, two stars for partial mention without further explanations, and one star for aspects not addressed at all [72]. Accessibility, pertaining to the graphical user interface (GUI) of an IDSS, was assessed considering factors such as map view, soil moisture monitoring, CWR estimation, irrigation planning and decision support visualization [73]. Scalability, addressing the system's capability to process a growing number of missions and IDSS was assessed considering factors such as farm division and the number of crops available [74]. Interoperability emphasizes the IDSS ability to integrate functions and knowledge from heterogeneous components and to work with external components or systems [75]; thus, it was assessed considering the possibility to incorporate local weather stations or sensors as IDSS input, the output export options and the notification methods.

In Table 3, we report results for the seven IDSS Accessibility, Scalability, and Interoperability. IRRIFRAME emerges as the top performer, excelling across all categories, particularly standing out in accessibility and interoperability. Its ability to integrate irrigation schemes and district data for water availability, together with the possibility to connect local weather station information underscores its comprehensive

Table 3
IDSS evaluation results for Accessibility, Scalability and Interoperability made by authors.

IDSS	Accessibility	Scalability	Interoperability
IRRIFRAME	★★★	★★★	★★★
IRRISIAS	★★★	★★★	★★
IRTO	★★★	★★★	★★
IrriNutri	★★★	★★★	★★
iCOLT	★★	★★	★★
FEM	★	★	★
BIdriCO	★	★	★

[12] Available online at: https://www.iso.org/standard/35733.html

approach. IRRISIAS faces challenges with accessibility, likely due to frequent service disruptions, and is limited in interoperability, restricting its capacity to download only the water requirements as CSV (Comma-Separated Values) file. IRTO exhibits strong accessibility and scalability but is constrained in interoperability, allowing only the download of water requirements with a .csv file. The FEM system receives notably low ratings across all evaluated criteria. FEM's service is minimal, as it provides only specific plots based on the SWAB model, SPI and SPEI indexes and plots showing ET and rainfall trade off. This narrow focus limits its compatibility with broader datasets or integration with other systems. The system's one-star ratings in all categories underscore significant shortcomings, raising concerns about its overall utility for users seeking a more versatile and user-friendly platform.

7. Discussion

Comparing the seven IDSS, limitations were highlighted in Table 2. Only IRRISIAS, iCOLT and IRRIFRAME, among the public IDSS, incorporate the capabilities for water stress forecasting and prediction. This lack of information in the remaining systems represents a disadvantage for an efficient management of the irrigation. Indeed, while IRRIFRAME forecasts water requirements up to the irrigation date, it generally does not extend predictions beyond one week.

None of the systems, except for iCOLT, allow for the retrieval of audit and historical data from remote sensing images or weather stations that are specific to individual farms or fields. This aspect restricts irrigation practices monitoring and analysis over time. Additionally, the examined IDSS vary in the specificity of parameters related to soil, WDS and crops, potentially hindering the delivery of accurate and tailored irrigation advice. Notably, IRRIFRAME exhibited the most comprehensive details for WDS and crop parameters. iCOLT showed the highest detail regarding soil parameters, while IRRISIAS included the largest variety of crops, offering up to 46 different crop species and varieties. However, the crop representation in these systems remains inadequate, especially in Italy, where around 350 different crops coexist.

Another significant constraint is weather and soil data dispersion across numerous different systems or platforms, rather than being centralized or integrated into a cohesive, unified system. Indeed, Italy account for more than 65 distinct soil and weather management systems are including National Flight Assistance Agency (ENAV), Meteorological Service of the Italian Air Force, Council for Agricultural Research and Economics Analysis (CREA-AA), National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA), National Research Council (CNR), regions, provinces, Regional Hydrographic Services, Universities, Civil Protection, Regional Agencies for Environmental Protection (ARPA), Irrigation Boards, and others. This generates difficulties in accessing, sharing and utilizing consistent and standardized data for agricultural and irrigation decision-making purposes [29]. Nevertheless, the integration of all weather station networks with the agrometeorological network, as described in [30], has shown the potential to address the challenges of data resolution and fragmentation in the context of agriculture in Italy. Fragmented ownership of the public IDSS owners represents an additional challenge to the effective management of water resources. With multiple entities responsible for different aspects of irrigation decision-making, coordination and integration become complex, often leading to inefficiencies and conflicting strategies. Moreover, different priorities and resource allocations across various IDSS owners or regions may hinder standardized protocols and interoperable systems development.

It is urgent to address fragmentation and develop a standardized method for evaluating IDSS. Currently, the lack of uniform criteria for assessing the performance and effectiveness of IDSS complicates decision-making processes and impedes the adoption of best practices. A standardized evaluation framework would enable stakeholders to objectively compare different systems considering factors such as usability, accuracy, reliability, scalability, and the ability to integrate with existing infrastructure and data sources. By establishing clear benchmarks and metrics, a standardized evaluation method would increase IDSS impact in optimizing water resource management for sustainable agriculture.

Addressing these challenges requires collaborative efforts among stakeholders to simplify communication channels, set common goals and implement harmonized water management approaches. The digital transformation of agriculture demands the availability of environmental, operational, machinery and process data in digital form for effective integration of software-based products and services. Agricultural data should be recorded automatically using advanced sensors and analyzed for informed decision-making in field work and animal husbandry. Data spaces can ensure more data availability while maintaining data sovereignty, security, and trustworthiness. The AgriDataSpace[13] initiative exemplifies these efforts. In Europe, the Data Act,[14] effective January 11, 2024, establishes harmonized rules for fair data access and use, supporting digital transformation in agriculture. Complementing the Data Governance Act, the Data Act clarifies who can derive value from data and under what conditions. These regulations ensure secure and reliable data access, promoting its use in key sectors and establishing a single EU data market. They also mandate that connected products allow easy and secure data access, use, and sharing for both businesses and consumers. Future legislation should align with the Data Act's principles, applicable across sectors, including precision agriculture.

The comparison of the examined IDSS evapotranspiration and kc estimation models' highlights additional disparities. None of the systems incorporate the latest kc table published by [26]. Similarly, none of the IDSS examined in this study utilize a remote sensing approach for kc estimation, following established procedures like that presented by [76] or utilizing openly available sentinel-2 products. While iCOLT uses satellite images analysis for crop classification, IRRISIAS employs a more refined approach using corrected kc values according to FAO56 guidelines and multispectral data. Additionally, to the corrected kc, ET is estimated by means of the Penman-Monteith equation, thus offering an overall superior accuracy compared to other IDSS. Conversely, the remaining IDSS exploit ET estimation through the Hargreaves-Samani equation and standard FAO56 kc values, occurring with an overall lower accuracy than the IRRISIAS. It is essential to recognize that ET estimation models and kc selection influences IDSS reliability for precise irrigation recommendations. This is corroborated by [77] which demonstrated the strength of CWR derived from vegetation indexes for their high resolution (daily frequency as temporal and the field scale as spatial resolution). Moreover, this technique resulted particularly advantageous where irrigation event dates are unknown, as commonly encountered in large-scale irrigation schemes. [78] explored farmers' concerns regarding IRRISAT attributes and their willingness to pay for the IDSS. Findings revealed farmers' strong appreciation for IDSS that work well at farm level. This behavior is reflected in their willingness to pay for such assistance. Despite farmers' preferences not to prioritize water saving, the significance of water conservation cannot be overlooked [79]. Indeed, water-saving measures should be tracked and acknowledged among agricultural practices and integrated into production certification mechanisms aimed at sustainability standards. Nevertheless, results emphasized that the issue of cost remains a pivotal consideration for the widespread adoption of irrigation advisory services. Therefore, enhancing the efficiency and reliability of public IDSS has the potential to increase their adoption rate.

Integrating remote sensing techniques into existing public IDSS could enhance precision and efficiency in agricultural water

[13] Available online at: https://agridataspace-csa.eu/

[14] Available online at: https://digital-strategy.ec.europa.eu/en/news/european-data-act-enters-force-putting-place-new-rules-fair-and-innovative-data-economy

management. Remote sensing data, such as satellite imagery can provide real-time information on soil moisture levels, crop health and environmental conditions and allow more informed and timely irrigation decisions. Furthermore, data estimation using the POWER NASA database offers a solution for addressing issues related to neglected or non-functioning weather stations. By utilizing the comprehensive and up-to-date weather data provided by POWER, IDSS can fill gaps in information and ensure reliable guidance for farmers, ultimately improving resource efficiency and agricultural productivity.

In addition to the technical aspects of IDSS, there is a growing need to address and explicitly integrate economic considerations into the decision-making frameworks of these systems. While IDSS have demonstrated potential in recommending optimized irrigation practices, including deficit irrigation, current implementations often lack this capability. To enhance their utility, efforts should be directed towards incorporating advice on water deficit and pricing strategies based on CWR and water availability at the scheme level. Integrating these economic aspects within IDSS a more balanced recommendations between agronomic and economic factors can be achieved.

In conclusion, while existing infrastructures provide a foundation for digitalization, further governmental efforts are crucial to drive this transformation and reduce fragmentation. Incorporating open access remote sensing techniques into public IDSS has demonstrated to improve the quality of the ET estimation and may enhance decision-making processes. Additionally, the establishment of a standardized framework for evaluating digital tools is essential for ensuring their efficacy and coherence across different sectors and regions. By prioritizing these actions, governments can advance digitalization, fostering informed governance, sustainable development, and equitable access to technological resources.

CRediT authorship contribution statement

Mino Sportelli: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Antonino Crivello:** Writing – review & editing, Validation. **Manlio Bacco:** Visualization, Validation. **Giovanni Rallo:** Supervision, Methodology, Conceptualization. **Gianluca Brunori:** Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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