Italian Journal of Agrometeorology
Rivista Italiana di Agrometeorologia

Firenze University Press
www.fupress.com/ijam

Citation: Borin, M. (2023). A wise irrigation to contribute to integrated water resource management. *Italian Journal of Agrometeorology* (2): 5-19. doi: 10.36253/ijam-2323

Received: September 25, 2023

Accepted: October 25, 2023

Published: January 20, 2024

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

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A wise irrigation to contribute to integrated water resource management

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Abstract. Irrigated agriculture accounts for about 20% of cultivated lands worldwide while currently generating an estimated 40% of crop production, and two-thirds of future gains in crop production are expected to come from irrigated lands. Therefore, irrigation is strategic to ensure food for the world's increasing population and slow down the pace of deforestation. Irrigated agriculture also accounts for more than 70% of global water withdrawals, and the way agriculture uses freshwater is crucial for ensuring availability for other activities and preserving water-related ecosystems. To give an agri-environmental interpretation of the water fluxes involved in irrigation, the total amount of water withdrawn from a source is called **white water** (W) and subdivided as follows: **gold water (G)** is the amount that is actually used by the crops. This fraction represents the ultimate goal of irrigation, which is to increase crop productivity and food availability. We can also consider this amount as the *irrigation water for crops*. The gold color means an income for the farm; **emerald water (E)** is the amount of water withdrawn for irrigation that does not reach the crops but provides ecosystem services, i.e., the benefits that people get from ecosystems. This amount of water is useful for the community and can be identified as *irrigation of the territory*; **red water (R)** is losses, i.e., the fraction of water that has to be reduced as much as possible if not eliminated. It is an economic, social and environmental cost; the red color is associated with the red traffic light that means STOP! The quantification of W has to be preceded by a careful evaluation of the benefits achievable with irrigation in relation to the environmental characteristics of the cultivation area. Strategic issues at this stage are the choice between full or deficit irrigation and the individuation of opportunities to exploration of opportunities to increase the availability of water resources by using non-conventional sources. The quantification of G and E fluxes is necessary to reduce losses, while strategies/techniques useful to reduce irrigation needs at the field level are key factors to allocate irrigation water within the framework of an integrated and sustainable management of water aimed at turning user conflicts into synergies. This implies multiple subjects and actors in a multi-disciplinary approach.

Keywords: irrigation efficiency, components of water fluxes, ecosystem services of irrigation.

"…let us not wait until the well is dry to understand the worth of water (Benjamin Franklin)"

1. IRRIGATION, A NECESSITY UNDER THREAT

Irrigated agriculture accounts for about 20% of cultivated lands worldwide, while generating an estimated 40% of crop production (FAO, 2015a, b; Turral et al., 2010). Yields are markedly higher and more stable with irrigation, also because farmers apply larger amounts of fertilizers and chemicals when they can fully meet the crop water requirements (Monjardino et al., 2013). Published estimates of the 2050 food demand vary hugely, but most of them agree with FAO projecting a 50-60% increase of the total global food demand between 2019 and 2050 (Falcon et al., 2022). Half or even two-thirds of future gains in crop production are expected to come from irrigated land (Kadiresan and Khanal, 2018), requiring a 10% increase of global water withdrawals (FAO, 2011; FAO, 2017) and calling for investments and interventions.

The role of irrigation is crucial with a view to a sustainable intensification of agriculture, but the need to "produce more with less" is underscored by the fact that the growing population has resulted in the freshwater resources available *per* person having declined by more than 20% in the last two decades. As the demand rises, freshwater becomes increasingly scarce, competition for it intensifies, and excessive water withdrawals threaten water-related ecosystems and the ecosystem services they provide (FAO, 2020). Globally, the world's freshwaters are distributed unevenly across space and time and subjected to contrasting driving forces between maintenance in the water bodies and withdrawals. On the one hand, living organisms, transportation, energy production and the many human activities associated with recreation (e.g., fishing, rowing, landscaping) require that water be maintained in lakes, basins, rivers, canals; on the other hand, agriculture, industry and households imply withdrawal and water body exploitation. This implies the issue of the equitability in water use, that is, the fair distribution of production factors among human beneficiaries based on their needs. Furthermore, the use of water for industry and domestic purposes most often does not imply any change of its physical status: water remains in its liquid phase. Water can be subjected to pollution. However, it can be re-used or returned to the water bodies very close to the withdrawal sites across space and time after appropriate treatment. Water used for irrigation is expected to be taken up and transpired by crops and dispersed into the atmosphere in the form of vapor; in this case, it enters the wider water cycle and is not reusable in the short term. Irrigated agriculture uses approximately 70% of the total amount of the freshwater withdrawn to supply the world's current food needs (Ingrao et al., 2023). The requirements are higher where water availability is low, as in dry areas and dry seasons. Industries and households are increasingly demanding water at the expense of agriculture, which is under pressure to release water to help meet these new needs. If agricultural production is to be sustainable, water resources must be used more efficiently while maintaining the goal of increasing productivity.

This scenario is complicated by the effects of climate change, which are already seriously disrupting rainfall patterns. Water scarcity is expected to increase with the modification of the distribution of rainfall patterns throughout the year, and so are water-related disasters. Increased drought frequency and subsequent water shortages in rainfed farmlands represent significant risks to livelihoods and food security, particularly of the most vulnerable populations in the least developed parts of the world (Kadiresan and Khanal, 2018). The amounts of water required to meet the future demand for food in a changing climate are estimated to be 40 to 100% higher than the needs in the absence of climate change (Turral et al., 2011).

At the world scale, the average irrigation efficiency is estimated to range between 40 and 50% (García-Tejero et al., 2011), and 41% of withdrawals are not compatible with sustaining ecosystem services (FAO, 2020). In Italy, total freshwater consumption ranges between 40 and 45 billion m^3 *per* year (ISTAT, 2019) (60% for agriculture, 25% for industry, and the remaining 15% for civil and domestic activities). It follows that the agricultural sector manages 24-27 billion m^3, the vast majority of which in irrigation systems. According to the 6th Census of Agriculture, irrigation is practiced by almost 40,000 Italian farms covering a total surface of about 2.5 million hectares (a little less than 20% of the national cultivated surface) and distributing 11.1 billion m^3 of water to their crops (Bellini, 2014). Northern Italy is the most hydro-driven agricultural system with the highest rate of irrigation investment on the land and the highest percentage of irrigated areas. Taking the distribution of the different irrigation methods into account (Figure 1) and their average values of field application efficiency (Brouwer et al., 1989), the overall application efficiency is estimated to be 50% at the farm level.

Irrigation systems need to be redesigned to reduce losses, alleviate the competitive pressure and tend toward an integrated water resource management.

2. PROPER USE OF WATER AND IRRIGATION EFFICIENCY

The first step to achieve a proper use of water is related to the evaluation of the benefits achievable with

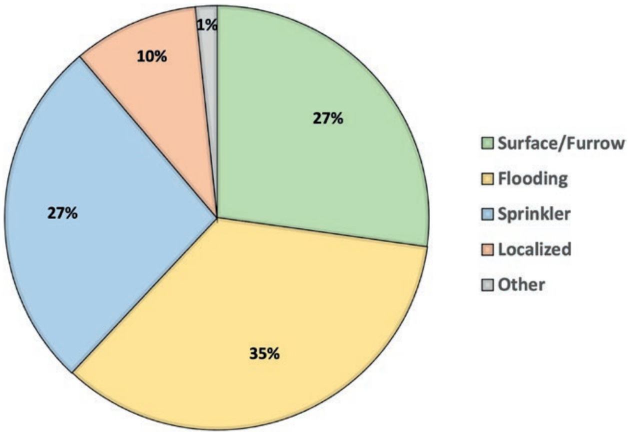

Figure 1. Distribution of the main categories of irrigation methods in Italy within the total irrigation volume (designed from ISTAT, 2014).

irrigation in relation to the environmental characteristics of the cultivation area. This implies that the transformation of a district from rainfed to irrigated has to be preceded by a suitability analysis of the land for irrigation to avoid the implementation of irrigation in unsuitable conditions. The assessment of land suitability for agriculture is a complex, multidisciplinary and multicriteria process which entails land topography, climate, water resources available for irrigation, soil capabilities and current management practices including land use and land cover (Seyedmohammadi et al., 2016; Aldababseh et al., 2018). The scientific literature is very rich of case studies regarding land suitability assessment for irrigation purposes, but their thorough analysis is out of the scope of this paper.

The traditional definition of irrigation efficiency given by Israelsen (1950) is "*the ratio of the irrigation water consumed by the crops of an irrigation farm or scheme to the water diverted from a river or other natural water source into the farm or scheme canal or canals*". It has evolved over time, and many different and sometimes conflicting definitions have been published (US Interagency Task Force, 1979). Despite variations and enhancements, the basic concept of irrigation efficiency implies that high efficiency reflects low losses; in other words, a high proportion of the water available at the head of a scheme is used to augment crop transpiration, and this is an appropriate engineering objective. Nevertheless, a more recent reflection on efficient irrigation (Perry, 2007) divides the water diverted to irrigation schemes into the following components:

The consumed fraction (essentially evapotranspiration (ET)) includes:

- beneficial consumption (for the intended purpose or another beneficial use such as environmental purposes);
- non-beneficial consumption such as weeds or consumption resulting from capillary rise during a fallow period.

The non-consumed fraction includes:

- recoverable flows (water flowing to drains and back into the river system for possible diversion downstream, and percolation to freshwater aquifers);
- non-recoverable flows (percolations to saline aquifers, outflow to drains that have no downstream diversions or direct outflow to the ocean).

This approach is relevant from a hydrological point of view because it fits in with the principle of continuity of mass. According to this interpretation, losses (the complement of efficiency) are composed of non-beneficial ET and the non-recoverable component of the non-consumed fraction. Nevertheless, once again the quantification of losses – and in turn irrigation efficiency – has to be calibrated according to the objectives. Strictly speaking, let us imagine a community of farmers and/or a related water authority obtaining authorization to withdraw water from a source (e.g., a lake, a river) and/or to build a dike to create a reservoir. They have to invest money, energy, professional skills, and gain best advantage from their investment. Consequently, they are interested in using water to increase crop productivity and the resulting farm income, so that they are only interested in the beneficial component of water consumption. They might be not interested in generating a recoverable flow, which is a more general type of "environmental demand" whose beneficiaries are the collectivity rather than the farmers. Then, the following questions arise: why do farmers and their water authority have to pay for this service? Who should pay?

3. AN AGRO-ENVIRONMENTAL VISION OF IRRIGATION WATER COMPONENTS

Following the concept of objectives and benefits associated with irrigation, the following theoretical approach can be proposed, figuring the world of irrigation in four components associated to colors (Figure 2):

- **White water (W)** is the total amount of water withdrawn from a source. The color suggests a white sheet, where a project is going to be written;
- **Gold water (G)** is the amount that is actually used by the crops. This fraction represents the ultimate goal of irrigation, enhanced productivity and food availability. We can also consider this amount as

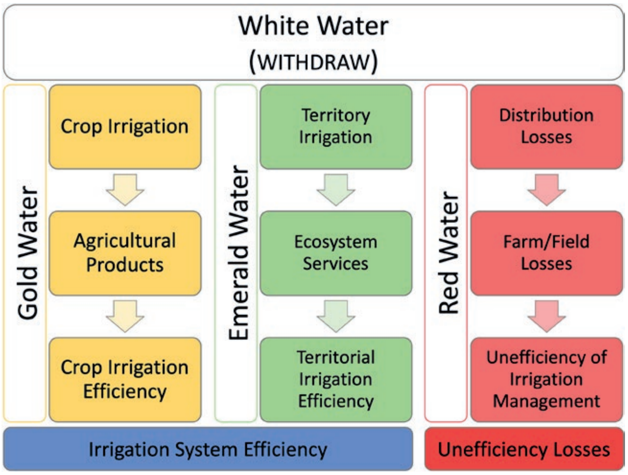

Figure 2. Classification of irrigation water according to the beneficiary.

the irrigation water for crops. The gold color means income for the farm;

– **Emerald water (E)** is the amount of water withdrawn for irrigation that does not reach the crops but provides ecosystem services. These are the benefits that people get from ecosystems (Millennium Ecosystem Assessment, 2005). They include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling, that maintain the conditions for life on Earth. This amount of water is useful for the community and can be identified as irrigation of the territory. The emerald color suggests something precious, the gemstone symbol of hope, future, growth and renewal. Emerald is characterized by facets that represent the variability of ecosystem services attributable to the presence of water in irrigated territories;
– **Red water (R)** is losses, i.e., the fraction of water that has to be reduced as much as possible, if not eliminated. It is an economic, social and environmental cost. The red color is associated with the red traffic light that says STOP!

$$W = G + E + R.$$

According to the rationale inspiring the concept of irrigation efficiency:

– Gold Water Efficiency (GWE) = crop irrigation efficiency = G/W
– Emerald Water Efficiency (EWE) = E/W
– Irrigation System Efficiency (ISE) = (G+E)/W
– Inefficiency = R/W

The idea of associating water fluxes to colors calls to mind the methodology of evaluation of the water footprint (Hoekstra et al., 2011), but in this case it is only focused on the water used in the irrigation sector.

3.1. White water

Quantifying the correct amounts of the crop water needs is the first step when it comes to planning and managing the water resource under the pressure of contrasting interests, risks and uncertainties. Theoretically, the amount of white water can be easily identified and quantified from the field scale to the basin scale. FAO papers nos. 24 (Doorenbos and Pruitt, 1977), 33 (Doorenbos and Kassam, 1979), 56 (Allen et al., 1988), and 66 (Steduto et al., 2012) well describe the basics and the methodologies for determining the crop water requirements.

At the planning stage, the choice between full or deficit irrigation is a strategic issue, especially where water availability is particularly subjected to competition and limitations of use. The main objective of deficit irrigation is to increase the water use efficiency (WUE) of a crop by eliminating irrigation systems that have little impact on yield (FAO, 2002). The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices. In other words, deficit irrigation serves a wider territory with the same amount of withdrawn water. This also implies socio-economic consequences such as a greater number of farms receiving water, higher skills to correctly manage water stress, adequate extension services for farmers, and/or available user-friendly systems or sensors for soil water measurements, together with flexible water prices (Rodrigues and Pereira, 2009). When looking for irrigation water sources, both quantity and quality have to be considered, and are related to each other. Relatively to the amount of water to be exploited, opportunities have to be explored and pursued to increase their availability. In this sense, the Italian territory needs deep rethinking of land reclamation, which is the result of a stratification of interventions and works performed over the centuries under changing objectives, priorities, technologies, policies, socio-economic and environmental conditions (Novello and McCann, 2017). The rationale of these interventions aims to quickly divert excess rainwater from the territory to guarantee its hydraulic safety. As a result, only 5% of rainfall is retained and used for irrigation in Italy at present (Coldiretti, 2021). The territory is also extremely fragile and vulnerable to severe climatic events. Therefore, it is urgent to plan and implement solutions combining the safety of the territory with the need to increase the number of water reservoirs. In this sense, the principles of the Varenne Agricole (Ministère de l'Agriculture et de la Souveraineté Alimentaire, 2022) can be an inspiring reference: store water during periods of high availability and make them available to crops during dry periods, and manage the water resources as close to the territory as possible.

The use for irrigation of marginal water resources such as drainage water, treated wastewater, of industrial and domestic origin, or desalinized water (Martínez-Alvarez et al., 2016) is an interesting option to widen the scope of water availability for irrigation and mitigate the demand for high-quality water. However, using these waters for irrigation may bring along various problems like toxicity to crops, damage to the soil quality, spreading of parasites, problems in irrigation systems and potential hazards to the environment and/or humans (Alcade Sanz and Gawlik, 2014). Theoretically, being able to use low-quality water for irrigation does not solely depend on its intrinsic characteristics, but also on its conditions of use (crop type, soil and climate conditions, or irrigation method) (Figure 3; Bortolini et al., 2018). Taking into consideration the water quality indicators, they can be categorized into three main groups, according to their effects on irrigation:

- Agronomic quality indicators: parameters causing toxicity effects on crops and/or degradation on soil fertility in the medium-long period. The most significative are: pH, giving general indications about the quality of the water resource; Electrical conductivity (EC), which is one of the major concerns with water used for irrigation; Sodium adsorption rate (SAR), expressing the toxicity effect on crops and degradation effects on soil fertility.
- Hygiene and health quality (Sanitary risk) indicators: parameters with no effect on crops yield but exerting dangerous effects on human health due to pathogens transmission, particularly when low quality water is used to irrigate fresh vegetables; some key indicators are: fecal indicator bacteria (*E. coli*), giving general indications about the quality of the water resource; Intestinal nematodos (Helminthes), very dangerous for human health.
- Management quality indicators: parameters as Total Suspended Solids (TSS), Bicarbonates (HCO_3), Sulphides, Mn, and Fe. They do not damage crops and

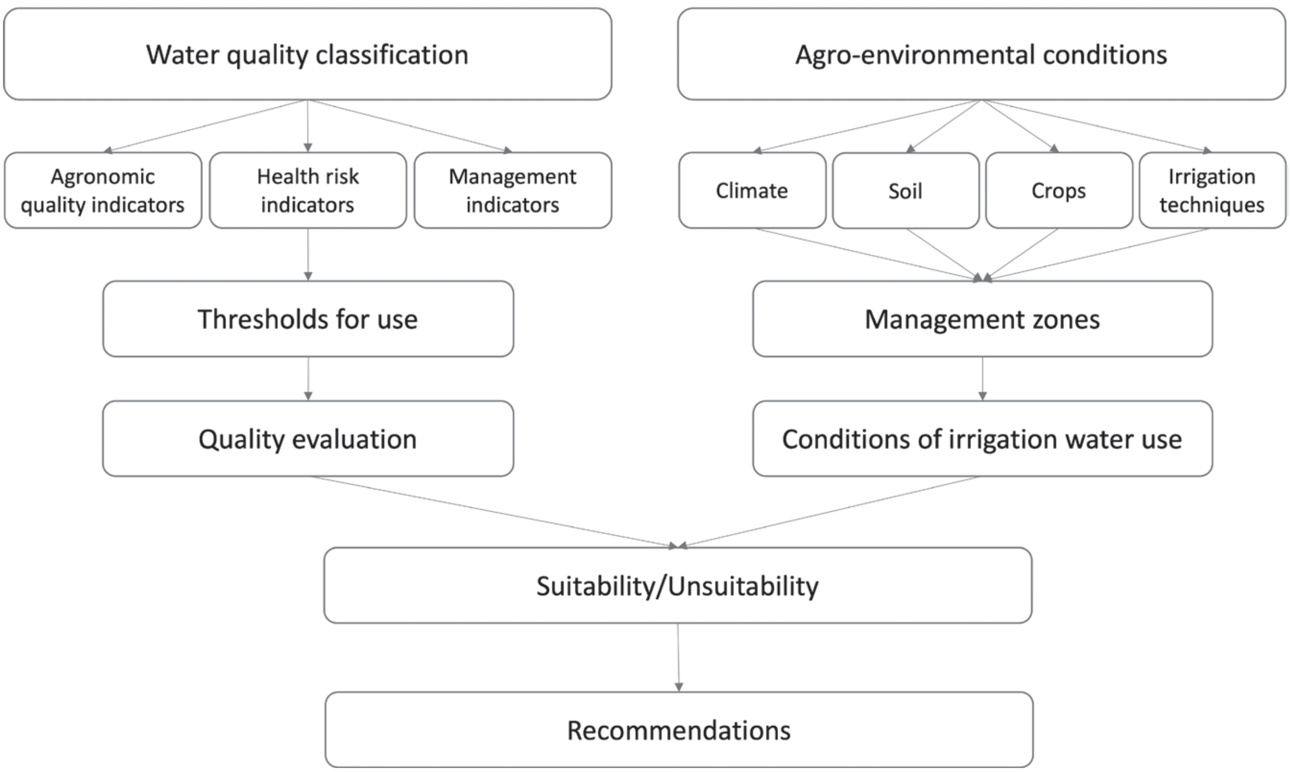

Figure 3. Scheme for a rational use of treated wastewater for crop irrigation.

soil, but cause negative effects in irrigation systems (especially clogging) resulting in a low distribution uniformity.

The use of low-quality water for irrigation deserves caution, attention and multi-criteria decision analysis (Paul et al., 2020), but can play a significant role in sustaining irrigation projects: at present almost 6 billion m^3 of treated wastewater are produced in Italy *per* year (more than half of the total irrigation volume applied to the crops), but their re-use in irrigation is infinitesimal (only 0.4% of the irrigated surface is supplied with these waters). When planning the valorization of marginal waters, matching production (which is continuous throughout the year) and water use (which is seasonal) has to be taken into account, and reservoirs have to be identified or created. Treated wastewater can be used in aquifer recharge schemes (Zheng et al., 2021) or temporarily stored in surface basins as multi-functional wetlands, which improve its quality (Smith, 2009).

3.2. Gold water

A wide availability of strategies and techniques can support the goal of reducing losses in the delivery and field distribution system, thus increasing the irrigation efficiency. The opportunities are offered by smart agriculture (Cesco et al., 2023) and advanced technologies, that are commonly known under the umbrella expression "smart irrigation" (Masseroni et al., 2020). These systems aim to adopt single or combined automation as well as information and communication technologies at the district and farm scales, besides customized and integrated model approaches at larger scales.

Without detailing this very large topic, some examples of technological innovation in the irrigation field are: i) mathematical models for the control of the main hydrological and agronomic variables; ii) the use of GIS environment for digital mapping of the territories and their geophysical and hydrological characteristics; iii) technologies for measuring quantifiable variables (flow rate, current speed levels) and water quality; iv) data transmission techniques; v) the observation of agricultural surfaces from remote sensors; and vi) the use of "smart" actuators that automate irrigation, known as the internet of things (IoT), which allow applying site-specific irrigation. Modernization or re-engineering of irrigation mostly include piped delivery systems, laser leveling of fields, conversion to pressurized systems for sprinklers, drips, or sub-surface drips.

Field irrigation systems with advanced technologies combined with good practices can increase efficiency and reduce water losses (Levidow et al., 2014; Tromboni et al., 2014). Precision agriculture methods are strategic for irrigation scheduling because they offer the potential to increase water use and economic efficiencies by optimally matching irrigation inputs to yields (Gobbo et al., 2019). In this context, unnecessary surface water runoff and water loss through evaporation is reduced. To this end, weather stations and IoT sensor networks provide information related to the soil moisture content, lower-soil moisture and evapotranspiration, while thermal aerial imagery data provide information on water availability.

Crop imagery remotely captured by cameras on board of satellites and other aerial platforms has opened the irrigation sector to the big data era. It provides timely updated spatial information on the crop status, and the opportunity to calculate vegetation indices such as NDVI, VHI, and others. Consequently, new and continuously updated tools are available to properly address irrigation scheduling and validate the results. The collected data are interpreted and analyzed at an appropriate scale and frequency, and this enables the delivery of innovative water management services in order to set the scene for the connection between water consumption and yield estimation during the growing season. The new technologies aim to: i) improve water supply efficiency at the farm level, as well as resilience to climate change; ii) plan irrigation based on the combination of physical and physiological parameters; iii) manage the effects of reducing irrigation regimes on crop yields; iv) test biostimulants – known and new ones – on crop use performance; v) manage irrigation with respect to the water salinization levels; and vi) optimize irrigation performance in terms of surface water ecological flow or groundwater levels. Thanks to these new technologies, the relationship between water stress levels and product quality parameters will be better controlled, and support for certification schemes for water savings based on new environmental labeling will be available.

GWE should be easily calculated because its two components can be measured.

3.3. Emerald water

The evaluation of the ecosystem services associated with the presence of water in irrigated territories is quite a recent topic, but the international literature has produced interesting contributions aiming to discriminate and describe positive and negative impacts (Avellán et al., 2018), highlight the need for stakeholders' involvement and payment systems (PES) (Jourdain and Vivithkeyoonvong, 2017; Ricart et al., 2019; Pérez-Blanco et al., 2022), and examine the advantages and disadvantages of saving water for irrigation to increase the environmental flow (e.g., Crossman et al., 2010; Estes et al., 2022).

Irrigation systems admittedly provide positive ecosystem services in all four categories: i) they contribute to provisioning, which includes food production (crops, fish and livestock), fodder, fuelwood, and pharmaceutical plant resources; ii) they support nature since irrigation systems host wildlife (birds, fish, biodiversity); iii) they regulate local climate, the water cycle, water purification and nutrient cycling; iv) they provide cultural services, since irrigation landscapes have a recreational value for many people, including urbanites, and a spiritual value especially in the rural communities managing ancient irrigation systems (Fleming et al., 2014; Raheem et al., 2015; Weerahewa et al., 2023). On the other hand, in some cases, human-built infrastructures related to irrigation can cause biodiversity losses and degrade ecosystem services (Avellán et al., 2018). In addition, in some cases the ecosystem services may become positive not immediately after the introduction of irrigation or the modification of the irrigation schemes: in fact, the environmental conditions are changed, a new climax has to be found and this takes time.

A same ecosystem service may be interpreted in contrasting ways, as exemplified in boxes 2 and 3.

Evaluating ecosystem services is complex because the processes can be difficult to measure, some services are non-material, and perception may differ among stakeholders and interests. Different economic approaches are available, but all of them are based on indirect estimations, not on measurements of the water volumes involved (Crossman et al., 2010; Estes et al., 2002; Pérez-Blanco and Sapino, 2022; Zucaro and Ruberto, 2019).

This short paragraph is not exhaustive, but it highlights how difficult it is to quantify the amount of emerald water necessary to support ESs and in turn EWE. This is a challenge for future research.

3.4. Red water

This fraction represents inefficiency. Therefore, it has to be reduced as much as possible. Nevertheless, Perry et al. (2017) warn on the risk of overestimating the beneficial effects of increasing irrigation efficiency by adopting modern technologies. According to their findings, the assumption that the saved water can be released into the environment or dedicated to other uses has not been confirmed in many projects in different parts of the world, particularly in the countries of the Near East and North Africa (NENA) region. The benefits of technology have to go along with physical control of the water resource by governments or other agencies responsible for sustainable use, followed by interventions to reduce allocations. Controlled access to water must precede the introduction of hi-tech, otherwise hi-tech might make the situation even worse: consumption *per* unit area increases, the irrigated area increases, and farmers will tend to pump more water from ever-deeper sources.

4. BENEFICIAL STRATEGIES FOR INCREASING GOLD WATER EFFICIENCY (GWE)

Field conservation practices typical of the rainfed agriculture can be useful to reduce irrigation needs at the field level and consequently cut down the amount of W. Indirectly, they enhance the GWE, since it is given by G/W. These practices can be aimed at increasing the water available to the plant roots or at ameliorating the productivity per unit of water consumed (Rockström and Barron, 2007).

4.1. Increasing the water available to the plant roots

Soil management strategies able to increase the soil organic matter content generally improve the soil structure and its water retention capacity. The effect is more visible in poor soils, where the enhancement of organic matter results in a field capacity higher than the wilting point, hence greater water availability for crops (Lal, 2020). Management options such as reduced soil tillage, organic biomass and amendment inputs, cover crops, crop rotation and others offer a wide choice of farming practices.

Controlled drainage is a rain-harvesting method aimed at retaining water in the soil. In areas with shallow groundwater, it aims to maintain the water table level at a desired depth by retaining an appropriate amount of drainage water in collecting ditches (Skaggs et al., 2012). The water table depth has to be regulated throughout the year with the aim of preserving as much water as possible without generating harmful conditions for crops and soil management purposes.

During the coldest and rainiest period, when rainfall exceeds the evapotranspiration rate (autumn and winter in northern Italy), controlled drainage can be used to avoid complete water outflow. However, special attention must be paid to prevent waterlogging (Gilliam and Skaggs, 1986) and allow agricultural soils to serve as temporary water storage units during heavy rainfall events to contribute to the hydraulic safety of the territory. In this sense, the management of controlled drainage at the field and district levels has to be accurate and integrated with land reclamation authorities and agro-meteorological services providing reliable rainfall forecasting in terms of timing, amounts, and spatial distribution. If heavy rain is forecast and the water table is close to the soil surface, the drainage network has to be promptly discharged to offer empty porosity to store the forthcoming precipitation. Correctly managed controlled drainage has proved to allow saving up to 80% of the outflow volumes as compared to conventional drainage (Bonaiti and Borin, 2010; Tolomio and Borin, 2018), with subsequent advantages for crops (Tolomio and Borin, 2019).

4.2. Increasing productivity of water

When switching a territory from rainfed to irrigated, cropping systems usually evolve, and a wider choice of crops is possible. This can lead to an increased water demand and has to be carefully considered in the planning phase. To optimize irrigation, the cropping system has to be adapted in a different way: with a given amount of water allocated to an area (basin, district, farm), the target becomes the individuation of the crops and varieties allowing the best profit from water use. If water availability is a limiting factor, crops with lower water requirements can be adopted, like sorghum or sunflower (Giannini et al., 2022). Promising results are related to the availability of drought-tolerant maize varieties that yield more in drought-stressed environments with no penalty in non-stressed environments (Adee et al., 2016), and require less water to maximize grain yield as compared to the conventional hybrid (Mounce et al., 2015). Therefore, careful selection of hybrids can increase corn yield and WUE under water-limited conditions (Hao et al., 2015). The adequate choice of crop and variety has to be accompanied by all the other options permitting to increase the proportion of evapotranspiration flowing as productive transpiration as to obtain “more crop per drop”. Adequate timing and spacing of sowing, weed and pest control, mulching, are only some examples of the wide range of the opportunities that can be adopted.

5. CONCLUDING REMARKS

Irrigation is indispensable to achieve the Zero hunger target of the 2030 UN Agenda because it is a powerful tool for sustainable intensification, and aims to produce more *per* surface unit.

Tackling the issue of ensuring more nutritious food for a growing population, the higher productivity of irrigated lands can slow down the pace of deforestation, hence “more irrigation, less deforestation”. As meeting the future worldwide food needs has to be nutrition-sensitive, with diets often composed of relatively water-intensive foods (e.g., legumes, nuts, poultry and dairy products), the sustainable use of water resources will be ever more crucial (FAO, 2020).

Agriculture has an important role to play on the path to sustainability, as irrigated agriculture accounts for more than 70% of global water withdrawals worldwide. The way agriculture uses freshwater is crucial to ensure availability for other activities and preserve water-related ecosystems. Wise irrigation can contribute to allocate water within the framework of an integrated and sustainable management with a view to turning conflicts among users into synergies. This implies multiple subjects and actors in a multi-disciplinary approach.

The process leading to an integrated and sustainable water management can be figured out as the recipe of a delicious pie requiring ingredients and a MasterChef®.

The ingredients are:

– **Awareness**: everybody is aware of the drama of water scarcity and shortage and related disasters under the climate change scenario. In Europe, June 2022 was the third warmest on record globally and a sweltering heatwave contributed to record-breaking temperatures in many locations and had disastrous consequences on the agricultural sector (Devot et al., 2023). In Italy the combination of low rainfall and high temperatures has led to losses in agricultural production exceeding 6 billion euros (Coldiretti, 2022). The UN World Water Day, celebrated yearly on March 22nd, is only one of the many initiatives raising awareness and inspiring actions to tackle the water and sanitation crisis.
– **Urgency**: about 3.2 billion people, 1.4 billion of whom live in rural areas, are experiencing moderate to high levels of water stress, and 2.2 billion are living without. These huge figures underline how urgent it is to act, as stated by the UN SDG 6 Clean water and sanitation.
– **Technology**: never in human history have available technologies been abundant as today, and progress is continuously running and offering new solutions. Technologies in the irrigation sector offer a wide range of choices, from satellite imagery, automated control systems, precision irrigation methods to the simple smartphone app supporting farmers in the management of irrigation. Technology itself is not sufficient to reduce water consumptions by irrigated agriculture (Perry et al., 2017), adequate prepara-

tion and policy measures are required. On the other hand, technology provides an enormous stimulus for innovation and training, and adequate updating of operators for optimal use of water resources (ANBI, 2023).

- **Knowledge**: public and private researchers, technicians, institutions are issuing publications, reports, guidelines, and many other documents that continuously increase the wealth of knowledge available on the topic on water management in agriculture. FAO and WMO are leading bodies in spreading updated information on tendencies and figures at the world scale.
- **Skills:** knowledge and technology have to be combined to design the right solutions for the specific problems to be tackled. Dealing with irrigation within a sustainable water management framework, no unique solution is to be adopted uncritically in all conditions and environments. The problem is typically multi-disciplinary, and experts have to be able to read and recognize local situations and design tailored solutions: common issue, multiple answers.
- **Vision,** related to skills: the people involved in sustainable irrigation should be open-minded, able to work together with experts in different disciplines, willing to consider different solutions with respect to their own point of view. The projects have to be visionary, turned toward the future, rather than replicate already existing solutions.

The MasterChef® is represented by decision makers…, but the emerald is a symbol of hope, future, growth and renewal. Let us be optimistic!

ACKNOWLEDGMENTS

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them. Spoke 4, Work Package 4.2, Task 4.2.1 "Farm network setup (Living Labs): a network of farms representative of the different agricultural systems to apply innovative technologies for the sustainable management of crops, animals and forests" and Work Package 4.3, Task 4.3.3 "Risk management strategies and policies in the context of climate change".

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BOX 1 – CLIMATE AND CLIMATE CHANGE IN ITALY

Italy is characterized by a wide variation of climatic conditions ranging from temperate to Mediterranean as a result of the interaction of a continental climate (northern and central-northern areas) with that of the Mediterranean basin (centre, south and islands) (Finke et al., 1998). This situation yields seven climatic regions described in Table 1 (Dal Ferro and Borin, 2017). The temperature trend shows increasing values, especially so since the 1990's (Figure 1).

Total rainfall is characterized by high variability across years, with a below-average period between 1985 and 1995. In the last 61 years, 2022, 2017 and 2001 have been the driest years, while 2010, 1976 and 1996 have been the wettest ones (Figure 2).

Increased lengths and frequencies of dry periods have been recorded in the last years, especially in the northern regions. The reduction of precipitations has clearly affected the aquifers, that have showed water retention values close to the historical minimum. In some Italian regions, a decrease of 60-70% in winter rainfall volumes has been recorded. In addition, winter snowfalls have also decreased, so that thawing and the overall water reservoirs have decreased too. Winter precipitations (both in the forms of rainfall and snow) almost completely infiltrate the rocks and soil and thus recharge groundwaters, also thanks to the low evapotranspiration rates. Thawing generally starts at the end of spring, and supplies surface water reservoirs before dry summers. Winter drought causes a deficit in the accumulation of water reserves, and its negative effects carry on into the irrigation season.

Table 1. Italian climatic regions.

Climatic regions	Annual temperature (°C)	Annual rainfall (mm)	Elevation range (m)	Wettest months	Driest months	Extension (%)
Alpine	2.8-10.7	838-1510	0-4000	Oct., May-Jun.	Jul.	17.7
Po Plain sub-continental	10.9-13.0	710-1030	0-600	Oct.	Jul.	17.5
Northern Apennines sub-continental	8.9-13.5	1000-1540	100-2000	Oct., Nov.	Jul.	13.4
Southern Apennines sub-continental	10.4-15.4	725-1160	0-2500	Jan.	Aug.	8.4
Coastal Mediterranean	11.7-16.4	735-1180	0-1300	Oct., Jan.	Jul.-Sept.	17.7
Semi-arid Mediterranean	13.9-18.5	560-1130	0-1700	Oct., Jan.	Jul.-Sept.	17.4
Arid Mediterranean	14.8-18.9	420-710	0-650	Nov.	May-Sept.	7.8

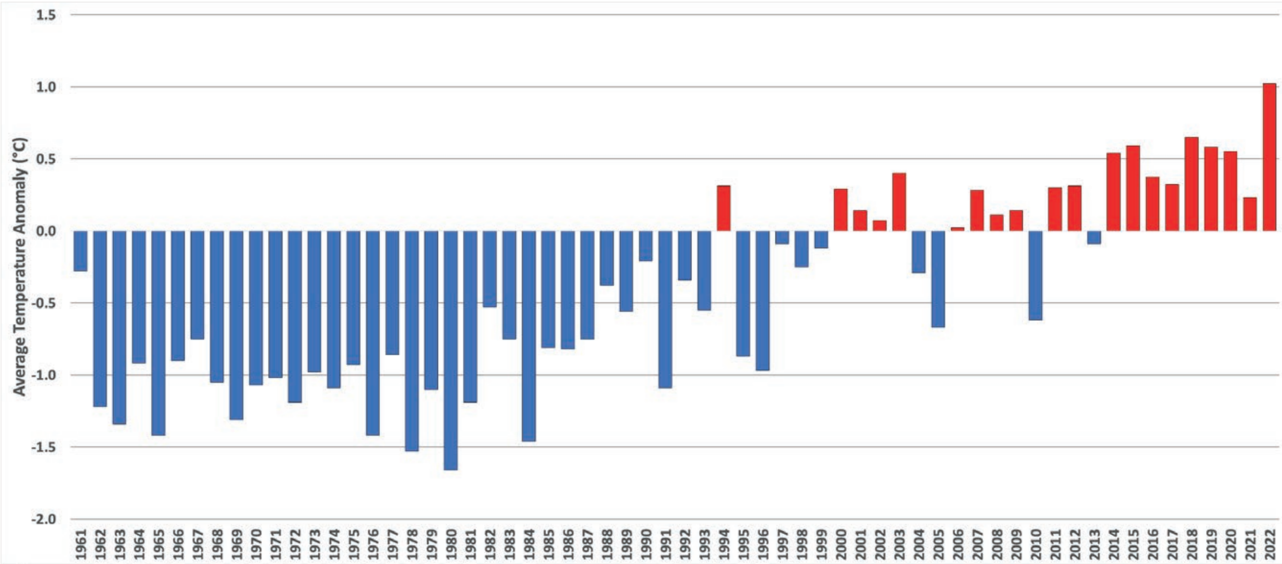

Figure 1. Time series of annual mean temperature anomalies (calculated from the normal value 1991-2020) during the 1961-2022 period. (Source: ISPRA https://www.isprambiente.gov.it/it/banche-dati/banche-dati-folder/clima-e-meteo/stato-variazioni-e-tendenze-del-clima-in-italia).

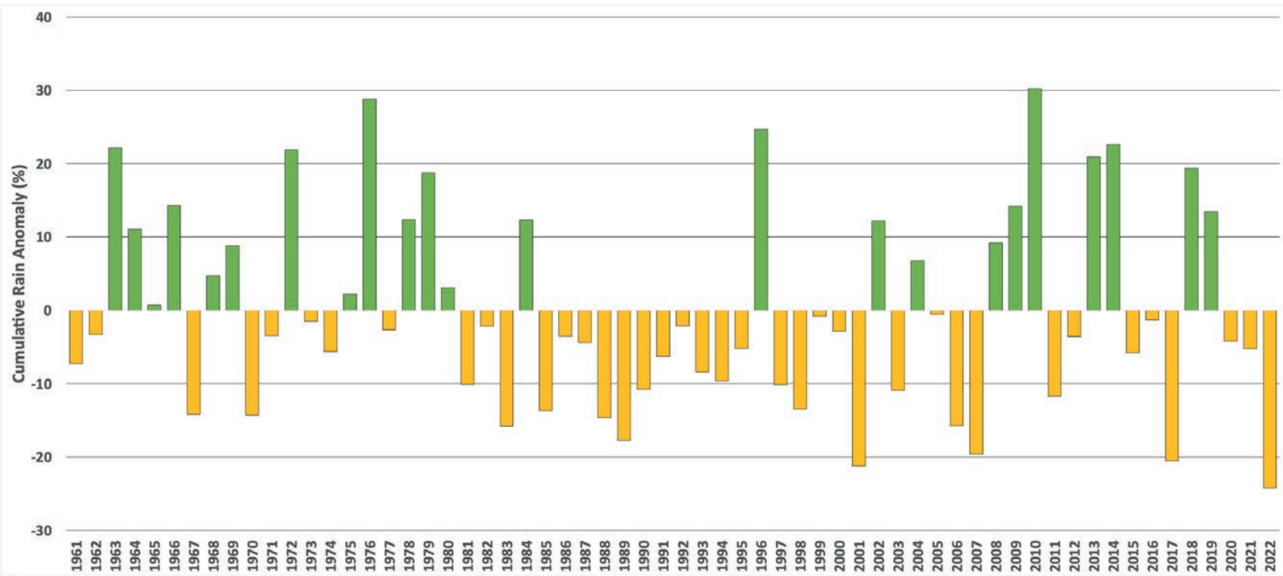

Figure 2. Time series of annual cumulative rainfall anomalies (calculated from the normal value 1991-2020) over the 1961-2022 period. (Source: ISPRA https://www.isprambiente.gov.it/it/banche-dati/banche-dati-folder/clima-e-meteo/stato-variazioni-e-tendenze-del-clima-in-italia).

BOX 2 – INEFFICIENT IRRIGATION AND AQUIFER RECHARGE: AN ECOSYSTEM SERVICE OR A DIS-SERVICE?

In the FAO Discussion Paper "Does improved irrigation technology save water? A review of the evidence", Perry et al. (2017) state that …*percolation from "inefficient" irrigation is often a major source of aquifer recharge*… and this can be interpreted as an ecosystem service. This statement contains the word "often", meaning that its validity is related to the majority of the case studies analyzed in the document but does not stand as a dogma. In other words, the role of aquifer recharge as a result of percolation from inefficient irrigation has to be defined in relation to local conditions.

In northern Italy, inefficient irrigation methods distribute 78% of the total irrigation volume; the value goes down to 31% if irrigation of rice (flooding) is excluded. Several water authorities and researchers are favorable to preserving surface and furrow irrigation, and highlight their contribution to groundwater recharge. Is this an ecosystem service or rather a dis-service? This brings about a few reflections:

1. Is it suitable to withdraw water from a river and decrease its flow during the most critical period of the year to use this water in an inefficient way?
2. Is it possible to manage aquifer recharge in other ways? The UNESCO report "Managing Aquifer Recharge: A Showcase for Resilience and Sustainability" (Zheng et al., 2021) presents 28 real-life examples of managed aquifer recharge (MAR) from around the world, and provides irrefutable evidence that water resources can be sustained, groundwater storage increased, environmental flows in streams enhanced, and seawater intrusion prevented, while passively "treating" water to improve its quality with natural processes. Different types of recharge methods are described, like in-channel modification, bank filtration, water spreading through infiltration basins, buried pipes, and recharge wells. The systems are functioning all over the year with different water sources, including treated waters. Special attention is paid to recovering water during the winter months. Therefore, alternative and sustainable solutions are available, a change of mindset is desirable.
3. (and not least) non-efficient irrigation and ensuing water percolation also cause non-point pollution, since nitrates and agrochemicals can be leached during irrigation.

The forested infiltration area (FIA) is a method for recharging groundwater aquifers by channeling surface waters during non-irrigation months (from September-October to April in northern Italy) to designated areas planted with various tree and/or shrub species (Figure 1). In addition to aquifer recharge, FIAs can offer ecosystem services such as renewable energy production, reduction of greenhouse gas emissions, landscape enhancement, or biodiversity increase.

These arguments suggest that in northern Italy the "dogma" stating that surface and furrow irrigation systems provide the ecosystem service of aquifer recharge has to be at least questioned.

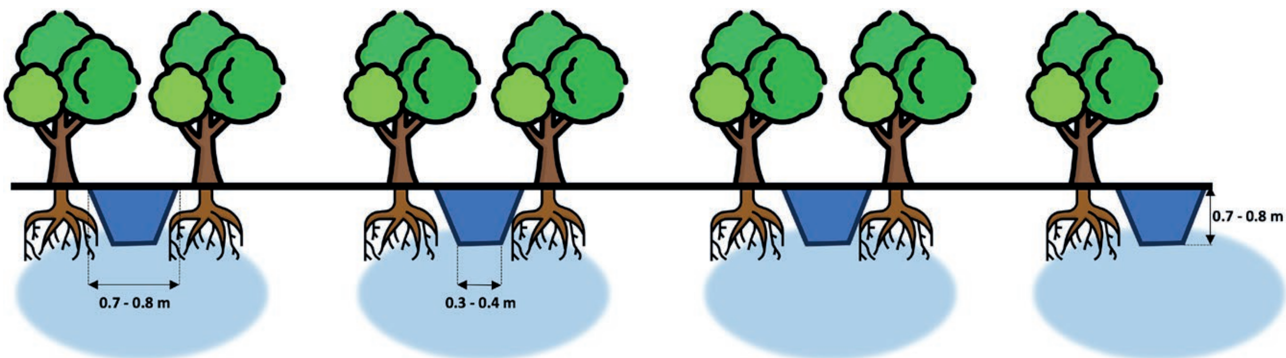

Figure 1. Scheme of a Forested Infiltration Area.

BOX 3 – IS THE DISTRIBUTION SYSTEM DELIVERING EMERALD OR RED WATER?

In Italy, around 150,000 out of more than 230,000 km of irrigation and drainage open-air canals and ditches are managed by the Reclamation and Irrigation Agencies (Consorzi di Bonifica) (www.anbi.it). This is a huge network, whose length is almost 4 times the Earth's circumference, that distributes water across the territory and stimulates life. On the other hand, only a fraction of the water delivered by such systems reaches the crops and is turned into gold water. A significant fraction is lost: does this provide ecosystem services or become red water?

Figure 1 shows an irrigation ditch distributing water withdrawn from Brenta River in northern Italy, in a typical historical system implemented in the medieval times. It is possible to assign this simple hydraulic element a list of ecosystem services, such as:

- Regulating services: microclimate regulation through shading, windbreaking, evapotranspiration, water cycle regulation, CO_2 sink in the riparian vegetation;
- Supporting services: supporting biodiversity as the stream itself and its hedgerows are ecological corridors; supporting life below water, pollinators, etc.;
- Provisioning services: wood, small fruits, fish, herbs;
- Cultural services: landscaping, visiting and relaxing, historical elements and infrastructures.

Substituting the open-air ditch with a pipeline would dramatically reduce water losses for sure , but is the change of landscape imaginable? Again, it is necessary to determine whether the ecosystem services appraised in this territory might cause dis-services in the lower part of the riverbed due to flux reduction and to quantify the amounts of water really necessary for the ecosystem services (emerald fraction) in order to avoid unnecessary losses.

Figure 1. Example of the ecosystem services of an irrigation ditch distributing water.