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Review

Methodologies for Water Accounting at the Collective Irrigation System Scale Aiming at Optimizing Water Productivity

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Abstract: To improve water use efficiency and productivity, particularly in irrigated areas, reliable water accounting methodologies are essential, as they provide information on the status and trends in irrigation water availability/supply and consumption/demand. At the collective irrigation system level, irrigation water accounting (IWA) relies on the quantification of water fluxes from the diversion point to the plants, at both the conveyance and distribution network and the irrigated field level. Direct measurement is the most accurate method for IWA, but in most cases, there is limited metering of irrigation water despite the increasing pressure on both groundwater and surface water resources, hindering the water accounting procedures. However, various methodologies, tools, and indicators have been developed to estimate the IWA components, depending on the scale and the level of detail being considered. Another setback for the wide implementation of IWA is the vast terminology used in the literature for different scales and levels of application. Thus, the main objectives of this review, which focuses on IWA for collective irrigation services, are to (i) demonstrate the importance of IWA by showing its relationship with water productivity and water use efficiency; (ii) clarify the concepts and terminology related to IWA; and (iii) provide an overview of various approaches to obtain reliable data for the IWA, on the demand side, both at the distribution network and on-farm systems. From the review, it can be concluded that there is a need for reliable IWA, which provides a common information base for all stakeholders. Future work could include the development of user-friendly tools and methodologies to reduce the bridge between the technology available to collect and process the information on the various water accounting components and its effective use by stakeholders.

Keywords: water demand; water availability; hydrant; distribution network; remote sensing; beneficial use; water losses; irrigation efficiency; irrigation requirements; monitoring

Citation: Ferreira, A.; Rolim, J.; Paredes, P.; Cameira, M.d.R. Methodologies for Water Accounting at the Collective Irrigation System Scale Aiming at Optimizing Water Productivity. *Agronomy* **2023**, *13*, 1938. https://doi.org/10.3390/agronomy13071938

Academic Editor: Huihui Zhang

Received: 14 June 2023
Revised: 14 July 2023
Accepted: 20 July 2023
Published: 22 July 2023

1. Introduction

Demand for food is expected to continue growing in the coming decades, which will increase pressure on water resources, leading to a shortage in rivers and aquifers [1,2]. A main challenge for agricultural water management will be to ensure food security and long-term environmental [3,4] and economic sustainability [5,6]. Other factors, such as the competition for water and land, droughts and anthropic water scarcity aggravated by climate change, and less-participatory water governance, will contribute to this challenge [1]. According to several authors, e.g., refs. [5,7], by the year 2050, food demand could increase by 70–90%. Although irrigated agriculture represents 16% of the world's cropped area, it is expected to produce 44% of world food by 2050 [2]. It is estimated that the net global irrigated area will continue to increase by at least 20 million hectares [8]. In some cases, water abstractions from nonrenewable aquifers and withdrawals can exceed 100% of the total renewable resources [9]. Irrigation plays a crucial role in food security by increasing and stabilizing production from farms to the global levels. It is agreed that irrigated agriculture will face a future with less water [7]; thus, the irrigation efficiency gap needs to be overcome. As stated by de Fraiture and Wichelns [10], it is more cost-effective to increase food production by improving output per unit of water in existing irrigated areas than by expanding irrigated areas. Thus, in low-productivity irrigated regions, additional food demand can be satisfied by improving water productivity (WP) [5,11,12].

In arid and semi-arid regions, where water is a scarce resource, farmers often rely on collective management to optimize water use and minimize conflicts among users [13–15]. Thus, in these regions, collective irrigation systems (CIS) are common. However, the performance of CIS around the world has been below expectations [16]. The assessment of the global irrigation system performance is, therefore, an essential primary step toward improving agricultural water use, particularly with regard to supporting decision-making on modernization investments and management changes. At this level, the improvement of irrigation must encompass both the conveyance and distribution network and the on-farm systems [17], as well as water availability at the source (surface water or groundwater).

Water accounting (WA) procedures can play a crucial role in improving irrigation water productivity and irrigation efficiency [18–20] since they involve the systematic measurement, monitoring, estimation, and reporting of water resources in irrigated systems [21,22]. A distinctive aspect of the WA methodology is that it considers and assesses both the supply and demand aspects of irrigation systems [23], allowing for the identification of possible failures and adjustment of water management at the collective irrigation system level.

Direct water metering of several water balance terms is the most accurate method for WA. Yet, the majority of agricultural water use is not monitored worldwide, with limited metering of irrigation amounts despite increasing pressure on both groundwater and surface water resources in many agricultural regions [24,25]. This lack of monitoring can hinder the implementation of WA procedures in irrigation. However, there are some methodologies to estimate agricultural water, e.g., databases, indicators, and remote sensing. Additionally, models, from simple empirical to process-based ones, can be used to estimate agricultural water terms.

The wide implementation of WA is also constrained by the vast terminology used in the literature for different scales and levels of application [19,20,26]. Thus, there is a need for clarifying terminology and procedures related to the use of water accounting in agriculture and water productivity.

This paper presents a thorough critical assessment of the literature on irrigation water accounting concepts and methodologies developed from the perspective of the demand component at the collective irrigation system level, highlighting the strengths, limitations, practical issues, and research gaps. In particular, it aims to achieve the following:

i. Demonstrate the importance of irrigation water accounting by showing its relationship with water productivity and water use efficiency;
ii. Clarify the terminology related to water accounting;
iii. Review the existing methodologies for water accounting both at the farm and at the irrigation distribution network and propose some adaptations.

A systematic literature search was not possible due to the lack of common terminology on the subject. Thus, an exploratory research methodology applied was characterized by not following a defined protocol and can be described as follows. It began with a general idea and the researcher's ability to change his direction due to the revelation of new data or insight. The purpose was to provide a broad approach to the topic area. The review used several search engines (e.g., ScienceDirect, Scopus, Springer, Wiley) and various languages for the search (English, Portuguese, Spanish, and French).

2. Irrigation Water Productivity and Irrigation Efficiency

Despite the numerous studies available in the literature, there is still a lack of agreement on terms and concepts related to water productivity and water use efficiency [20,26,27]. This may lead to confusion in the interpretation of data and constrain the comparison between different studies [28]. In its broadest sense, agricultural water productivity (WP) is the ratio of the benefits that stem from crop, forestry, fishery, livestock, and mixed agricultural systems to the amount of water used to produce those benefits [20,26,27]. WP usually focuses on crops (crop water productivity), e.g., refs. [26,29], or on livestock (livestock water productivity, e.g., refs. [30,31]. Thus, the optimization of WP in agriculture allows growing more food with less water, aiming to meet the goals of food security while better using the water resources, particularly in a climate change context due to the expected increase in water scarcity [20,32,33].

Hereinafter, WP will focus solely on crops. The most commonly used concept of WP refers to the physical ratio between marketable yields and water applied or used [18,27,34]. Despite the apparent simplicity of this indicator, several authors argue that there are numerous ways of developing it since the denominator of the ratio varies with the scales and objectives [26,27,35].

The concept of WP may be applied at different scales, from the plant to the collective irrigation system (Figure 1).

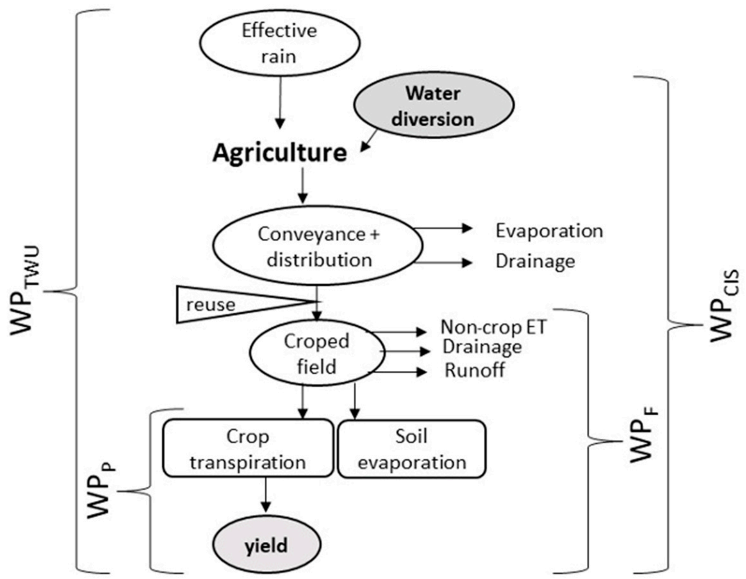

Figure 1. Water productivity in agriculture at various scales, the plant (WP_P), the field (WP_F), and the collective irrigation system (WP_{CIS}), including precipitation (WP_{TWU}) (Adapted from [26]).

The first step in the estimation of WP is an adequate definition of a domain linked in space (3D) and time [32], from the plant to the field and to the collective irrigation system. Various authors estimate WP using the total water use (TWU), the gross irrigation, or the crop evapotranspiration as a denominator [26,27,29,36]. However, we argue that the use of these variables does not adequately mirror the water that is effectively consumed. On one hand, there are losses at the field level that occur since the water is delivered at the hydrant/turnout, which can represent a large fraction of the water supplied. On the other hand, at the collective irrigation system level (CIS), the denominator should encompass the water that is diverted into the conveyance and distribution network (CDN), including the losses due to leakage, seepage, and evaporation in channels and pipes, and the on-farm application losses. Thus, we propose the following physical WP indicators:

At the field level:

(a) WP relative to the total water use (WP_{F_TWU}), estimated as

$$WP_{F\_TWU}(\mathrm{kg\,m^{-3}}) = \frac{Y}{I_{SH} + P + \Delta S + CR} \tag{1}$$

where Y is the crop yield for the field (kg), I_{SH} is the irrigation supply at the fields' hydrant, P is the precipitation, ΔS is the variation of the soil water storage, and CR is the capillary rise from a shallow water table; with all the variables expressed in m^3;

(b) irrigation water productivity (WP_{F_Irrig}), estimated as

$$WP_{F\_Irrig}(\mathrm{kg\,m^{-3}}) = \frac{Y}{I_{SH}} \tag{2}$$

At the collective irrigation system:

(c) WP relative to the total water (WP_{CIS_TWU}), estimated as

$$WP_{CIS\_TWU}(\mathrm{kg\,m^{-3}}) = \frac{Y_{CIS}}{DIV + P} \tag{3}$$

where Y_{CIS} is the average yield for the entire irrigation perimeter weighted by the area occupied by each crop (kg), DIV is the water diverted into the conveyance and distribution network of the CIS; with all the variables expressed in m^3; and

(d) irrigation water productivity (WP_{CIS_Irrig}) estimated as

$$WP_{CIS\_Irrig}(\mathrm{kg\,m^{-3}}) = \frac{Y_{CIS}}{DIV} \tag{4}$$

where Y_{CIS} is the average yield for the entire irrigation perimeter weighted by the area occupied by each crop (kg).

However, improving physical WP does not necessarily lead to reduced water use or an improvement in farm profit [26,28,35,37]. Economic water productivity, which refers to the ratio between the value of the product and the water applied, allows for the assessment of the economic yield value per unit of water supplied. However, aiming at providing a better perception of the farmers' economic return and therefore of the feasibility of a certain cropping system [18,26–28,38], both the numerator and denominator in Equations (1)–(4) should be expressed in economic terms [26,35,39].

Agricultural water use efficiency (WUE) is in certain cases synonymous with water conservation and water savings [40], but for irrigation specialists, it is a measure of how efficiently water is used in agricultural production [20,26,41]. One of the WUE components is irrigation efficiency (IE). It is defined as the ratio between the amount of water used to meet the beneficial use by the crop (ET) plus the amount necessary to maintain a favorable salt balance in the crop root zone, and the total volume of water diverted for irrigation (DIV) [41,42]. Thus, at the CIS level, IE depends upon the water losses occurring at each stage as water flows from the origin (e.g., reservoir with storage losses), conveyed and distributed to the farm gate (conveyance and distribution losses), from the farm gate to the irrigation system (on-farm transport losses), and in the soil root zone (application losses).

In the present work, we propose the following irrigation efficiency (IE) indicators:

(a) at the field level (IE_F)

$$IE_F(\%) = \frac{ET + LF}{I_{SH}}100 \tag{5}$$

(b) at the conveyance and distribution level (IE_{CDN})

$$IE_{CDN}(\%) = \frac{\sum_{j=1}^{n} I_{SHj}}{W_{CDN}}100 \tag{6}$$

(c) at the collective irrigation system level (IE_{CIS})

$$IE_{CIS}(\%) = \frac{ET + LF}{W_{CDN}}100 \tag{7}$$

where ET is the crop evapotranspiration, LF is the salt leaching requirement, I_{SH} is the water delivered at the hydrants/turnouts working simultaneously, j is the hydrants/turnouts, and W_{CDN} is the water diverted into the conveyance and distribution network of the CIS.

IE is variously linked to WP depending on circumstances. As discussed by [43], IE can paradoxically increase water consumption from irrigated farming systems. A higher IE can, as a result of lower 'losses' in the WP denominator, reflect greater transpiration correlated with higher crop growth and higher WP (e.g., refs. [26,44]). However, a higher IE resulting from changes in infrastructure and equipment can increase costs and reduce the net crop value in the WP numerator and, in turn, reduce WP [45,46]. Higher IE can reflect the maintenance of more uniform soil moisture within a field leading to higher WP (e.g., [34,47]. On the other hand, lower IE impacts crop stress and reduces productivity by slowing the timing of water delivery between neighboring irrigators sharing a local network, thus leading to lower yields, and possibly lowering WP. Similar findings were reported by [48], while [49] reported an improvement of WP at the irrigation scheme by improving the irrigation system performance at the field level.

The calculation of the above indicators, WP and IE, relies upon the quantification of the intervenient terms, e.g., irrigation water supply and beneficial and nonbeneficial uses. This extensive set of data can only be obtained through an appropriate irrigation water accounting framework, providing accurate and timely information, as described below.

3. Water Accounting

3.1. Definitions and Evolution

Water accounting can be defined as the systematic quantitative assessment of the status and trends in water supply, demand, distribution, accessibility, and use in specified domains, producing information for water science, management, and governance to support sustainable development outcomes for society and the environment [21,22]. The WA procedure relies upon the law of conservation of mass through water balances, which in turn identify the destination of the water used and distinguish between consumptive and nonconsumptive uses [18,22,50,51].

The WA concept has evolved over time, with different researchers and organizations contributing to its development. In the late 19th and early 20th centuries, irrigation technology advanced in Europe and North America, and new methods for measuring irrigation water supply and use were developed. For example, water meters were installed on irrigation systems to measure water applied, allocated, or delivered, and irrigation districts began charging farmers based on the volume of water used [52–54]. In the mid-20th century, with the increasing demand for water resources for other uses, such as industrial and urban applications, WA became more important for water resources management (WRM) among users at a larger scale [32].

The United Nations (UN) established the International Hydrological Program (IHP) in 1975 (https://www.unesco.org/en/ihp, accessed on 2 May 2023), which has evolved into a holistic program facilitating the sustainable WRM and governance, based on science, reliable data, and dissemination of knowledge. Food and Agriculture Organization of the UN (FAO) is one of the organizations that has played a major role in the development and promotion of WA in irrigated agriculture. In the 1960s and 1970s, FAO developed guidelines for WA, focused on measuring water use in agriculture for the improvement of irrigation management. In the early 2000s, FAO initiated the AQUASTAT program, Global Information System on Water and Agriculture (https://www.fao.org/aquastat/en/, accessed on 2 May 2023), which aimed to improve the global knowledge base on water resources by collecting, analyzing, and disseminating information on water resources and their use by country.

The International Water Management Institute (IWMI) developed the Water Accounting Plus (WA+) framework (https://wateraccounting.un-ihe.org/wa-framework-0, accessed on 2 May 2023) in 2013, in partnership with the IHE-Delft Water Accounting team and FAO. It applies a comprehensive approach to measuring and managing water resources in agriculture at the basin level, with a strong focus on satellite-based remote sensing (RS) data. It has been widely used in different regions and contexts [55–57]. The framework combines RS data with other available global datasets and ground measurements to produce WA sheets supported by graphs and tables, which provide a standardized approach to tracking water resources and their use in different sectors, including agriculture. The approach is based on the principles of Integrated Water Resources Management that emphasize the need for WRM using a holistic approach, considering social, economic, and environmental factors.

In 2018, FAO and World Water Council released a white paper on water accounting for agriculture [58], an initiative that contributed to the work plan of the Global Framework on Water Scarcity previously launched at the Marrakech Climate Conference in November 2016. The World Bank also contributed to the development of WA by developing its own framework and methodologies for tracking water resources and use [59].

Recently, FAO developed and made available the portal WaPOR (https://wapor.apps.fao.org/home/WAPOR_2/1, accessed on 2 May 2023) that monitors WP through open access of remotely sensed derived data to support water accounting at different scales. Data are available at diverse resolutions (250 m, 100 m, and 30 m) and temporal resolutions (10–day, seasonal, annual). This tool is available for monitoring and reporting on agricultural WP over the African continent and Near East.

In recent years, the concept of WA has been incorporated into the United Nations Sustainable Development Goals, which aim to ensure by 2030 universal access to clean water and sustainable water management practices (https://sdgs.un.org/goals, accessed on 2 May 2023).

To standardize the concept of water use for the different stakeholders, Molden [50] defined WA as the art of classifying the components of the water balance into water use categories, considering the consequences of human intervention in hydrological cycles and the domain of inputs and outputs according to their uses and productivity. Different definitions of WA can be found in the literature, e.g., refs. [21,22,51,60].

Agricultural WA, or more precisely and within the scope of the present review, irrigation water accounting (IWA), involves the systematic measurement, monitoring, estimation, and reporting of water resources in irrigated systems [21,22]. The methodology considers and assesses both the supply and demand aspects of irrigation supply systems [23] and integrates different uses of water, as conceptually presented in Figure 2, into the water balance.

An initial and critical step of IWA is to define the system (3D) domain and specify spatial and temporal boundaries, which are dependent on the study objectives. It can be the root zone of an irrigated field for an irrigation event, from the water diversion to the farm gate, or an entire water basin, including surface water and groundwater, over a period of several years [61]. It also involves classifying inflows and outflows across the domain borders according to their uses. Gross inflow (Figure 2) is the total amount of water flowing into the water balance domain from precipitation and surface and subsurface sources. Net inflow is the gross inflow plus any changes in storage. Water depletion is the use or removal of water that renders it unavailable or unsuitable for further use. It entails water that goes to the atmosphere (beneficial water consumption) or other sinks (nonbeneficial use). An example of the latter is the non-recoverable runoff and drainage because (i) it is not economically exploitable, such as saline water bodies and deep aquifers, or (ii) its quality prevents its reuse.

Outflow is the part of the diverted water that can be reused. It is divided into committed and uncommitted fractions. The first fraction encompasses the outflow that is allocated to other uses, e.g., downstream water rights, while the latter corresponds to water flowing out of the considered domain due to a lack of storage or operational measures. It is the case of water flowing to the sea, in excess of the requirements for beneficial uses [61].

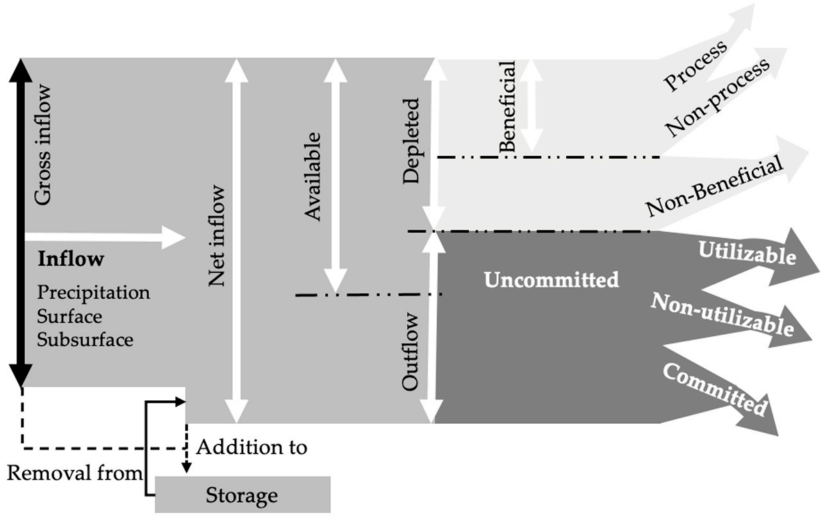

Figure 2. Global water accounting considering inflows and outflows according to different uses (Adapted from [62]).

3.2. Different Perspectives on Irrigation Water Accounting

IWA has been approached from various perspectives, each one providing different insights into the WRM and the role of irrigation in sustainable development. According to some authors, e.g., refs. [18,32], water accounting has developed from three distinct perspectives.

- The hydrology perspective: This perspective focuses on understanding the natural water cycle and quantifying the role of precipitation, evaporation, and transpiration, runoff to streams and rivers, recharge to aquifers, outflows to the sea and storage, to determine water availability in a particular region [18,50], usually a basin;
- The irrigation engineering perspective: This perspective focuses on interventions designed to utilize surface water or groundwater flows to meet irrigation requirements. It also focuses on the design, construction, and operation of storage structures, conveyance and transport of irrigation water, control structures, and on-farm irrigation systems [11,22,63,64]. From this perspective, IWA can help identify the water requirements of different crops and quantify nonbeneficial uses, such as evaporation and leakage, at both the field and the conveyance and distribution network levels. In this case, the impact of different management practices on water use efficiency and WP can be assessed. Ultimately, it can identify opportunities to modernize the CDN [63,65];
- The monitoring and evaluation perspective: This perspective focuses on the use of water accounting to support management decisions. Examples are the optimization of water distribution to farmers, optimization of irrigation schedules, use of more efficient irrigation systems, adoption of drought-tolerant crops, or accessing incremental improvements in policy and practice on both the supply and demand sides of water supply and delivery services [6,21,22]. Decisions on water management are usually made at different levels, including farms, water users' associations, and regional water planning agencies.

Other authors also debated the following perspectives of IWA, which can be considered transversal to the previous ones.

- The environmental perspective: This perspective focuses on the assessment of the impact of irrigated agriculture activities on water quality and the environment. This includes monitoring the discharge of pollutants from agricultural sources, such as fertilizers and pesticides, and evaluating the impact of agriculture on water quality and aquatic ecosystems [66–69];

- The economic perspective; This perspective focuses on the value of water resources in agriculture and the costs and benefits of its use [20,47,70–72]. It seeks to optimize the use of water resources to maximize agricultural productivity and profitability. This involves evaluating the costs and benefits of different irrigation systems, crop varieties, and water management practices, and developing policies and programs that promote the efficient use of water resources in agriculture and effective water allocation [11], pricing, and management [65,73];
- The social perspective: This perspective is concerned with issues such as access to water for irrigation, equity, social justice, and participation in water governance [74,75]. It involves assessing the social and cultural values of water, identifying the needs and priorities of different stakeholders, and developing policies and programs that promote social equity and participation [76,77].

An integrated perspective on IWA considers all the above perspectives and seeks to balance economic, environmental, and social considerations [78]. It aims to promote sustainable water management in agriculture that meets the needs of all stakeholders while preserving the environment.

3.3. Scales and Levels for Which Agricultural Water Accounting Procedures Are Developed

Agricultural WA can provide information about water availability and use at different scales [61]. The scale of application depends on the purpose of water accounting and the availability of data and resources. The following scales can be considered:

- Macro scale: This scale corresponds to the basin or sub-basin level, often encompassing multiple uses and services, including agriculture, industry, landscape, and households. Furthermore, at this scale, data should be collected on water use from multiple sources. This scale of application is useful for identifying areas of conflict and cooperation among different water users, for developing integrated water resource management plans, and for understanding the spatial and temporal dynamics of water availability and use in the basin. The WRM at the basin level sets limits to water allocations to reduce consumption to sustainable levels and encourages and supports all users to maximize the net benefit of allocated water [11]. So far, different frameworks have been introduced in this regard, e.g., IWMI-WA [50], SEEAW [79], GPWA [51], and Water Accounting Plus" (WA+) [55]. Delavar et al. [73] present a water accounting framework based on a modified SWAT model for better policymaking at the basin level. Perez-Blanco et al. [80] discuss water basin accounting definitions and concepts. Wheeler et al. [81] use water accounting at the basin level to investigate the rebound effect of groundwater extraction from subsidizing irrigation infrastructure in Australia, while the authors of [67] propose WA to study climate change effects on water resources in different river basins.
- Mezzo scale: This scale corresponds to the service level of analysis within a basin area, typically involving multiple users who share common water supply, conveyance, and distribution [63,82]. At this scale, WA is used to quantify and balance the supply and demand at the collective irrigation system [13–15,63], to determine WP and IF from water diversion to the root zone, and to promote effective water allocation, pricing, and management. It is the scale for which fewer scientific studies are found in the literature, and thus, further research is required.
- Local scale: This is where water availability and use are assessed for a specific area, such as a field or a farm [36,83]. WA involves measuring and monitoring water inputs and outputs, such as rainfall, irrigation water delivered at the hydrant/turnout, water use by crops, and nonbeneficial uses, such as drainage, runoff, and wind drift. Local water accounting can be used to calculate on-farm WP and IF, helping farmers to better manage their water resources, to identify opportunities for water conservation, and to reduce water waste [84].

Agricultural WA can also be applied at different levels, depending on the complexity of the system being analyzed and the level of detail required for decision-making. The following are the common levels of application.

- Sector level: This level involves analyzing the water balance and water use within the agricultural sector, including the water supply and uses for crops [36,83] and livestock [7,30]. This level of application is useful for understanding the water requirements and water use patterns of the sector and for developing strategies to sustainably manage water within the sector.
- System level: This level involves analyzing the water balance and water use for a specific system within a sector. This level of application is useful for optimizing water use efficiency within the system, identifying areas of water loss or waste, and improving the performance of the system. Examples of systems are the irrigated field and the collective irrigation service [63,84], and the specific term irrigation water accounting (IWA) can be used to characterize the system [17,65].

By applying WA at different scales and levels of detail, decision-makers can gain insights into the water requirements and water use patterns of different systems, sectors, and regions, and develop targeted strategies to manage water sustainably for the benefit of people and the environment according to the water availability. A key output of water accounting should be a common information base available and acceptable to all the key stakeholders involved in using, planning, or other decision-making processes [21,22].

3.4. Different Terminology with Similar Meanings: Are We Speaking the Same Language?

Several terms related to understanding and managing the use of water resources are used interchangeably with WA, despite their different meanings and implications. The vast terminology used in the literature for the different scales and levels of application constitutes a setback for a wide implementation of water accounting. The disagreement between terms and concepts often leads to poor use of the published results [19,20,26], confusion in the interpretation of data on crop water use, and comparison between different studies [79]. It is therefore important to identify and distinguish these terms and concepts, being the most common:

Water balance—refers to the calculation of the total amount of water that enters and leaves a particular system, such as a watershed or aquifer, over a specific period. It is important to adequately set the system spatial and temporal boundaries. Water balance is a key component of WA; however, it is only one part of a broader set of activities that make up water accounting [85];

Water footprint—refers to the quantification of the amount of water used throughout the entire supply chain of a product or service, from its production to its disposal. It has three components: the green component is related to the precipitation stored in the root zone, the blue one to the surface or groundwater resources, and the grey component is related to freshwater pollution [71,86,87];

Water auditing—is a process that places the findings, outputs, and recommendations of WA into a broader framework comprising governance, institutions, public and private expenditures, legislation, services delivery, and the wider political economy of specified domains [21,22,51,82];

Water allocation—is the process of assigning available water resources to various uses or users, such as agriculture, industry, and households [11,67,85,88];

Water governance—encompasses a set of political, social, economic, and administrative systems that are in place to develop the WRM and the delivery of water services at different levels of society. It comprises the rules, mechanisms, and processes through which water resources are accessed, used, controlled, transferred, and related conflicts are managed [24,58,89];

Water pricing—is the practice of setting prices for water use to reflect the true cost of water resources and encourage more efficient and sustainable use of water [72,77,90].

Furthermore, the science of hydrology and the practice of irrigation engineering have been developed at different scales [91], which contributes to a large set of different terms to conceptualize WA. A divergence of terminology can pose a challenge to understanding irrigation and other categories of water use within a broader context when irrigation becomes a significant component of basin hydrology [11]. The interpretation of the results depends on both the analyst's background and the scale of the analysis [32]. A farmer or an agronomist usually considers drainage as a loss (depleted/consumptive nonbeneficial use). However, a hydrologist working at the basin level may quantify it as a flux of water within the same system that can be allocated to other uses (nonconsumptive use), with a negligible impact on the basin water balance [19,79,92].

Understanding the interactions between the levels of analysis helps us understand the impact of management decisions and means to benefit from improvements in policy. In order to match irrigation service or basin requirements with field-level interventions, it is necessary to account for water use at the field level and then place it within the context of the irrigation service and basin levels.

4. Water Accounting at the Collective Irrigation System Level: Why Is It So Important?

Collective irrigation systems (CIS) are a type of infrastructure that assures the diversion/abstraction, storage, conveyance, and distribution of irrigation water to the farmers [63] in close relation to the crops and the irrigation systems existing at the field level. Water is diverted from surface sources (rivers and reservoirs) or groundwater wells. The conveyance and distribution is provided either through open channels or pressurized pipes. The delivery of irrigation water to the farm gate is performed through diversion structures, also known as hydrants or turnouts. CIS are usually managed by Water Users Associations (WUA), which are responsible for system operation and for assuring an adequate level of service for the consumers. CIS are common in many parts of the world, especially in arid and semi-arid regions, where water is a scarce resource and farmers often rely on collective management to optimize water use and minimize conflicts among users [13–15]. The assessment of CIS performance is, therefore, an essential primary step toward improving agricultural water use, particularly for making decisions on modernization investments and management changes [16,64,93]. It must encompass both the delivery and the on-farm systems and requires extensive datasets both in time and space.

The objective of the global irrigation water accounting at the CIS level is to quantify and compare or balance irrigation water supply with the demand for both individual irrigated fields and the entire cropping pattern installed within the irrigated perimeter. The relation between the two variables, supply and demand, is called relative irrigation supply (RIS) and is one of the primary performance indicators used to determine the suitability of the supply of irrigation water for agricultural production [16,75,94,95]. Benavides et al. [16] concluded that the on-farm irrigation system clearly affected the RIS, although the global analysis also reflected the effect on the RIS of the characteristics of the collective distribution. Plusquellec [96] stated that one of the main actions toward improving WP in a collective irrigation system was upgrading the hydraulic infrastructure.

Thus, it is very important to apply WA procedures both at the conveyance and distribution network (CDN) and at the irrigated field, the hydrant or the turnout at the farm gate being the link between the network and the field.

At the CIS level, the methodology is applied to a system where the boundaries are the water diversion into the collective network and the bottom of the root zone in the irrigated fields [59,63]. Figure 3 presents the water accounting diagram for the referred domain of application. Furthermore, it is mandatory that the definition of the analysis period should coincide with the irrigation period starting on the first day of water distribution and ending on the last day of water delivery to farmers.

For the convenience of analysis, we propose to divide the CIS into two subsystems, one being the conveyance and distribution network, or CDN (from water diversion/abstraction to farm gate), and the other the irrigated fields, or IF (from farm gate to the bottom of the root zone). Figure 4 shows the CDN subsystem, where the reservoir upstream of the abstraction is not part of the target system.

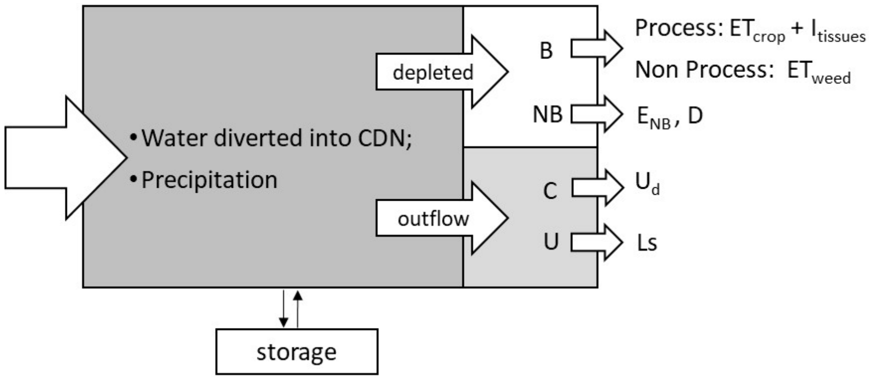

Figure 3. Water accounting diagram for the case when the domain of application is a collective irrigation system (conveyance and distribution network—CDN + irrigated fields). B and NB represent the beneficial and nonbeneficial uses, respectively; U and C represent the uncommitted and committed uses, respectively; ET_{crop} and ET_{weed} represent crop and weed evapotranspiration, respectively; $I_{tissues}$ is the water incorporated in the tissues; E_{NB} represents nonbeneficial evaporation; D is the drainage, U_d is the water liberated from the system for downstream users; Ls represents the excess water liberated from the system.

On one hand, Figure 4 shows the water inputs into the system, including abstraction from the surface water or groundwater, water imported from other CIS, and precipitation over intermediate reservoirs and conveyance and distribution channels, as well as runoff into these structures. On the other hand, Figure 4 shows the respective water loss components.

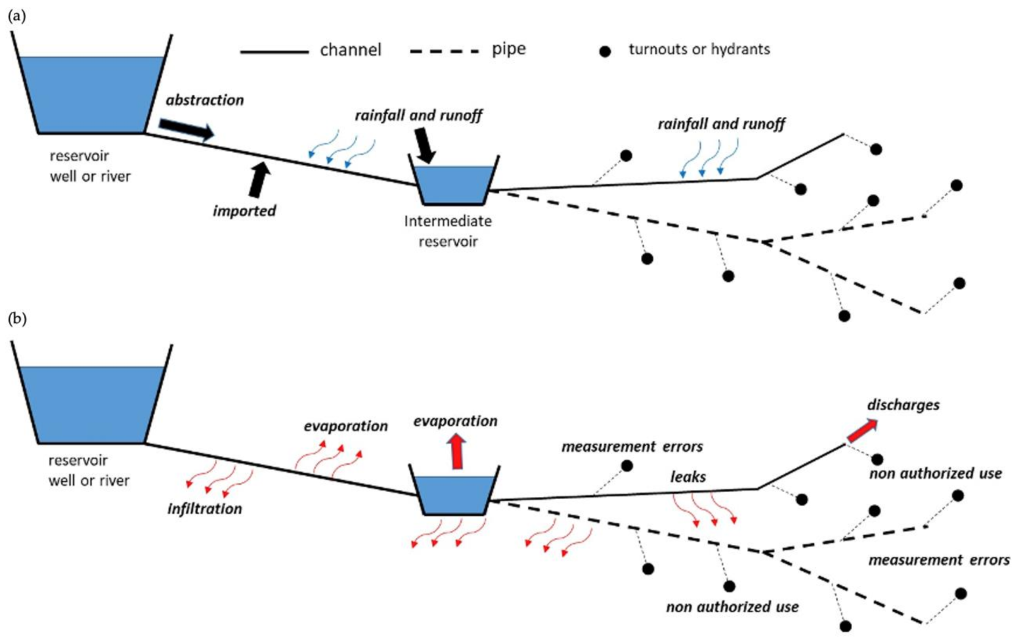

Figure 4. Water accounting terms in the conveyance and distribution network of a collective irrigation system: (**a**) water inputs components; (**b**) water loss components (adapted from [97]).

The water loss component includes (i) evaporation from the water surface in channels and intermediate reservoirs; (ii) apparent losses, due to unauthorized consumption, which is common in channels, and measurement errors; and (iii) real water losses by percolation in channels and reservoirs and leaks in pressurized pipes (Figure 5). Water discharges at the end of the channels classify as uncommitted outflow since it corresponds to water that leaves the system due to operational actions.

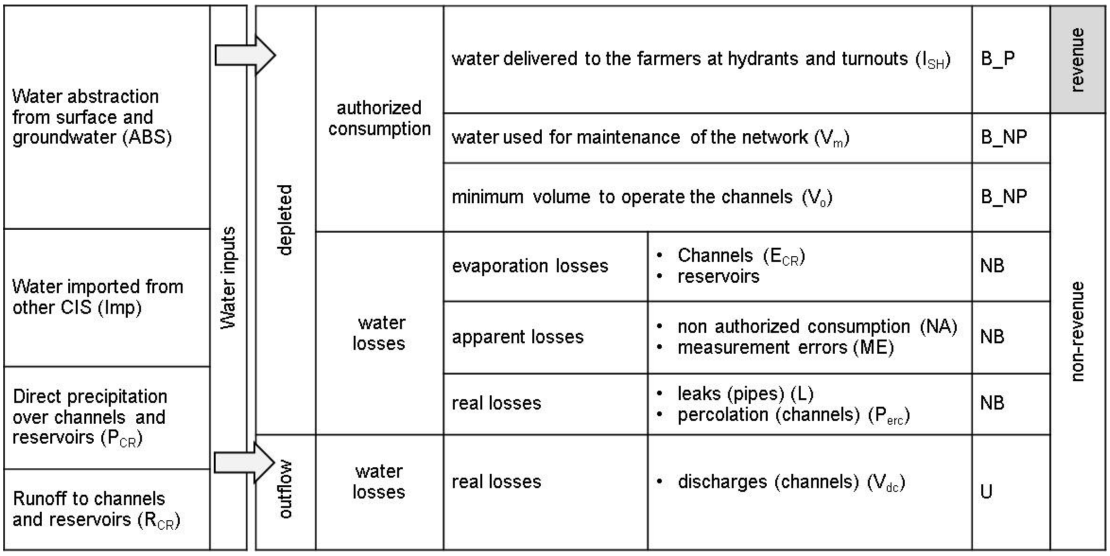

Figure 5. Quantifying water accounting terms in conveyance and distribution network of collective irrigation systems (B_P is a beneficial process use; B_NP is a beneficial nonprocess use; NB is a nonbeneficial use; U is an uncommitted use).

The relationship between the water balance terms at the CIS level is shown in Equation (8), and the variables are identified in Figure 5. Thus, the balance may be computed as follows:

$$ABS + IMP + P_{CR} + R_{CR} = (I_{SH} + V_m + V_o) - (E_{CR} + NA + ME + L + P_{erc}) - V_{dc} \quad (8)$$

where ABS is the water abstraction from surface and/or groundwater, IMP is the water imported from other CIS, P_{CR} is the precipitation over channels and reservoirs, R_{CR} is the runoff to channels and reservoirs, V_m is the water used for network maintenance, V_o is the minimum volume to operate the channels, E_{CR} is the evaporation loss from channels and reservoirs, NA is the unauthorized consumption, ME is the measurement errors, L is the leaks in pressurized pipes, P_{erc} is the percolation in channels, and V_{dc} is the discharges in channels (excess water). The terms are usually quantified in m^3 or hm^3.

At the conveyance and distribution network, water accounting is vital because it provides accurate and reliable data that can be used as a basis to accomplish the following:

i. Identify the amount of water entering the CDN over time, which we designate as water diverted (DIV = ABS + IMP) [63,97]. This information can help the WUA manager in planning the water resources more efficiently, facilitating water allocation decisions, minimizing the risk of water scarcity, and maximizing WP.
ii. Identify the total amount of water that reaches the farm gate hydrants/turnouts. This information, together with (i.) allows us to evaluate the performance of the irrigation infrastructure, such as the efficiency of water delivery and distribution. In this sense, the authors of [64] present a water and energy efficiency assessment based on trustworthy and well-organized water accounting information for collective irrigation systems, designated as PAS.
iii. Identify losses as leaks, blockages, infiltration, or other issues that can lead to water waste [64,98,99] and improve CDN efficiency.
iv. Detect unauthorized irrigation water diversion in open channel distribution, from which illegal offtakes are common [100,101].
v. Apply irrigation water taxing or charging, which is a mechanism used to generate revenue for water management and to encourage the efficient use of water resources [52,102–105]. However, it is important to ensure that water taxes or fees are

implemented in an equitable and transparent manner and that they do not place undue burden on small-scale or low-income farmers. Furthermore, the revenue generated from water taxes or fees must be used to support water management activities that benefit all users and promote sustainable water use.

Figure 6 represents the irrigated field subsystem of the CIS, showing the variables to include in the water accounting procedure. The terms are usually quantified in mm (L m^{-2}).

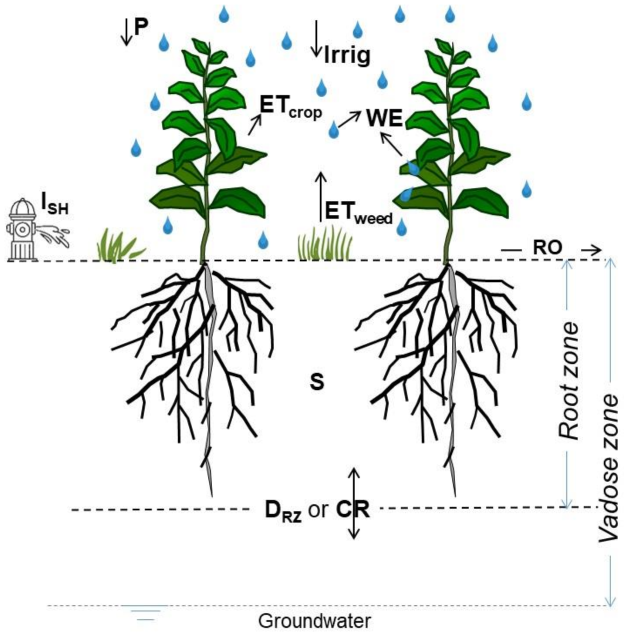

Figure 6. Terms to consider for the water accounting procedure at the irrigated field level (P—precipitation, I_{SH}—water delivered at the hydrant or turnout, Irrig—gross irrigation amount, ET_{crop}—crop transpiration, ET_{weed}—transpiration from weeds, WE—is the wind drift and evaporation, RO—runoff, ΔS—variation of soil water storage, D_{ZR}—drainage at the bottom of the root zone, CR—capillary rise).

The relation between the variables is presented in Equation (9), which can be applied with different time steps according to the objective.

$$P + \text{Irrig} - \left(ET_{crop} + ET_{weed} + WE + RO + D - CR\right) = \Delta S \tag{9}$$

where P—precipitation, Irrig—irrigation requirement to be applied by the on-farm irrigation system, ET_{crop}—crop transpiration, ET_{weed}—transpiration from weeds, WE—wind drift and evaporation, RO—runoff, ΔS—variation of soil water storage, D_{RZ}—drainage at the bottom of the root zone, CR—capillary rise. Usually, ET is assumed to be the sum of crop and weed evapotranspiration (ET_{crop} + ET_{weed} = ET).

The following relations are further applied in the following equation:

$$Irrig = \frac{N_{Irrig}}{E_a} \tag{10a}$$

$$I_{SH} = \frac{Irrig}{E_T} \tag{10b}$$

where Irrig is the amount of water applied by the on-farm irrigation system, N_{Irrig} is the net irrigation requirement, I_{SH} is the water delivered at the hydrant or turnout, E_a is the application efficiency of the on-farm irrigation system and E_T is the transport efficiency of the on-farm irrigation system (tertiary network). Thus, the on-farm irrigation efficiency, E_F, is the product of E_a and E_T.

Figure 7 relates the water balance terms at the irrigated field level to the types of uses as defined by [61]. Thus, it clearly shows the differences between the beneficial and nonbeneficial water fractions.

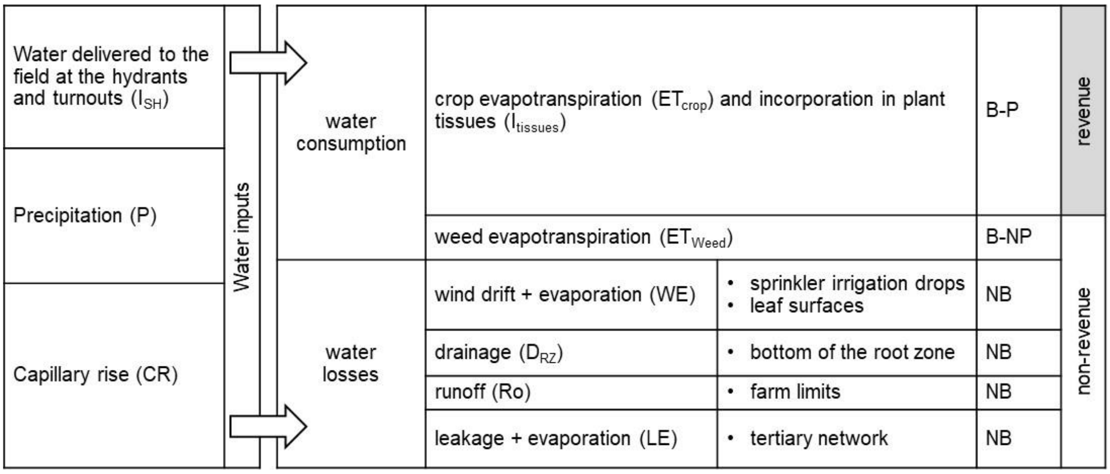

Figure 7. Quantifying water balance terms at the irrigated field level, for water accounting at the collective irrigation system level (B-P—beneficial process use; B-NP—beneficial nonprocess use; NB—nonbeneficial use).

At the irrigated field level, water accounting is vital because it provides accurate and reliable data, which can be used as a basis for [6,36,83] the following:

i. Estimating the crop water and irrigation needs in each field of the CIS;
ii. Informing farmers whether they are paying for the irrigation water they spend;
iii. Identifying losses that can lead to water waste and quantifying on-farm efficiency;
iv. Optimizing irrigation practices, such as adjusting the timing and frequency of irrigation to match crop needs and soil moisture levels as it can help to reduce water losses and improve crop yields, leading to increased WP;
v. Identifying the crops that are most water-efficient and, thus, better suited to local water availability, boosting WP.

The integration of both types of information at the CIS level allows to accomplish the following:

i. Quantify/estimate the amount of water used/needed for irrigation within the irrigation perimeter (which we designate as irrigation requirements at the source, SIR) by identifying the water requirements of different crop patterns [106].
ii. Identify areas of water loss or inefficiency both at the field and at the distribution network levels.
iii. Compare the water delivered at the hydrants/turnouts (I_{SH}) with the irrigated field water demand (IR) and to quantify performance indicators such as the relative water supply [16,107].
iv. Maintain adequate supply at the hydrants/turnouts, making adjustments when necessary.
v. Provide relevant, reliable, comparable, and understandable information, allowing an informed debate among the stakeholders [25,91]. This is very important, since local-level water users may have a very different perception of their levels of water services compared with organizations that are responsible for delivering these services [21,22,89,91].
vi. Facilitate the dialogue and cooperation among different irrigation water users within the collective irrigation system, and develop mechanisms for solving conflicts and sharing water resources fairly by promoting equitable use (together with ii.)
vii. Improve the CIS global irrigation efficiency and productivity.

5. Methodologies in the Framework of Water Accounting: Strengths and Limitations

IWA at the collective irrigation system level requires the quantification of water from the point where water is diverted from the reservoir, river, or groundwater source into the network to the point where it is used by the plants, both in the conveyance and distribution network and at the level of irrigated fields [17]. Direct measurement of the water balance terms is the most accurate method. Despite increasing pressure on both groundwater and surface water resources in many agricultural regions, most of the agricultural water use worldwide is not monitored, with limited metering of irrigation [17,24,25]. Thus, alternative methods are used to estimate agricultural water use, such as tabulated values or remote sensing methods. Additionally, there are models that can be used to estimate agricultural water use terms.

5.1. Water Accounting at the Collective Irrigation System Level Based on In Situ Measurements

5.1.1. Conveyance and Distribution Network

At this level, the main components to account for are the amount of water entering the CDN over time, which we designate as water diverted (DIV) and different water uses. The beneficial use corresponds to the water delivered to each field or irrigation unit (I_{SH}) plus the water used for the maintenance of the network (V_m), plus the minimum volume to operate the channel (Vo). Committed nonbeneficial uses include losses by evaporation in reservoirs and channels (E_{CR}), seepage or percolation in channel and intermediate reservoirs (Perc), and leaks in pressurized pipes (L). Finally, any uncommitted use or loss corresponds to discharges in channels (V_{dc}), representing an operational requirement of the system (Figures 4 and 5). Cunha et al. [63] show that V_{dc} can be one of the most relevant components of nonrevenue water, representing approximately half of its total volume, followed by leakage in canals.

Measuring equipment should be installed at key points of the conveyance and distribution network to measure DIV and I_{SH} [25,108,109]. When the transport and distribution of water is performed in open channels, the water level is controlled through weirs and/or gates (e.g., AMIL gates), and flow is typically measured by reading the water level in the weirs and flumes. In pressurized pipes, flow is controlled through valves and measured through propeller, electromagnetic, or ultrasonic flowmeters. Regarding the water delivery at the farm gate, turnouts can be equipped with flowmeters, which in some cases also control the flow rate (e.g., Neyrpic modules). In pressure delivery, hydrants are frequently equipped with hydrometers that regulate the flow rate and delivery pressure [97]. The discharge of excess water in channels, V_{dc}, is usually measured through a weir and its calibration curve. The remaining terms are generally not measured but estimated based on various methods, as described in Section 5.2.2.

Flowmeters have different characteristics according to their working principle. Totalizer and instantaneous meters can be used, depending on the specific requirements of the application [110]. The first type of flowmeter measures the total volume of water diverted or delivered over time and is suitable for pressurized systems where high head losses are unacceptable and water is priced based on volume [111]. The registration of the accumulation can be automatic, via mechanical or electronic methods, or manually, by averaging multiple discrete flow measurements over an irrigation event [110,111]. Propeller meters are an example of totalizer meters that provide accurate measurements [112–114]. Instantaneous meters, such as differential pressure flowmeters, electromagnetic or ultrasonic, on the other hand, measure the flow rate at a specific point in time and are useful for monitoring changes in flow over time [115,116].

Continuous measurements over time are essential to water accounting when water for farmers is provided on demand from the CDN [110,115]. Without these devices, frequent measurements are required to characterize the demand pattern and to make delivery changes or seasonal corrections in flow [110]. This type of device presents advantages compared with manually read water meters since they enable real-time remote continuous flow monitoring and automatic data collection of water flow rates and quantities (e.g., the

SCADA system which is a supervisory control and data acquisition system), as well as more efficient and accurate data analysis. Moreover, the ability to monitor water flow rates and quantities remotely can help identify and address potential problems early, such as leaks or water losses, before problems escalate. Regarding the placement of water meters in remote locations, battery power or solar power can be used to power the devices, providing a sustainable and reliable power source.

The selection of the proper measurement device depends on site-specific aspects and variables, such as accuracy requirements, cost, range of flow, head loss, adaptability to the site and variable operating conditions, and maintenance requirements [109,115,117]. It is important to select the most appropriate measuring device aiming at minimizing errors since most of water measurement devices present small errors of less than 5% [109,110,115]. Selecting an inappropriate device can occasionally lead to high errors because measurement techniques are only useful for a limited range of flow conditions [110,115]. Sediment deposits and suspended debris can also alter the conditions of flow within the measurement devices [115].

Table 1 summarizes different types of measurement equipment, analyzes their strengths and weaknesses, and provides references for examples of their application.

The difficulty faced by managers and regulators in implementing and enforcing in situ metering is a key factor underpinning the low levels of metering of irrigation water abstraction/diversion. Farmers may oppose or lobby against the installation of meters due to concerns about increased future regulation [118,119]. In situ measurements using flowmeters have high maintenance costs, so great efforts must be made when covering large irrigated areas [17]. When meters are installed, collecting readings and maintaining monitoring infrastructure can be extremely costly and time-consuming for resource-limited regulators [120] and must be accompanied by strong sanctions and penalties to deter rule breaking or cheating [121]. In many regions, metering systems are never installed or quickly fall into disrepair due to meter tampering, poor maintenance, and insufficient penalties for rule breaking [122].

5.1.2. Irrigated Field

Water supply to the irrigated fields (I_{SH}) can be measured at the turnouts or hydrants as described in Section 5.1.1., while precipitation inputs are measured in rain gauges installed in situ or retrieved from the meteorological stations' network.

Beneficial consumptive use, evapotranspiration (ET) or its terms, evaporation (E_s) and transpiration (T), can be obtained directly from measurements with in situ sensors and equipment (Table 2). However, ET measurements are not able to distinguish process (crop transpiration) from nonprocess (weed transpiration) consumption.

The measurement of nonbeneficial use, including drainage (D) and runoff (RO), can also be performed using in situ sensors and equipment (Table 2). The most direct measurement of D is taken by a drainage lysimeter where the volume of water passing through the bottom boundary can be collected and quantified [123].Another option is to install tensiometers within the root zone and measure the water potential to calculate the vertical water flux through a soil plane applying Darcy's equation [124,125]. Tensiometers should be installed at multiple locations to account for spatial variability. This equipment when coupled with a pressure transducer may provide for continuous remote readings.

As for runoff (RO), the most basic measurement method involves diverting flow to a small reservoir [126,127] and then quantifying the volume received in a certain period. This setup is typically inexpensive and easy to install but requires that the reservoirs be periodically emptied if long-term monitoring is desired. Alternative systems have been designed to mitigate these problems, including dividing flow into multiple containers or using electronic water sensors [128] or tipping buckets [129,130]. The soil water storage (S) is calculated from soil water content (SWC) measurements obtained directly from gravimetric sampling or indirectly by using a variety of sensors [131] (Table 3).

Table 1. Measuring devices to monitor irrigation water in conveyance and distribution networks.

	Device	Description	Example	Measurement	Strengths	Weaknesses	References
Channel	Weirs	overflow structure perpendicular to a channel axis	broad and sharp-crested weir; V-notch, Cipolletti	instantaneous; flow rate; manual	wide flow range	sensitive to sediment deposits	[110,111,115,116]
	Flumes	sections that force flow to accelerate	long and short-throated flumes; Parshall Flume	instantaneous; flow rate; manual	very accurate if designed and installed properly; low head loss	sensitive to sediment deposits	
	Submerged orifices	flow rate depends on the pressure difference	meter gates; orifice plates	instantaneous; flow rate; manual	used when cost and space are limited	high head loss; sensitive to debris	
	Acoustic velocity meters	measure the velocity by directing ultrasonic pulses	acoustic Doppler; transit time	instantaneous; flow rate	low head loss	narrow range of flow	
	Flow control structures	used in channel check structures to control canal flows and water levels	check gates, radial gates (e.g., AMIL), sluice gates	instantaneous; volume	expensive; can be used in lined and unlined canal	high head loss; sensitive to debris	
Pressurized pipes	Deferential head meters	use Bernoulli's principle to measure the flow	Venturi, orifice, pitot, shunt meters	totalizer, the flow rate	inexpensive; very accurate	not suitable for high flow rates	[111–113,115]
	Mechanical velocity meters	rotation velocity is proportional to the flow rate velocity	propeller meters, turbine meters, paddle wheel meters	totalizer; flow rate volume	measure instantaneous flow and volume; low head loss; no need for supply power	narrow range of flows; Sensitive to debris	
	Magnetic meters	based on Faraday's law of induction	magnetic electrodes	instantaneous; flow rate	no obstructions, no problem with debris, and no head loss	low head loss narrow range of flows	
	Acoustic flowmeters	measure flow velocity by directing ultrasonic pulses	diametral-path flowmeter and chordal-path flowmeter	instantaneous; flow rate and volume	high accuracy, nonintrusive, incurring no head loss	expensive	

Table 2. Determination of beneficial and nonbeneficial components for WA at the irrigated field scale using in situ sensors and equipment.

Term	Equipment	Base of the Method	Comments	Reference
E_s	Microlysimeters Minilysimeters	water balance of the surface layer (up to 0.20 m)	difficult to install without soil disturbance; need several repetitions; tend to overestimate Es due to lack of account for water consumed by the plant; noncontinuous measurements; low cost; research	[132,133]
T	Sap flow	heat pulse velocity method, Granier heat dissipation method, tissue-heat balance method	requires good skills for sensor implementation; requires repetitions; good accuracy; continuous measurements; requires calibration and adequate skills for data processing; sensors are fragile; research	[134,135]
ET	Eddy covariance/OPEC	statistical covariance between vertical fluxes of vapor or sensible heat	no installation disturbance; continuous measurements; good accuracy; calibration and skills for data processing; large fetch; fragile sensors; high cost; research/practical applications	[136,137]
	Bowen ratio energy balance	energy balance in the near-surface layer above the evaporating surface	practical and relatively reliable; no need for replications; large fetch; good skills for data processing; fragile sensors; high cost; research	[138,139]
	Scintillometers	measurement of the sensible heat flux	good accuracy; continuous readings; needs post-processing correction; covers large areas; simple to operate and maintain; high cost; research	[140,141]
	Weighing lysimeter	containers with soil dug from the field and repacked; ET is obtained by weight differences over time	disturbance during installation; good accuracy after calibration; may not represent the average field conditions; high maintenance; continuous measurements; high cost; research	[142]
D	Drainage lysimeter	containers with soil dug from the field and repacked; measurement of the drainage collected at the bottom	disturbance in installation; need replications; accurate; may not represent average field conditions; continuous measurements; high cost; research	[143,144]
	Tensiometers	measure matric potential profiles for the application of Darcy's law	some disturbance during installation; needs many replications; accurate; continuous measurements; research/practical applications	[145]
RO	Reservoirs Tipping buckets Flumes	the runoff is directed to a reservoir, where its volume is measured each time the bucket is filled, it empties automatically measure water depth above crest	easy to install, cheap, high maintenance (must be emptied frequently); water loss due to evaporation; unable to sample small runoff events needs calibration; can be expensive to install and maintain.	[129]

(E_s) soil evaporation, (T) transpiration, (ET) evapotranspiration, (D) drainage, (RO) runoff. NOTE: Symbols, abbreviations and acronyms are given in Appendix A.

Table 3. Soil water sensors based upon the soil dielectric constant for the measurement of soil water content *.

Type	Description	Examples	Characteristics	Weaknesses	Website
TDR	Parallel rods act as transmission lines. Voltage is launched along the rods and reflected back to the sensor. The velocity of the voltage pulse is related to the dielectric permittivity of the soil	TRASE	one probe measures one depth	expensive; technical knowledge; soil disturbance during installation	(https://www.soilmoisture.com, accessed on 2 May 2023)
		TDR 305-315H	portable; high accuracy	limited to soils with high conductivity; expensive; technical skills	(https://acclima.com, accessed on 2 May 2023)
		SoilVUE	six or nine depths measured with one sensor	power and connection for transmitting data; expensive	(https://campbellsci.com, accessed on 2 May 2023)
FDR (capacitance)	Measures the charge time of a capacitor, which uses soil as a dielectric medium. The capacitance sensor forms a pair of electrodes and the soil acts as a dielectric. The capacitor charge time is a linear function of the dielectric permittivity of the soil.	EnviroSCAN	permanent; multi-depth	support and license; expensive	(https://sentektechnologies.com, accessed on 2 May 2023)
		Drill & Drop	permanent; multi-depth	when damaged, it cannot be repaired; technical skills	(https://sentektechnologies.com, accessed on 2 May 2023)
		Teros 12	simple installation; multi-depth	expensive; air gaps or disturbances that could affect the measurements	(https://www.metergroup.com, accessed on 2 May 2023)
		Diviner	portable, multi-depth; affordable	limited range (0% to 40% of volumetric water content)	(https://sentektechnologies.com, accessed on 2 May 2023)
		ECH2O	hand insert or buried in situ; affordable	it may experience sensor drift	(https://www.metergroup.com, accessed on 2 May 2023)
TDT	Similar to TDR, but measures the transmission of a pulse along a looped rod. It measures the time from the start to the end of the loop.	Aquaflex	solar battery; adjusts to the soil conductivity	technical skills	(https://aquaflex.co.nz, accessed on 2 May 2023)
		VH400	low cost; portable	experiences sensor drift	(http://vegetronix.com, accessed on 2 May 2023)
Impedance	It has two components: the dielectric constant and the soil electrical conductivity.	ThetaProbe	maintenance-free; buried or portable; ± 1% SM accuracy	one single depth; technical skills	(https://delta-t.co.uk, accessed on 2 May 2023)
		PR2Profile	installed or portable	expensive; regular calibration is necessary to ensure accuracy	(https://delta-t.co.uk, accessed on 2 May 2023)

* Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the authors.

During recent years, several dielectric sensors have been developed, assessed under site-specific conditions, and compared. Those sensors, also called permittivity sensors, are classified into four groups: (i) time-domain reflectometers (TDR), (ii) frequency-domain reflectometers or capacitive (FDR), (iii) time-domain transmitters (TDT), and (iv) impedance. The accuracy of soil water sensors depends on several factors, such as the technologies used, calibration procedures used to convert raw data into soil water content, soil texture and salinity, and installation specifications [131,146–148]. Neutron probes, which have been forbidden in the EU but are still used worldwide, present high accuracy [149]. The gravimetric method is employed as a reference method for sensor calibration [150]. Recent reviews have compared the working principles, advantages, and limitations of various soil moisture sensors developed over the past three decades [146,148,151,152]. Table 3 summarizes different types of soil water sensors, analyses their strengths and weaknesses, and provides references for examples of their application.

5.2. Water Accounting at the Collective Irrigation System Based upon Estimations

Access to reliable and up-to-date information on water demand and availability is crucial for effective water management in CIS, but the lack of complete records is a major challenge [25]. Estimation methods that use available data and advanced technologies, such as remote sensing or modelling, have become popular for estimating water use. Additionally, they can provide valuable insights into water use patterns and trends. Estimation methods, which are theoretically less accurate, are often less expensive and easier to implement and maintain than direct in situ measurement methods. However, whenever possible, the two approaches should be used in a complementary way. WA methods that can be used to estimate agricultural water use at the CIS level include approaches with varying degrees of accuracy and complexity, ranging from the tabulated values of annual irrigation water demand to modelling. The accuracy of these estimates depends on several factors, including the quality and availability of input data, their representativeness for a given region, the type of statistical models used, and the spatial resolution of the analysis. Some of these methods are described in the following sections.

5.2.1. Estimation of the Water Use at the Collective Irrigation System Level

Irrigation water requirements at the source of the collective irrigation system (SIR) are obtained from the global irrigation requirements (GIR) of all the crops in the CIS at the field level, and the conveyance and distribution efficiencies (Equation (11))

$$SIR = \left(\frac{GIR}{E_C.E_D}\right)\left(\frac{A_T}{100,000}\right) \tag{11}$$

where SIR is the irrigation demand at the source (hm^3), GIR is the global irrigation requirements for the CIS cropping pattern (mm), E_C and E_D are the conveyance and distribution efficiencies (Section 5.2.2), and A_T e the total area to irrigate (ha).

In its turn, GIR (mm) is calculated as:

$$GIR = \sum_{i=1}^{n} IR_i\left(\frac{A_i}{A_T}\right) \tag{12}$$

where IR_i is the irrigation requirements for each crop (mm), A_i is the area occupied by each crop (ha), and A_T is the total irrigated area of the CIS (ha).

The calculation of GIR and SIR requires the previous determination of the crop irrigation requirements. The main estimation methods are as follows:

(i) Tabulated values of annual irrigation water demand

The irrigation water demand accounting over large areas can be based upon tabulated values of irrigation needs per crop and per irrigation system, for different regions. It is the case of the information made available by national or regional irrigation authorities. Prior to the irrigation season and after the farmers have declared the crops they will produce and associated areas, the CIS manager can estimate the annual volume of water needed at the source of the collective distribution network (SIR).

Tabulated values of IR for each crop are commonly obtained through empirical or simple modelling approaches using data from field experiments, observations, and historical records of consumption. They allow for a quick accounting of water demand at the collective irrigation system level. However, they may not account for variations in local factors that can influence water use, namely, climate conditions, as well as for changes in land use and management practices that can affect water use patterns. In Europe, several water management authorities provide tabulated values of annual IR for different crops grown in different regions, including cereals, horticulture, and vineyards [153,154]. Other examples refer to Spain, France, Australia, New Zealand, Canada, and Colombia [155–160]. Table 4 shows an extract of a table produced by the Portuguese irrigation authority.

Table 4. Tabulated values of annual irrigation requirements for the Alentejo region in Portugal for different crops, irrigation systems, and wet and dry years (adapted from [154]).

Crop	Crop Annual Irrigation Requirements (IR, mm)					
	Scenario A—Wet Year			SCENARIO B—Dry Year		
	Sprinkler	Centre Pivot	Drip	Sprinkler	Centre Pivot	Drip
Maize	725	640	605	877	772	730
Tomato	465	410	385	551	488	462
Potato	495	435	415	599	525	641
Sunflower	345	305	290	415	368	347

This method provides a straightforward way to balance availability and demand for the upcoming irrigation season and, thus, to support the decision-making of the WUA manager regarding the CIS cropping pattern. However, since the irrigation requirements vary during the season, reaching a maximum in the peak period, this method cannot inform if the balance is positive for the peak period.

(ii) Water balance modelling

Irrigation requirements at the field level can be obtained indirectly from the soil water balance (Equation (9)) applied to the crop root zone, once all the other terms (ET, D, RO, S) are known. Usually, for practical engineering purposes, ET is estimated through modelling rather than measurements, given climate data, the initial conditions for soil water storage, soil characteristics, and crop parameters. There is a range in the complexity and variety of models for assessing irrigation requirements at the field level. Considering the approach by which the various models simulate water dynamics in the soil–plant–atmosphere continuum, it is possible to distinguish comprehensive, fully process-driven models from simple empirical applications. Examples of these types of models applicable at the field scale are given in Table 5, including application case references. Process base models are computationally intense, require expertise, and are demanding in terms of input data. Furthermore, they need preparatory work of calibration and validation prior to being used with different crops and soils, which is a rather expensive and time-consuming task. Conceptual models are process informed and require greater empirical evidence to support the selection of coefficients. Although they do not offer a full process representation, they provide simple, useful, and accurate information for water accounting when properly calibrated. They are frequently used to assess irrigation requirements at the field scale, specifically in terms of adopting adequate irrigation schedules, which should result in optimal yields, and agricultural practices that allow reducing yet optimizing water use, aiming particularly to reduce nonbeneficial uses [83]. When integrated at the CIS level (e.g., through a GIS), some of these models allow for the estimation of GIR (Equation (12)) and SIR (Equation (11)).

Table 5. Models for the determination of irrigation water requirements at the field level.

	WB Model	Reference	Determination of ET
Conceptual	CROPWAT	[161,162]	Empirical—single crop coefficient
	ISAREG	[106,163]	
	SIMETAW#	[164,165]	
	WATNEEDS	[166,167]	
	AQUACROP	[168,169]	
	FAO-2K$_c$	[170]	Empirical—dual crop coefficient
	MOPECO	[171,172]	
	OptIrrig (PILOTE)	[173,174]	
	SIMDualKc	[175,176]	
Process-based	Hydrus-1D, -2D	[177,178]	Process-based—T; Empirical—E$_s$
	CERES	[179,180]	Process-based
	DAISY	[181,182]	
	RZWQM2	[183,184]	
	STICS	[185,186]	

Conceptual water balance models usually present empirical modules and/or energy balance approaches [187,188] for the estimation of crop water requirements (ET). The most commonly used empirical approach for estimating crop ET is the FAO K_c-ET_o, which provides good estimations of ET under various climatic conditions [189]. Crop evapotranspiration estimated by this method is designated as ET_c (Equation (13)). This approach, known as single K_c, considers the average effects of both soil evaporation and plant transpiration and is used in most cases. When ET_c is partitioned into crop transpiration (T, mm) and soil evaporation (E_s, mm), these are computed using the basal crop coefficient and the evaporation coefficient (K_{cb} and K_e, dimensionless) (Equation (14)). This approach is used mainly for research purposes, using a daily time step to compute ET_c for row crops and other situations where the soil is exposed [170,190]. Several authors, e.g., refs. [189,191–193], developed tables that provide information on crop coefficients and the crop growth stages, which may be improved by using GDD (growth degree days) and RS (remote sensing) and other factors, such as the canopy shading area.

$$ET_c = ET_o\ K_c \tag{13}$$

$$ET_c = ET_o\ (K_{cb} + K_e) \tag{14}$$

where ET_c is crop evapotranspiration (mm), ET_o is the reference evapotranspiration (mm) and K_c is single dimensionless crop coefficient, K_{cb} is the basal crop coefficient, and K_e is the soil evaporation coefficient.

The ET_c estimated for all the crops is used as input to the soil water balance for the determination of the crop net irrigation requirements, N_{Irrig}, which are affected by the on-farm efficiency (transport and application), in order to obtain the irrigation demand of each crop (Equation (15)).

$$IR_i = \frac{\text{NIrrigi}}{\text{E}_\text{f}} \frac{\text{A}_i}{100{,}000} \tag{15}$$

where IR_i is the irrigation demand of crop i (hm^3), N_{Irrigi} is the net irrigation demand of crop i, occupying an area A_i (ha), and E_f in the on-farm efficiency, considering the losses in transport and application within the irrigated field (fraction).

When the irrigated field presents more than one crop, the total irrigation requirement of the field is given by the crop average IR, weighted by the area occupied by each crop.

WA at the irrigated field scale also involves the quantification of nonbeneficial ET, such as the consumption of weeds, wind drift, and evaporation losses in sprinkler irrigation [83,194]. Mohammadpour et al. [195] estimated the nonbeneficial evapotranspiration relative to the surface and pressurized irrigation at 22% and 32%, respectively, using the water accounting framework. Wind drift and evaporation to the atmosphere associated with sprinkler irrigation can be estimated using water balance, energy balance, and semi-empirical/empirical methods [196–198].

(iii) Remote sensing

The implementation of accurate WA procedures to provide reliable estimates of the agricultural water demand at the CIS level is dependent on the ability to obtain data representative of the actual field conditions. Since agricultural water use is often not measured, the WUA databases present frequently incorrect and outdated data.

IWA based on remote sensing (RS) data has been proposed as a solution for spatially explicit monitoring of agricultural water use over large areas such as CIS, assessing beneficial water consumption, especially when there is negligible in situ water use monitoring infrastructure to support agricultural water management [25,55,61]. RS can be used both independently or in combination with soil water balance modelling and in situ monitoring, allowing in this case also for the estimation of nonbeneficial uses. Furthermore, the World Bank [199] has emphasized the important role of satellite monitoring of irrigated areas concerning evapotranspiration (ET) and irrigation water use in supporting future water resource planning and decision-making. This approach has the potential to address the gap in the lack of in situ monitoring of agricultural water withdrawals from both groundwater and surface water sources [17,101,200]. In fact, remote sensing-based water accounting has been used for different purposes, such as detecting unauthorized water use [200], monitoring water abstraction [101], estimating water use in small parcels with detailed crop patterns [201], and monitoring large irrigated areas [17].

The use of RS in IWA includes mapping of irrigated crop areas and their actual evapotranspiration ET [188,201]. The methods include surface energy balance models [202,203] and reflectance-based crop coefficient methods [17,100,101,187]. Remote sensing-based energy balance (RSEB) models, such as Surface Energy Balance Algorithm for Land (SEBAL) [202] and Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) [203], have been used for over three decades to estimate evapotranspiration (ET) over large areas [188,202–204]. These models are cost-effective and produce reliable ET maps. However, they may miss the effects of precipitation events, and it can be challenging to interpret narrow vegetation systems [187]. Energy balance methods can be used to calibrate simpler empirical methods that estimate crop coefficients using general vegetation indices, combining data from multiple sources, such as weather data, satellite imagery, and ground-based measurements, to estimate ET [187].

The empirical RS methods to estimate crop evapotranspiration use vegetation indices (VI) to determine actual crop coefficients (K_c) and actual basal crop coefficients (K_{cb}), which will be used to estimate ET (Equations (13) and (14)), respectively [205]. However, VI-based methods may not be as accurate as energy balance methods. Ground data can serve as a complement to minimize bias in ET estimates [206]. A linear relationship between the Normalized Difference Vegetation Index (NDVI), the most used vegetation index, and K_c was introduced by Heilman et al. [207]. The K_c derived from remotely sensed vegetation indices, such as NDVI, makes it possible to account for variations in plant growth due to specific growing and weather conditions. Several studies concluded that K_c generated from NDVI enables us to obtain better ET estimates, than tabulated K_c values, by representing the actual crop growth conditions and capturing the spatial variability among different crop fields. Some examples of the empirical relationships between K_c and vegetation indices, available in the literature, are presented in Table 6.

VI-based K_c and K_{cb} estimation methodologies present advantages such as quick analyses by mid-level technicians, cost-effective large-area coverage, calibration using satellite-based energy balance, and high spatial resolution [187,203]. However, these relationships may vary with the type of vegetation, and quality estimates of ET_o are required to transform K_c into ET [187]. In addition, satellite pixels are too coarse to properly estimate K_c in narrow plots. Low-flying unmanned aerial vehicles (UAV) can overcome such limitations by capturing imagery on days not covered by satellite overpasses and even under clouds [208]. As an example, K_c can be estimated from UAVs equipped with multispectral cameras [208].

Table 6. Empirical relationships between the crop coefficient and vegetation indexes.

Empirical Relation	References	Empirical Relation	References
K_c = 1.25 NDVI + 0.2 K_{cb} = 1.56 NDVI − 0.1	[205]	K_{cb} = 1.181 NDVI − 0.026 K_{cb} = 1.64 NDVI − 0.14	[209] [210]
K_c = 1.15 NDVI + 0.17 K_{cb} = 1.56 NDVI − 0.1	[211]	K_c = 1.5141 SAVI + 0.4077 K_{cb} = 1.416 SAVI + 0.017	[212] [213]
K_c = 0.918 NDVI + 0.303 K_{cb} = 1.464 NDVI − 0.253	[214]	K_{cb} = 1.414 SAVI − 0.02	[215]

NDVI—Normalized Difference Vegetation Index; SAVI—Soil Adjusted Vegetation Index. NOTE: Symbols, abbreviations and acronyms are given in Appendix A.

5.2.2. The Estimation of Nonbeneficial Uses in the Conveyance and Distribution Network

Regarding the water inputs in the CIS, whereas the water abstracted (ABS) from the surface and groundwater and the water eventually imported from other CIS (IMP) are measured (as described in Section 5.1.1), other inputs are subject to estimations. The inflows (R_{CR}) to the canals and intermediate reservoirs due to runoff from the watershed are usually estimated based on a precipitation-runoff transformation. However, data for the application of a hydrological model must be previously calibrated and validated for the site.

As referred to previously, in the CDN, the majority of the nonbeneficial use terms are estimated. Regarding evaporation losses (E_{CR}), the accumulated evaporation in each section of the channel or intermediate reservoir can be obtained based on the daily evaporation series measured directly or indirectly at the meteorological stations. The pan evaporation method, energy balance method, and aerodynamic method have been applied to estimate evaporation from channels [44]. The Thornthwaite Model [216] is a widely used empirical method for estimating monthly evaporation when there are no records from an evaporation pan, although the values obtained tend to underestimate evaporation in reservoirs [217]. Empirical methods to estimate pan evaporation are also presented by Christiansen [218] and Linacre [219], although in some cases they overestimate evaporation in reservoirs [217].

Unauthorized use of water (NA) can occur when users collect water directly from the channel or when the distribution is carried out by a pressurized system (e.g., tampering with meters or routing water around the meter). While WUA can perform periodic inspections to identify suspicious areas, estimating the volume associated with unauthorized uses is a challenging task. Users whose consumption significantly deviates from the water demand of a specific crop should be studied to understand such discrepancies [220–222].

Real losses in open channel systems can include leakage in pressurized pipes (L). The WUA technicians can identify localized leaks of significant size and estimate the volume lost [99]. However, some types of small and dispersed leaks are only detected by conducting tests. Leak tests have been performed by isolating pipe sections between access shafts and measuring the change in the water level after one week. Loureiro et al. [97] present volume decreases in the shafts of 1.5 m^3 km^{-1} day^{-1} and 7.5 m^3 km^{-1} day^{-1} for two pressurized pipes subject to such test. On the other hand, in the pressure decay test, the pipeline is pressurized to a specific level, and then the pressure is monitored over a period of time. If there is a leak in the system, the pressure will decrease. The losses depend on the material, age, and cross-sectional area, as well as the operating pressure of the pipeline and the conditions of operation and maintenance [221]. There is little information available in the literature about this type of loss.

The percolation in channels (P_{erc}) is estimated from seepage tests due to the variety of conditions that one can encounter in channels. Among the various methods used to estimate canal seepage, ponding tests have been proven to be a method capable of producing results with a higher accuracy level [33,223,224]. Loureiro et al. [97] present values for water losses by percolation of 25 L m^{-2} day^{-1} and 50 L m^{-2} day^{-1} for irrigation channels in good and bad conditions, respectively.

A methodology proposed by Cunha et al. [63] takes a holistic approach to improving water use in CIS with conveyance and distribution in open channels. It considers the unique components of CIS, such as open channels and intermediate reservoirs, and provides a system-wide view of the different water components. The methodology calculates revenue water, nonrevenue water, unbilled authorized consumption, and total water loss volume. In addition, the methodology uses a top-down approach to estimate real loss components, followed by a bottom-up approach to assess real loss components. The methodology is flexible, scalable, and applicable to different CIS sizes and complexities.

6. Conclusions and Outlook

The above review clearly highlights the need for a reliable irrigation water accounting method, particularly due to the increasing competition among water users and the pressure to improve water use efficiency and productivity in irrigated areas. The impacts of climate change will also contribute to this increase in water competition, particularly in water-scarce regions.

Water accounting at the collective irrigation system level allows for a holistic approach to understanding the interactions among different farmers, the environment, and the irrigation infrastructure, and to developing sustainable management strategies that benefit all stakeholders involved, from the farmer to the WUA manager. Data can be used to identify opportunities to optimize irrigation practices, reduce water losses, and select crops and varieties that are better adapted to local water conditions. It can also help farmers and water managers to allocate water resources more efficiently, ensuring that water is used sustainably and productively.

However, most agricultural water use is not monitored using direct flows and/or volume measurements. Thus, alternative estimation methods must be applied according to the scale and level of detail required.

The concepts and methodologies presented in this paper can provide tools for the water user association stakeholders to apply water accounting procedures aiming to improve irrigation efficiency and water productivity both in the irrigated fields and in the conveyance and distribution network.

Several key aspects need to be considered when it comes to the sustainability and future of water accounting:

- An output of water accounting should be a common information base that is acceptable to all the key stakeholders;
- Investment in education and training programs that can equip individuals with the skills and knowledge needed to work in the field of irrigation water accounting at the collective irrigation system level;
- The use of advanced technologies that allow for more precise and detailed results, leading to better-informed decisions about water management but are more demanding relative to input data.

All three concepts, irrigation water productivity, irrigation efficiency, and irrigation water accounting, are important because they provide a comprehensive framework for ensuring that farmers, water user association managers, and policymakers can optimize water use in agriculture and ensure the long-term sustainability of water resources. As more and more farmers adopt water accounting procedures, one can expect to see significant improvements in water productivity and irrigation efficiency. Future works could include the development of user-friendly tools and methodologies to reduce the gap between the technology available for acquiring and treating information on the different water accounting components and its effective use by the stakeholders.

Author Contributions: conceptualization, A.F., M.d.R.C. and J.R.; methodology, A.F.; resources, A.F., M.d.R.C., J.R. and P.P.; writing—original draft preparation, A.F.; writing—review and editing, M.d.R.C., J.R. and P.P.; supervision, M.d.R.C. and J.R.; project administration, M.d.R.C.; funding acquisition, M.d.R.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by HubIS Project (PRIMA/0006/2019). The support of FCT—Fundação para a Ciência e a Tecnologia, I.P., under the projects UIDB/04129/2020 of LEAF-Linking Landscape, Environment, Agriculture and Food, Research Unit and LA/P/0092/2020 of Associate Laboratory TERRA is also acknowledged. Antónia Ferreira gratefully acknowledges funding from the Portuguese Foundation for Science and Technology (FCT) under the Ph.D. grant PRT/BD/154133/2022. João Rolim (DL 57/2016/CP1382/CT0021) and Paula Paredes (DL 57/2016/CP1382/CT0022) also acknowledge FCT.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations and Acronyms

AQUASTAT	FAO's Global Information System on Water and Agriculture
CIS	Collective Irrigation Systems
CDN	Conveyance and Distribution Network
EU	European Union
FAO	Food and Agriculture Organization
FDR	Frequency Domain Reflectometers
GPWA	General-Purpose Water Accounting
IF	Irrigated fields
IHE-Delft	Institute for Water Education in Delft
IHP	International Hydrological Programme
IWA	Irrigation Water Accounting
IWMI	International Water Management Institute
IWMI-WA	International Water Management Institute Water Accounting
PAS	Water accounting information for collective irrigation systems
RS	Remote Sensing
RSEB	Remote sensing-based energy balance
SCADA	Supervisory Control and Data Acquisition
SEBAL	Surface Energy Balance Algorithm for Land
SEEAW	System of Environmental-Economic Accounts for Water
TDR	Time Domain Reflectometers
TDT	Time Domain Transmitters
UAV	Unmanned Aerial Vehicle
UN	United Nations
VI	Vegetation Index
WA	Water Accounting
Wa+	Water Accounting Plus
WaPOR	Water Productivity through Open access of Remotely sensed derived data
WP	Water Productivity
WRM	Water Resources Management
WUA	Water Users Associations

Appendix A

Table A1. List of symbols.

Symbol	Meaning	Symbol	Meaning
ABS	Water abstraction from sources	Ke	Soil water evaporation coefficient
A_i	Area occupied by each crop	L	Leaks in pressurized pipes
A_T	Total irrigated area of the CIS	LF	Salt leaching requirement
B	Beneficial water use	Ls	Excess water liberated from the system
B_NP	Beneficial nonprocess water use	SIR	Irrigation requirements at the water source
B_P	Beneficial process water use	U	Uncommitted water use
C	Committed water use	V_m	Water used for network maintenance
CR	Capillary rise	WP_{F_TWU}	Water productivity at the field level relative to the total water use
D	Drainage	Perc	percolation in channels and reservoirs
DIV	Water diverted to the CIS	ME	Measurement errors
D_{RZ}	Drainage at the bottom of the root zone	NA	Un auhorized consumption
Ea	Efficiency of application of the on-farm irrigation system	NB	Non-beneficial water use
E_C	Conveyance efficiency	NDVI	Normalized Difference Vegetation Index
E_{CR}	Evaporation loss from channels and reservoirs	Nirrig	Net irrigation requirements
E_D	Distribution efficiency	P	Precipitation
E_f	On-farm irrigation efficiency	P_{CR}	Precipitation over channels and reservoirs
E_{NB}	Non-beneficial evaporation	R_{CR}	Runoff to channels and reservoirs
E_s	Soil water evaporation	RIS	Relative irrigation supply
E_T	Transport efficiency on farm	RO	Runoff
ET	Evapotranspiration	SAVI	Soil Adjusted Vegetation Index
ET_{crop}	Crop evapotranspiration	S	Soil water storage
ET_{weed}	Weed evapotranspiration	SWC	Soil water content
ET_o	Reference evapotranspiration	T	Transpiration
ET_a	Actual evapotranspiration	TWU	Total water use
ETc	Crop evapotranspiration from the Kc method	U_d	Water liberated for downstream users
GIR	Global requirements for the CIS	V_{dc}	discharges in channels (excess water)
i	Crops	Vo	Minimum water volume to operate the channels
IE	Irrigation efficiency	WE	Losses by wind drift and evaporation
IE_{CDN}	Irrigation efficiency of the conveyance and distribution network	WP_{CIS}	Water productivity at the collective irrigation system level
IE_{CIS}	Irrigation efficiency at the collective irrigation system level	WP_{CIS_Irrig}	Irrigation water productivity at the collective irrigation system level
IE_F	Irrigation efficiency at the field level	WP_{CIS_TWU}	Water productivity relative to the total water use at the collective irrigation system level
IMP	Water imported from other CIS	WP_F	Water productivity at the field level
IR	Crop seasonal irrigation requirements	WP_{F_Irrig}	Irrigation water productivity at the field level
Irrig	Irrigation requirements at the field level	WP_P	Water productivity at the plant level
I_{SH}	Irrigation supply at the fields' hydrant	W_{CDN}	water diverted into the conveyance and distribution network
$I_{tissues}$	Water incorporated in plant tissues	WP_{TWU}	Water productivity including precipitation
j	Hydrants or turnouts	WUE	Water use efficiency
Kc	Single crop coefficient	Y	Crop yield at the field level
Kcb	Basal crop coefficient	Y_{CIS}	Average yield for the collective irrigation system
ΔS	Changes in soil water storage		

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