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REVIEW

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Performance assessment and indicators for agricultural water management—A review

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Abstract

The complexity of irrigation systems and the need to adapt them to uncertainties requires developing approaches to synthesize their performances. This paper reviews performance assessment and indicators for agricultural water systems. It is aimed at finding various methods and indices used for irrigation performance assessment and standard classes for their characterization. The global application of the metrics was also documented. Adopting a systematic review approach, peer-reviewed journal articles published in the English language in the last two decades (1 March 2001 to 31 December 2020) were surveyed. Case studies were presented demonstrating the application of the indicators. The study revealed a lack of standardization and the use of a wide range of indicators among others, and recommended representing certain indicators as single. However, this review considered one indicator as the best. Suggestions for further studies were made.

KEYWORDS
irrigation management, performance assessment, performance indicators, review

Highlights

- A systematic review of methods and indices for agricultural performance assessments was conducted.
- Performance indicators are applied globally in small and large agricultural systems under different spatial and temporal scales, scales of analysis, and management types.
- Some categories of PIs need further studies to come up with a single PI that will represent them.

KEYWORDS
irrigation management, performance assessment, performance indicators, review

1 | INTRODUCTION

Water management becomes complex because of uncertainties associated with climate change and population growth, and thus performance improvements of water systems, especially irrigated agriculture (Ghahroodi et al., 2015), is a step forward in dealing with the pressure on water resources (Akhbari & Grigg, 2013; Kifle et al., 2017). The complexity of water systems and the need to adapt

them to changing conditions require developing approaches able to synthesize system performance (performance assessment) through specific parameters measured or evaluated by numerical models (performance indicators). Irrigation performance is essential because both donors and communities are interested in knowing if the interventions or investments made have a measurable effect on the projects. At the same time, implementing agencies want to demonstrate success. This is achieved by the use of indicators.

In our context, performance assessment (PA) is defined as evaluating the resource use and the efficacy or achievements of processes involved (Neely et al., 2005). Similarly, performance indicators (PIs) are quantitative measures of the performance of a system, in that it reveals information about an entity in the form of a value or parameter (Vieira et al., 2015). PA aims to ensure the efficient and effective use of resources by providing appropriate feedback to the management at all levels (Bos et al., 2005; Small & Svendsen, 1990). PA has played an enormous role in water resources management and design, in that they allow a basis for comparing similar systems (Dejen et al., 2012; Kazbekov et al., 2009) or identifying areas with potential for improvements (García-Bolaños et al., 2011; Van Halsema et al., 2011), provides a framework for monitoring progress (Mateos et al., 2010), and inform investment decisions (Dembele et al., 2012). Similarly, PIs play an important role in attaining sustainable development, in that they help in disseminating information, simplifying complex scientific data (Bastiaanssen et al., 2001; Brown et al., 2015; UN-Water, 2006), and informing decision-makers on the status of the water system in question (Bos et al., 2005). Therefore, consistent PA is essential for sustainability because it is almost impossible to properly inform decision-makers, implementing agencies, or donor agencies if little or no knowledge of how existing schemes perform (Dembele et al., 2012). For example, using PIs, large-scale irrigation's low performance had diverted donors' and governments' attention from large irrigation schemes (Borgia et al., 2012). Many case studies showed an actual state of the systems or evidence of improvement after analysing irrigation systems using the reviewed PIs, for example, in Awulachew & Ayana (2011). Research had used indicators to assess how water is distributed among small farm holders (Abou Kheira, 2009; Abuzar et al., 2017; Agam et al., 2013; Ahadi et al., 2013; Ahmed et al., 2010; Awan et al., 2011; Awulachew & Ayana, 2011; Sánchez et al., 2015a; Setegn et al., 2011) or upstream with downstream farmers (Ahmad et al., 2017; Shanono et al., 2014).

Because of its great importance and wide acceptability, PA has been applied globally to improve the performance of irrigated agriculture in Africa (Ahmad et al., 2017; Al Zayed et al., 2015), Asia (Chandran & Ambili, 2016; Jiang et al., 2015), Europe (Andrés & Cuchí, 2014; Moreno-Pérez & Roldán-Cañas, 2013), North America (Ahadi et al., 2013; Lecina et al., 2011), South America (Bastiaanssen et al., 2001) and Oceania (Abuzar et al., 2019) covering various standpoints—from researchers, donors, farmers, irrigation managers and government (Carr et al., 2012; Chandran & Ambili, 2016).

The choice of PA is influenced by whether it examines internal objectives (in terms of analysing a system, e.g., Kuscu et al., 2009) or external objectives (by looking at two or more different systems (e.g., Dejen et al. [2012]). It is also influenced by the purposes of the PA as reported by Bos et al. (2005) that categorized the purpose into; accountability PA (e.g., Akkuzu et al., 2007; Kazbekov et al., 2009; Kukul et al., 2008; Lorite et al., 2012), diagnostic PA (e.g., Abou Kheira, 2009; Ahmad et al., 2009; Gomo et al., 2014; Van Halsema et al., 2011; Zema et al., 2019; Zwart & Leclert, 2010), intervention PA (Barros et al., 2011; García-Garizábal et al., 2011; Jayatillake, 2004; Mateos et al., 2010; Merchán et al., 2015; Vandersypen et al., 2006), operational PA (e.g., Ahadi et al., 2013; Ahmad et al., 2017; Al Zayed & Elagib, 2017; Bandara, 2003; Dejen et al., 2015; Lorite et al., 2004; Taghvaeian et al., 2018) and sustainability PA (e.g., Yilmaz & Harmancioglu, 2010). Defining the extent or boundaries of PA to effectively evaluate performance is pertinent. This is achieved by relating it to spatial (area or number of schemes covered) and temporal (duration of the PA) scales. Other boundaries relate to if PA cover technical aspects only, or if it should include institutional and financial aspects (Bos et al., 2005).

Data are crucial to PA. The sources of data used as input in PA are many. The main sources are ground measurements (e.g., Dejen et al., 2015; Dembele et al., 2012; Ghahroodi et al., 2015; Mateos et al., 2010; Phengphaengsy & Okudaira, 2008; Rowshon et al., 2011; Sekyi-annan et al., 2018), remote sensing (Akbari et al., 2007; Karatas et al., 2009; Kharrou et al., 2013; Ray et al., 2002; Santos et al., 2010; Segovia-cardozo et al., 2019; Usman et al., 2015; Zwart & Leclert, 2010) and a combination of the two (Ahadi et al., 2013; Ahmad et al., 2009; Ahmed et al., 2010; Awulachew & Ayana, 2011; Bastiaanssen et al., 2001; Hamid et al., 2011; Lecina et al., 2011; Taghvaeian et al., 2018). Also, simulation models were used, but they are unpopular because of inadequate data for calibration and validation, hence the use of water balance models (Santos et al., 2010). For a successful PA, many factors, such as, socioeconomic and political have to be taken into cognizance in addition to the technical factors (Boelens & Vos, 2012; Gain & Giupponi, 2015; Vilanova et al., 2015; Wichelns, 2014; Yadav et al., 2014; Zhou et al., 2017).

Despite increasing literature on PA and PIs (e.g., Elshaikh et al., 2018), further understanding of their application in the agricultural context is crucial for sustainability. This paper presents a systematic review of literature on PA and PIs to identify (1) the varied methods and indices used to assess agricultural water use, (2) differences in scale of analysis focusing on where why, and for how long and (3) to characterize the state of knowledge on performance types. Specifically, our objectives address the following research questions; what are various methods and indices used for agricultural water PA? What are the common classes for organizing indicators that measure agricultural water performance? Towards achieving these objectives, several studies and techniques were reviewed. The theoretical aspect of PA and PIs was discussed, then types of PA concerning how it applied to irrigation systems by examining some case studies described in the literature were presented. Moreover, different sources of data used in evaluating the PIs were explored. Relevant questions were considered, including the most popular PIs and their characterization. The limitations of this review are that only PA for agricultural systems and related to technical aspects (state of drainage

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and irrigation infrastructure and water management) were considered. PA for urban systems and catchment is excluded because agriculture, urban, and catchment have such different end goals and needs. Moreover, social and financial aspects are beyond the scope of this article because they require a different approach for computing their PIs, for example, data envelopment analysis (DEA).

2 | METHODS

This paper adopts a systematic review approach to study recent literature on performance assessment and indicators for agricultural water management. The following questions guided the search: what are the various methods and indices used for irrigation performance assessment? What are the common classes for organizing indicators for measuring irrigation performance? Peer-reviewed journal articles published in the English language in the last two decades (1 March 2001 to 31 December 2020) that employed indices in evaluating the performance of irrigation systems were surveyed. Peer-reviewed articles were chosen as data source because of their rigorous scientific nature and their easy accessibility for consistent evaluation and knowledge tracking over time (McDowell et al., 2014). To further guide the search in conformity with answering the research questions as stated previously, the following search terms were developed and used in the database of ISI Web of Science: '(performance indicators) AND (irrigation) AND (water management)'.

Inclusion/exclusion criteria were employed to confirm that reviewed articles have a significant emphasis on performance assessment and indicators for agricultural water management as tabulated in Table 1. To ensure that the majority of related papers were surveyed, an iterative approach was employed as done by McDowell et al. (2014) and is described below.

The initial keyword search produced 335 possible citations. Results were imported into EndNote, and duplicates were removed. Titles of the remaining 331 articles were studied, and articles not relevant were removed (e.g., articles focus on benchmarking, and, urban and environmental systems were not considered). Environmental performance indicators were left out of the study because they usually have higher uncertainty (Córcoles et al., 2010).

Inclusion/exclusion criteria were applied to the remaining 126 relevant abstracts to make sure they are appropriate for a full review. Finally, 59 papers were reviewed fully and were used as the source for a secondary backward/forward citation-tracking search. Thereafter, another inclusion/exclusion criterion was employed to produce 23 more studies by citation tracking included for a full review. In all, 82 relevant articles were selected for the review, but 10 articles were removed based on the exclusion criterion. Consequently, 72 related articles were finally reviewed. The analysis was conducted in line with the questions posed and the indicators were categorized as defined by Bos et al. (2005).

To ensure credibility in the manner data was extracted, a questionnaire and codebook were employed to review the document. The questionnaire was intended to extract important features regarding the articles and performance assessment and indicators, while the codebook presented explanations of basic questions and feasible answers. Errors arising from researchers' subjectivity were minimized using the tactics employed by McDowell et al. (2014). Data derived from the questionnaire and codebook analysis were processed in Excel to quantify the study findings. Details on research materials and procedures can be found in the supplementary materials. Final scrutiny of the remaining 72 papers revealed 52 different indicators used for PA evaluated 288 times. This is so because individual articles have used multiple PIs.

The lists of publications within the databases are not comprehensive as they may exclude articles in which PIs were used to assess performance in a non-explicit manner.

TABLE 1 Inclusion/exclusion criteria for the systematic literature review as adopted in this study.

S/no.	Inclusion	Exclusion
1.	Peer-reviewed	Significant focus on benchmark techniques and DEA
2.	In the English language	Future projections/ hypothetical scenarios
3.	Published on or after 13 March 2001/on or before 31 December 2020	Evaluating economic indicators, financial indicators, production indicators, and energy use indicators
4.	Primary focus on PA and PIs	PIs not clearly stated with indices and/or equations
5.	Presence of assessment instruments; indices/ indicators	Papers assessing financial indicators and level of farmer's satisfaction
6.	-	Papers whose conclusions depend on indicators such as financial indicators, production indicators, and energy use indicators.

3 | RESULTS

Information regarding publication details was extracted and quantified (i.e. case studies, what indicators were used, data sources, and at what temporal and spatial scale). There is an indication of a growing number of articles on PA and PIs for irrigation water management in peer-reviewed journals over the last two decades. Yet the total number of articles with this focus remain low ($n = 72$) (Figure 1). The first authors were mainly affiliated with academic institutions (Figure 2) and the majority are based in Europe (Figure 3). In terms of geographical coverage of the publications, PIs were applied mainly in Asia and are discussed in detail and presented as a map in Section 4.5.

Fifty-two (52) different PIs analysed two-hundred-and-eighty-eight (288) times were documented (Figure 4). Note that only metrics

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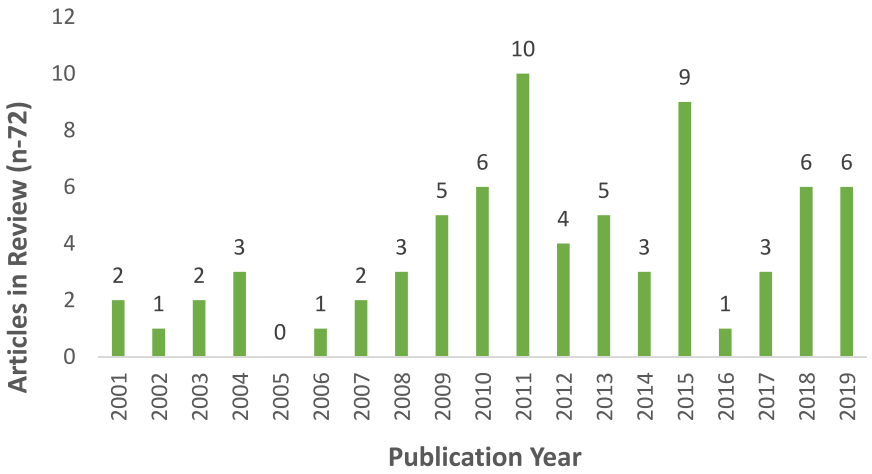


FIGURE 1 Number of publications over the last two decades. Note: 2001 = only articles from 1 March 2001 = only articles until 31 December 2020.

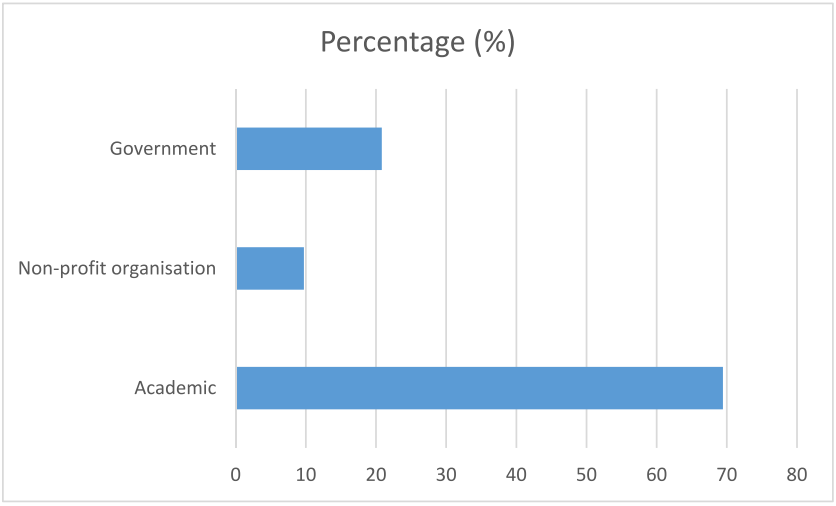


FIGURE 2 First authors' institutional affiliation.

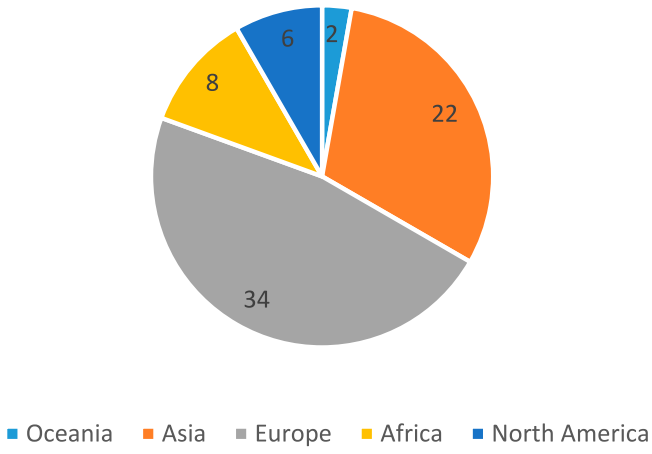


FIGURE 3 First authors' affiliation by continent (no recorded work from Antarctica).

or indices appearing more than two times were plotted for clarity. Most of the PIs were evaluated using data from field measurements and in some cases using remote sensing or combination of two (Figure 5). PA is employed to cover either a single irrigation season or multiple seasons (Figure 6). Many PAs were done at the level of irrigation scheme, farm level, basin level or a combination of the three levels (Figure 7). The irrigation systems reported are managed predominantly by the governments and some are community-managed. Other forms of management employed were documented (Figure 8). Characterizing the consulted literature based on their classification revealed that operational PA dominated with a very small number of sustainability-based PA. (Figure 9). A comprehensive analysis of the results is shown in the supporting information.

The review identified Haie's (2021) Sefficiency chosen by the US government as the best form of efficiency indicator. This Sefficiency (which is a contraction of Sustainable efficiency) computes the performance of a water system, such as an irrigated region, from both the supply and the demand side. It comprehensively unifies water quantity, quality and benefits; hence, transparency increases and water consumption pressures and impacts become more visible. It also integrates and quantifies various levels of water management (e.g., two levels: farm and sub-basin) thereby engaging all stakeholders in a transparent process of decision-making at various levels of governance.

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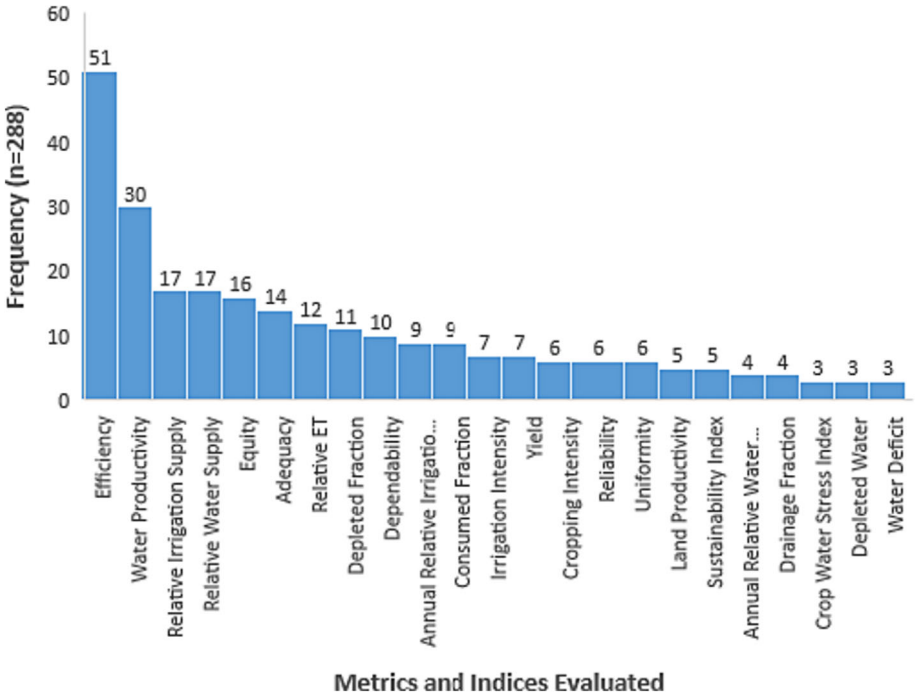


FIGURE 4 Metrics and indices evaluated.

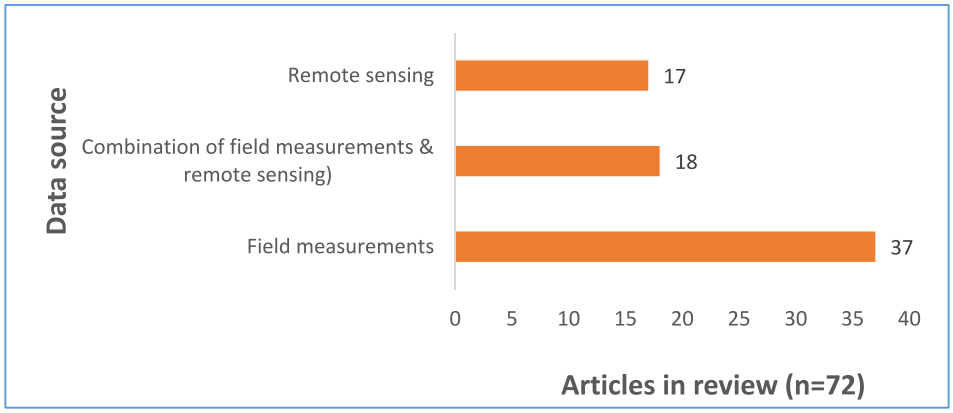


FIGURE 5 Data source.

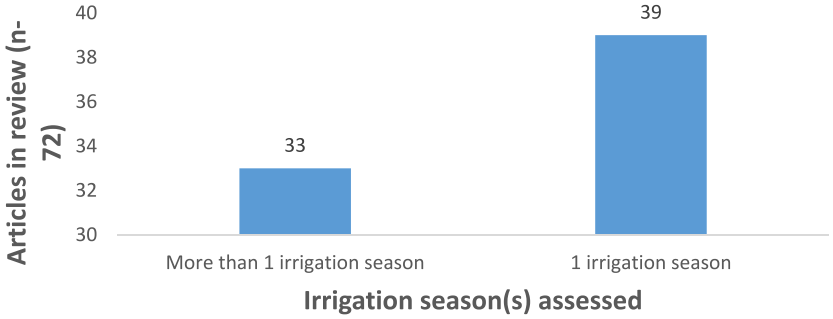


FIGURE 6 Temporal scale of analysis.

4 | DISCUSSION

4.1 | Performance indicators (PIs): Conceptual framework

A synthesis of what the reviewed papers identified as PIs is presented here. Several definitions were proposed by different authors in the context of water management in general, and irrigation water management in particular. Vieira et al. (2008) defined PI as '[…] a quantitative measure of the effectiveness and efficiency of a specific aspect of service delivered by a water supplier'. Based on irrigation perspective, Soto-García et al. (2013) defined PIs as 'ratios that describe a variety of irrigation domains (inputs, processes, outputs, impacts, etc.) through relating variables in such a way that a large amount of

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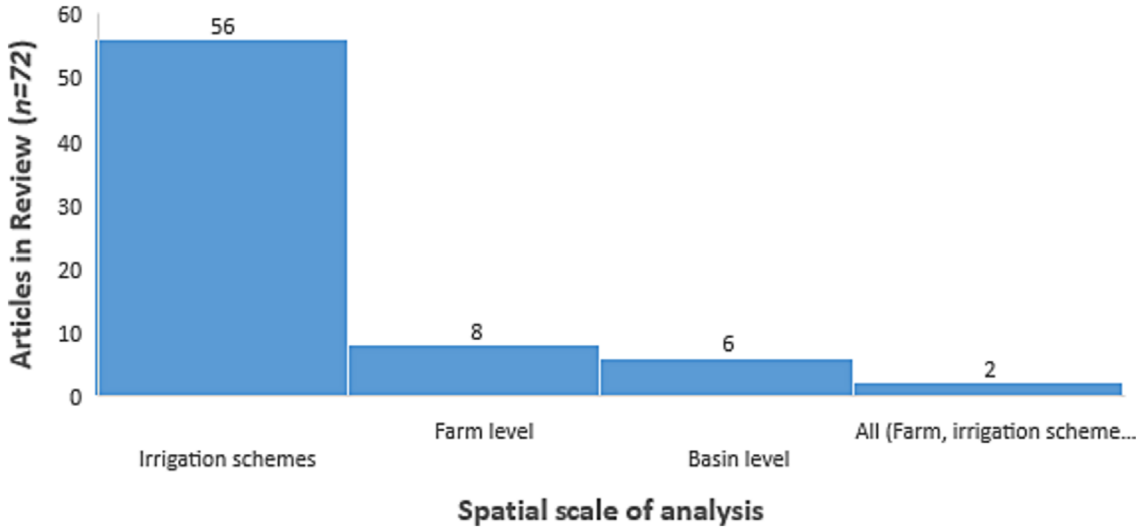


FIGURE 7 Spatial scale of analysis.

FIGURE 8 Types of management employed in the systems.

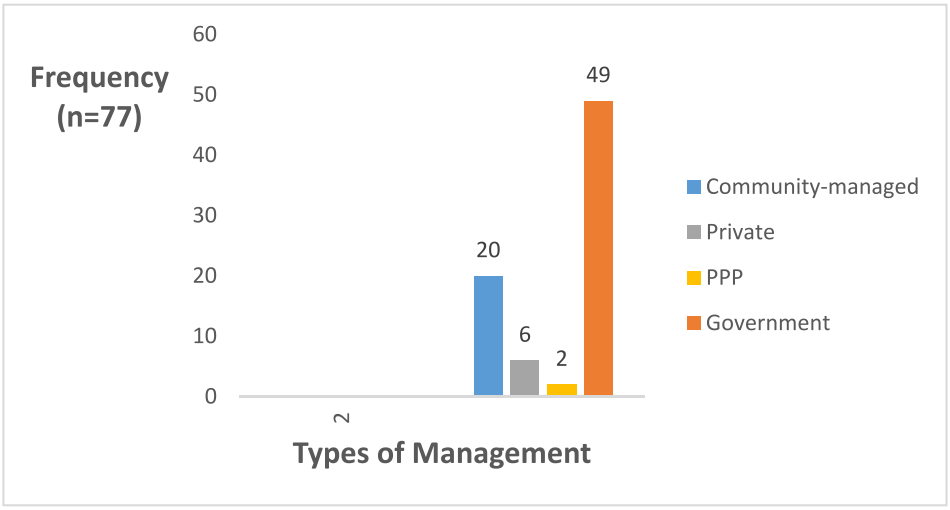
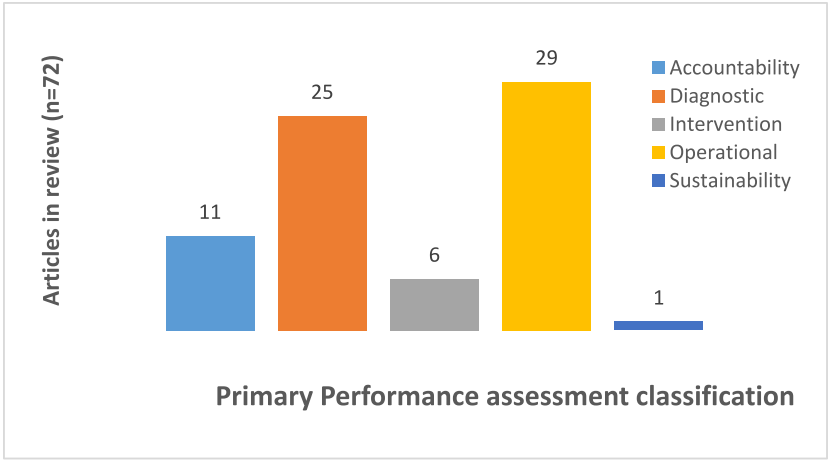


FIGURE 9 Primary performance assessment classification performance assessment (PA).



information is reduced to a single annual index'. Similarly, Bos & Nugteren (1990) defined PIs as indices describing the behaviour of irrigation schemes through a few understandable numbers. Awulachew & Ayana (2011) described PIs as a measure of current achievements attained for the objective(s) of irrigation. Also, Bandara (2003) identified PIs as those depicting system performance in

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different dimensions used by decision-makers. Even though few and selective, the above definitions represent sum up the definition given by authors. In conclusion, different authors have accepted these definitions and used them in agricultural water management domain.

The nine most frequently used PIs across all papers according to this review are efficiency, water productivity, relative irrigation supply, relative water supply, equity, adequacy, relative ET, depleted fraction, dependability and annual relative irrigation supply. These PIs are important because of the frequency of their appearance in the reviewed papers and what they measure (see Table 2). The PIs were used in different PAs (details in Section 4.2) and have played a significant role in water allocation, in that many have used indicators to assess how water is distributed between small farm holders (Abou Kheira, 2009; Abuzar et al., 2017; Agam et al., 2013; Ahadi et al., 2013; Awan et al., 2011; Awulachew & Ayana, 2011; Sánchez et al., 2015a; Setegn et al., 2011), upstream versus downstream farmers (Ahmad et al., 2017; Shanono et al., 2014). Table 2 describes the set of reviewed indicators that appear the most and what metrics might be good for measuring them.

Some PIs have the same metric but different concepts (Borsato et al., 2019), while others are conceptually and computationally the same (e.g., relative water supply [RWS], cumulative relative water supply [CRWS] and annual relative water supply [ARWS]). The only difference is the temporal magnitude, that is, referring to a day, month or year. These categories of PIs need further studies to come up with a single PI that will represent them, thereby reducing the use of a wide range of PIs. This could be achieved by engaging stakeholders who need to define PIs that could reliably be used to compare different water management alternatives, including access to water resources (Le Grusse et al., 2009) for sustainability. There are also emerging PIs based on remotely-sensed data.

TABLE 2 PIs and what they measure.

PI	What metrics might be good for measuring	Reference
Efficiency	The volume delivered within a set time to crop water requirement	Bos et al. (1994)
Water productivity	Measures how much water is consumed to produce yield	Bastiaanssen & Bos (1999)
Relative irrigation supply	Describes temporal coefficient of variation of evaporative fraction in a season	Al Zayed et al. (2015)
Relative water supply	Assesses the delivery performance of irrigation water	Kloezen & Garcés-Restrepo (1998)
Equity	Estimates actual water flow for each irrigated area at various spatial scales	Molden & Gates (1990)
Adequacy	Depicts the degree to which a sufficient amount of water is provided for the crops' needs	Ray et al. (2002).
Relative ET	Shows relative decrease in evapotranspiration revealing areas where water is short (water stress)	Bos et al. (2005).
Depleted fraction	Traces water flow from the intake to the field	Awan et al. (2011)
Dependability	Expresses the extent to which water application is done as planned	Hamid et al. (2011)

4.1.1 | Definition of the PIs and their formulae

Although many PIs were reviewed, this section is not intended to discuss all the PIs, but merely a summary of the first nine most frequently used PIs including their formulae.

Efficiency

Since the 1930s, the design and operation of irrigation systems have been analysed using classical irrigation efficiency (CE) (Haie & Keller, 2014). Israelsen (1932) defined it as the ratio between crop water requirements and the applied water. Over time, authors improved and refined this definition (Bos et al., 2005; Burt et al., 1997; Jensen, 1966, 2007; Keller et al., 1996; Pereira et al., 2002; Perry, 2007; Van Halsema & Vincent, 2012; Wichelns, 2002). Presently, several scholars have defined CE as the ratio of water volume beneficially used by plants to the volume of water delivered through an irrigation system, adjusted for effective rainfall and changes in the water storage in the root zone.

$$CE = \frac{ET}{VA} \quad (1)$$

where CE = classical efficiency; ET = net crop evapotranspiration; VA = diverted water.

Nevertheless, CE is insufficient in advancing sustainable design and management of WUS because of uncertainties involved as a result of the enormous pressure put on water. Hence, the need for composite PIs. Consequently, multiple studies have proposed Effective Efficiency and Net Efficiency that incorporate the variables like water quality, water reuse, and the distinction between water use and consumption (Haie & Keller, 2008; Keller et al., 1996). Unfortunately, the terms are mostly used erroneously (Birkenholtz, 2017; Boelens & Vos, 2012; Haie, 2016; Heydari, 2014; Jensen, 2007; Lankford, 2012; Perry, 2007), specifically when dealing with water quality (Ayars & Schoneman, 2006; Haie & Keller, 2014; Qureshi et al., 2011), and socio-economic analysis ignored (Keller et al., 1996; Qureshi et al., 2011; Wichelns, 2002). To avoid that, attention to employing the correct terminology was drawn (Heydari, 2014; Pereira, 1999; Perry et al., 2009; Qureshi et al., 2011; Vilanova et al., 2015) using the conservation of mass law (Frederiksen & Allen, 2011; Pereira et al., 2012). Hence, the need for PIs that address those shortcomings. As stated in Section 3, the Sefficiency indicator was identified as the

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best. A brief on Sefficiency is made here and for details on the formulation of the Sefficiency framework and its application, refer to Haie and Keller (2012), (2014) and Haie (2016).

The following equations represent different levels of Sefficiency.

$$MacroEs = \left[\frac{ET + NR + i(VD + RP)}{VU + OS + PP - c(VD + RP)}\right]_S \quad (2)$$

i + c = 1 with $i, c \in \{0, 1\}$

$$MesoEs = \left[\frac{ET + NR + i(RF + RP)}{VA + OS + PP - c(RF + RP)}\right]_S \quad (3)$$

$$MicroEs = \left[\frac{ET + NR}{VA + OS + PP}\right]_S \quad (4)$$

The two indices *i* (inflow models) and *c* (consumptive models) correspond to two water totals: useful inflow and effective consumption. Each index is either zero or one, with its sum equals to one. Their appearance before say MesoE shows the type of indicator. For instance, iMesoE means meso-efficiency and calculated as an inflow model ($i = 1, c = 0$). The minimum necessary conditions in using Sefficiency are that useful outflow must be less than useful inflow and useful consumption must be less than effective consumption. Both assumptions are met in any kind of agricultural or urban setting.

Figure 10 shows the schematic of WUS indicating the water flow path types used to define the Sefficiency terminology upon which the indicators such as in Equations (2)–(4) can be developed.

Water productivity

Water productivity (WP) measures how much water is consumed to produce yield. WP (grain yield per unit of actual ET) constituted two parts; physical biomass or yield per unit of water and overall consumed ratio (Bastiaanssen & Bos, 1999). WP was estimated using the indicator given by

$$WP = \frac{Y}{ET_c} \quad (5)$$

where *WP* is water productivity in kg m^{-3}, *Y* is the seasonal crop fresh yield in kg ha^{-1} and ET_c is the seasonal crop water consumption by evapotranspiration, in m^3 ha^{-1}.

Relative irrigation supply

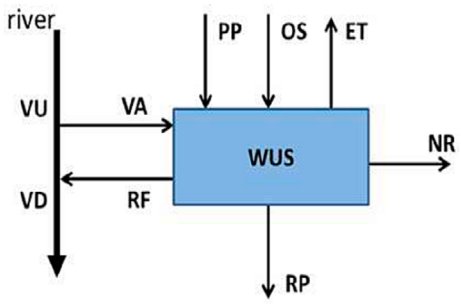
Relative irrigation supply (RIS) describes the reliability of water supply (Bastiaanssen & Bos, 1999) at different time scales and levels of schemes. It describes the temporal coefficient of variation of evaporative fraction in a season. In the case of an arid environment where rainfall is negligible compared to irrigation supply, RIS could be used to find the performance of irrigation water supply (Al Zayed et al., 2015) because it informs managers whether enough supplied water meets the overall crop demand or not. It is given by Sakthivadivel et al. (1999) as follows:

$$RIS = \frac{irrigation\ supply}{irrigation\ demand} \quad (6)$$

The volume of irrigation demand (m^3/ha) is the same as the potential ET after deducting effective rainfall. RIS is a suitable PI for measuring the extent of water shortage or otherwise relative to demand (Dejen et al., 2012). However, RIS is neither an indication of the application of the right amount of water in time nor the water consumed by the crop. But just an indication of the general status of supply and demand. It is worthy of note that a RIS value greater than 1 does not necessarily guarantee adequate irrigation.

Relative water supply

Relative water supply (RWS) is defined as the ratio of the total water supply to the total water demand, expressed by ET_c. In the same way, the inverse of RWS called the coefficient of variation signifies reliable water supplies throughout the cropping season. RWS values from 0.9 to 1.2 (using ET_c) suggest satisfactory irrigation efficiency (Moreno-Pérez & Roldán-Cañas, 2013). RWS is chosen to assess the delivery performance of irrigation water (Kloezen & Garcés-Restrepo, 1998) expressed as



Variables	Description
ET	Evapotranspiration
NR	Non-reusable
OS	Water from other sources
PP	Total precipitation
RF	Return flow
RP	Potential return (does not return to the main source)
VA	Abstracted/applied water from the main source
VD	Volume of water downstream after return flow in the main source
VU	Volume of water upstream before abstraction in the main source

FIGURE 10 General schematic of WUS and description of variables as formulated in Sefficiency.

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$$RWS = \frac{precipitation + irrigation\ supply}{ET_c} \quad (7)$$

Equity

Equitable allocation of water to various parts of a water system is central to equity. Equity indicator (P_E) estimates the actual water flow for each irrigated area at various spatial scales. It is calculated using a coefficient of variation (CV) of the ratio of water delivered (Q_D) to water required (Q_R) over a region R during the period T, respectively (Molden & Gates, 1990):

$$P_E = \frac{1}{T}\sum_T CV_R\left[\frac{Q_D}{Q_R}\right] \quad (8)$$

where P_E is the performance measure relative to equity; $CV_R\left[\frac{Q_D}{Q_R}\right]$ is the spatial coefficient of variation of the Q_D/Q_R over the region R. The ideal value of this index is zero. It is worth noting that actual evapotranspiration is the basis for equity (Bastiaanssen & Bos, 1999). According to Kharrou et al. (2013), equity is assessed using average seasonal ET_c and their coefficient of variation over cropped areas.

Adequacy

An abundance of water in an irrigation system is known as adequacy. It is used to assess the decrease in consumptive water use and to evaluate the right amount of irrigation water delivery to a selected command area (Usman et al., 2015). It is also described by Ahmad et al. (2009) as the capacity to meet the crop water requirements and depict the degree to which a sufficient amount of water is provided for crop needs (Ray et al., 2002). Evaporative fraction maps (Bastiaanssen & Bos, 1999) or average seasonal evaporative fraction (Usman et al., 2015) are used to evaluate adequacy because it tells the situation of crop supply. Higher values of evaporative fraction (≥0.8) show no stress and lower values (<0.8) indicate inadequate moisture to satisfy crop water. Equation (9) is used to quantify adequacy (Molden & Gates, 1990).

$$P_A = \frac{1}{T}\sum_T\left[\frac{1}{R}\sum_R(P_a)\right],\ P_a = \frac{Q_D}{Q_R} \le 1 \quad (9)$$

where P_A is the distribution adequacy; P_a is the operation function in each point (actually defined for any intake structure) related to adequacy, Q_D and Q_T are the amount of delivered water (actual amount) and the amount of water required for an intake canal during the period of T, respectively.

Relative evapotranspiration

Relative evapotranspiration (RET) shows a relative decrease in evapotranspiration revealing areas where water is short (water stress). In other words, it indicates the existence of crop water deficits. The ratio of the crop over maximum evapotranspiration gives valuable information to the water manager (Bos et al., 2005).

RET is defined as

$$RET = \frac{actual\ evapotranspiration\ (ET_c)}{potential\ evapotranspiration\ (ET_P)} \quad (10)$$

A critical value of 0.75 having a permissible range of 0.75–1.0 is allowed for irrigation during the growing season, even though it can change with time (Kharrou et al., 2013). In a different, but complementary study, Kharrou et al. (2013) calculated RET in terms of the K_c ratio as the water stress coefficient or ET deficit. They concluded that RET indicator is more appropriate when crops are fully covered to avoid evaporation side effects.

Depleted fraction

Actual water use is related to the amount of water applied through depleted fraction (DF) (Kharrou et al., 2013). DF traces water flow from the intake to the field and takes into account the water lost during conveyance or as a result of low application efficiency (Awan et al., 2011). It is particularly attractive as it allows for the comparison of spatiotemporal situations of consumed water across irrigation networks comprehensively. This indicator is defined as

$$DF = \frac{ET_c}{V + P_g} \quad (11)$$

where ET_c is the actual evapotranspiration, V (mm) is the volume of irrigation supply and P_g (mm) is the gross precipitation. Bastiaanssen et al. (2001) proposed 0.6 as the critical value of DF with an acceptable range of 0.6–1.1 for arid and semi-arid regions.

Dependability

The extent to which water application is done as planned is defined by the dependability indicator (D_P). It is calculated as the temporal coefficient of variation of the ratio (Q_D/Q_R) over time as in Equation (11) (Molden & Gates, 1990) and employed by Hamid et al. (2011):

$$D_P = 1 - 1/R\sum^{R} C_{VT}(Q_D/Q_R)\ ;\ Q_D \le Q_R \quad (12)$$

where C_{VT} (Q_D/Q_R) is the temporal coefficient of variation of the ratio (Q_D/Q_R) over time T. As D_P approaches 1, RIS becomes more uniform over time T.

4.2 | General categories of PIs

The choice of PA is influenced by what it examined which could be internal (in terms of analysing a system; e.g., Kuscu et al., 2009) or external objectives (by looking at two or more different systems; e.g., Dejen et al., 2012). Therefore, PIs can be grouped into two (2) main classes: internal and external PIs (Fan et al., 2018). The PIs can be expressed either as quantitative (in terms of quantities or

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numbers) or qualitative (qualitative approximations of how well the plots were irrigated or drained) (Borgia et al., 2012). Qualitative PIs are determined as scores expressed on a scale from 0 to 3 according to prescribed criteria which are then normalized to 0–1 scale (García-Bolaños et al., 2011).

4.2.1 | Internal irrigation PIs

Internal irrigation PIs are employed to evaluate internal processes, i.e. water delivery systems (Dejen et al., 2015) or hydraulic processes (Akkuzu et al., 2007) of irrigation systems. They are also referred to as water supply indicators. The aim is to assess whether the system delivers water at the intended rate in precise time and space and to evaluate whether water delivery conforms with the set standards. Adequacy, efficiency, equity, and dependability are the most indicators of internal water delivery performance studied (Akkuzu et al., 2007; Dejen et al., 2015; Hamid et al., 2011; Kazbekov et al., 2009; Nam et al., 2016; Ray et al., 2002; Sanaee-Jahromi & Feyen, 2001; Unal et al., 2004; Usman et al., 2015; Vandersypen et al., 2006; Zema et al., 2019). Furthermore, there are other PIs used to assess adequacy and efficiency of water delivery, which include relative water supply, relative irrigation supply, water delivery ratio, conveyance efficiency, relative irrigation supply, depleted fraction and relative evapotranspiration.

4.2.2 | External PIs

External irrigation PIs are those relating outputs to inputs such as water and land productivity and irrigation intensities (Borgia et al., 2012).

4.3 | Performance assessment (PA)

In a general context, performance assessment (PA) involves 'quantifying the efficiency of resources use and the effectiveness of processes linked to these actions' (Bos et al., 1994; Neely et al., 2005). The discussion on the meaning of efficiency is still ongoing (Birkenholtz, 2017; Boelens & Vos, 2012; Haie, 2008; Lankford, 2012; Pereira et al., 2002; Perry, 2007, 2008, 2011). However, efficiency denotes the extent to which resources of a water utility are utilized optimally to produce a service (Vieira et al., 2008). Specifically, irrigation PA is concerned with the assessment of water flow paths in irrigation systems (Akbari et al., 2007; Al Zayed et al., 2015; Bandara, 2003), by estimating factors like water inflows and outflows, water need (crop demand), water use, system losses, crop production and the extent cultivated.

It is important here to differentiate between the goal of management of the system (against which performance is being assessed) and the goal of the performance assessment process. For instance, sustainability is a goal or normative concern for the water management of the system. Efficiency, equity, and dependability could be equally valid goals/concerns. These are usually arrived at by political processes and the PA is assessed against them, that is, if equity was the goal of management, a PA process might assess if that goal was met, using appropriate indicators. This is different from the purpose of the PA itself—diagnostic, intervention design, and so on. This is independent of the goal/concern.

PA covers various standpoints—from researchers, donors, farmers, irrigation managers, and government (Carr et al., 2012; Chandran & Ambili, 2016). PA is viewed differently by different professionals, such as hydrologists, biologists and agronomists. However, the set of PIs is normally similar in different regions regardless of different names and data at hand (Vilanova et al., 2015). Thus, what is important is choosing the proper set of PIs (Bos et al., 1994) that will suit the purpose of the PA.

4.4 | Characterization of performance assessment (PA)

Identifying the class to which a particular PA belongs is essential for its proper evaluation because PA type is closely associated with the purpose or rationale for that PA. Authors have tried to characterize PA based on different criteria. However, one interesting characterization linking PA to performance purpose was done by Small & Svendsen (1990) into; accountability, intervention, operational, and sustainability performance. Considering this concept Bos et al. (2005) added an additional PA as a diagnostic. This paper has attempted to characterize the consulted literature based on this classification. Table 3 presents the classification of reviewed articles (n = 72) based on performance assessment types. It was found that operational PA dominated the literature with a very small number of sustainability-based PA.

4.5 | Spatial and temporal applications of PA and PIs

Different types of analysis require different types of PIs. The choice of PIs is influenced by a lack of sufficient and quantifiable data from which to create a PI. PIs selected are essentially those for which the variables needed are obtainable from surveys, measurements and monitoring (Le Grusse et al., 2009). In this regard, measured or observed data is very important. Also, the number of PIs required for PA depends on boundary conditions and purposes of PA (Bos et al., 2005). PIs are used in different types of analyses for small scales (Gomo et al., 2014) and large scales irrigation systems (Dejen et al., 2015; Dembele et al., 2012). However, most of the PIs are applied to all types of irrigation schemes, ranging from simple gravity-fed to highly technical computer-controlled systems (Gomo et al., 2014).

The PIs were applied in Africa (Ahmad, Haie, Yen, & Tuqan, 2018; Al Zayed et al., 2015), Asia (Chandran & Ambili, 2016; Rowshon et al., 2014), Europe (Andrés & Cuchí, 2014; Gadanakis et al., 2015; Merchán et al., 2015), Middle-east (Yigezu et al., 2013), North

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TABLE 3 Classification of reviewed articles ($n = 72$) based on performance assessment types.[a]

Classes of PA	Definition	References
Accountability	Evaluate the performance of managers of the scheme	Akkuzu et al., 2007; Kukul et al., 2008; Kuşçu et al., 2008; Karatas et al., 2009; Kazbekov et al., 2009; Kuscu et al., 2009; Uysal & Atiş, 2010; Awan et al., 2011; Dejen et al., 2012; Lorite et al., 2012; Ahmad et al., 2017
Diagnostic	Pin-point reason(s) of performance for improvements to be made or present levels maintained	Abera et al., 2019; Abou Kheira, 2009; Ahmad et al., 2009; Ahmed et al., 2010; Alexandridis et al., 2014; Andrés & Cuchí, 2014; Awada et al., 2019; Awulachew & Ayana, 2011; Bastiaanssen et al., 2001; Fan et al., 2018; García-Bolaños et al., 2011; Gomo et al., 2014; Gonzalez-Dugo et al., 2015; Haj-amor et al., 2018; Jiang et al., 2015; Kharrou et al., 2013; Kifle et al., 2017; Lecina et al., 2011; Moreno-Pérez & Roldán-Cañas, 2013; Ray et al., 2002; Sekyi-annan et al., 2018; Shahrokhnia & Olyan-ghiasi, 2019; Van Halsema et al., 2011; Zema et al., 2019; Zwart & Leclert, 2010
Intervention	Impact of rehabilitation or transformation from one system to another	Barros et al., 2011; García-Garizábal et al., 2011; Jayatillake, 2004; Mateos et al., 2010; Merchán et al., 2015; Vandersypen et al., 2006
Operational	Day-to-day, season-to-season monitoring and assessment of performance	Abuzar et al., 2017; Agam et al., 2013; Ahadi et al., 2013;; Akbari et al., 2007; Akhtar et al., 2018; Al Zayed et al., 2015; Al Zayed & Elagib, 2017; Bandara, 2003; Bellvert et al., 2015; Borgia et al., 2012; Borsato et al., 2019; Dejen et al., 2015; Dembele et al., 2012; Ghahroodi et al., 2015; Hamid et al., 2011; Lorite et al., 2004; Mondal & Saleh, 2003; Nam et al., 2016; Phengphaengsy & Okudaira, 2008; Rowshon et al., 2011; Sanaee-Jahromi & Feyen, 2001; Sánchez et al., 2015a; Santos et al., 2010; Segovia-cardozo et al., 2019; Setegn et al., 2011; Taghvaeian et al., 2018; Unal et al., 2004; Usman et al., 2015
Sustainability	Examine the longer-term resource use and impacts	Yilmaz & Harmancioglu, 2010

[a]As defined by Bos et al. (2005).

America (Haie & Keller, 2012; Lecina et al., 2011) and South America (Ahadi et al., 2013; Angella et al., 2016). The geographical coverage of the publications is presented in Figure 11.

4.6 | Data sources

In PA, the components of the water balance are estimated either by employing hydrological field measurements or remote sensing techniques. However, many indicators require incorporating field measurements with spatially distributed measures. Recent developments in remote sensing (RS) have made it possible to obtain such information in a spatially distributed way from satellite imagery.

Despite being most expensive, requiring much time and restricted to a particular location, field measurements were found to have dominated the literature consulted (Andrés & Cuchí, 2014; Dejen et al., 2012; Gomo et al., 2014; Jiang et al., 2015; Kharrou et al., 2013; Mondal & Saleh, 2003; Singh et al., 2006). Although, recent studies have proven RS as reliable and how it is fast gaining ground in water management (Bastiaanssen et al., 2001; Singh et al., 2006; Akbari et al., 2007; Ahmad et al., 2009; Karatas et al., 2009; Rowshon et al., 2011; Ahadi et al., 2013; Karimi et al., 2013; Usman et al., 2015), not all users can afford the tool (Tarjuelo et al., 2015), especially in developing countries. Moreover, resource limitations and the small size of plots are some of the reasons why this technology could not be used (Gomo et al., 2014). Table 4 presents references based on the data sources.

Across the globe, some of the publications include Ahadi et al., 2013; Semmens et al. (2016) in the United States; Toureiro et al. (2017) in Portugal; Santos et al. (2010) in Spain; Karatas et al. (2009) in Turkey; and Bastiaanssen et al. (2001) in South America. In Asian countries studies were conducted in such places as Afghanistan (Karimi et al., 2013), India (Ray et al., 2002; Singh et al., 2006), China (Jiang et al., 2015; Karimi et al., 2013), Malaysia (Rowshon et al., 2011), Pakistan (Ahmad et al., 2009; Usman et al., 2015), Iran (Akbari et al., 2007) and Uzbekistan (Awan et al., 2011). Moreover, African countries were found to be the least; Ethiopia (Setegn et al., 2011), Mali (Zwart & Leclert, 2010), Morocco (Kharrou et al., 2013), South Africa (Hellegers et al., 2010), Sudan (Ahmed et al., 2010; Al Zayed et al., 2015; Al Zayed & Elagib, 2017; Hamid et al., 2011). The low economic status and poor funding of research are some of the reasons for lack of researches in Africa and some Asian countries. Impact all the studies in Africa and some Asian countries were done in developed countries like The Netherlands (Hamid et al., 2011; Hellegers et al., 2010; Karimi et al., 2013), Germany (Al Zayed et al., 2015; Al Zayed & Elagib, 2017) and Japan (Ahmed et al., 2010). However, more research is needed to establish this assertion.

4.7 | Application of the developed PIs: Some selected case studies

This subsection highlighted how well the developed PIs have worked for PAs considering some case studies (Table 5). PIs have proved very

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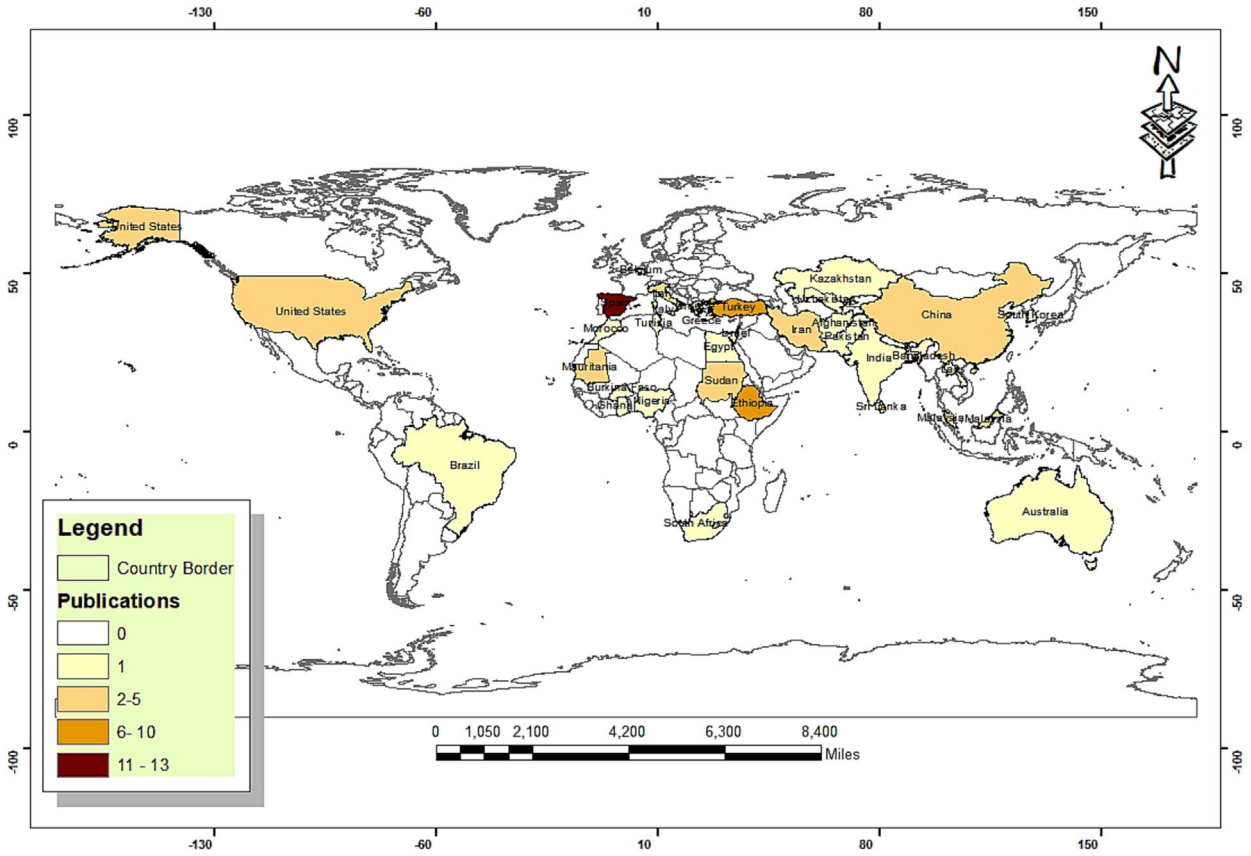


FIGURE 11 Geographical coverage of the publications from 2001 to 2020.

TABLE 4 References based on data sources.

Types of data source	References
Field measurements	(Abera et al., 2019; Abou Kheira, 2009; Ahmad et al., 2017; Borsato et al., 2019; Dejen et al., 2012, 2015; Dembele et al., 2012; Fan et al., 2018; Ghahroodi et al., 2015; Jayatillake, 2004; Kazbekov et al., 2009; Kuscu et al., 2009; Kuscu, Demir and Korukcu, 2008; Mateos et al., 2010; Nam et al., 2016; Phengphaengsy & Okudaira, 2008; Rowshon et al., 2011; Sanaee-Jahromi & Feyen, 2001; Sekyi-annan et al., 2018; Shahrokhnia & Olyan-ghiasi, 2019; Soto-García et al., 2013; Unal et al., 2004; Uysal & Atiş, 2010; Van Halsema et al., 2011; Vandersypen et al., 2006; Yilmaz & Harmancioglu, 2010)
Remote sensing	Ray et al., 2002; Akbari et al., 2007; Karatas et al., 2009; Zwart & Leclert, 2010; Santos et al., 2010; Setegn et al., 2011; Kharrou et al., 2013; Usman et al., 2015; Gonzalez-Dugo et al., 2015; Abuzar et al., 2017; Sekyi-annan et al., 2018; Akhtar et al., 2018; Awada et al., 2019; Segovia-cardozo et al., 2019
Both	(Agam et al., 2013; Ahadi et al., 2013; Ahmad et al., 2009; Ahmed et al., 2010; Awulachew & Ayana, 2011; Bastiaanssen et al., 2001; Borgia et al., 2012; Hamid et al., 2011; Lecina et al., 2011; Taghvaeian et al., 2018)

useful in assessing water management at different spatial scales: field, farm, irrigation district, and basin scale (Ghahroodi et al., 2015; Haie & Keller, 2012, 2014; Qureshi et al., 2011; Rowshon et al., 2014) as well as greenhouse horticultural production area (Sánchez et al., 2015b). In addition, PIs successfully assessed the performance of irrigated areas through external indicators and analysed the internal irrigation processes related to timing, duration or water flows to diagnose performance (Abou Kheira, 2009; Causapé et al., 2006; Gorantiwar & Smout, 2005; Jayatillake, 2004; Sanaee-Jahromi & Feyen, 2001).

Furthermore, PIs facilitated assessing irrigation schemes before and after rehabilitation or intervention, and in analysing scenarios (Angella et al., 2016; Barros et al., 2011; García-Garizábal et al., 2011; Mateos et al., 2010; Merchán et al., 2015; Van Halsema et al., 2011; Vandersypen et al., 2006; Yilmaz & Harmancioglu, 2012) and to identify the best irrigation practices and to compare different and complex irrigation systems (Borgia et al., 2013; García-Bolaños et al., 2011; Kifle et al., 2017; Poussin et al., 2015). Spatiotemporal patterns of PIs could give information on the functioning of the water users associations (WUAs) and allow different irrigation systems to be compared and many researches have shown differences between different types of WUAs globally (Awan et al., 2011; Chandran & Ambili, 2016;

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TABLE 5 Performance assessment studies: location, methodology, indicators used, and major findings.

No.	Reference	Location/methodology	Indicators evaluated	Major findings
1.	Ahadi et al. (2013)	Location: Mexico Techniques: remote sensing, ground-level measurements	On-farm irrigation efficiency, district efficiency	PIs are capable of determining the inefficiency of the system
2.	Ahmad et al. (2009)	Location: Pakistan Techniques: remote sensing	Equity, adequacy, reliability, water productivity,	PIs provide better estimates of irrigation performance at a variety of scales
3.	Andrés & Cuchí (2014)	Location: Spain Techniques: field data, water balance	Irrigation efficiency, irrigation drainage fraction, water deficit, relative irrigation supply, water productivity	Indicators provided an opportunity to analyse large and mature sprinkler irrigation district
4.	Awan et al. (2011)	Location: Uzbekistan Techniques: remote sensing (SEBAL), hydrological field measurements	Relative evapotranspiration, delivery performance ratio, drainage ratio, depleted fraction, overall consumed ratio, field application ratio, conveyance ratio	Delivery performance ratio, relative evapotranspiration, and drainage ratio show inadequacy, inequity, and unreliability of an irrigation system, and the overall consumed ratio and depleted fraction show the inefficiency at system levels
5.	Borgia et al. (2013)	Location: Mauritania Techniques: Cluster and data envelopment analyses	Adequacy, energy cost, relative irrigation supply, irrigation intensity, land productivity	Comparative performance assessment based solely on indicators might be challenging to interpret as the result may vary significantly depending on the indicators used
6.	Córcoles et al. (2010)	Location: Spain Techniques: benchmarking	Total annual volume of irrigation water supply, the total annual volume of irrigation water delivery, the total annual volume of water supply, annual irrigation water supply per unit command area, annual irrigation water supply per unit irrigated area, main system water delivery efficiency, annual relative water supply, annual relative irrigation water supply, water delivery capacity	Annual irrigation water supply per unit irrigated area is a useful indicator in explaining the key features of WUAs. CEN per unit irrigated area and per unit irrigation delivery are significant in describing the characteristics and differences between WUAs
7.	Dejen et al. (2012)	Location: Ethiopia Techniques: field survey, GIS-based	Annual relative water supply, annual relative irrigation supply, output per unit irrigation water diverted/supplied, output per unit irrigation water delivered to the command, output per unit water diverted/supplied, and output per unit water consumed	Indicators are useful for cross-comparison in irrigation schemes.
8.	García-Garizábal et al. (2011)	Location: Spain Techniques Irrigation Land Environmental Evaluation Tool	Net hydric needs, irrigation, efficiency, water deficit	PIs assessed irrigation management alternatives and the effect of multi-annual climatic and agronomic variables
9.	Ghahroodi et al. (2015)	Location: Iran Techniques: physical measurements, field data	Classical efficiency, effective efficiency, water productivity	Effective efficiency represents irrigation systems performance at farm scale more correctly, and combined application of the concepts is suitable for improving irrigation water management
10.	Gomo et al. (2014)	Location: South Africa Techniques: Field survey, AHP	Conveyance efficiency, dependabilityof an interval	

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TABLE 5 (Continued)

No. 1.	Reference	Location/methodology	Indicators evaluated	Major findings
			between water applications, relative irrigation supply, output per unit irrigation supply, output per unit water consumed	PIs employed are capable of assessing smallholder irrigation schemes
11.	Haie & Keller (2012)	Location: Nile, Grand Valley, City 12 020 and hypothetical case Techniques: Sefficiency	Micro, meso, and macro Sefficiency	PIs assessed performance both from the supply and demand side including unifying water quantity, quality, and benefits
12.	Jayatillake (2004)	Location: Sri Lanka Techniques: Benchmarking	Cropping intensity, length of the irrigation season, irrigation duty, water duty	PIs compared regional variation in performance and among different types of schemes such as reservoir-backed schemes and diversion schemes
13.	Kazbekov et al. (2009)	Location: Kyrgyzstan Techniques: field survey	Adequacy, efficiency, dependability, equity	Viable and simple PIs are pre-requisite for the development of operational WUAs universally
14.	Mateos et al. (2010)	Location: Mauritania Techniques: case study application, network distribution model, and field water balance	Water delivery capacity, relative irrigation supply, adequacy, reliability	PIs effectively analysed different elements and farmers' perceptions of the system performance before and after rehabilitation
15.	Mondal & Saleh (2003)	Location: Bangladesh Techniques: field measurements and questionnaire survey	Delivery performance ratio, water delivery performance, conveyance loss ratio, relative water supply, overall reliability, equity, irrigated area ratio, yield ratio, production ratio, total financial viability, fee collection performance, the profitability of farmers, sustainability of an irrigated area	Hydraulic, agricultural, and socioeconomic indicators used were recommended for evaluation of the performance of irrigation projects and also for comparative analysis of performance of similar irrigation projects
16.	Moreno-Pérez & Roldán-Cañas (2013)	Location: Spain Techniques: GIS	Relative irrigation supply, relative water supply, relative rainfall supply	Relative irrigation supply permits farmers' actual irrigation management practices to be determined and interpreted
17.	Ray et al. (2002)	Location: India Techniques: remote sensing, field data	Adequacy (relative water supply), equity, water use efficiency	remote sensing-based PIs could identify the problem in distributaries, intensively managed and studied irrigation system
18.	Rowshon et al. (2014)	Location: Malaysia Techniques: field data	Relative water supply, adequacy, equity, dependability	PIs capable of assessing (quantitative assessment) not only water allocation for irrigation but also for day-to-day or periodic irrigation delivery performance
19.	Sánchez et al. (2015a)	Location: Spain Techniques: statistical analysis	Relative irrigation supply, annual relative water supply	RIS indicated that irrigation water exceeded net irrigation needs and the high ARIS variability observed was confirmed to be a result of the farmer management decisions
20.	Sanaee-Jahromi & Feyen (2001)	Location: Iran	Adequacy, reliability, equity	besides spatial and temporal variability, uniformity of the

(Continues)

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TABLE 5 (Continued)

No. 1.	Reference	Location/methodology	Indicators evaluated	Major findings
		Techniques: physical measurements, analytical method (Matrix D)		variability is also needed to assess the water delivery system
21.	Unal et al. (2004)	Location: Turkey Techniques: field survey, physical measurements (Electronic limnigraphs)	Adequacy, efficiency, dependability, equity	PIs were shown to have contributed to efficient water delivery monitoring and could identify the problems causing the poor performance of the system
22.	Yilmaz & Harmancioglu (2010)	Location: Turkey Techniques: WEAP	Agricultural sustainability index, environmental sustainability index, water exploitation rate, yield reliability, irrigation water deficit, domestic supply reliability, benefit/cost ratio, irrigation water use efficiency, total production value	PIs verified that efficient water management is crucial to ensure the sustainable use of water resources for environmental, social, and economic dimensions
23.	Zwart & Leclert (2010)	Location: Mali Techniques: remote sensing, statistical analysis	Cropping intensity, water productivity, uniformity, head–tail performance indicator	Diagnostic PIs identified needs for rehabilitation, whereas comparative PIs could set a benchmark, detect processes that could lead to higher performance, and quantify the impact of an intervention

Córcoles et al., 2010; Córcoles et al., 2012; Karatas et al., 2009; Kazbekov et al., 2009; Uysal & Atiş, 2010).

Table 5 presented the developed PIs as implemented in selected case studies.

5 | CONCLUSIONS

Studies on performance assessment and indicators were reviewed using a systematic review approach. The study was able to characterized the state of knowledge on PA and PIs based on metrics/indices used and their characterization, data sources, the scale of analysis, and types of management involved. The study revealed that different authors have accepted common definitions and used them in the domain of agricultural water management. However, there is lack of standardization and the use of a wide range of indicators. Some categories of PIs need further studies to come up with a single PI that will represent them. This review identified and recommended one type of efficiency indicator that is considered the best indicator called Sefficiency.

The results also showed that many methods were developed and successfully applied globally in both small and large irrigation systems under different spatial and temporal scales, different scales of analysis (farm, irrigation system, and basin levels), and management types (community-managed and state-owned). Field measurement is the predominant technique despite its difficulties, with remote sensing being mostly used in developed countries, probably because of its nature of technology. However, it is gradually gaining ground in Africa, yet the researchers are affiliated with the developed nations' institutions. Thus, this paper recommends further research to establish a relationship between remote sensing technology and third-world countries.

Despite the need for sustainability in the irrigation water sector, it was found that operational PA dominated the literature, with a very small number of sustainability-based PA research recorded. Therefore, a further study that will systematically evaluate methods and indices used to assess agricultural water sustainability is needed. Another important aspect for further study is the need to develop software and models that will make the performance evaluation of complex irrigation systems easy and effective.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

Data are available in the article supporting information.

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REFERENCES

Abera, A., Verhoest, N.E.C., Tilahun, S.A., Alamirew, T., Adgo, E., Moges, M.M., et al. (2019) Performance of small-scale irrigation schemes in Lake Tana Basin of Ethiopia: technical and socio-political attributes. *Physical Geography*, 40(3), 227–251. Available from: https://doi.org/10.1080/02723646.2018.1516445

Abou Kheira, A.A. (2009) Comparative assessment of new design criteria for irrigation improvement in Egypt. *Water Resources Management*, 23(11), 2317–2342. Available from: https://doi.org/10.1007/s11269-008-9383-0

Abuzar, M., Whitfield, D. & McAllister, A. (2017) Farm level assessment of irrigation performance for dairy pastures in the Goulburn-Murray District of Australia by combining satellite-based measures with weather and water delivery information. *ISPRS International Journal of Geo-Information*, 6(8), 239. Available from: https://doi.org/10.3390/ijgi6080239

Abuzar, M., Whitfield, D., McAllister, A. & Sheffield, K. (2019) Application of ET-NDVI-relationship approach and soil-water-balance modelling for the monitoring of irrigation performance of treed horticulture crops in a key fruit-growing district of Australia. *International Journal of Remote Sensing*, Taylor & Francis, 40(12), 4724–4742. Available from: https://doi.org/10.1080/01431161.2019.1573337

Agam, N., Cohen, Y., Berni, J.A.J., Alchanatis, V., Kool, D., Dag, A., et al. (2013) An insight to the performance of crop water stress index for olive trees. *Agricultural Water Management*. Elsevier B.V., 118, 79–86. Available from: https://doi.org/10.1016/j.agwat.2012.12.004

Ahadi, R., Samani, Z. & Skaggs, R. (2013) Evaluating on-farm irrigation efficiency across the watershed: a case study of New Mexico's lower Rio Grande Basin. *Agricultural Water Management*. Elsevier B.V., 124, 52–57. Available from: https://doi.org/10.1016/j.agwat.2013.03.010

Ahmad, M.T., Haie, N., Yen, H. & Tuqan, N.A.S. (2017) Sefficiency of a water use system: the case of Kano River irrigation project, Nigeria. *International Journal of Civil Engineering*. Springer International Publishing, 16(8), 929–939. Available from: https://doi.org/10.1007/s40999-017-0235-2

Ahmad, M.D., Turral, H. & Nazeer, A. (2009) Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan. *Agricultural Water Management*, 96(4), 551–564. Available from: https://doi.org/10.1016/j.agwat.2008.09.017

Ahmed, B.M., Tanakamaru, H. & Tada, A. (2010) Application of remote sensing for estimating crop water requirements, yield and water productivity of wheat in the Gezira scheme. *International Journal of Remote Sensing*, 31(16), 4281–4294. Available from: https://doi.org/10.1080/01431160903246733

Akbari, M., Toomanian, N., Droogers, P., Bastiaanssen, W. & Gieske, A. (2007) Monitoring irrigation performance in Esfahan, Iran, using NOAA satellite imagery. *Agricultural Water Management*, 88(1–3), 99–109. Available from: https://doi.org/10.1016/j.agwat.2006.10.019

Akhbari, M. & Grigg, N.S. (2013) A framework for an agent-based model to manage water resources conflicts. *Water Resources Management*, 27, 4039–4052. Available from: https://doi.org/10.1007/s11269-013-0394-0

Akhtar, F., Awan, U., Tischbein, B. & Liaqat, U. (2018) Assessment of irrigation performance in large river basins under data scarce environment — a case of Kabul River basin, Afghanistan. *Remote Sensing*, 10(972), 972. Available from: https://doi.org/10.3390/rs10060972

Akkuzu, E., Unal, H.B., Karatas, B.S., Avci, M. & Asik, S. (2007) General irrigation planning performance of water user associations in the Gediz Basin in Turkey. *Journal of Irrigation and Drainage Engineering - ASCE*, 133(1), 17–26. Available from: https://doi.org/10.1061/(ASCE)0733-9437(2007)133:1(17)

Al Zayed, I.S. & Elagib, N.A. (2017) Implications of non-sustainable agricultural water policies for the water-food nexus in large-scale irrigation systems: a remote sensing approach. *Advances in Water Resources*, Elsevier Ltd, 110, 408–422. Available from: https://doi.org/10.1016/j.advwatres.2017.07.010

Al Zayed, I.S., et al. (2015) Spatio-temporal performance of large-scale Gezira irrigation scheme, Sudan. *Agricultural Systems*, Elsevier Ltd, 133, 131–142. Available from: https://doi.org/10.1016/j.agsy.2014.10.009

Alexandridis, T.K., et al. (2014) Combining remotely sensed surface energy fluxes and GIS analysis of groundwater parameters for irrigation system assessment. *Irigation Science*, 32, 127–140. Available from: https://doi.org/10.1007/s00271-013-0419-8

Andrés, R. & Cuchí, J.A. (2014) Analysis of sprinkler irrigation management in the LASESA district, Monegros (Spain). *Agricultural Water Management*. Elsevier B.V., 131, 95–107. Available from: https://doi.org/10.1016/j.agwat.2013.09.016

Angella, G., et al. (2016) Quantifying yield and water productivity gaps in an irrigation district under rotational delivery schedule. *Irrigation Science*. Springer Berlin Heidelberg, 34(1), 71–83. Available from: https://doi.org/10.1007/s00271-015-0486-0

Awada, H., Ciraolo, G., Maltese, A., Provenzano, G., Moreno Hidalgo, M.A. & Còrcoles, J.I. (2019) Assessing the performance of a large-scale irrigation system by estimations of actual evapotranspiration obtained by Landsat satellite images resampled with cubic convolution. *International Journal of Applied Earth Observation and Geoinformation* Elsevier, 75, 96–105. Available from: https://doi.org/10.1016/j.jag.2018.10.016

Awan, U.K., Tischbein, B., Conrad, C., Martius, C. & Hafeez, M. (2011) Remote sensing and hydrological measurements for irrigation performance assessments in a water user Association in the Lower Amu Darya River Basin. *Water Resources Management*, 25(10), 2467–2485. Available from: https://doi.org/10.1007/s11269-011-9821-2

Awulachew, S.B. & Ayana, M. (2011) Performance of irrigation: an assessment at different scales in Ethiopia. *Experimental Agriculture*, 47-(August 2015), 57–69. Available from: https://doi.org/10.1017/S0014479710000955

Ayars, J.E. & Schoneman, R.A. (2006) Irrigating field crops in the presence of saline groundwater. *Irrigation and Drainage*, 55(3), 265–279. Available from: https://doi.org/10.1002/ird.258

Bandara, K.M.P.S. (2003) Monitoring irrigation performance in Sri Lanka with high-frequency satellite measurements during the dry season. *Agricultural Water Management*, 58(2), 150–170. Available from: https://doi.org/10.1016/S0378-3774(02)00132-4

Barros, R., Isidoro, D. & Aragüés, R. (2011) Long-term water balances in La Violada Irrigation District (Spain): II. Analysis of irrigation performance. *Agricultural Water Management*. Elsevier B.V., 98(10), 1569–1576. Available from: https://doi.org/10.1016/j.agwat.2011.04.014

Bastiaanssen, W.G.M. & Bos, M.G. (1999) Irrigation performance indicators based on remotely sensed data: a review of literature. *Irrigation and Drainage Systems*, 13(1999), 291–311. Available from: https://doi.org/10.1023/A:1006355315251

17476593, 2024, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/wej.12913 by Universidade Do Minho, Wiley Online Library on [09/01/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Bastiaanssen, W.G.M., et al. (2001) Low cost satellite data for monthly irrigation performance monitoring: benchmarks from Nilo Coelho, Brazil. *Irrigation and Drainage Systems*, 15(1), 53–79. Available from: https://doi.org/10.1023/A:1017967021198

Bellvert, J., Marsal, J., Girona, J. & Zarco-Tejada, P.J. (2015) Seasonal evolution of crop water stress index in grapevine varieties determined with high - resolution remote sensing thermal imagery. *Irrigation Science*, 33(2), 81–93. Available from: https://doi.org/10.1007/s00271-014-0456-y

Birkenholtz, T. (2017) Assessing India's drip-irrigation boom: efficiency, climate change and groundwater policy. *Water International*. Routledge, 42(6), 663–677. Available from: https://doi.org/10.1080/02508060.2017.1351910

Boelens, R. & Vos, J. (2012) The danger of naturalizing water policy concepts: water productivity and efficiency discourses from field irrigation to virtual water trade. *Agricultural Water Management*, 108(May), 16–26. Available from: https://doi.org/10.1016/j.agwat.2011.06.013

Borgia, C., García-Bolaños, M., Li, T., Gómez-Macpherson, H., Comas, J., Connor, D., et al. (2013) Benchmarking for performance assessment of small and large irrigation schemes along the Senegal Valley in Mauritania. *Agricultural Water Management*, 121, 19–26. Available from: https://doi.org/10.1016/j.agwat.2013.01.002

Borgia, C., García-Bolaños, M. & Mateos, L. (2012) Patterns of variability in large-scale irrigation schemes in Mauritania. *Agricultural Water Management*, 112, 1–12. Available from: https://doi.org/10.1016/j.agwat.2012.03.013

Borsato, E., Martello, M. & Marinello, F. (2019) Environmental and economic sustainability assessment for two different sprinkler and a drip irrigation systems: a case study on maize cropping. *Agriculture*, 9, 187.

Bos, M. G., Burton, M. A. & Molden, D. J. (Eds.) (2005) *Irrigation and Drainage Performance Assessment - Practical Guidelines*. Wallingford, UK: CABI. Available from: https://doi.org/10.1079/9780851999678.0000

Bos, M.G. & Nugteren, J. (1990) *On Irrigation Efficiencies*, 4th Editio edition, Vol. 19. Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement *ILRI Publication* Available at: http://www1.frm.utn.edu.ar/laboratorio_hidraulica/Biblioteca_Virtual/Publicaciones de ILRI/On irrigation efficiencies.pdf.

Bos, M., et al. (1994) Methodologies for assessing performance of irrigation and drainage management. *Irrigation and Drainage Systems*, 7(4), 231–261. Available from: https://doi.org/10.1007/BF00881553

Brown, C.M., et al. (2015) The future of water resources systems analysis: toward a scientific framework for sustainable water management. *Water Resources*, 51, 6110–6124. Available from: https://doi.org/10.1002/2015WR017114.Received

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., et al. (1997) Irrigation performance measures: efficiency and uniformity. *J. Irrig. Drainage Eng-ASCE*, 123(6), 423–442. Available from: https://doi.org/10.1061/(ASCE)0733-9437(1997)123:6(423)

Carr, G., Blöschl, G. & Loucks, D.P. (2012) Evaluating participation in water resource management: a review. *Water Resources Research*, 48(11), 1–17. Available from: https://doi.org/10.1029/2011WR011662

Causapé, J., Quílez, D. & Aragüés, R. (2006) Irrigation efficiency and quality of irrigation return flows in the Ebro River basin: an overview. *Environmental Monitoring and Assessment*, 117(1–3), 451–461. Available from: https://doi.org/10.1007/s10661-006-0763-8

Chandran, K.M. & Ambili, G.K. (2016) Evaluation of minor irrigation schemes using performance indicators: case studies from South India. *Sustainable Water Resources Management*, Springer International Publishing, 2(4), 431–437. Available from: https://doi.org/10.1007/s40899-016-0074-3

Córcoles, J.I., de Juan, J.A., Ortega, J.F., Tarjuelo, J.M. & Moreno, M.A. (2010) Management evaluation of water users associations using benchmarking techniques. *Agricultural Water Management*, 98(1), 1–11. Available from: https://doi.org/10.1016/j.agwat.2010.07.018

Córcoles, J., et al. (2012) Evaluation of irrigation systems by using benchmarking techniques. *J. Irrig. Drainage Eng-ASCE*, 138(3), 225–234. Available from: https://doi.org/10.1061/(ASCE)IR.1943-4774.0000386

Dejen, Z.A., Schultz, B. & Hayde, L. (2012) Comparative irrigation performance assessment in community-managed schemes in Ethiopia. *African Journal of Agricultural Reseearch*, 7(35), 4956–4970. Available from: https://doi.org/10.5897/ajar11.2135

Dejen, Z.A., Schultz, B. & Hayde, L. (2015) Water delivery performance at Metahara large-scale irrigation scheme, Ethiopia. *Irrigation and Drainage*, 64(4), 479–490. Available from: https://doi.org/10.1002/ird.1917

Dembele, Y., Yacouba, H., Keïta, A. & Sally, H. (2012) Assessment of irrigation system performance in South-Western Burkina Faso. *Irrigation and Drainage*, 61(3), 306–315. Available from: https://doi.org/10.1002/ird.647

Elshaikh, A.E., Jiao, X. & Yang, S. (2018) Performance evaluation of irrigation projects : theories , methods , and techniques. *Agricultural Water Management*. Elsevier, 203(January), 87–96. Available from: https://doi.org/10.1016/j.agwat.2018.02.034

Fan, Y, Gao, Z., Wang, S., Chen, H. & Liu, J. (2018) Evaluation of the water allocation and delivery performance of Jiamakou irrigation scheme, Shanxi, China. *Water*, 10(5), 654. Available from: https://doi.org/10.3390/w10050654

Frederiksen, H.D. & Allen, R.G. (2011) A common basis for analysis, evaluation and comparison of offstream water uses. *Water International*, 36(3), 266–282. Available from: https://doi.org/10.1080/02508060.2011.580449

Gadanakis, Y., Bennett, R., Park, J. & Areal, F.J. (2015) Improving productivity and water use efficiency: a case study of farms in England. *Agricultural Water Management*. Elsevier B.V., 160, 22–32. Available from: https://doi.org/10.1016/j.agwat.2015.06.020

Gain, A.K. & Giupponi, C. (2015) A dynamic assessment of water scarcity risk in the lower Brahmaputra River basin: an integrated approach. *Ecological Indicators* Elsevier Ltd, 48, 120–131. Available from: https://doi.org/10.1016/j.ecolind.2014.07.034

García-Bolaños, M., Borgia, C., Poblador, N., Dia, M., Seyid, O.M.V. & Mateos, L. (2011) Performance assessment of small irrigation schemes along the Mauritanian banks of the Senegal River. *Agricultural Water Management*, 98(7), 1141–1152. Available from: https://doi.org/10.1016/j.agwat.2011.02.008

García-Garizábal, I., Causapé, J. & Abrahao, R. (2011) Application of the irrigation land environmental evaluation tool for flood irrigation management and evaluation of water use. *Catena*. Elsevier B.V., 87(2), 260–267. Available from: https://doi.org/10.1016/j.catena.2011.06.010

Ghahroodi, E.M., Noory, H. & Liaghat, A.M. (2015) Performance evaluation study and hydrologic and productive analysis of irrigation systems at the Qazvin irrigation network (Iran). *Agricultural Water Management*. Elsevier B.V., 148, 189–195. Available from: https://doi.org/10.1016/j.agwat.2014.10.003

Gomo, T., Senzanje, A., Mudhara, M. & Dhavu, K. (2014) Assessing the performance of smallholder irrigation and deriving best management practices in South Africa. *Irrigation and Drainage*, 63(4), 419–429. Available from: https://doi.org/10.1002/ird.1815

Gonzalez-Dugo, V., Goldhamer, D., Zarco-Tejada, P.J. & Fereres, E. (2015) Improving the precision of irrigation in a pistachio farm using an unmanned airborne thermal system. *Irrigation Science*, 33(1), 43–52. Available from: https://doi.org/10.1007/s00271-014-0447-z

Gorantiwar, S.D. & Smout, I.K. (2005) Performance assessment of irrigation water management of heterogeneous irrigation schemes: 1. A framework for evaluation. *Irrigation and Drainage Systems*, 19(1), 1–36. Available from: https://doi.org/10.1007/s10795-005-2970-9

Haie, N. (2008) Comment: efficient irrigation; inefficient communication; flawed recommendations comment: efficient irrigation; inefficient communication; flawed recommendations (C. Perry, irrigation and

17476593, 2024, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/wej.12913 by Universidade Do Minho, Wiley Online Library on [09/01/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

drainage 56: 367–378). *Irrigation and Drainage*, 57(2), 245–247. Available from: https://doi.org/10.1002/ird.422

Haie, N. (2016) Sefficiency (sustainable efficiency) of water–energy–food entangled systems. *International Journal of Water Resources Development*, 32(5), 721–737. Available from: https://doi.org/10.1080/07900627.2015.1070091

Haie, N. (2021) Sefficiency (sustainable efficiency), Transparent Water Management Theory. In: *Sefficiency in Sequity*. Edited by P. P. US National Institutes of Health. US: Springer. https://doi.org/10.1007/978-981-15-6284-6_4

Haie, N. & Keller, A.A. (2008) Effective efficiency as a tool for sustainable water resources management. *Journal of the American Water Resources Association*, 44(4), 961–968. Available from: https://doi.org/10.1111/j.1752-1688.2008.00194.x

Haie, N. & Keller, A.A. (2012) Macro, Meso, and micro-efficiencies in water resources management: a new framework using water Balance1. *JAWRA Journal of the American Water Resources Association*, 48(2), 235–243. Available from: https://doi.org/10.1111/j.1752-1688.2011.00611.x

Haie, N. & Keller, A.A. (2014) Macro, meso, and micro-efficiencies and terminologies in water resources management: a look at urban and agricultural differences. *Water International*, 39(1), 35–48. Available from: https://doi.org/10.1080/02508060.2013.863588

Haj-amor, Z., Ritzema, H., Hashemi, H. & Bouri, S. (2018) Surface irrigation performance of date palms under water scarcity in arid irrigated lands. *Arabian Journal of Geosciences*, 11, 27. https://doi.org/10.1007/s12517-017-3374-5

Hamid, S., Mohamed, A. & Mohamed, Y. (2011) Towards a performance-oriented Management for Large-scale Irrigation Systems: case study, Rahad scheme, Sudan. *Irrigation and Drainage*, 60(1), 20–34. Available from: https://doi.org/10.1002/ird.546

Hellegers, P.J.G.J., Soppe, R., Perry, C.J. & Bastiaanssen, W.G.M. (2010) Remote sensing and economic indicators for supporting water resources management decisions. *Water Resources Management*, 24(11), 2419–2436. Available from: https://doi.org/10.1007/s11269-009-9559-2

Heydari, N. (2014) Water productivity in agriculture: challenges in concepts, terms and values. *Irrigation and Drainage*, 63(1), 22–28. Available from: https://doi.org/10.1002/ird.1816

Israelsen, O. W. (1932) '*Irrigation principles and practices*'. New York: John Wiley & Sons, Inc., p. 472. Available at: http://books.google.com.co/books?id=Z19RAAAAMAAJ

Jayatillake, H.M. (2004) Application of performance assessment and benchmarking tool to help improve irrigation system performance in Sri Lanka. *Irrigation and Drainage*, 53(2), 185–193. Available from: https://doi.org/10.1002/ird.132

Jensen, M.E. (1966) Discussion: irrigation requirements of lawns. *Journal of the Irrigation and Drainage Engineering-ASCE*, 92(IRI), 95–100. Available from: https://doi.org/10.1061/JRCEA4.0000418

Jensen, M.E. (2007) Beyond irrigation efficiency. *Irrigation Science*, 25(3), 233–245. Available from: https://doi.org/10.1007/s00271-007-0060-5

Jiang, Y., Xu, X., Huang, Q., Huo, Z. & Huang, G. (2015) Assessment of irrigation performance and water productivity in irrigated areas of the middle Heihe River basin using a distributed agro-hydrological model. *Agricultural Water Management*, 147, 67–81. Available from: https://doi.org/10.1016/j.agwat.2014.08.003

Karatas, B.S., Akkuzu, E., Unal, H.B., Asik, S. & Avci, M. (2009) Using satellite remote sensing to assess irrigation performance in water user associations in the lower Gediz Basin, Turkey. *Agricultural Water Management*, 96(6), 982–990. Available from: https://doi.org/10.1016/j.agwat.2009.01.010

Karimi, P., Bastiaanssen, W.G.M., Molden, D. & Cheema, M.J.M. (2013) Basin-wide water accounting based on remote sensing data: an application for the Indus Basin. *Hydrology and Earth System Sciences*, 17(7), 2473–2486. Available from: https://doi.org/10.5194/hess-17-2473-2013

Kazbekov, J., Abdullaev, I., Manthrithilake, H., Qureshi, A. & Jumaboev, K. (2009) Evaluating planning and delivery performance of water user associations (WUAs) in Osh Province, Kyrgyzstan. *Agricultural Water Management*, 96(8), 1259–1267. Available from: https://doi.org/10.1016/j.agwat.2009.04.002

Keller, A., Keller, J., & Seckler, D. (1996) Integrated water resource systems: theory and policy implications. Colombo, Sri Lanka: International Irrigation Management Institute (IIMI); IWMI. iii, 15p. (IIMI Research Report 3 / IWMI Research Report 3). https://doi.org/10.3910/2009.004

Kharrou, M.H., le Page, M., Chehbouni, A., Simonneaux, V., Er-Raki, S., Jarlan, L., et al. (2013) Assessment of equity and adequacy of water delivery in irrigation systems using remote sensing-based indicators in semi-arid region, Morocco. *Water Resources Management*, 27(13), 4697–4714. Available from: https://doi.org/10.1007/s11269-013-0438-5

Kifle, M., Gebremicael, T.G., Girmay, A. & Gebremedihin, T. (2017) Effect of surge flow and alternate irrigation on the irrigation efficiency and water productivity of onion in the semi-arid areas of North Ethiopia. *Agricultural Water Management*. Elsevier B.V., 187, 69–76. Available from: https://doi.org/10.1016/j.agwat.2017.03.018

Kloezen, W.H. & Garcés-Restrepo, C. (1998) *Assessing Irrigation Performance with Comparative Indicators: The Case of the Alto Rio Lerma Irrigation District*. Sri Lanka: Mexico.

Kukul, Y.S., Akc, S. & Anac, S. (2008) Temporal irrigation performance assessment in Turkey : Menemen case study. *Agricultural Water Management*, 95(9), 1090–1098. Available from: https://doi.org/10.1016/j.agwat.2008.04.005

Kuşçu, H., Demir, A.O. & Korukçu, A. (2008) An assessment of the irrigation management transfer programme: case study in the Mustafakemalpaşa irrigation scheme in Turkey. *Irrigation and Drainage*, 57(1), 15–22. Available from: https://doi.org/10.1002/ird.326

Kuscu, H., Eren, F. & Demir, A.O. (2009) Performance assessment for irrigation water management : a case study in the Karacabey irrigation scheme in Turkey. *Journal of Agricultural Research*, 4(February), 124–132.

Lankford, B. (2012) Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency. *Agricultural Water Management*. Elccsevier B.V., 108, 27–38. Available from: https://doi.org/10.1016/j.agwat.2011.08.010

Le Grusse, P.H., et al. (2009) Indicators and framework for Analysing the technical and economic performance of irrigation Systerms at farm level. *Irrigation and Drainage*, 58, S307–S319. Available from: https://doi.org/10.1002/ird

Lecina, S., Neale, C.M.U., Merkley, G.P. & dos Santos, C.A.C. (2011) Irrigation evaluation based on performance analysis and water accounting at the Bear River irrigation project (U.S.a.). *Agricultural Water Management*. Elsevier B.V., 98(9), 1349–1363. Available from: https://doi.org/10.1016/j.agwat.2011.04.001

Lorite, I.J., García-Vila, M., Carmona, M.A., Santos, C. & Soriano, M.A. (2012) Assessment of the irrigation advisory services. Recommendations and Farmers' irrigation management: a case study in southern Spain. *Water Resources Management*, 26(8), 2397–2419. Available from: https://doi.org/10.1007/s11269-012-0023-3

Lorite, I.J., Mateos, L. & Fereres, E. (2004) Evaluating irrigation performance in a Mediterranean environment: I. Model and general assessment of an irrigation scheme. *Irrigation Science*, 23(2), 77–84. Available from: https://doi.org/10.1007/s00271-004-0095-9

Mateos, L., Lozano, D., Baghil, A.B.O., Diallo, O.A., Gómez-Macpherson, H., Comas, J., et al. (2010) Irrigation performance before and after rehabilitation of a representative, small irrigation scheme besides the Senegal River, Mauritania. *Agricultural Water Management*,

17476593, 2024, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/wej.12913 by Universidade Do Minho, Wiley Online Library on [09/01/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

97(6), 901–909. Available from: https://doi.org/10.1016/j.agwat.2010.01.021

McDowell, G., Stephenson, E. & Ford, J. (2014) Adaptation to climate change in glaciated mountain regions. *Climate Change*, 126(1-2), 77–91. Available from: https://doi.org/10.1007/s10584-014-1215-z

Merchán, D., Causapé, J., Abrahão, R. & García-Garizábal, I. (2015) Assessment of a newly implemented irrigated area (Lerma Basin, Spain) over a 10-year period. I: water balances and irrigation performance. *Agricultural Water Management*. Elsevier B.V., 158, 277–287. Available from: https://doi.org/10.1016/j.agwat.2015.04.016

Molden, D. & Gates, T. (1990) Performance measures for evaluation of irrigation water delivery systems. *J. Irrig. And Drainage Engineering, ASCE*, 116(6), 804–823. Available from: https://doi.org/10.1061/(ASCE)0733-9437(1990)116:6(804)

Mondal, M.S. & Saleh, A.F.M. (2003) Evaluation of some deep and shallow tubewell irrigated schemes in Bangladesh using performance indicators. *Agricultural Water Management*, 58(3), 193–207. Available from: https://doi.org/10.1016/S0378-3774(02)00087-2

Moreno-Pérez, M.F. & Roldán-Cañas, J. (2013) Assessment of irrigation water management in the Genil-Cabra (Córdoba, Spain) irrigation district using irrigation indicators. *Agricultural Water Management*, 120, 98–106. Available from: https://doi.org/10.1016/j.agwat.2012.06.020

Nam, W.-H., Hong, E.-M. & Choi, J.-Y. (2016) Assessment of water delivery efficiency in irrigation canals using performance indicators. *Irrigation Science*. Springer Berlin Heidelberg, 34(2), 129–143. Available from: https://doi.org/10.1007/s00271-016-0488-6

Neely, A., Gregory, M. & Platts, K. (2005) Performance measurement system design a literature review and research agenda. *International Journal of Operations & Production Management*, 25(12), 1309–1327. Available from: https://doi.org/10.1108/01443570510633675

Pereira, L.S. (1999) Higher performance through combined improvements in irrigation methods and scheduling: a discussion. *Agricultural Water Management*, 40(2–3), 153–169. Available from: https://doi.org/10.1016/S0378-3774(98)00118-8

Pereira, L.S., Cordery, I. & Iacovides, I. (2012) Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management*. Elsevier B.V., 108, 39–51. Available from: https://doi.org/10.1016/j.agwat.2011.08.022

Pereira, L.S., Oweis, T. & Zairi, A. (2002) Irrigation management under water scarcity. *Agricultural Water Management*, 57(3), 175–206. Available from: https://doi.org/10.1016/S0378-3774(02)00075-6

Perry, C. (2007) Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage*, 56(4), 367–378. Available from: https://doi.org/10.1002/ird.323

Perry, C. (2011) Accounting for water use: terminology and implications for saving water and increasing production. *Agricultural Water Management*. Elsevier B.V., 98(12), 1840–1846. Available from: https://doi.org/10.1016/j.agwat.2010.10.002

Perry, C., Steduto, P., Allen, R.G. & Burt, C.M. (2009) Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. *Agricultural Water Management*, 96(11), 1517–1524. Available from: https://doi.org/10.1016/j.agwat.2009.05.005

Phengphaengsy, F. & Okudaira, H. (2008) Assessment of irrigation efficiencies and water productivity in paddy fields in the lower Mekong River basin. *Paddy and Water Environment*, 6(1), 105–114. Available from: https://doi.org/10.1007/s10333-008-0108-z

Poussin, J.C., Renaudin, L., Adogoba, D., Sanon, A., Tazen, F., Dogbe, W., et al. (2015) Performance of small reservoir irrigated schemes in the upper Volta basin: case studies in Burkina Faso and Ghana. *Water Resources and Rural Development*. Elsevier B.V., 6, 50–65. Available from: https://doi.org/10.1016/j.wrr.2015.05.001

Qureshi, M.E., Grafton, R.Q., Kirby, M. & Hanjra, M.A. (2011) Understanding irrigation water use efficiency at different scales for better policy reform: a case study of the Murray-Darling basin, Australia. *Water Policy*, 13(1), 1–17. Available from: https://doi.org/10.2166/wp.2010.063

Ray, S.S., Dadhwal, V.K. & Navalgund, R.R. (2002) Performance evaluation of an irrigation command area using remote sensing: a case study of Mahi command, Gujarat, India. *Agricultural Water Management*, 56(2), 81–91. Available from: https://doi.org/10.1016/S0378-3774(02)00006-9

Rowshon, M.K., Amin, M.S.M. & Shariff, A.R.M. (2011) GIS user-interface based irrigation delivery performance assessment: a case study for Tanjung Karang rice irrigation scheme in Malaysia. *Irrigation and Drainage Systems*, 25(2), 97–120. Available from: https://doi.org/10.1007/s10795-011-9115-0

Rowshon, M.K., Mojid, M.A., Amin, M.S.M., Azwan, M. & Yazid, A.M. (2014) Improving irrigation water delivery performance of a large-scale Rice irrigation scheme. *Journal of Irrigation and Drainage Engineering*, 140(8), 04014027. Available from: https://doi.org/10.1061/(ASCE)IR.1943-4774.0000747

Sakthivadivel, R., de Fraiture, C., Molden, D.J., Perry, C. & Kloezen, W. (1999) Indicators of land and water productivity in irrigated agriculture. *International Journal of Water Resources Development*, 15(1–2), 161–179. Available from: https://doi.org/10.1080/07900629948998

Sanaee-Jahromi, S. & Feyen, J. (2001) Spatial and temporal variability performance of the water delivery in irrigation schemes. *Irrigation and Drainage Systems*, 15(3), 215–233. Available from: https://doi.org/10.1023/A:1012645831068

Sánchez, J.A., Reca, J. & Martínez, J. (2015a) Irrigation water Management in a Mediterranean Greenhouse District: irrigation adequacy assessment. *Irrigation and Drainage*, 64(3), 299–313. Available from: https://doi.org/10.1002/ird.1908

Sánchez, J.A., Reca, J. & Martínez, J. (2015b) Water productivity in a mediterranean semi-arid greenhouse district. *Water Resources Management*, 29(14), 5395–5411. Available from: https://doi.org/10.1007/s11269-015-1125-5

Santos, C., Lorite, I.J., Tasumi, M., Allen, R.G. & Fereres, E. (2010) Performance assessment of an irrigation scheme using indicators determined with remote sensing techniques. *Irrigation Science*, 28(6), 461–477. Available from: https://doi.org/10.1007/s00271-010-0207-7

Segovia-cardozo, D.A., Rodríguez-sinobas, L. & Zubelzu, S. (2019) Water use e ffi ciency of corn among the irrigation districts across the Duero river basin (Spain): estimation of local crop coe ffi cients by satellite images. *Agricultural Water Management*. Elsevier, 212(February 2018), 241–251. Available from: https://doi.org/10.1016/j.agwat.2018.08.042

Sekyi-annan, E., et al. (2018) Performance evaluation of reservoir-based irrigation schemes in the upper east region of Ghana. *Agricultural Water Management*. Elsevier, 202(February), 134–145. Available from: https://doi.org/10.1016/j.agwat.2018.02.023

Semmens, K.A., Anderson, M.C., Kustas, W.P., Gao, F., Alfieri, J.G., McKee, L., et al. (2016) Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach. *Remote Sensing of Environment*, 185, 155-170. Available from: https://doi.org/10.1016/j.rse.2015.10.02

Setegn, S.G., Chowdary, V.M., Mal, B.C., Yohannes, F. & Kono, Y. (2011) Water balance study and irrigation strategies for sustainable Management of a Tropical Ethiopian Lake: a case study of Lake Alemaya. *Water Resources Management*, 25(9), 2081–2107. Available from: https://doi.org/10.1007/s11269-011-9797-y

Shahrokhnia, M.A. & Olyan-ghiasi, A. (2019) Determination of overall water delivery performance based on adequacy, efficiency, equity and dependability in the Doroodzan irrigation network. *Irrigation and Drainage*, 68(July), 637–645. Available from: https://doi.org/10.1002/ird.2356

Shanono, N.J., Nasidi, N.M., Zakari, M.D. & Bello, M.M. (2014) Assessment of Field Channels Performance at Watari Irrigation Project Kano, Nigeria. In: *1st International Conference on Dryland, Center for Dryland*

17476593, 2024, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/wej.12913 by Universidade Do Minho, Wiley Online Library on [09/01/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Agriculture, Bayero University Kano, Nigeria. 8th–12th December, 2014, pp. 144–150.

Singh, R., Kroes, J.G., van Dam, J.C. & Feddes, R.A. (2006) Distributed eco-hydrological modelling to evaluate the performance of irrigation system in Sirsa district, India: I. Current water management and its productivity. *Journal of Hydrology*, 329(3–4), 692–713. Available from: https://doi.org/10.1016/j.jhydrol.2006.03.037

Small, L.E. & Svendsen, M. (1990) A framework for assessing irrigation performance. *Irrigation and Drainage Systems*, 4(4), 283–312. Available from: https://doi.org/10.1007/BF01103710

Soto-García, M., Martínez-Alvarez, V., García-Bastida, P.A., Alcon, F. & Martin-Gorriz, B. (2013) Effect of water scarcity and modernisation on the performance of irrigation districts in South-Eastern Spain. *Agricultural Water Management*, 124, 11–19. Available from: https://doi.org/10.1016/j.agwat.2013.03.019

Taghvaeian, S., Neale, C.M.U., Osterberg, J.C., Sritharan, S.I. & Watts, D.R. (2018) Remote sensing and GIS techniques for assessing irrigation performance : case study in Southern California. *Journal of Irrigation and Drainage Engineering - ASCE*, 144(6), 05018002-1–10. Available from: https://doi.org/10.1061/(ASCE)IR.1943-4774.0001306

Tarjuelo, J.M., Rodriguez-Diaz, J.A., Abadía, R., Camacho, E., Rocamora, C. & Moreno, M.A. (2015) Efficient water and energy use in irrigation modernization: lessons from Spanish case studies. *Agricultural Water Management*. Elsevier B.V., 162, 67–77. Available from: https://doi.org/10.1016/j.agwat.2015.08.009

Toureiro, C., Serralheiro, R., Shahidian, S. & Sousa, A. (2017) Irrigation management with remote sensing : evaluating irrigation requirement for maize under Mediterranean climate condition ☙. *Agricultural Water Management*. Elsevier B.V., 184, 211–220. Available from: https://doi.org/10.1016/j.agwat.2016.02.010

Unal, H.B., Asik, S., Avci, M., Yasar, S. & Akkuzu, E. (2004) Performance of water delivery system at tertiary canal level: a case study of the Menemen left Bank irrigation system, Gediz Basin, Turkey. *Agricultural Water Management*, 65(3), 155–171. Available from: https://doi.org/10.1016/j.agwat.2003.10.002

UN-Water. (2006) Water: a shared responsibility the United Nations world water development report. *Water Resources*, 3(4), 120–156. Available from: https://doi.org/10.7748/nm.21.4.12.s12

Usman, M., Liedl, R. & Awan, U.K. (2015) Spatio-temporal estimation of consumptive water use for assessment of irrigation system performance and management of water resources in irrigated Indus Basin , Pakistan. *Journal of Hydrology*. Elsevier B.V., 525, 26–41. Available from: https://doi.org/10.1016/j.jhydrol.2015.03.031

Uysal, Ö.K. & Atiş, E. (2010) Assessing the performance of participatory irrigation management over time: a case study from Turkey. *Agricultural Water Management*, 97(7), 1017–1025. Available from: https://doi.org/10.1016/j.agwat.2010.02.007

Van Halsema, G.E. & Vincent, L. (2012) Efficiency and productivity terms for water management: a matter of contextual relativism versus general absolutism. *Agricultural Water Management*. Elsevier B.V., 108, 9–15. Available from: https://doi.org/10.1016/j.agwat.2011.05.016

Van Halsema, G., et al. (2011) Performance assessment of smallholder irrigation in the central rift valley of Ethiopia. *Irrigation and Drainage*, 60(5), 622–634. Available from: https://doi.org/10.1002/ird.613

Vandersypen, K., Bengaly, K., Keita, A.C.T., Sidibe, S., Raes, D. & Jamin, J.Y. (2006) Irrigation performance at tertiary level in the rice schemes of the office du Niger (Mali): adequate water delivery through over-supply. *Agricultural Water Management*, 83(1–2), 144–152. Available from: https://doi.org/10.1016/j.agwat.2005.11.003

Vieira, P., Alegre, H., Rosa, M.J. & Lucas, H. (2008) Drinking water treatment plant assessment through performance indicators. *Water Science and Technology: Water Supply*, 8(3), 245–253. Available from: https://doi.org/10.2166/ws.2008.068

Vieira, P., Jorge, C. & Covas, D. (2015) Novel performance assessment indices for domestic water use. *Procedia Engineering*. Elsevier B.V., 119(1), 813–819. Available from: https://doi.org/10.1016/j.proeng.2015.08.943

Vilanova, M.R.N., Magalhães Filho, P. & Balestieri, J.A.P. (2015) Performance measurement and indicators for water supply management: review and international cases. *Renewable and Sustainable Energy Reviews* Elsevier, 43, 1–12. Available from: https://doi.org/10.1016/j.rser.2014.11.043

Wichelns, D. (2002) An economic perspective on the potential gains from improvements in irrigation water management. *Agricultural Water Management*, 52(3), 233–248. Available from: https://doi.org/10.1016/S0378-3774(01)00134-2

Wichelns, D. (2014) Do estimates of water productivity enhance understanding of farm-level water management. *Water (Switzerland)*, 6(4), 778–795. Available from: https://doi.org/10.3390/w6040778

Yadav, S.M., Singh, N.P., Shah, K.A. & Gamit, J.H. (2014) Performance evaluation of water supply services in developing country: a case study of Ahmedabad city. *KSCE Journal of Civil Engineering*, 18(7), 1984–1990. Available from: https://doi.org/10.1007/s12205-014-0306-8

Yigezu, Y.A., Ahmed, M.A., Shideed, K., Aw-Hassan, A., el-Shater, T. & al-Atwan, S. (2013) Implications of a shift in irrigation technology on resource use efficiency: a Syrian case. *Agricultural Systems*, 118, 14–22. Available from: https://doi.org/10.1016/j.agsy.2013.02.003

Yilmaz, B. & Harmancioglu, N.B. (2010) An indicator based assessment for water resources Management in Gediz River Basin, Turkey. *Water Resources Management*, 24(15), 4359–4379. Available from: https://doi.org/10.1007/s11269-010-9663-3

Yilmaz, B. & Harmancioglu, N.B. (2012) Comparative assessment of water management indicators in the Gediz river basin with foreseen climate scenarios. *European Water*, 37, 27–32.

Zema, D.A., Nicotra, A. & Santo, M.Z. (2019) Improving management scenarios of water delivery service in collective irrigation systems : a case study in southern Italy. *Irrigation Science*. Springer Berlin Heidelberg, 37(1), 79–94. Available from: https://doi.org/10.1007/s00271-018-0604-x

Zhou, Q., Deng, X., Wu, F., Li, Z. & Song, W. (2017) Participatory irrigation management and irrigation water use efficiency in Maize Production: evidence from Zhangye City, Northwestern China. *Water*, 9, 822. Available from: https://doi.org/10.3390/w9110822

Zwart, S.J. & Leclert, L.M.C. (2010) A remote sensing-based irrigation performance assessment: a case study of the office du Niger in Mali. *Irrigation Science*, 28(5), 371–385. Available from: https://doi.org/10.1007/s00271-009-0199-3

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