

# Misconceptions and misunderstandings in agricultural water management: Time for revisiting, reflection and rethinking

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## Abstract

Over the past years, several concepts in water management have emerged and were further developed. They included approaches for saving water and improving water use efficiency and productivity, sustainable water management strategies, salinity control, remote sensing applications to estimate crop evapotranspiration ( $ET_c$ ), soil moisture, crop yield and land cover, using models as water management tools and for designing reservoirs and dams. The intention was great, but the application of the concepts did not always match the intention. Examples of misunderstandings and misconceptions include incorrect application of deficit irrigation, using water use efficiency instead of water productivity, misunderstanding the water accounting system elements, misuse of the term sustainability, leaching with every irrigation, using the term upscaling instead of aggregation, incorrect use of long-term average flow for designing dams and reservoirs, believing that remote sensing data are direct measurements for  $ET_c$  or soil moisture and believing that well-calibrated/validated models do not have inaccuracy and uncertainty in their results. This paper highlights these concepts and their misuse and misunderstandings as well as explains the true meaning and application of each concept. The paper also explains why concepts were misunderstood and suggests approaches to improve the understanding and accurate application of the concepts.

## KEYWORDS

deficit irrigation, designing dams and reservoirs, misconceptions in water management, models' inaccuracy and uncertainty, remote sensing evapotranspiration and soil moisture, salinity control, sustainability, upscaling, water accounting system, water use efficiency and productivity

## Résumé

Au cours des dernières années, plusieurs concepts de gestion de l'eau sont apparus et ont été approfondis. Il s'agit notamment des approches visant à

Article title in French: Idées fausses et malentendus dans la gestion de l'eau agricole: il est temps de revisiter, de réfléchir et de repenser.

This paper is based on a presentation of the International Commission on Irrigation and Drainage (ICID) President in the 74th International Executive Council Meeting of ICID in Visakhapatnam, India, 4 November 2023. [https://icid-ciid.org/icid\\_data\\_web/25thCongress-Inaug\\_pres\\_address.pdf](https://icid-ciid.org/icid_data_web/25thCongress-Inaug_pres_address.pdf).

économiser l'eau et à améliorer l'efficacité et la productivité de son utilisation, des stratégies de gestion durable de l'eau, le contrôle de la salinité, l'application de la télédétection pour estimer l'évapotranspiration d'un couvert (ET), l'humidité du sol, le rendement agricole et la couverture terrestre, en utilisant des modèles comme outils de gestion de l'eau et pour concevoir des réservoirs et des barrages. L'intention était excellente, mais l'application des concepts ne correspondait pas toujours à l'intention. Les exemples de malentendus et d'idées fausses comprennent l'application erronée de l'irrigation déficitaire, l'utilisation efficace de l'eau au lieu de la productivité de l'eau, la mauvaise compréhension des éléments du système de comptabilité de l'eau, l'utilisation erronée du terme durabilité, le lessivage à chaque irrigation, l'utilisation du terme d'augmentation d'échelle au lieu d'agrégation, l'utilisation erronée de débit moyen à long terme pour la conception de barrages et de réservoirs, estimant que les données de télédétection sont des mesures directes de l'ET ou de l'humidité du sol, et estimant que les modèles bien calibrés/validés ne présentent pas d'inexactitude ni d'incertitude dans leurs résultats. Cet article met l'accent sur ces concepts, leur mauvaise utilisation et leurs malentendus, et explique la véritable signification et l'application de chaque concept. Le document explique également pourquoi les concepts ont été mal compris et propose des approches pour améliorer la compréhension et l'application précise des concepts.

#### MOTS CLÉS

idées fausses sur la gestion de l'eau, irrigation déficitaire, système de comptabilité de l'eau, télédétection ET et humidité du sol, efficacité et productivité de l'utilisation de l'eau, durabilité, conception de barrages et de réservoirs, contrôle de la salinité, mise à l'échelle, inexactitude et l'incertitude du modèle

## 1 | INTRODUCTION

'Misconception' is essentially a false belief or idea that is not accurate or true. This may arise from a lack of information, incorrect information or a misinterpretation of information. The misconception may lead to incorrect decisions or actions while 'Misunderstanding' refers to a failure to comprehend or correctly interpret the intended meaning of a situation. This may arise from a miscommunication or from language barriers while, however, there can be some overlap between the two and in some cases both words may be appropriate. The following sections will highlight some of the misunderstandings and misconceptions currently practised in agricultural water management.

Over the past decades, as well as in recent years, some concepts were developed. They were intended to improve agricultural water management, water saving such as enhancing water use efficiency (WUE) and water

productivity (WP), water accounting, deficit irrigation, sustainable management, salinity leaching and more. However, the application of these concepts suffered misunderstandings and the concepts were sometimes wrongly applied, without due care of their true physical meaning and the limitation of their application. Some of these concepts were developed with minimum or insufficient hydrology knowledge taken into consideration, some concepts also did not clearly state the scale of their application and their limitations, and some concepts did not describe how properly and accurately one can obtain the parameters of the concept. In the following sections, a number of these concepts and their misunderstandings and incorrect application by practitioners will be highlighted. The reader will also be provided with evidence and guidelines to use the concepts properly and accurately according to their true physical meaning, the scale of application and the uncertainty level in their applications.

## 2 | ISSUE 1: MISUNDERSTANDING THE TRUE MEANING OF DEFICIT IRRIGATION

The current literature shows that many publications to save water were based on the application of deficit irrigation. Researchers reported obtaining equal yield at deficit irrigation (e.g. at 50% or 60% or 70% of full irrigation requirement) to the yield obtained when they applied 100% full irrigation requirement. Although these results are true, one would wonder why deficit irrigation gave the same yield as full irrigation.

*The question here is:* Is the deficit irrigation really a deficit or is it just the actual requirement, and the estimated full irrigation requirement was exaggerated due to the overestimation by the method used to determine the crop water requirement (CWR)? To investigate this, one needs to look at how the CWR were calculated in the first place. This will be explained hereunder.

### 2.1 | CWR determination methods

1. Equations based on meteorological data: temperature, radiation or a combination, wind speed, relative humidity and empirical equations (site specific);
2. Soil measurements: moisture content, soil moisture deficit (SMD) zero flux plain, moisture profiles, soil water balance, etc.;
3. Plant measurements: sap flow;
4. Lysimeters: A lysimeter is a measuring device to measure the amount of actual ET released by plants;
5. Direct and indirect measurements of the evaporation flux: Class A pan, Bowen ratio, eddy covariance, scintillometers.

However, the users should be aware of the accuracy of all those methods; the scale they represent and their limitations.

### 2.2 | Deficit irrigation definition

Deficit irrigation is usually defined as a reduced irrigation water amount that represents a fraction of the full CWR or a percentage less than 100% of CWR.

CWR can be measured as mentioned above (e.g. lysimeters, SMD and direct/indirect measurements by Bowen ratio, eddy covariance or scintillometers) or calculated from equations such as the widely used Food and Agriculture Organization of the United Nations (FAO)-56 modified Penman–Monteith equation (Allen et al., 1998) as

$$ET_c = ET_o(K_{cb} + K_e), \quad (1)$$

where  $ET_c$  is the crop evapotranspiration (= CWR),  $ET_o$  is the reference evapotranspiration,  $K_{cb}$  is the crop coefficient representing the crop transpiration, and  $K_e$  is a coefficient representing the bare soil evaporation.

Deficit irrigation = % < 100 of  $ET_c$  (e.g. 90% $ET_c$ , 50% $ET_c$ , ...).

The following section will discuss how CWR is determined, how CWR calculated from equations compares with the measured CWR and how canopy resistance assumed by the FAO modified Penman–Monteith equation compares with the measured values. This will help to understand why deficit irrigation in some cases, even at 50% of full CWR, gives the same yield as 100% CWR. Is there overestimation of CWR? And if so, why?

### 2.3 | Penman–Monteith ET equation to estimate CWR

In presence of stomata/canopy surface resistance data, one could use the well-known equation of Penman–Monteith (Monteith, 1965) in the following form:

$$\lambda E_p = \frac{\Delta R_n - \rho C_p \frac{e_s^* - e_a}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (2)$$

But due to the difficulty in providing canopy resistance values, the above equation was modified.

### 2.4 | Modified Penman–Monteith, FAO-56 (Allen et al., 1998) version

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma U_2(1 + 0.34U_2)} \quad (3)$$

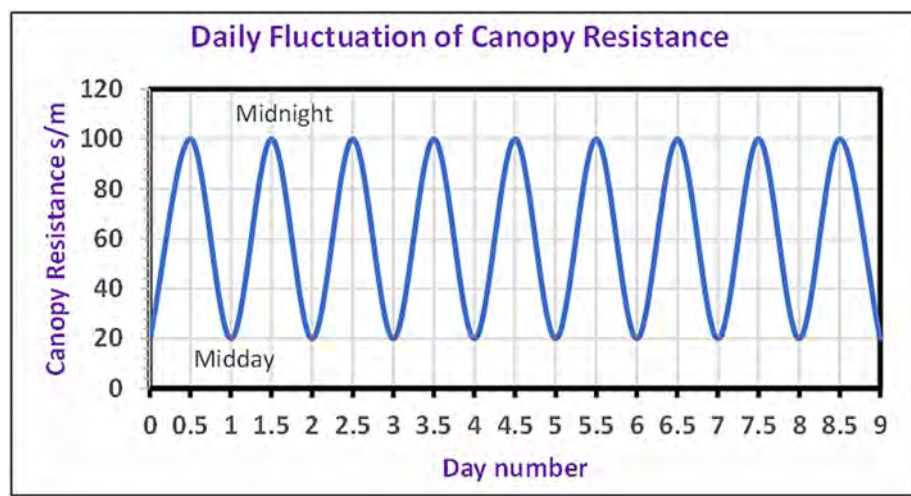
where  $ET_o$  (=  $\lambda E_p$ ) is the reference evapotranspiration ( $\text{mm day}^{-1}$ ),  $r_s$  and  $r_a$  are the bulk surface and aerodynamic resistance ( $\text{s m}^{-1}$ ),  $R_n$  is the net radiation ( $\text{MJ m}^{-2} \text{day}^{-1}$ ),  $G$  is the soil heat flux density ( $\text{MJ m}^{-2} \text{day}^{-1}$ ),  $T$  is the mean daily air temperature at 2-m height ( $^{\circ}\text{C}$ ),  $\Delta$  is the slope of the saturated vapour pressure curve ( $\text{kPa } ^{\circ}\text{C}^{-1}$ ),  $\gamma$  is the psychrometric constant ( $66 \text{ Pa } ^{\circ}\text{C}^{-1}$ ),  $e_s$  is the saturated vapour pressure at

air temperature (kPa),  $e_a$  is the prevailing vapour pressure (kPa), and  $U_2$  is the wind speed at 2-m height ( $\text{m s}^{-1}$ ). The calculated  $ET_o$  here is for short well-watered green grass. In this formula, a hypothetical reference crop with an assumed height of 0.12 m and an albedo of 0.23 was considered.

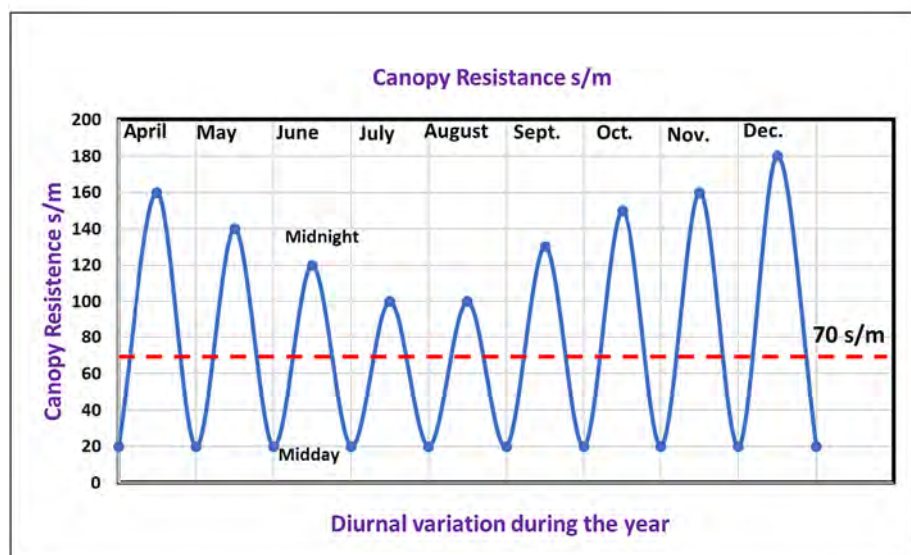
The Penman–Monteith equation was a unique equation as it did include the presence of the plant instead of focusing only on weather data (radiation and temperature) to determine ET. However, the difficulty in getting the plant parameter (canopy resistance) confined it to a limited application by mostly academics. In cooperation between FAO and the International Commission on Irrigation and Drainage (ICID), Allen et al. (1998) attempted to simplify the Penman–Monteith equation by assuming canopy resistance  $r_s = 70 \text{ s m}^{-1}$  to be the

average seasonal value for crops. This simplification led to the modified Penman–Monteith equation.

However, the use of the arithmetic mean of seasonal canopy/stomata resistance that takes a sine wave function shape has possibly introduced inaccuracy to the  $ET_c$  estimation. The canopy resistance time course,  $r_s$ , is maximum at the middle of the night and lowest at midday, to maximize the intake of  $\text{CO}_2$  and the radiation for photosynthesis and biomass production and minimize water losses from the plant during night-time (Figure 1a). It was also found that  $r_s$  changes during the seasons (Figure 1b), where the daytime and photoperiod has impact on canopy resistance. The longer the daytime and the photoperiod, the lower is the canopy resistance, that is, low in summer and increasing from autumn to winter when daytime and photoperiod get shorter.



(a)



(b)

FIGURE 1 (a) Illustration of diurnal variation of canopy resistance. (b) Illustration of diurnal and seasonal variation of canopy resistance (in northern hemisphere). Red dashed line represents  $70 \text{ s m}^{-1}$ , the average seasonal canopy resistance value used in modified FAO Penman–Monteith equation.

Similar trends to those presented in Figure 1a,b were reported by Han et al. (2022) and by Maruyama and Kuwagata (2008). Diurnal variation in stomatal conductance, regardless of the growth period, commonly shows lower values in the morning and evening and higher values during midday because of its dependence on solar radiation. The results of Zheng et al. (2022) showed that the daytime canopy resistance of grapevines was maintained between 200 and 250 s m<sup>-1</sup> during two growing seasons. They also found that the modified Penman–Monteith equation overestimated transpiration at the early growth stage and underestimated transpiration at the middle and late growth stages. The canopy resistance in early growth stage was significantly higher than that in the middle growth stage and the late growth stage.

Lin et al. (2020) analysed the two-year eddy covariance flux measurements above a humid cypress forest. They observed a canopy resistance around 190 s m<sup>-1</sup> for the two warm seasons and canopy resistances of 670 and 320 s m<sup>-1</sup> for the two cool seasons. Hsieh et al. (2023) conducted ET measurements using the eddy covariance method above three sites: a grassland in south Ireland, a cypress forest in north Taiwan and a *Cryptomeria* forest in central Taiwan. They found the average canopy resistances for the grassland, cypress forest and *Cryptomeria* forest were 163, 346 and 321 s m<sup>-1</sup>, respectively. They noticed that for the grassland, canopy resistance was larger in the early morning and then decreased to its lowest value of around 150 s m<sup>-1</sup> at 12:00 and then maintained this value till 18:00.

It is clear from Figure 1b that the assumed constant value of canopy resistance of 70 s m<sup>-1</sup> is an unrealistic approximation of the diurnal and seasonal trend of the canopy resistance that is better represented by a sine wave equation, and this crude approximation is expected to cause a great deal of inaccuracy in ET calculations. In its most general form, the sine wave can be described using the function  $y = a * \sin(bx)$ , where  $a$  is known as the amplitude of the sine wave and  $b$  as the periodicity.

Kashyap and Panda (2001) found that the ET<sub>o</sub> obtained by several methods including FAO Penman–Monteith, Penman, Hargreaves, Blaney–Criddle and Turc was in general higher than the ET<sub>o</sub> obtained from lysimeters. In addition, they also reported that the crop coefficient K<sub>c</sub>-measured values were lower than those reported by Allen et al. (1998). The calculated high ET<sub>o</sub> and high K<sub>c</sub> led to higher estimations of CWR of potato crop in India when compared with the measured values of ET<sub>o</sub> and K<sub>c</sub>. Eddy covariance was also used to estimate the K<sub>c</sub> of drip-irrigated tomato in the Jordan Valley (Amayreh & Al-Abed, 2005). Eddy covariance was used to estimate the ET<sub>c</sub>, and then the K<sub>c</sub> was calculated as a ratio between ET<sub>c</sub> and the ET<sub>o</sub> obtained by the FAO modified version of the Penman–Monteith equation (Allen et al., 1998). They

found that the K<sub>c</sub> values obtained using eddy covariance were, on average, 36% lower than those reported by the FAO (Allen et al., 1998). Higher K<sub>c</sub> values would lead to overestimation of CWR of the tomato crop. In Portugal, Paço et al. (2006) measured the ET over a 3–4-year-old orchard using eddy covariance. They reported that the FAO-56 Penman–Monteith equation (Allen et al., 1998) overestimated ET<sub>c</sub> when compared with eddy covariance.

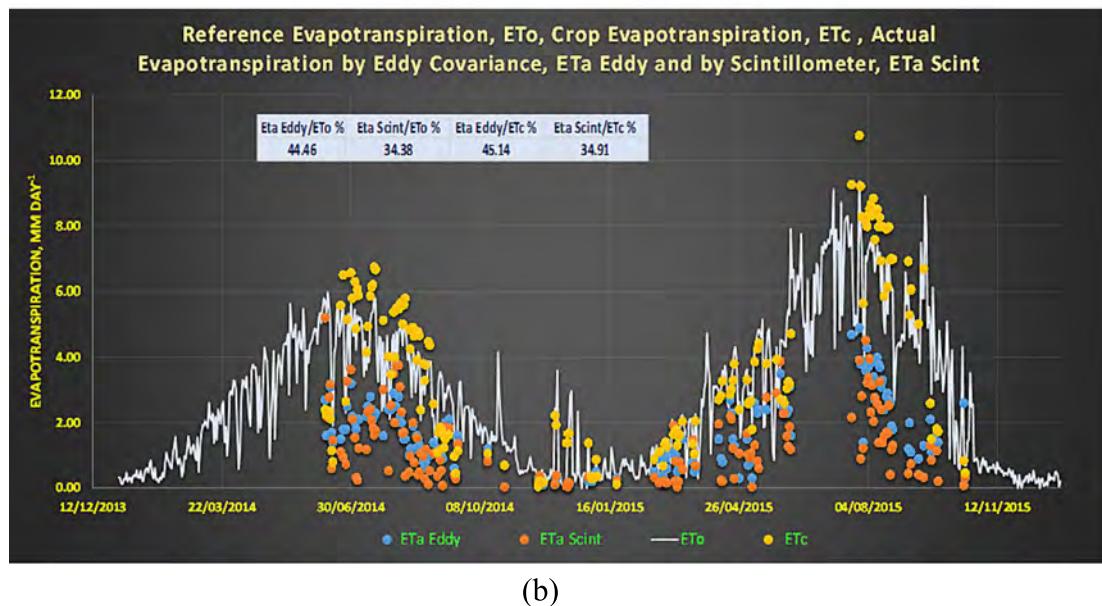
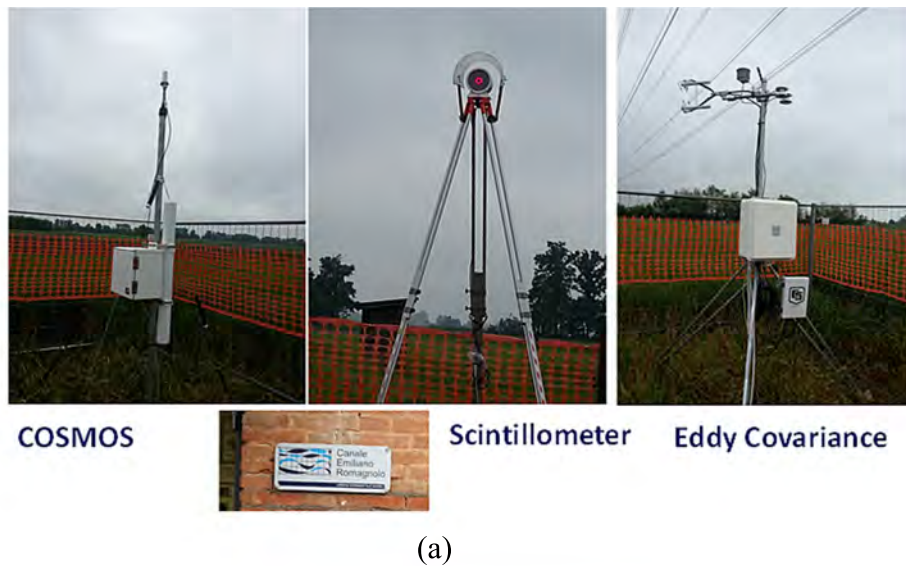
In a study by Ragab et al. (2017a, 2017b), using eddy covariance and a scintillometer (Figure 2a) at an experimental site in the north of Italy, it was found that the ET<sub>c</sub> and ET<sub>o</sub> obtained by the modified Penman–Monteith equation (Allen et al., 1998) showed higher values than those of actual ET obtained by eddy covariance and the scintillometer.

The results illustrated in Figure 2b show that, on average, the actual ET of eddy covariance and scintillometers for the cropping seasons 2014 and 2015 represented 45% and 35% of the ET<sub>o</sub> and ET<sub>c</sub> obtained by the modified Penman–Monteith equation, respectively. These are quite significant differences.

#### 2.4.1 | In conclusion

The use of deficit irrigation as a percentage of potential ET is not correct. Some methods and equations lead to overestimation of CWR and that is the reason why some researchers were able to obtain a similar yield to the full irrigation at a significantly reduced percentage of full irrigation (e.g. 50%). The true deficit irrigation must represent a fraction or a percentage of actual ET reliably measured or calculated but calibrated against measurements. Equations based only on meteorological data to produce ET values need to be calibrated against measured ET values. The FAO-56 modified Penman–Monteith equation (Allen et al., 1998), as reported by several scientists, overestimates the ET due to the low value of the assumed canopy resistance of 70 s m<sup>-1</sup> when compared with the high values reported above. One should also be aware that the single and very low flat line value of 70 s m<sup>-1</sup> (Figure 1b) does not reflect the diurnal or seasonal variation, and the arithmetic mean of the season's canopy resistance does not seem to be a good representative of a sine wave trend of canopy resistance.

Given that the modified FAO Penman–Monteith equation is 25 years old and was subjected over the past years to several evaluations, which proved that the equation does not accurately estimate the ET, it is about time to revisit the crude estimation of canopy resistance. This value needs to be revised by the FAO and ICID to replace it with more dynamic realistic and physically sound values representing the diurnal and seasonal variations.



**FIGURE 2** (a) Field instrumentation to measure actual evapotranspiration ( $ET_a$ ) measured by eddy covariance and scintillometer and SMD measured by COSMOS (Ragab et al., 2017a) at experimental farm near Bologna, Italy. (b) Comparison between  $ET_a$  measured by eddy covariance and scintillometer, reference evapotranspiration ( $ET_o$ ) estimated from Penman–Monteith equation and crop evapotranspiration ( $ET_c$ ) calculated from  $ET_o$  and weighted mean  $K_c$ . Source: Ragab et al. (2017a).

As this parameter is not part of routine field measurements and mostly measured by researchers, a database listing these values for different species needs to be created and used as a look-up table. A simple dynamic function or growth stage-based value canopy resistance (similar to the  $K_c$  curve) as crude approximation together with a look-up table could be the first step forward.

In addition, it must be kept in mind that calculating the  $ET_o$  or the  $ET_c$  from meteorological data with no plant representation is expected to produce potential ET that would represent the atmospheric demand for water

rather than the crop demand for water. It should be clear that accurate CWR should be based on crop demand rather than on atmospheric demand for water.

### 3 | ISSUE 2: MISUNDERSTANDING THE DIFFERENCE BETWEEN WUE AND WP

Some agronomists still use the terms ‘water use efficiency’ and ‘water productivity’ interchangeably. This is

a misconception. There should not be a confusion between the different meanings of each term. Back in the 1960s, authors tended to use ‘water use efficiency’ to describe ‘water productivity’. Since the early 1980s, high-impact journals no longer accept papers where ‘water use efficiency’ (WUE) and ‘water productivity’ (WP) are not used correctly. For clarification, the section below, will highlight the definition of WUE and WP and how they should be used and not confused.

### 3.1 | Irrigation efficiency

The irrigation efficiency has different components:

$$1. \text{Storage efficiency } E_s = V_d/V_e \quad (4)$$

The ratio between the volume diverted for irrigation ( $V_d$ ) and the volume entering a storage reservoir ( $V_e$ ) for the same purpose.

$$2. \text{Conveyance efficiency } E_c = V_p/V_d \quad (5)$$

The ratio between the volume of water delivered to irrigation plots ( $V_p$ ) and the volume diverted from the supply source ( $V_d$ ).

$$3. \text{Irrigation use efficiency } E_u = V_u/V_p \quad (6)$$

The ratio between the volume of water used by plants throughout the ET process ( $V_u$ ) and the volume that reaches the irrigation plot ( $V_p$ ). Note that  $V_u$  is equal to the volume of ET by plants minus the volume of effective rainfall.

In general,

$$\text{efficiency of any process} = (\text{useful output}/\text{total input}) \times 100. \quad (7)$$

Also note that efficiency has no units, it is dimensionless, as it is a ratio of output to input, and both the output and input must have the same units.

WUE in agriculture is equal to the percent of water supplied to the plant and is effectively taken up by the plant, that is, that is not lost due to drainage, bare soil evaporation or interception. If, for example, 10 mm water is supplied to the plant and the plant uses 8 mm through root water uptake and this is lost by transpiration while the remaining 2 mm water is lost through drainage below the root zone or via bare soil evaporation from the surface, then the WUE is  $(8 \text{ mm}/10 \text{ mm}) \times 100 = 80\%$ .

### 3.2 | Water productivity

Productivity refers to what you can produce from a unit of input (Molden et al., 2010). Note that input and output do not need to have the same units. WP in agriculture is defined as the crop yield produced per unit of water supplied, for example, 50 kg grains per  $1 \text{ m}^3$  of water. Modern agriculture aims to increase yield production per unit of water used, both under rainfed and irrigated conditions.

Unlike WUE, the productivity could refer to multi-use/user benefits from water use. For example, people using water for both irrigation and fisheries, such as rice and shrimps, clearly contribute well to their livelihoods and to the regional economy by increasing WP, not necessarily by increasing WUE.

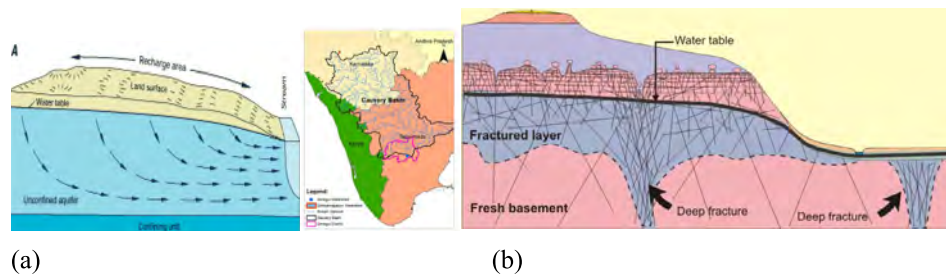
WP refers to the benefits of water (income, jobs, crop production) as a ratio to volume of water used. Productivity is an expression of the bio-economic output from the gross amount of water used. Unlike WUE, WP can be expressed in various ways such as yield in  $\text{ton}/\text{m}^3$ , income in  $\text{US}\$/\text{m}^3$ , protein amount  $\text{grams}/\text{m}^3$ , number of calories the food can supply,  $\text{calories}/\text{m}^3$ . More details can be found in the note published online in Ragab (2014) as part of the Water4Crops Project (<https://www.google.com/search?q=Ragab++A+note+on+water+use+efficiency+and+productivity>).

#### 3.2.1 | In conclusion

It is clear that both terms WUE and WP do exist in real life, have different meanings and are interlinked, for example, in order to increase the WP, the WUE needs to increase, not the other way around. Also, increase of WP follows the increase of WUE and other efficiencies such as weed control, fertilization and pest and disease control.

## 4 | ISSUE 3: THE MISUNDERSTANDING THAT THERE IS NO NEED TO IMPROVE IRRIGATION EFFICIENCY AS WHAT IS LOST UPSTREAM WILL BE GAINED DOWNSTREAM

The concept that advocates ‘no need to improve irrigation efficiency as what is lost upstream will be gained downstream’ ignores the hydrology, the environmental conditions and the geology of the subsurface layers of river basins. It also ignores whether the basin (also referred to as catchment or watershed) is located in arid,



**FIGURE 3** (a) Hypothetical situation where ideal homogeneous subsurface geology favours subsurface flow from upstream to downstream. (b) Real situation at Cauvery basin, India, with fractured subsurface layers preventing subsurface flow from upstream to downstream. *Source:* After Maréchal et al. (2009).

semi-arid or humid region and greatly ignores the possible discontinuity of subsurface flows between upstream and downstream due to geological changes and the presence of fractures. It also goes a long way against development of efficient irrigation systems and strategies for water saving such as nano-irrigation, subsurface drip irrigation, partial root drying (PRD), variable irrigation rate (VRI) and low-nozzle centre pivot, dry rice and drip rice cultivation.

This concept assumes that the subsurface layers are homogeneous and that there are no barriers, fractures or change in the geology. However, what is lost upstream may not appear downstream. Even if it is gained downstream, it will not appear promptly, not with the equivalent amount and not with the same quality due to the leaching of salts and agrochemicals all the way from upstream to downstream.

In terms of hydrology, subsurface flow is usually generated only when the subsurface soil layer is saturated. Saturation of subsurface layers in arid or semi-arid regions might not happen unless under extreme flood events.

In regions with deep groundwater, water lost by inefficient use could take a long time to reach the aquifer as it also requires saturation of the subsurface layers all the way down to the aquifer, which might not happen, again especially not in arid or semi-arid regions.

In addition, the discontinuity of subsurface flow due to fractures and heterogeneity of the subsurface geology can disrupt the subsurface flow and cause a barrier for water to move horizontally to the downstream (Figure 3b). Hydraulic tests (pumping tests) were carried out in several boreholes of a river basin (Bangalore Plateau) in the Kaveri basin, South India. The 18-h pumping tests indicated 'no-flow' boundaries as the groundwater level did not change in a borehole near to the borehole where the pumping test was carried out (Maréchal et al., 2009). They also found that the groundwater table

is always disconnected from the stream. This explains the absence of springs in the river basin and the absence of baseflow measured at the outlet. In such a fractured system, the localized recharge through cracks and fractures cannot be neglected. The presence of fractures (Figure 3b) acts as an underground barrier. The aquifer being disconnected, there is no base flow to the stream. (Maréchal et al., 2009).

#### 4.1 | In conclusion

Generally, the WUE at farm and river basin scale should be improved without expecting what is lost upstream will be gained downstream, as this might not take place at all. Even if it happens, the lost water will not be available downstream at the same time when it was lost, not with equivalent amount to what is lost upstream and not with the same water quality of upstream. The concept of increasing WUE and water saving on every scale, from farm to basin, needs to be adopted.

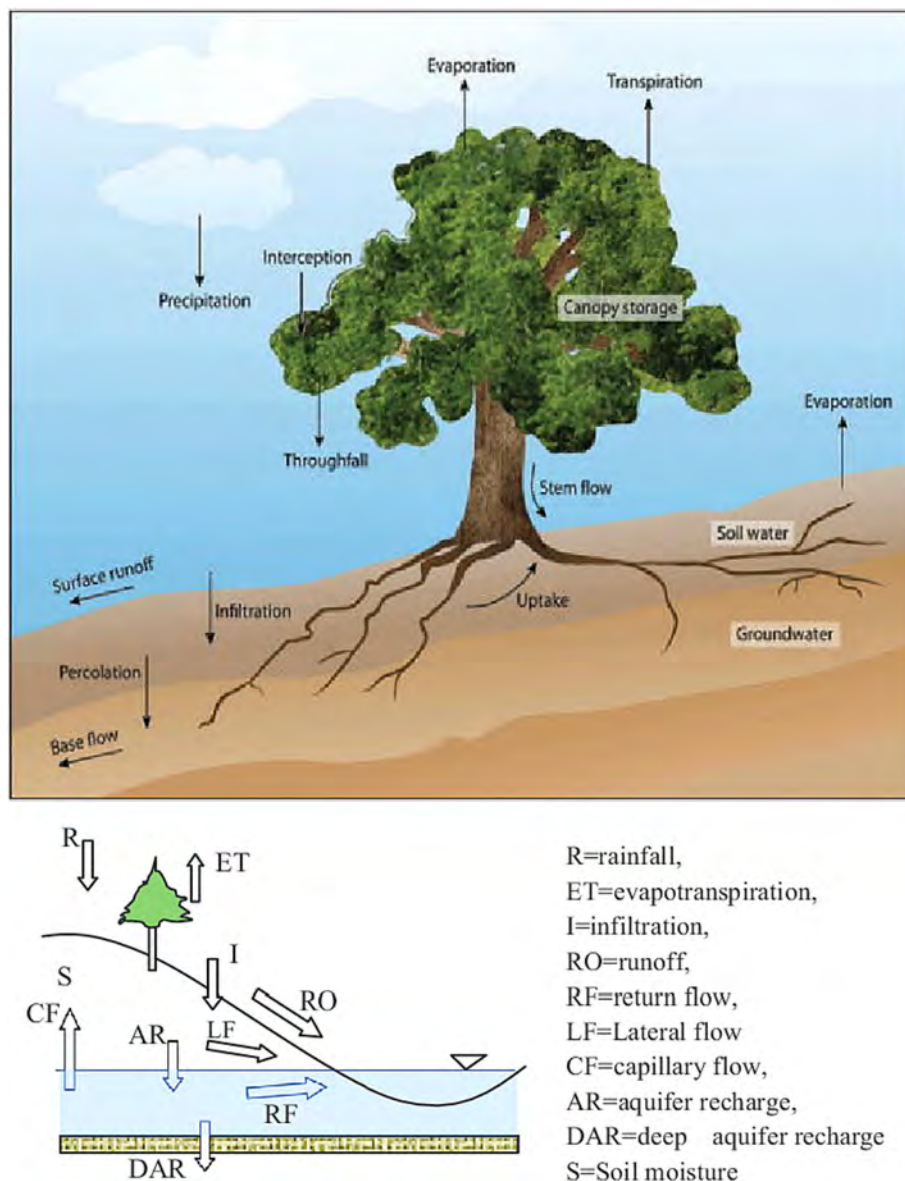
## 5 | ISSUE 4: MISUNDERSTANDING THE REAL MEANING OF THE ELEMENTS OF WATER ACCOUNTING SYSTEMS

The water accounting idea is gaining interest for water resources planning. However, accounting for the different elements of the water within the hydrological cycle can face a number of problems, and some elements are misunderstood by non-hydrologist practitioners. Figure 4 top and bottom show the elements of the water balance.

Water balance means: The rate of water flow into a river basin minus the rate of water flow out of a river basin equals the rate of change in the amount of water stored  $\Delta S$ :



FIGURE 4 Top: schematic illustration of conceptual water balance. Bottom: water balance components.



$$\Delta S = P - R - G - ET, \quad (8)$$

where  $P$  is precipitation,  $R$  is runoff,  $G$  is groundwater recharge, and  $ET$  is evapotranspiration.

### 5.1 | Issues that could lead to inaccurate water accounting

$P$ : the precipitation commonly used in water accounting is the total precipitation where the rainfall intercepted by vegetation canopies is not excluded. The amount of intercepted rainfall could be significant, especially over dense cropping and woodland. What should be used is the amount that is readily available at soil surface for infiltration and runoff, which is the net

precipitation after deducting the interception amount, that is,  $P_{\text{net}} = P - \text{Interception}$ . However, most practitioners use gross rainfall not the net rainfall. This leads to over overestimation of the main input to the water balance/water accounting equation.

$G$ : the groundwater recharge is difficult to quantify. Most practitioners calculate groundwater recharge as the unknown parameter of the water balance equation or as a difference between gross rainfall and potential  $ET$ , which is also inaccurate. Methods to quantify recharge include chloride mass balance, groundwater fluctuation, geophysical investigations, pumping tests and groundwater flow models. These are not direct measurements as there are no devices available to measure the groundwater recharge. Inaccurate estimation of the recharge has a negative impact on water resources quantification. Quantifying the groundwater recharge is important as the

correct estimate of natural recharge is a key element for the good management of groundwater resources.

ET is mostly calculated from equations as potential evapotranspiration (PET), and that is what is commonly used in water accounting. What should be used is the actual ET not the potential. In most of arid and semi-arid regions, the actual ET falls well below the calculated potential ET, and in humid regions, actual ET gets closer to the potential ET only at certain times of the year, mostly during the rainy season.

### 5.1.1 | In conclusion

The three elements precipitation, ET and groundwater recharge are misunderstood and not accurately used in the water accounting system. Net precipitation, actual (not the potential) ET as well as accurate determination of groundwater recharge are required for sound water resources accounting and planning.

## 6 | ISSUE 5: THE MISBELIEF THAT REMOTE SENSING CAN DIRECTLY MEASURE CWR

At present, satellite images are widely available for a several applications. Some of these images are useful for agriculture activities and are used to obtain spatial distribution of ET, soil moisture, leaf area index (LAI) biomass, land cover and plant water stress level. However, obtaining these parameters by remote sensing is not by direct measurement. For example, ET or soil moisture are obtained after the remotely sensed parameters such as temperature are converted into ET or soil moisture. The conversion process includes algorithms, models and empirical equations. During this process, some approximation and assumptions are used to obtain meaningful results. This process could lead to a certain degree of inaccuracy in the results and needs to be calibrated against ground truth data. The latter is often carried out at a smaller scale, and this mismatch between the two scales leads to an additional level of inaccuracy and uncertainty in the data obtained by remote sensing. The following section will highlight the issue and the cause of inaccuracy in obtaining the ET and soil moisture/SMD from remote sensing.

### 6.1 | Obtaining ET from remote sensing data

The satellite remotely sensed land surface temperature (LST) and roughness length are used to calculate

instantaneous sensible and latent heat fluxes. The estimation of surface resistance is a major issue in most remote sensing ET models, especially the estimation of canopy and aerodynamic resistances. In addition, empirical direct methods used remotely sensed data directly in semi-empirical models to estimate ET using thermal infrared (TIR) data. Also, crop water use was calculated using ground measurements and satellite data to calculate the cumulative temperature difference ( $T_s - T_a$ ), where  $T_s$  is the LST obtained from remote sensing and  $T_a$  is the air temperature obtained from ground measurements.

Although the satellite data produce spatially distributed estimates of albedo, normalized difference vegetation index (NDVI) and surface temperature, and these data are used to estimate the daily ET (Figure 5), the results must be cross-validated with ground measurements. The role of wind speed and its impact on ET values must be examined thoroughly, since it might have the biggest influence on the ET and the reliability of the methods with remote sensing input.

### 6.2 | Obtaining SMD from remote sensing data

Soil moisture content is sometimes used to estimate the CWR. The difference between the soil moisture and the soil moisture content at field capacity is known as SMD. The irrigation amount that would bring the SMD to zero is calculated and added as CWR. However, the problem is how to obtain an area-based representative SMD value given the natural spatial variability of soil moisture conditions caused by the heterogeneity of soil properties,

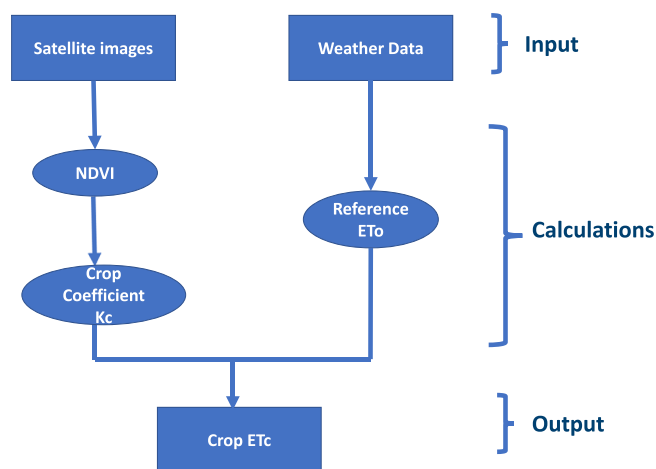


FIGURE 5 Example of indirect calculation of crop evapotranspiration using weather data and satellite normalized difference vegetation index (NDVI) data. ET, evapotranspiration.

topography, land cover and precipitation. Field measurements of soil moisture include, according to the scale from point to larger scale: soil cores samples, time domain reflectometry (TDR), neutron probe, profile probe, electromagnetic resistivity tomography (ERT)

(transects) and recently cosmic rays (area-measured 300–700-m radius) (Figure 6). The large area sensed by COSMOS (Figure 2a) makes it the second-best large-scale measurement after remote sensing. Example of results obtained by COSMOS are shown in Figure 7.

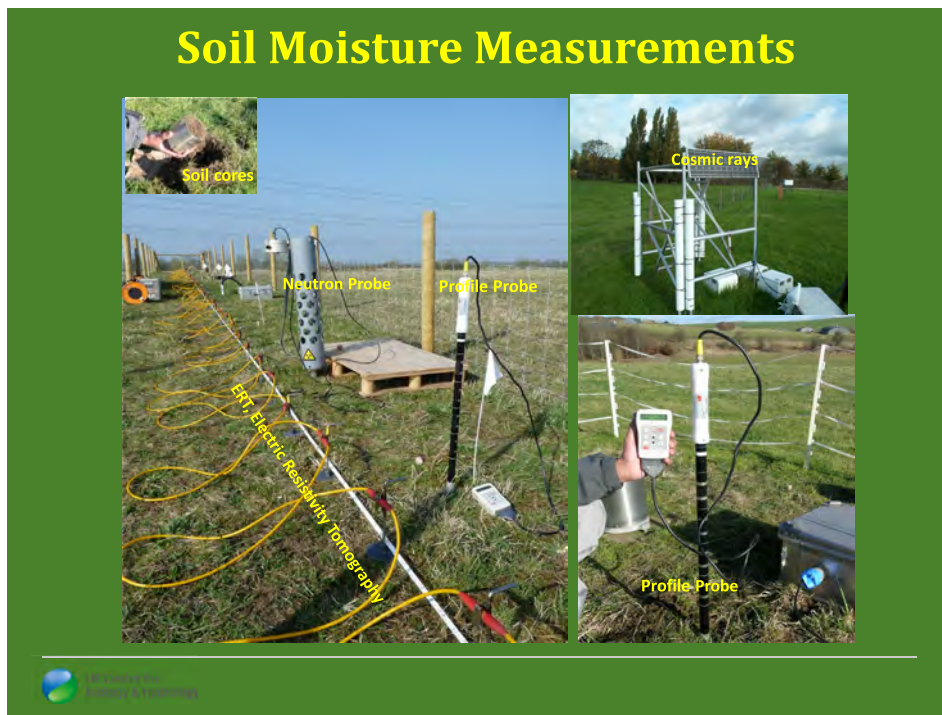


FIGURE 6 Methods for soil moisture determination in the field.

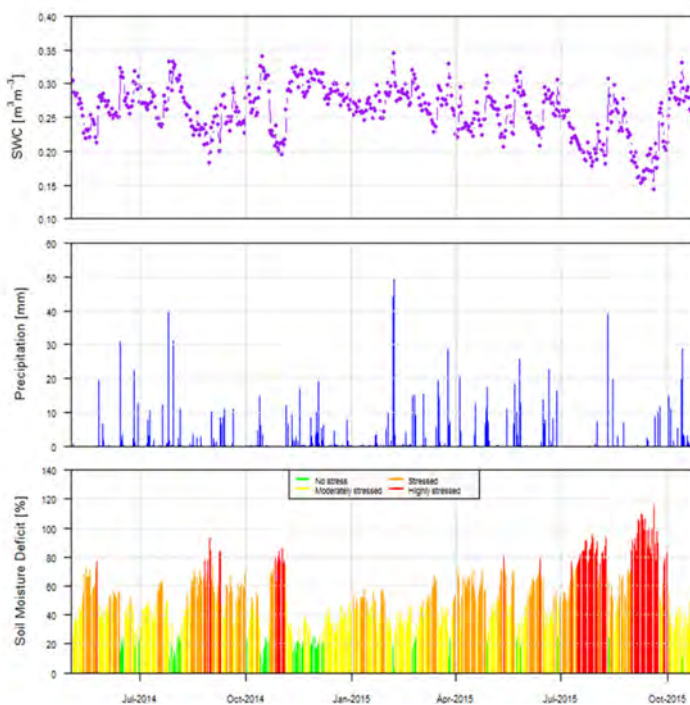


FIGURE 7 COSMOS soil water content (SWC) and soil moisture deficit (SMD) for 60-cm soil depth. Source: Ragab et al. (2017b).

Estimating CWR can be carried out using the cosmic ray soil moisture observing system (COSMOS) (<https://cosmos.ceh.ac.uk/>). In this area-based system, probes measure the neutrons that are generated by cosmic rays within the air. The high-energy neutrons generated by cosmic rays are slowed and partly absorbed by the hydrogen atoms in the soil water while some neutrons are scattered back from the soil and counted by the probe. The smaller number of fast neutrons detected by the probe reflects high soil moisture content and vice versa. COSMOS senses soil moisture of large-scale areas, 300–700 m in radius.

COSMOS is non-invasive, completely passive and uses background fast neutrons generated by cosmic rays, which are scattered (slowed) by H atoms. COSMOS gives the representative soil moisture of an area, not a single point. It could help to obtain the SMD to estimate irrigation water requirement over a certain area, giving a representative integrated soil moisture and avoiding the point scale measurements, which would not address soil heterogeneity. The COSMOS method has been applied successfully, as reported by Ragab et al. (2017b). This system is now covering the whole of the United Kingdom, and stations are now also covering parts of India and China (recently, on 16 November 2023, reported by the international news channel CNN at <https://edition.cnn.com/world/cosmic-radiation-monitor-floods-drought-scn-spc/index.html>).

The results of the work carried out using COSMOS and scintillometers merited a press release by Wiley and Sons (<https://johnwiley2020news.q4web.com/press-releases/press-release-details/2017/Research-May-Lead-to-Improvements-in-Water-Use-for-Crop-Irrigation/default.aspx>).

In addition, other approaches such as ‘inversion’ methods for computing surface soil water content from measurements of LST and NDVI were developed. However, these approaches suffered some weakness and inaccuracy in their results as they were calibrated using point measurements of soil moisture by TDR neutron probe, profile probe, soil cores or other point scale methods. This is a clear example of mismatch of the remote sensing and point measurement scales.

### 6.2.1 | Microwave remote sensing

Typical wavelengths only see the top few centimetres of soil water and canopy water, which is impacted by soil surface condition (roughness), and not the whole profile soil water is measured. Approaches to retrieve soil moisture from microwave radiometric measurements include statistical approaches, forward model inversion, neural

networks and data assimilation. Factors affecting accuracy are the vegetation cover, most importantly dense vegetation such as corn and forest, which can obscure the soil surface. Active microwaves depend on back scattering and that is related to the dielectric constant value of the soil. Passive microwaves depend on radiation or brightness temperature. The latter depends on emissivity and the physical temperature.

Thermal inertia is the square root of the product of the volumetric heat capacity and the thermal conductivity and represents the temporal stability of the temperature of materials. Thermal inertia has been used for estimating the soil moisture of the subsurface layer because the magnitude of the thermal inertia of water and that of other materials are sufficiently different from each other, and it can be theoretically shown that thermal inertia and soil water content have a significant positive correlation. The thermal inertia can be retrieved from a surface heat budget model that uses surface temperatures measured by polar orbiting satellites and meteorological data.

## 6.3 | Remotely sensed ET and SMD scale issue and limitations

The scale mismatch between large-scale remote sensing data and local actual ET measurements or ground truth data of soil moisture that are used in the calibration of remote sensing are commonly carried out at point scale. The large-scale remote sensing data are usually subjected to transformation through algorithms, empirical equations and models to obtain either the actual ET or soil moisture. During this process, approximation and assumptions are made and that introduces another level of uncertainty and inaccuracy. Both calculated actual ET and soil moisture are usually calibrated against local ET measurement or point-measured soil moisture content using TDR, soil cores and so forth. Another limitation is the remotely sensed soil moisture, which is restricted to the top 10–12 cm. SMD/CWR requires root zone soil moisture. In order to estimate subsurface/root zone soil moisture content, Ragab (1995) developed a model to predict subsurface soil moisture using the top layer remotely sensed soil moisture (Figure 8). The model has been calibrated and validated in UK and US studies.

### 6.3.1 | In conclusion

Remote sensing images of large-scale soil moisture or ET are based on indirect measurements and need to be calibrated. Images based on temperature are converted into

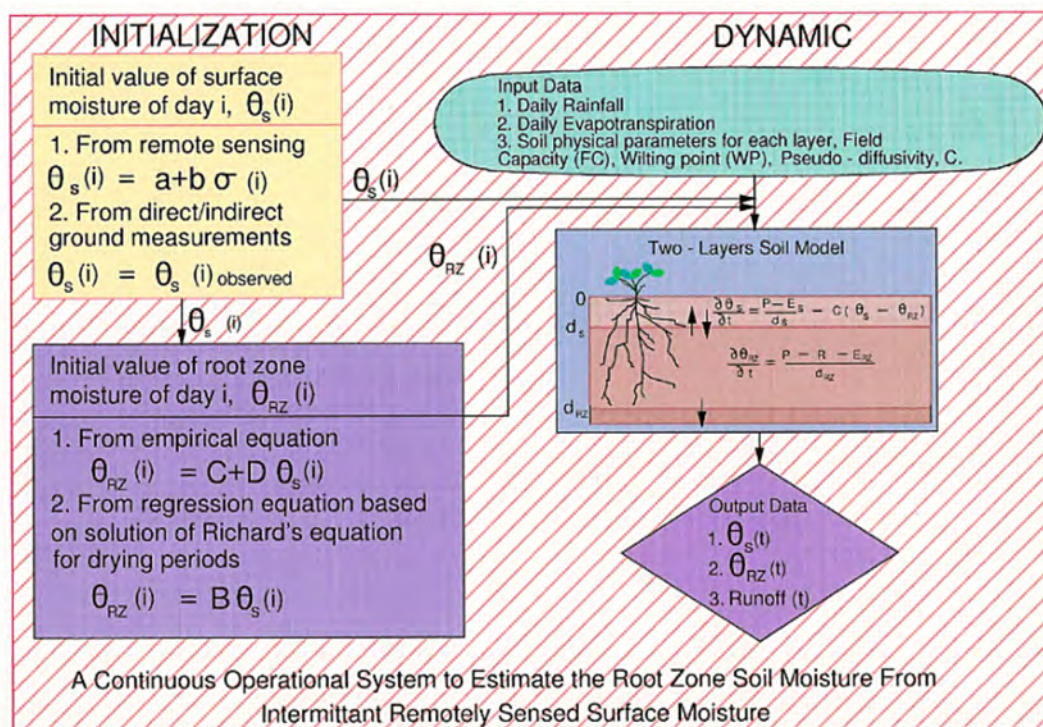


FIGURE 8 Predicting soil moisture of subsurface layer using top-layer remotely sensed data. Source: Ragab (1995).

ET. Images based on back scattering coefficients/dielectric constant (microwave based) are converted into soil moisture. The calibration using point measurements and the conversion methods/models/algorithms to obtain ET and SMD are major contributions to the inaccuracy and uncertainty of the results obtained from remote sensing technology. Calibration of remote sensing data using large-scale actual ET measurements using scintillometers (up to 10-km footprint) and COSMOS (300–700 radius area) could reduce the uncertainty and inaccuracy level in ET and soil moisture, respectively.

## 7 | ISSUE 6A: THE MISBELIEF THAT FIELD SALINITY CAN BE ACCURATELY MEASURED IN THE LABORATORY

Field salinity is either measured directly in the field using several methods, including in situ salinity sensors, or by taking soil cores and determining salinity in the laboratory. However, field salinity cannot be accurately measured in the laboratory. The salinity expressed as electric conductivity (EC) measured in the laboratory using saturated paste extract (ECe), does not represent the salinity of the field because the soil moisture of the field gets altered in the laboratory. Salinity of the field is associated

with a concurrent soil moisture usually less than saturated moisture content. This makes the soil salinity in the field to be higher than what is measured in the saturated soil paste extract where salinity is diluted by bringing the soil sample to saturation, which is well above the soil moisture of the field. This is the reason why practitioners found that plants growing in the field can tolerate higher salinity levels than those reported in several guidelines. The reason is the guidelines are mostly based on the value of 'ECe' known as the salinity of saturated soil paste extract, which gives a diluted salinity lower than the actual salinity of the field at lower soil moisture content below saturation.

Both salinity and soil moisture should be measured at the same time and at the same depth. Attempts were made to introduce a correction factor based on the ratio of field soil moisture to saturated soil moisture to correct the ECe values. One must keep in mind that plants grow between the wilting soil moisture content and close to saturated soil moisture content. In that range, salinity goes from low at saturation to high at wilting point. These are difficult to be represented by laboratory measurements.

The most accurate field salinity measurements are to be conducted using salinity sensors coupled with soil moisture sensors to provide continuous salinity and soil moisture measurements at different depths.

However, the spatial variability and soil heterogeneity make area-based measurements more representative.

Model values of soil salinity are associated with a twining value of soil moisture. Model users often make mistakes by comparing the soil salinity of the model with the laboratory salinity measured from the saturated paste extract.

In addition, the salinity relation with yield or other crop parameters is better described using scaled relations, for example, relative yield versus salinity rather than absolute yield versus salinity.

## 7.1 | In conclusion

In situ continuous measurements of both soil moisture and salinity at the same time are more accurate than laboratory methods. The most accurate field salinity measurements are conducted using salinity sensors coupled with soil moisture sensors to provide continuous salinity and soil moisture measurements at the same depth. However, the spatial variability and soil heterogeneity make area-based measurements more representative to field salinity. An example is the use of a vehicle-mounted electromagnetic induction (EMI) device combined with global positioning systems (GPS) to measure field salinity at different points along transects.

## 8 | ISSUE 6B: THE MISUNDERSTANDING THAT LEACHING MANAGEMENT REQUIRES ADDING A FIXED LEACHING FRACTION TO EACH IRRIGATION

Some irrigation practitioners automatically apply a leaching fraction to the total irrigation requirement. Literature showed that some practitioners add a fixed amount, such as 15% extra water, with each irrigation as a leaching fraction regardless of the soil salinity level or crop tolerance level and without monitoring the soil salinity. It might be thought of as a preventative measure. However, there are better ways to prevent salinity build-up as discussed below.

The leaching fraction is commonly calculated as a ratio of irrigation water salinity to drainage water salinity or rootzone soil salinity. However, the rootzone salinity if measured in the laboratory might not be representative of the field salinity, as explained earlier, and could lead to an inaccurate leaching fraction value.

The most commonly used equation for CWR that includes leaching fraction is:

$$IR = [ET_o \times K_c] / E_i - R + LR, \quad (9)$$

where IR = irrigation requirement, mm/day;  $ET_o$  = reference evapotranspiration, mm/day;  $K_c$  = crop coefficient (Allen et al., 1998);  $E_i$  = irrigation efficiency, %;  $R$  = water received by the plant from sources other than irrigation, for example rainfall, mm; and LR = amount of water required for the leaching of salts, mm.

### 8.1 | The misunderstanding about leaching is related to when, how and how much water to apply

#### 8.1.1 | When

Only when the salt concentration exceeds the plant tolerance limit.

#### 8.1.2 | How

By unavoidable irrigation inefficiency, occasional rain, seasonal fresh water application (recommended) and fresh water application after each irrigation (not recommended, unless there is a great risk for the crop if no leaching is considered).

Due to the strong link between LR and CWR, accurate estimation of the leaching requirement and the CWR are necessary.

Accurate estimation of CWR has an impact as adding more water means adding more salts, especially when irrigating with brackish/saline water, as well as leaching of nutrients and fertilizers, which decreases soil and groundwater quality. Adding more water also decreases the WP and WUE. As water is limited, using water for leaching means less water will be available for irrigation; water resources, labour, energy and money are wasted; and in addition, there will be an increased volume of drainage water that needs to be considered.

To minimize salt accumulation in soil and the need for leaching, some other field management approaches, such as selection of the most suitable irrigation system and land management, are necessary. Using saline water requires a suitable irrigation system. Low-nozzle sprayers/sprinklers below the canopy and close to the ground and subsurface drip irrigation are suitable systems. However, nano-drip subsurface irrigation using ultra-low drip irrigation systems (flow 0.1–0.3 L/h) with continuous low flow would be a good option to keep the soil wet, dilute salts and save significant amounts of irrigation water.

When two sources of water, for example, fresh and saline water are available, use of the fresh water at the beginning of the growth season, as the young crop is sensitive to salinity, followed by irrigating with the saline water at the later stage, when the crop is less sensitive, is a better management (Figure 9) than irrigating with the mix of the two water resources for the whole season.

Land management is also important when using saline water for irrigation. Land preparation is necessary to ensure uniform distribution of irrigation water, infiltration, and better salinity control. Subsoiling, chiselling and ploughing break up compaction and improve water infiltration and leaching. Special treatments such as deep ploughing, adding and mixing sand with the soil layer, and addition of organic matter, gypsum or green manure improve soil permeability. Conservative tillage, zero or minimum tillage have advantages as they reduce soil evaporation, increase water availability, reduce surface salinity, increase organic matter, reduce soil erosion, increase nutrient availability, reduce agrochemical use and machinery use and reduce labour requirement. It is also essential to have an efficient drainage system controlling the groundwater table.

Salinization is a slow process, and models are useful for long-term predictions. Calibrated and validated models (e.g. SALTMed) can be used as a good management tool to predict the long-term salinity impact on soil, plant, groundwater and leaching requirement without the need to conduct field experiments. With the

knowledge of yield, they can also be used in a non-conventional way to estimate through calibration some crop parameters that are difficult to measure (i.e.  $P_i$  50,  $K_{cb}$ ,  $K_c$ , photosynthesis efficiency, etc.), to predict climate change impact ( $CO_2$ , radiation, rainfall, temperature, etc.); produce an experimental design such as the best crop rotation, tillage level, fertilizer management and scheduling; and estimate the CWR and time to irrigate (scheduling). The model can also be used to design a program for data collection. The SALTMed model (Ragab, 2015, 2023) can be downloaded at [http://icid-ciid.org/inner\\_page/41](http://icid-ciid.org/inner_page/41). The model online course is available at <https://www.youtube.com/watch?v=JRMeUFzuBYU>.

A SALTMed special issue on worldwide applications is available at [https://onlinelibrary.wiley.com/doi/toc/10.1002/\(ISSN\)1531-0361.saltmed-publications](https://onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1531-0361.saltmed-publications).

### 8.1.3 | In conclusion

Leaching is not a routine application of a fixed amount of water with each irrigation. Leaching should only be considered when the salt concentration exceeds the plant tolerance limit. Leaching can be carried out by the unavoidable irrigation inefficiency, occasional rain, seasonal application of fresh water and after harvest and before the next crop planting. Excessive or routine leaching with each irrigation is not recommended as leaching can also leach nutrients, wastes water and adds extra salt

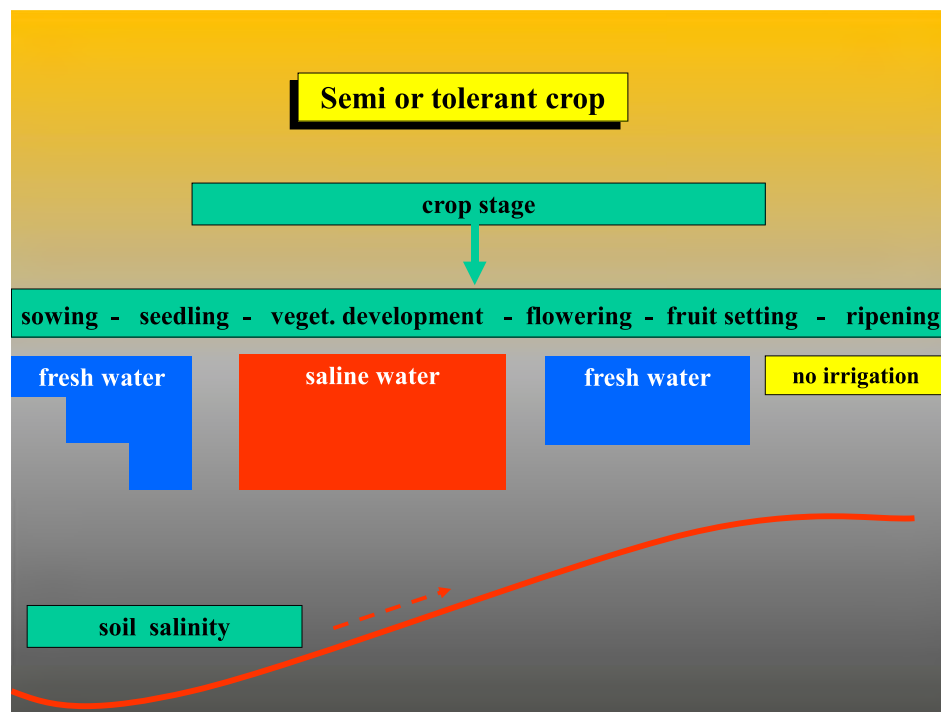


FIGURE 9 Management of fresh and saline water for irrigation during crop growth stages.

if leaching water is saline. To avoid leaching, we need to avoid salinity build-up by using a suitable irrigation system, drainage system and good land management. Models can be used to predict the long-term impact of using saline water on soil and the environment and plan for a suitable water management.

## 9 | ISSUE 7A: THE MISUNDERSTANDING THAT WELL-CALIBRATED AND VALIDATED MODELS DO NOT HAVE INHERENT INACCURACY AND UNCERTAINTY IN THEIR RESULTS

Some model users believe that well-calibrated and -validated models have no or little uncertainty in the results. Although models have been improved over the years thanks to the increase in data availability and the improved measurement accuracy of new technologies, they still have inherent inaccuracy that leads to some level of uncertainty in their results, despite their good performance during the calibration and validation processes. The model uncertainty and accuracy may vary according to the scale of application, data period and the time step. Some research funding organizations nowadays require reporting the level of uncertainty alongside the model results.

Uncertainty and inaccuracy in model results could be attributed to a number of reasons:

1. Representation of the physical processes at field scale is an issue as most models are based on point scale equations and most models struggle with the representation of heterogeneity in soil and plant cover in their equations. In addition, there are difficulties in the calibration of models, especially due to data adequacy/gaps and the scale mismatch between model output and measurements.
2. In nature, hydrological processes are associated with different spatial and temporal scales. Describing hydrological processes at point scale might not represent those operating at river basin scale (Figure 10).
3. Uncertainty in results could also be attributed to model assumptions, process descriptions, mechanisms, mathematical formulations and the numerical scheme. In nature, all processes operate simultaneously, while in models they do not; they follow an order of execution. If evaporation is calculated after infiltration, expect recharge/soil moisture to be different if the order of calculation was reversed. Linearity exists in model processes but not in nature where nothing is linear.

## 10 | ISSUE 7B: MISUNDERSTANDING THE TRUE MEANING OF UPSCALING AND CONFUSING UPSCALING WITH AGGREGATION

In some model applications, there is confusion about the use of the term ‘upscaling’ to describe a process that in reality it is not upscaling but rather an aggregation process. This misconception is mainly due to the misunderstanding of the difference between the two terms. For clarity, the terminology of scaling includes:

- *Scaling*. Refers to the use of information on one spatial or temporal scale to infer characteristics on another scale, for example, similitude and dimensional analysis approaches in fluid dynamics.
- *Upscaling*. Transferring information from a given scale to a larger scale or ‘bottom-up’ modelling, for example, from plot to river basin scale or leaf to canopy scale.
- *Downscaling*. Transferring information from a given scale to a smaller scale or ‘top-down’ modelling.
- *Aggregation*. Denotes that small-scale equations are applied at the small-scale level at which they were derived and that the outputs are aggregated to larger-scale units. This allows the smaller-scale parameters to be assigned directly from field data.

In the process of upscaling, process equations and associated parameters are modified or substituted when moving from the small scale to the larger scale. This process can be conducted in three ways:

1. The small-scale equations are assumed valid at larger scale without change. In this case the effective parameters are corresponding to the larger-scale computational unit and produce bulk behaviour of a heterogeneous medium. The estimation of parameter values in such case needs to be done by calibration of key parameters.
2. The small-scale equations are extended in a theoretical framework to account for spatial variability of small-scale parameter over a larger scale. This is often carried out in a stochastic framework. Here it is possible to assess the large-scale parameters directly from field data. However, effective parameters need to be assessed through calibration.
3. New equations are developed particularly for larger scale.

The issue of scaling represents not only a scientific challenge but also a practical problem in water resources



FIGURE 10 The upscaling issue in hydrology. Source: Adapted from Refsgaard and Butts (1999).

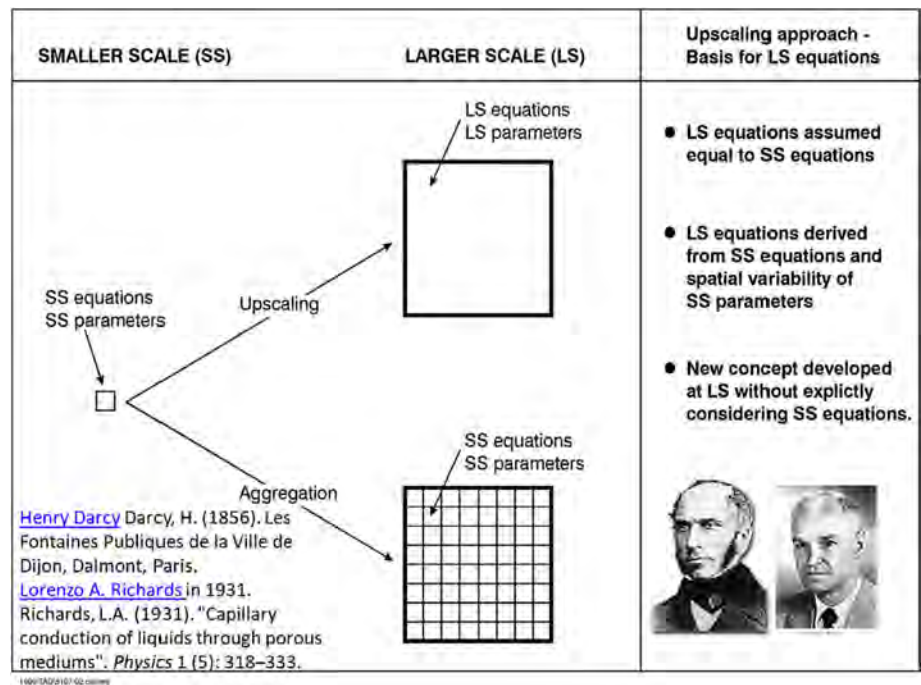


TABLE 1 Spatial scales in hydrology according to Refsgaard and Butts (1999).

Spatial scale	Length	Area
Point scale	<10 cm	
Field or hillslope	100 m	
River basin scale (catchment/watershed)	3–100 km	$10^{-10^4}$ km <sup>2</sup>
Regional scale	100–1000 km	$10^4$ – $10^6$ km <sup>2</sup>
Continental or global scale	>1000 km	> $10^6$ km <sup>2</sup>

management and hydrological modelling. Models are scale specific because different processes are important at different scales. Hydrological modelling is being carried out at spatial scales ranging from point scale to global scale (Table 1). The importance of scale effects has been recognized by hydrologists, water resources managers and other water practitioners. The unanswered questions are:

1. Do the mathematical descriptions often developed in laboratories or plot scale apply to river basin scale?
2. How can physical properties such as hydraulic conductivity, measured at isolated points, be used to accurately represent river basin scale water fluxes such as groundwater recharge or contaminant fluxes such as nitrate flows?
3. How can this spatial variability be incorporated in a model grid square and how is this affected by the size of the grid?

Some equations developed at point scale are being applied at larger scales. This assumes that the point scale equations are applicable at larger scale. Examples are the well-known equations of Darcy (1856) and Richards (1931) that are point scale equations applied at river basin scale. These small-scale equations with small-scale parameters were applied at each grid square of river basins, and the results were aggregated to the river basin level to obtain mean values (Figure 10).

Scientists tried to improve the results by applying the small-scale equations but using effective area-representative parameters of each grid square to account for the heterogeneity within the grid square and the river basin. Attempts were also made to derive large-scale equations mostly empirical for river basin scale such as the conceptual models of rainfall-runoff models; these models are site specific. Other hydrologists developed different water transport approaches and derived representative parameters accounting for the heterogeneity of soil and land covers within each grid square of the river basin (Ragab et al., 2010; Ragab & Bromley, 2010).

## 11 | ISSUE 8. MISCONCEPTION OF USING LONG-TERM AVERAGE FLOW IN DESIGNING DAMS AND RESERVOIRS

Dam and reservoir engineers believe that a long-term average flow is the most reliable element in designing the reservoir storage capacity. The longer the record, the most

reliable it is. This ignores the peak flows, extreme events, which are currently more frequent due to climate change. Some dams have recently overtopped and collapsed as the storage capacity did not account for possible extreme events, as they were based on long-term average flow.

Irrigation requires steady flow during the year to produce food. For that reason, dams are needed to regulate the flows. Commonly, dams are accompanied by reservoirs. Building dams and reservoirs is not only a civil engineering construction business, it also requires good knowledge about the hydrology, economy, environment and societies. Dams are constructed jointly with reservoirs as a twin project. In designing reservoirs, the constructors decide on the storage capacity, mostly by using a long-term average annual flow. They also build a spillway to release water should the reservoir receive above average runoff flow. However, in the recent years, due to climate change and extreme flood events, some dams have been destroyed due to dams' water overtopping and the inability of the spillway to release the excess water fast.

### 11.1 | The issue here is

Is the long-term average flow reliable for a dam's safety and to design reservoirs?

Although the long-term average flow is one of the useful indicators, it does mask the peak flows of above average and extreme events. The daily, monthly, seasonal and annual flow records look different with smoother curves for annual flow. When the temporal scale increases from daily to annual (Figure 11), the high and low flows are averaged. By averaging daily flows to obtain monthly flows, the peak flows disappear, and one gets a smoother flow curve. The same happens when averaging the monthly flows to obtain seasonal flows and averaging daily or monthly or seasonal flows to obtain annual flows; the peak flows turn into a smooth curve due to the averaging process.

In terms of hydrology, although long-term historical records of flows need to be considered, attention has also to be paid to the temporal variations, especially those associated with extreme events as they currently are more frequent than in the past due to climate change. Paying attention to the extreme events and peak flows are essential for the safety of dams and to prevent them from overtopping. For dams' safety one needs to

- estimate accurately the volume of the reservoir that has minimum risk and low probability of failure, conduct probability of failure test analysis (Ragab, Austin, & Moidinis, 2001a, 2001b; Ragab, Moidinis,

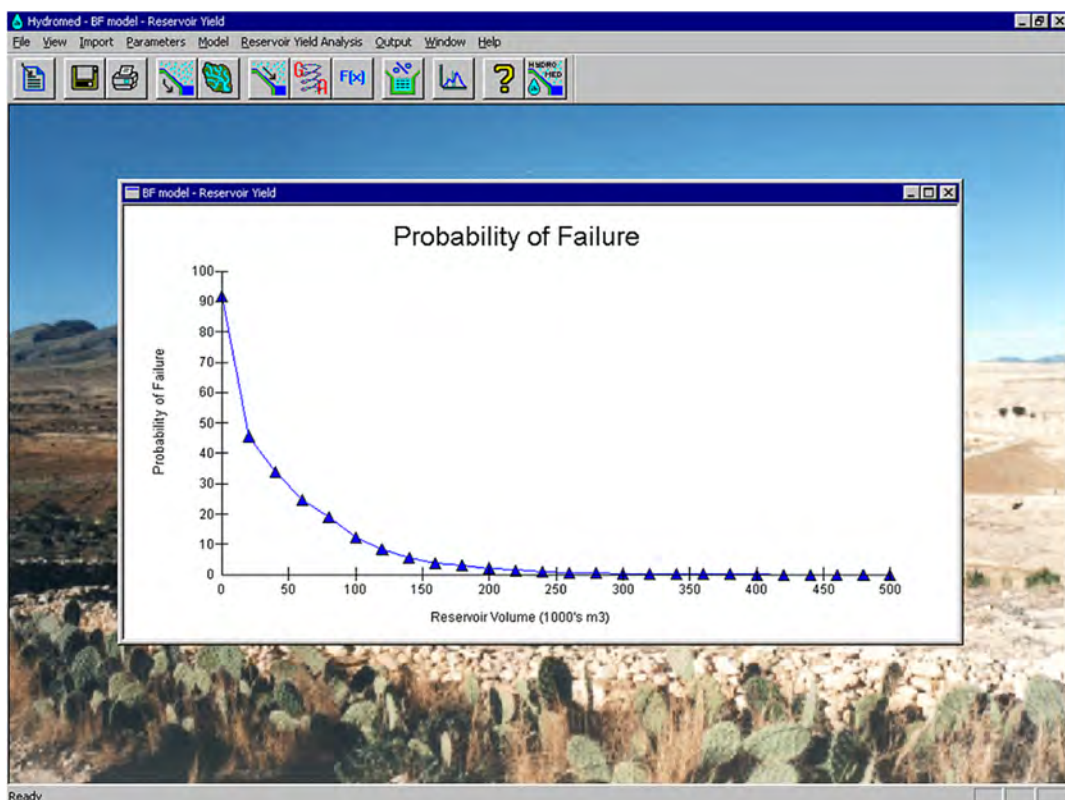


FIGURE 11 Probability of failure analysis for designing reservoirs. Source: Ragab, Moidinis, et al. (2001).

et al., 2001). The constructors try, of course, to minimize the cost of digging, but that comes with a risk, as shown in Figure 11;

- conduct an uncertainty analysis for river flow as the uncertainty level varies from daily to monthly to seasonal to annual (Ragab et al., 2020).

Figure 12 shows how the daily flow peaks disappeared by the averaging process and produced a less spiky smooth curve for annual flow. The results, details are given in Ragab et al. (2020), indicate that the uncertainty level in the results get better when moving from daily to monthly to seasonal to annual flow. The CR parameter shown in the figure represents the containment ratio, which is the percentage of observed river flows that are enveloped by the prediction bounds of 5% and 95% confidence levels (Q5%–Q95%) likelihood-weighted quantiles. CR is probably the most basic requirement for the prediction bounds. A high CR for the estimated prediction bounds is always the aim. The analysis of Don River flow (United Kingdom) showed that the CR value changed from daily (57%) to monthly (70%) to seasonal (76%) to annual (85%). Clearly, the uncertainty level decreases when flow is averaged over a longer period. This is the dilemma for dam and reservoir designers, who would consider the annual flow with less flow uncertainty rather than considering the daily or monthly flows with clear peak flows and clearly visible

extreme events with relatively more uncertainty. However, the safety of dams requires more attention to peak flows and extreme events. Ignoring this commonly results in disasters. A few examples of dam failure and collapse due to overtopping are (I) the Derna Dam in Libya that collapsed when it overtopped on the night of 10–11 September 2023 in the aftermath of Storm Daniel; (II) the overtopping of the dam immediately downstream of the Pau Branco landslide in Brazil on 8 January 2022; (III) ‘Dam I’ at an iron ore mine about 5 miles outside the city of Brumadinho, a municipality in the Brazilian state of Minas Gerais, in the country’s mineral-rich southwest, which collapsed due to static liquefaction in 2019; (IV) the overtopping and a landslide above the Vajont Dam in north Italy on 9 October 1963, which created a wave that destroyed several villages in the valley, killing about 2000 people; (V) the failure of the Edenville Dam, immediately upstream of the Sanford Dam, which caused a large inflow into Sanford Lake (Michigan, USA) and caused the Sanford Dam to collapse on 19 May 2020; (VI) and finally the Banqiao Dam in China, which collapsed in 1975, and an estimated 171,000 lives were lost, making it the worst dam failure in history.

The International Commission on Large Dams (ICOLD, 2023) produced the world register of dams and produced several bulletins on dam safety and failure with worldwide cases of failure. Several countries also developed dam registries and listed incidents of dam failure,

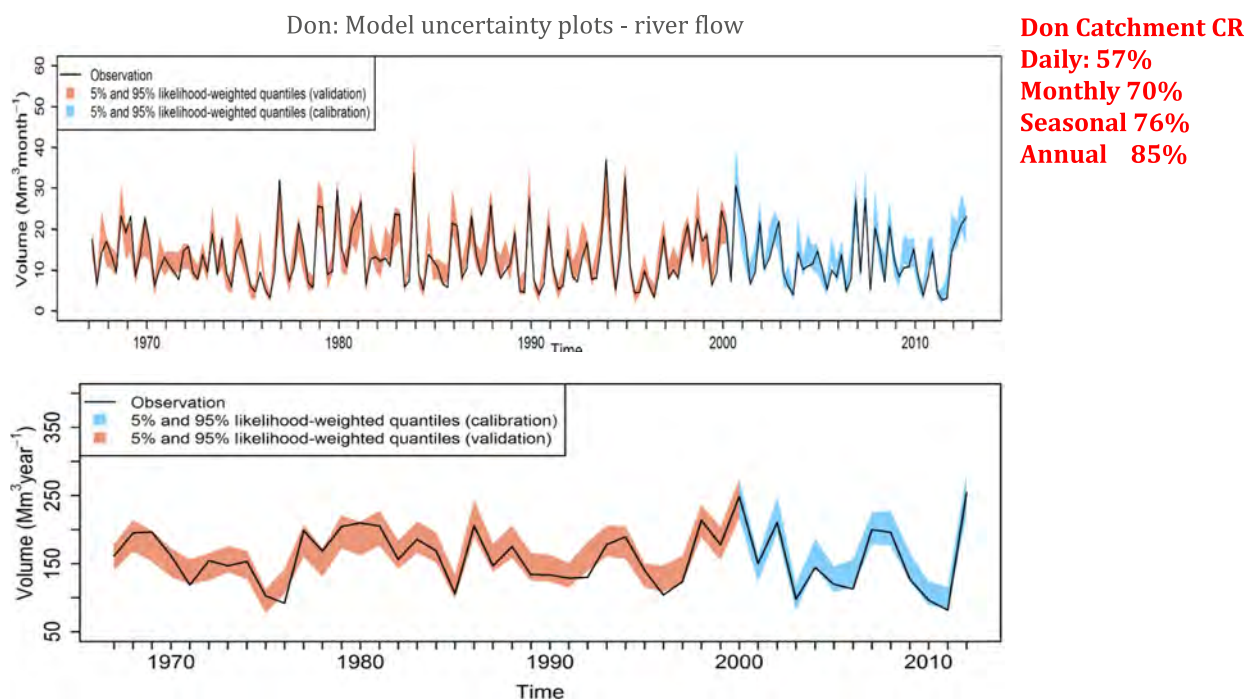



FIGURE 12 Uncertainty analysis of monthly and annual flow. Example of Don River, United Kingdom (Ragab et al., 2020). CR, containment ratio.

### Summary of 10 Rivers That Are Running Dry in 2023

Here's a recap of the rivers throughout the world running dry that we took a close look at:

Number	River	Location
1	The Colorado River	United States
2	The Rio Grande River	United States
3	The Indus River	Pakistan
4	The Teesta River	India, Bangladesh
5	The Arkansas River	United States
6	The Red River	United States
7	The Murray River	Australia
8	The Amu Darya River	Uzbekistan, Afghanistan, Turkmenistan, Tajikistan
9	The Yellow River	China
10	The Canadian River	United States

<https://a-z-animals.com/blog/10-rivers-that-are-running-dry/>




The iconic Colorado River is running at historically low levels.



A significant water source for the American Southwest and Mexico is the Rio Grande River.



The mighty Indus River is the longest river in Pakistan and one of the largest rivers in the world



Water flow in the Arkansas River is decreasing due to severe drought and overuse



Fed from the Ogallala Aquifer, the Canadian River is an important water source in the U.S.



The Murray River ran dry in 2006

Some 100,000 years ago, three large rivers snaked through what is today the bone-dry Sahara Desert



Tia Ghose. 2013. Buried Saharan Rivers May Have Led Humans Out of Africa. <https://www.livescience.com/39575-ancient-saharan-rivers-existed.html>

The Sahara was not a desert during the African humid period. Instead, most of northern Africa was covered by grass, trees, and lakes



[https://en.wikipedia.org/wiki/African\\_humid\\_period](https://en.wikipedia.org/wiki/African_humid_period)

FIGURE 13 Rivers at risk of running dry (top and middle) in the next decades and example of some rivers that disappeared in North Africa (bottom).

(e.g. US Association of State Dam Safety Officials [ASDSO, 2023]). These organizations and others reported that dam overtopping during extreme flood events is the most common cause of failure.

## 11.2 | In conclusion

Safe dam and reservoir design requires the consideration of the hydrological aspects, especially the peak flow and extreme events caused by climate change. In designing dams and reservoirs, it is recommended to conduct a probability of failure analysis and account for extreme events, not only the long-term average annual flows. Minimizing the cost of digging when creating a reservoir, should not come ahead of a dam's safety.

## 12 | ISSUE 9: THE MISBELIEF THAT SUSTAINABILITY IS SYNONYMOUS TO ETERNITY, THAT IS, NOT TIME LIMITED

Water resources management is always associated with the word 'sustainability'. Sustainability should be associated with management of water resources not the resource itself, as there are doubts about the existence of sustainable (eternal) water resources. History shows that a good number of rivers disappeared, and a number of rivers might disappear in the next decades (Figure 13).

In a report by Haase (2023) entitled *10 Rivers That Are Running Dry in 2023*, it is pointed out that those 10 rivers could be entirely out of water within the next few decades. Those rivers are the Colorado River, which is running dry at a rapid and unsustainable rate; the Rio Grande, which already temporarily ran out of water in the summer of 2022 for the first time in four decades; the Indus River, which has been experiencing below-average rainfall for the past few years and is the driest it has been in 60 years—the river's flow in Pakistan already decreased by more than 50%; the Teesta River, which is at risk as the rainfall in the area has decreased significantly in recent years leading to less water being available for the river; the Arkansas River, as the water flow in the river is decreasing due to severe drought and overuse; the Red River, which is running dry due to climate change and overuse of the river's water resources; the Murray River, which is at risk due to insufficient rainfall and ran low in 2006 due to a relentless drought—in 2007 the river had stopped flowing altogether, and in 2022, the Murray–Darling Basin itself was in grave danger of drying up for good; the Amu Darya River in Central Asia, whose flow decreased due to climate change and the

increased demand for irrigation; the Yellow River, also in Central Asia, which has been running dry in recent years due climate change and overuse of the river's resources; and the Canadian River, which is running dry due to several years of drought, which is still ongoing, water depletion from the Ogallala Aquifer and climate change. Climate change, overall, is causing more evaporation and less precipitation, leading to reduced flows in the rivers.

There was a time when rivers reaching the sea was taken for granted, but now this is no longer guaranteed, and even the greatest of the world's rivers can no longer be assured of reaching the sea. The Rio Grande/Rio Bravo River often fails to reach the Gulf of Mexico, its strength is weakened by dams and irrigation works diverting water to farmers' fields and city water supplies. The Indus, the Nile, the Murray–Darling and the Colorado—these are but a few of the once mighty rivers that now struggle to touch the ocean (Wong et al., 2007). The authors also reported that the world's top 10 rivers at risk and most endangered are the Salween, La Plata, Danube, Rio Grande, Ganges, Murray–Darling, Indus, Nile, Yangtze and Mekong.

The above information indicates that it is difficult to identify an infinite sustainable water resource. The history tells us that some 100,000 years ago, there were three large rivers that snaked through what is today the bone-dry Sahara Desert. They were comparable to the Missouri, the Rhine or even the Nile (Ghose, 2013).

A recent study found that between 51% and 60% of the 64 million km of rivers and streams on Earth stop flowing periodically or run dry for part of the year. This indicates that most rivers run dry now and then (Messenger et al., 2021).

The above information clearly shows that sustainability is a difficult term to apply, especially to surface and groundwater resources, as surface runoff and groundwater recharge are difficult to forecast over a long period of time as both depend on the rainfall. Rainfall can usually be forecasted with reasonable accuracy for a short period of time; however, it is not feasible for a long period of time to know with a reasonable level of accuracy or certainty the rainfall quantity, intensity or frequency. For that reason, sustainability should not be considered a synonymous to eternity; it should be associated with a time span. Most of the hydrologists like the time span to be rather short as a longer period carries with it more uncertainty.

## 12.1 | In conclusion

Sustainability in water management should be associated with a time span indicating how far ahead one can look:

5, 10, 50 years? As water resources are associated with rainfall forecast, the shorter the time span, the less uncertainty in quantifying, planning and managing water resources.

### 13 | GENERAL CONCLUSION

Over the years, several concepts for agricultural water management have been suggested. However, some practitioners either misunderstood them or wrongly applied them. The most widely misunderstood concepts include deficit irrigation, WP versus WUE, water accounting, sustainability, leaching for salinity control, upscaling versus aggregation, the temporal nature of river flows and using long-term average flow for designing dams and reservoirs. This paper highlighted these conceptions, their misuse and misunderstanding, and explained the true meaning and application of each. The paper did not only explain why these concepts were misunderstood but suggested approaches to improve the understanding and how one can accurately apply them.

### DATA AVAILABILITY STATEMENT

No data was used.

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