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WHAT IS THE REAL POTENTIAL FOR IRRIGATION WATER SAVINGS AT THE PLOT LEVEL RESULTING FROM MODERNIZATION OF IRRIGATION SYSTEMS?

WITTLING Claire¹, MOLLE Bruno² and CHEVIRON Bruno³

ABSTRACT

As water scarcity intensifies in most countries due to climate change, water savings are of increasing concern and European water-resource policy targets sustainable water management and water savings. For this purpose, farmers' investments in efficient irrigation equipment are supported by the European Agricultural Fund for Rural Development (EAFRD), provided the new irrigation installation can potentially allow water savings of 5 to 25%, without having a negative impact on crop yield. However, no methodology was available so far for the expected *ex ante* quantification of these water savings.

The aims of this study were (1) to gather data of water savings achieved through irrigation system modernization (i.e. change of irrigation system or adoption of irrigation scheduling tools) and to analyze how they are influenced by soil and climate context; (2) to develop a simple tool for the *ex-ante* assessment of potential water savings, those deemed achievable by changing the irrigation system or adopting scheduling tools (3) to use the Optirrig crop and irrigation model on two case studies to quantify irrigation water losses and irrigation efficiency at the plot level.

For this purpose, we compiled available studies conducted over the past 30 years on the French metropolitan territory dealing with documented water savings realized by switching from an irrigation system (hose reel machine, lateral move, center pivot or solid set system) to a more efficient one (center pivot, surface drip, subsurface drip or microsprinkler) or by using soil hydric status probes (tensiometric or capacitive) for irrigation scheduling. Nearly 100 records were collected from experimental field trials representative of a wide range of pedo-climatic conditions and crops (field crops, vegetables, fruits on perennial crops). Each record represents the water consumption of two different irrigation systems or two scheduling systems (without soil probe vs with soil probe) at plot scale and is used to assess the obtained water saving.

Results show that (1) the achieved irrigation water savings (when changing irrigation system or adopting soil probes for irrigation scheduling) are highly variable, ranging from 0% to more than 70% and thus are not generalizable; (2) water savings obtained from localized systems significantly decrease when the hydric deficit of the cropping season increases and when soil water holding capacity is high; (3) those obtained from irrigation scheduling using soil probes do not seem to be influenced by the hydric deficit, soil water holding capacity or soil probe type; (4) a referential of potentially achievable water savings through the change of irrigation equipment and/or irrigation management could be established; (5) the use of Optirrig model allowed quantifying water savings originating from the reduction of technical losses (linked with the type of system) and tactical losses (linked with irrigation management and scheduling).

Keywords: Irrigation water efficiency, drip, subsurface drip, microsprinkler, scheduling,

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1. Introduction

In the context of global and climate changes, every region of the world has to face increasing food demand, declining water availability and competing water uses. Agriculture is responsible for approximately 70% of total freshwater withdrawal in the world (FAO, 2015). In the European Union, water abstraction rate for agriculture (mostly for irrigation) is estimated at 24% (European Environment Agency, 2009), but is highly variable among countries: 73% for Portugal, 61% for Spain and 12% for France (Gleick, 2014). To promote sustainable water management and water savings, the European water-resource policy supports investments in efficient irrigation equipment via the European Agricultural Fund for Rural Development (EAFRD), provided that the equipment is assessed *ex ante* as offering potential water savings above a given threshold (European Union (2013), Article 46, point 4).

Yet definitions of irrigation efficiency and water savings have been varying among users, scales and over the course of time (Seckler et al, 2003; Jensen, 2007). For example, the historical approach defined the “classical irrigation efficiency” that focuses on the ratio of water beneficially used by the crop (evapotranspiration) to the water delivered, or the ratio of yield to water delivered. In this case, water leaving the plot is considered as a loss (Hsiao et al, 2007). Later on, the “neoclassical” approach took into account the part of delivered water potentially available for downstream reutilization and water resource management at the basin scale (Richter et al, 2017). The coexistence of multiple definitions and calculations of irrigation efficiency is the subject of many debates (Perry, 2007; Lankford, 2012; Van Halsema and Vincent, 2012), mainly because of the wide range of hydrological scales considered, the different actors and the diversity of water concerns. This led Lankford et al (2020) to propose the irrigation efficiency matrix that is a conceptual framework that situates ten discursive dimensions of irrigation efficiency (science, practice and policy) across five spatial scales (sub-field, field, tertiary/secondary/main canal systems, basin/catchment, national/international/supranational). Actions and outcomes in lower scales create impacts in upper scales and vice versa. The ten dimensions illustrate different viewpoints and influences on irrigation efficiency.

The present study is located at the interface of scale 2 (field) and dimensions E (science approaches) and especially F (views on irrigation losses, wastes and savings) of the matrix. Therefore, it is near to the classical approach of irrigation efficiency, used at the agricultural plot scale. Within this framework, improving irrigation efficiency is achieved through the reduction of irrigation water losses, thus through water savings. Irrigation water losses at the plot scale include direct evaporation and wind drift during sprinkler irrigation, interception and storage by the crop canopy, run-off and drainage related to excessive or non-uniform application, soil evaporation, weed transpiration, and residual soil water after harvest (for a comprehensive review, see Hsiao et al, 2007). Commonly admitted averaged values of efficiency at plot scale over a cropping season taking into account direct evaporation, drift, canopy interception, run-off and drainage losses (but not soil evaporation, weed transpiration, and residual soil water) are: 65% (55–75%) for hose reel machines, 75% (60–85%) for solid sets, 80% (75–90%) for traditional center pivots, 85% (70–95%) for microsprinklers and surface drip systems, and 90% (75–95%) for subsurface drip systems (Howell, 2003).

Several literature reviews have demonstrated that water savings in the field could be realized through modernization of irrigation infrastructures and methods, i.e. the adoption of water-efficient technologies, with some of the savings being released as environmental flows (Chai et al, 2014; Richter et al, 2017; Koech and Langat, 2018; Fishman et al, 2023). These technologies can concern application devices and/or scheduling tools including monitoring systems (soil-, weather- or plant-based sensors) combined, or not, with model predictive control (Bwambale et al, 2022). Although it is recognized that improvement of irrigation technology and management is likely to generate water savings, in practice, little is known about the extent of water savings that can be really expected at plot scale. The aims of this study were (1) to gather data of water savings achieved through irrigation systems modernization (i.e. change of irrigation system or adoption of irrigation scheduling tools) and to analyze how they are influenced by soil and climate context; (2) to develop a simple tool for the *ex-ante* assessment of potential water savings, those deemed achievable by changing the irrigation system or adopting scheduling tools (3) to use the Optirrig crop and irrigation model on two case studies to quantify irrigation water losses and irrigation efficiency at the plot level.

2. Materials and methods

2.1. Observing achieved water savings

Data were collected from experimental field trials conducted on the French metropolitan territory (Figure 1) in the past 30 years, representative of a wide range of pedo-climatic conditions and crops (field crops, vegetables, fruits on perennial crops). Only data describing water savings achieved without significant yield loss were selected: a yield reduction of up to 15% was tolerated. The entire database is accessible in the article of Serra-Wittling et al (2019).

Soil and climatic conditions for each experimental trial were described by soil water holding capacity (WHC expressed in mm) and hydric deficit of the cropping season calculated as:

$$HD = ETo / P$$

where HD (unitless) is the hydric deficit, ETo (mm) is the cumulated potential evapotranspiration and P (mm) the cumulated precipitation during the cropping season. HD values above 1 represent situations characterized by effective hydric deficit for crops, and thus requiring irrigation. HD values equal or below 1 would generally not require irrigation and were therefore not considered in this study. As HD is linked with precipitation, it was not computed for trials on vegetables under plastic tunnels.

Water savings at the plot scale over the cropping season were assessed by comparing the water consumption of two different irrigation systems (Syst1 vs Syst2) or two scheduling systems (without soil probe vs with soil probe), always within the same context (same year, same soil, same crop). Syst1 is the most water-consuming system and includes reel machine with spray gun (SG), lateral move or center pivot (CP) and solid set (SS). Syst2 is the least consuming system comprising center pivot (CP) or localized systems such as surface drip (SD), subsurface drip (SSD) and microsprinkler (MS). Scheduling without soil probes is based on either traditional farmer practices, weekly irrigation recommendation bulletins, or maximal evapotranspiration evaluations; scheduling with soil probes consists in employing tensiometric or capacitive probes to adjust the irrigation dose to soil hydric status. Water savings achieved between both systems were evaluated as:

$$WS-IS = [(Irr1 - Irr2) / Irr1] \times 100$$

$$WS-SP = [(IrrNoSP - IrrSP) / IrrNoSP] \times 100$$

where WS-IS (in %) is the water saving obtained when comparing Syst1 and Syst2, Irr1 (mm) and Irr2 (mm) are the total amounts of irrigation water applied during the cropping season with Syst1 and Syst2 respectively, WS-SP (in %) is the water saving obtained when comparing two scheduling systems, IrrNoSP (mm) and IrrSP (mm) are the total amounts of irrigation water applied with the scheduling system using no probe and using soil probes respectively.

Statistical analysis with analysis of variance (ANOVA) followed by Fisher's Least Significant Difference (LSD) test was performed using XLStat Software (Addinsoft, 2017).

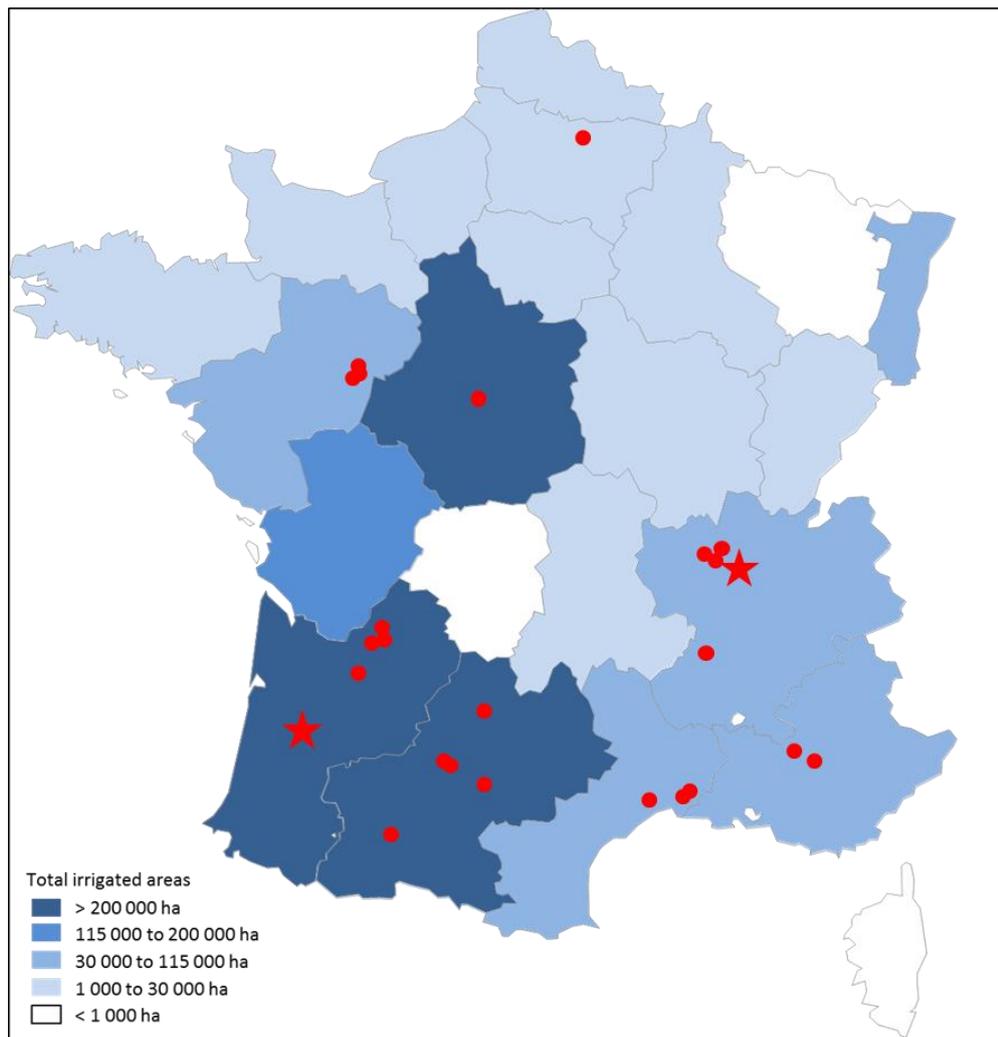


Figure 1. Irrigated areas in France (2010) and location of the 25 experimental sites where data were collected. The stars indicates the two sites whose data were processed with Optirrig model to assess irrigation efficiency.

2.2. Assessing potentially achievable water savings

Water saving by changing irrigation system or adopting irrigation scheduling tools

To establish a frame of reference for potentially achievable savings when an irrigator switches from one irrigation system to another, or adopts scheduling tools, we based on the references of water savings actually achieved (WS-IS and WS-SP), collected as described above, and made some adaptations. As these data were observed under experimental conditions, values were systematically lessened by 10% to be more representative of real on-farm conditions. Extreme and outlier data representing excessively high observed savings were removed.

Compiled data of achieved water saving in a given crop-soil-climate condition are within a range of values, between a minimum and a maximum observed from different trials. We kept the same presentation in intervals for achievable water savings values, just rounding them to the nearest 0 or 5.

Particular case of water saving by changing irrigation system

In the case of water savings achievable with a new irrigation system, in order to give a generic water saving value for an average climatic year, neither very dry nor very rainy, only the value of an average year for a given experimental trial (or the average of average years) was kept. When no average year value was available, the average value between dry and wet years was used. To assess the water savings that could be achieved when an equipment is renewed identically, for example an old hose reel

replaced by a new one, we used references of previous studies which quantify the decline of equipment performance as a function of ageing and maintenance (Molle, 1998; Molle et al, 2009): 10% when renewing a hose reel or solid set system, due to the absence of leaks in the new equipment; 15 to 20% when renewing a localized irrigation system (micro-jet or drip), because of the suppression of leaks or clogging of old drippers or micro-sprinklers; 5% when changing the nozzles of a center pivot or moving lateral. In a few rare cases where no reference from experimental trial could be collected, e.g. water saving achieved between SD and SSD, data from expert opinions were used.

In windy regions, drift losses due to wind on a spray gun can occasionally reach 20%, with an average of about 10% (Granier et al, 2003). If we consider a cropping season with 10 irrigation events including 5 windy days with 10% drift, losses represent 5% over the season. Thus, in very windy areas, the switch from hose reel to localized irrigation makes it possible to avoid drift losses. Therefore, water savings potentially achievable by changing a hose reel or a solid set with a localized system are to be increased by 5% in windy regions. This correction does not concern pivots, as they generally operate at low pressure and produce large-diameter drops that are not very sensitive to wind.

2.3. Modelling irrigation efficiency

Study sites

Data collected on two case studies were extracted from the database described above (two red stars on Figure 1). On each experimental site, trials were conducted on corn and two irrigation systems (SG or CP vs SSD) were compared. Characteristics on both sites and their irrigation systems are presented in table 1.

Table 1. Characteristics of experimental sites where data of WS-IS were collected for modelling

	Site 1	Site 2
Locality	Saint-Maurice-de-Gourdans	Villeneuve-de-Marsan
Department (Number)	Ain (01)	Landes (40)
Trial years	2007, 2009	2013, 2014, 2015
Soil type	Alluvial	Sandy
Soil water holding capacity (WHC)	70 mm	50 mm
Crop	Corn	Corn
Scheduling type	Tensiometric probes	Hydric balance and tensiometric probes
Irrigation Syst1	Hose reel with spray gun (SG) Hose length 400 m Hose diameter 100 mm Principal nozzle diameter 24 mm	Center pivot (CP), 3 spans Total length 211 m Pipe diameter 216 mm Sprinklers: Rotator R3000 Pressure 4,5 bars
Number of irrigation events in the cropping season with Syst1	3 – 7	13 – 14
Water dose applied at each irrigation event with Syst1	30 – 45 mm	16 – 18 mm
Irrigation Syst2	Subsurface drip (SSD) Depth 50 cm Dripper flow rate 1,14 L.h ⁻¹ Space between drippers 30 cm	Subsurface drip (SSD) Depth 33 cm Dripper flow rate 0,6 L.h ⁻¹ Space between drippers 50 cm Space between drip lines 1,0 m

	Space between drip lines 1,0 m	
Number of irrigation events in the cropping season with Syst2	14 – 55	35 – 56
Water dose applied at each irrigation event with Syst2	3,1 – 4,6 mm	1,5 – 5,5 mm

Simulation with Optirrig model

The “Efficiency” module of Optirrig crop model allows evaluating the global irrigation efficiency (ratio of transpired irrigation water to irrigation water entering the plot) by simulating the successive volumes of irrigation water lost at each step of irrigation water course from the plot entry to the roots (Cheviron et al, 2020). For each experimental trial on both sites, corn yield was simulated, as well as the amount of irrigation water actually transpired by the crop and the lost water amounts (direct evaporation and wind drift during sprinkler irrigation, drainage, soil evaporation and residual soil water after harvest). It was hypothesized that no irrigation water loss due to leaks occurred in the plot, so that all water entering the plot flow out from nozzle or dripper. Irrigation water lost by direct evaporation in the air and wind drift was arbitrarily fixed at 5% of the total amount of water entering the plot for SG (Molle et al, 2012). It was assumed to be 0% for CP as the large droplets produced by CP are less sensitive to evaporation and drift. Soil evaporation of irrigation water does not occur with SSD as irrigation water applied at more than 30 cm depth cannot evaporate from soil.

3. Results and discussion

3.1. Observing achieved water savings

Magnitude of achieved water savings

Achieved water saving between two irrigation systems (WS-IS) ranges from 0% to 77%, evidencing high variability (Figure 2). It is therefore necessary to avoid generalizing water saving values when switching from one irrigation system to another, as they depend on several factors including the type of system itself, but also the climatic conditions, scheduling mode and crop type (Serra-Wittling and al, 2019).

Largest WS-IS are observed with Syst1 as SS, SG and CP (means of 38%, 21% and 18% respectively), whereas smallest WS-IS occur with MS as Syst1 (mean of 6%). This is in accordance with the lower application efficiency (ratio of the water volume reaching the soil to the outgoing volume of the equipment) of sprinkler systems (SS, SG and CP) which allow a greater water saving margin compared to localized systems such as MS that are already efficient. Bryla et al (2005) report water savings between MS and SSD from 13% to 18% for peaches. They attribute the lower irrigation requirements of SSD to the additional water needed by MS to compensate for soil evaporation in early spring prior full canopy development.

Regarding Syst2, greatest WS-IS are achieved with MS, SD and SSD (means of 45%, 31% and 21% respectively). Lowest WS-IS are realized with CP (8%), which is admittedly the most efficient sprinkler system, but still less efficient than localized systems (MS, SD and SSD).

WS-IS obtained with SSD are sometimes higher, but not significantly, than those obtained with SD (in the case of Syst1 being SG or MS), and sometimes significantly lower (- 31 points, with Syst1 as SS). This is quite surprising as SSD reduces water losses by evaporation from the soil, thus is expected to increase water savings. Han et al (2018) reported WS-IS of 27% to 52% between SSD and SD, with no significant difference on apple trees ‘development in Korea. Likewise, Robles et al (2016) observed WS-IS of 15% and 24% in two different years with SSD compared with SD for lemon trees in Spain.

The significantly highest WS-IS are observed when changing from SS to MS and SD (means of 45% and 43% respectively) as these combinations offer the highest water saving potential. From an experimental trial on winter wheat in North China Plain, Jha et al (2019) present WS-IS between SS and SD ranging from 14% to 25%, that are values in the lower range of those observed in our study.

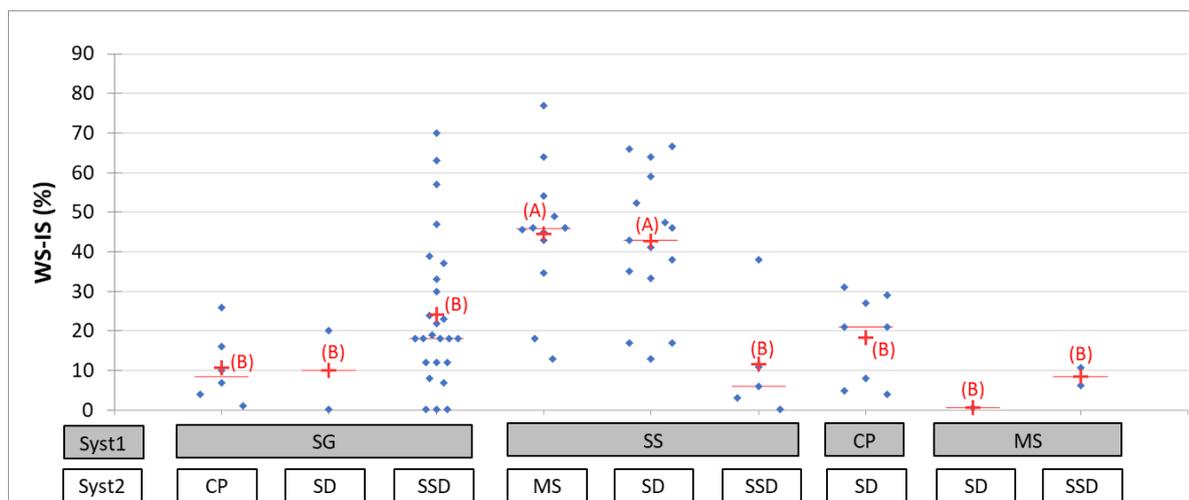


Figure 2. Water saving achieved between two irrigation systems (WS-IS). Syst1: most water consuming system; SG: spray gun; SS: solid set; CP: center pivot; MS: microsprinkler. Syst2: least water consuming system; CP: center pivot; SD: surface drip; SSD: subsurface drip; MS: microsprinkler. Red crosses denote mean values; those with the same red capital letter (between parentheses) are not significantly different (LSD test at 5% level). Red horizontal lines indicate median values.

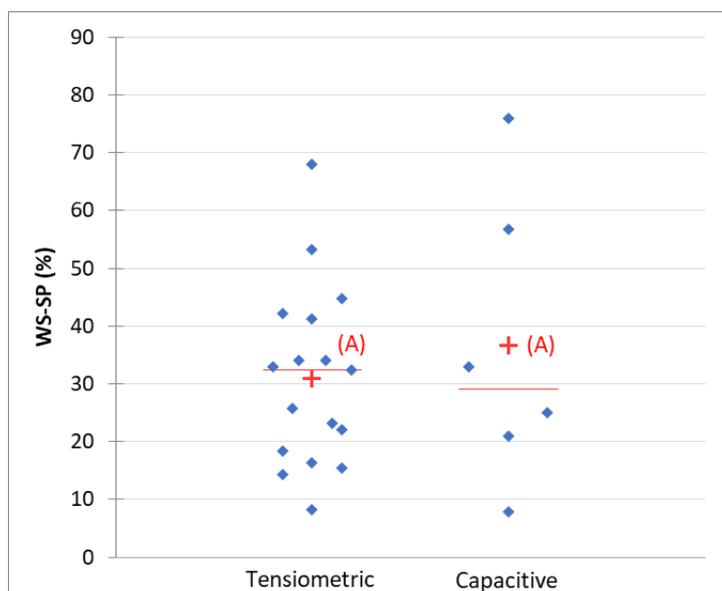


Figure 3. Water saving achieved when using tensiometric or capacitive soil probes (WS-SP) for irrigation scheduling in comparison with scheduling without probes. Red crosses denote mean values; those with the same red capital letter (between parentheses) are not significantly different (LSD test at 5% level). Red horizontal lines indicate median values.

Water savings achieved when irrigation is managed using soil probes compared with no probe (WS-SP) vary between 8% and 76% (fig). As well as WS-IS, WS-SP exhibit a high variability and may depend on various factors (especially irrigation system and crop type) as authors have shown in a previous study (Serra-Wittling et al, 2019). Yadav et al, (2020), by using capacitive probes for lettuce irrigation in comparison with scheduling based on crop evapotranspiration assessment, observed WS-SP of 45%,

which is close to the mean value of our observations. In Greece, irrigation amounts could be reduced by 12.5% on sorghum when scheduling with capacitive probes (Papanikolaou and Sakellariou-Makrantonaki, 2013). On corn irrigated with SD in Italy, Ghinassi et al (2003) show that scheduling with tensiometers resulted in water saving of 30% compared to scheduling based on advisory services. Numerous studies report that combining capacitive probes with automated irrigation can also lead to WS-SP, as shown by Wheelers et al (2020) in a commercial nursery (WS-SP of 50%) and Guéry et al (2018) on strawberry under plastic tunnels (WS-SP of 59%).

Probe type (tensiometric or capacitive) has no significant effect on WS-SP (Figure 3), as shown also by Muñoz-Carpena et al (2008), who realized, in a field test on tomato, WS-SP from 72 to 79% and from 64 to 74% with tensiometers and capacitance probes respectively, with respect to the typical grower scheduling method. This highlight that the key factor to save water is to schedule irrigation with in-situ measurement, regardless of the type of probe.

Impact of hydic deficit on achieved water savings

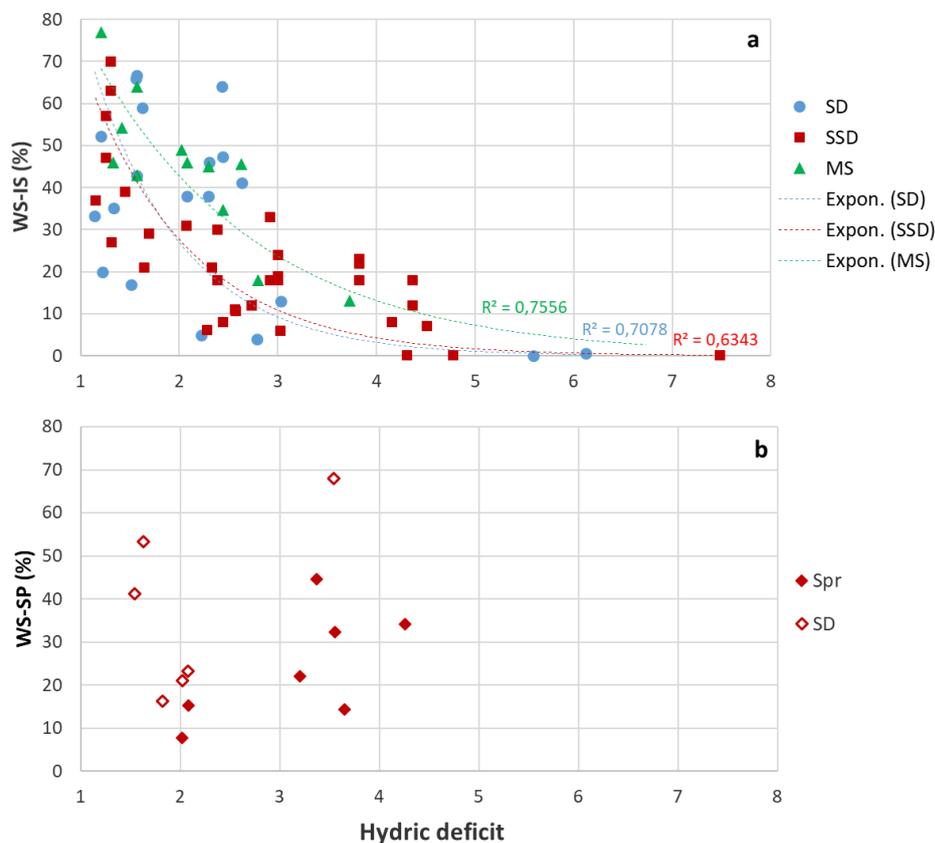


Figure 4. Water saving observed according to the hydric deficit (ETo/P) of the cropping season. (a) WS-IS: water saving between a sprinkler system and a localized irrigation system (SD: surface drip, SSD: subsurface drip, MS: microsprinkler), exponential curves for each type of localized system. (b) WS-SP: water saving realized by using soil probes to schedule irrigation in open field conditions (data from experiments under plastic tunnels were excluded), Spr: Sprinkler irrigation, SD: surface drip.

The effect of hydric deficit (HD) on WS-IS is shown on Figure 4a for a sprinkler system as Syst1 and a localized system as Syst2. WS-IS tends to decrease when hydric deficit increases. It appears that, for hydric deficits greater than 4.5, WS-IS always approaches 0%, regardless of the localized irrigation

system used. This can be explained by the reduction in drainage losses occurring during sprinkler irrigation in dry years. In wet years, rainwater can partly fill the soil water reserve, so that a portion of the irrigation amounts applied with sprinkler systems (large doses) can be lost through deep percolation or by storage in the profile at the end of the growing season, unlike with automated localized systems where small doses of water are applied daily. In dry years, all the irrigation water contributes to the soil reserve replenishment so that no loss occurs and global irrigation efficiency (ratio of transpired irrigation water to irrigation water entering the plot) of the sprinkler systems increases and draws near to that of localized systems, thus reducing the water savings observed between both systems. Lamm (2005) also reported that water savings made for a corn crop during a seven-year field experiment were dependent on weather conditions. SSD allowed a 4% water saving compared to LEPA (Low Energy Precision Application) sprinkler irrigation in normal years, but this water saving was not observed in extreme dry years.

Contrary to WS-IS, water savings obtained from irrigation scheduling using soil probes (WS-SP) do not seem to be influenced by hydric deficit (Figure 4b). Water savings higher than 30% are even observed for hydric deficit between 3 and 4.5. As scheduling with soil probes is based not on the total precipitation amounts since the beginning of the cropping season, but on their real effect on soil water status (water tension or moisture content), it is understandable that WS-SP do not depend on the hydric deficit of the year. However, more data would be necessary to confirm this trend and further experiments are needed to check if soil probes are likely to allow WS in extreme dry years ($HD > 4.5$).

Impact of soil water holding capacity on achieved water savings

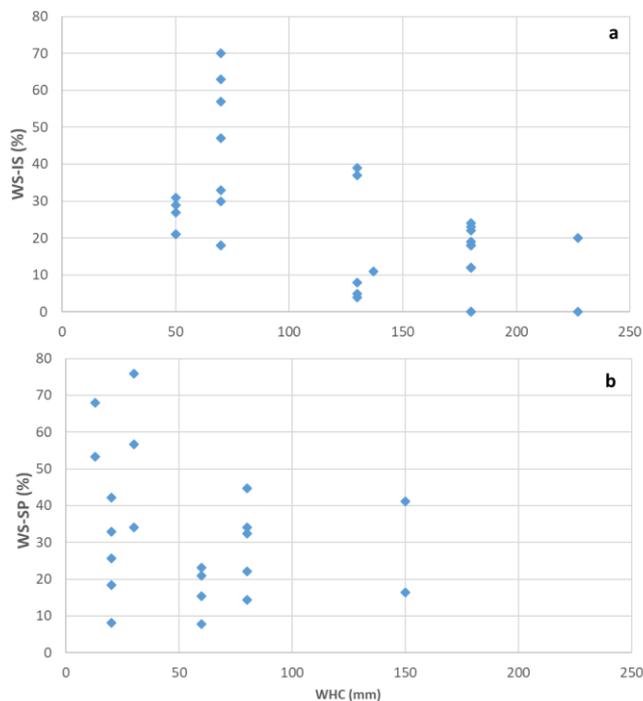


Figure 5. Water saving according to the water holding capacity (WHC) of the soil. (a) WS-IS in corn crops realized between sprinkler and drip systems (SD or SSD). (b) WS-SP between scheduling without probes and with soil probes (tensiometric or capacitive).

Figure 5a shows the influence of WHC on WS-IS in the particular case of corn, because this crop presents the highest soil WHC variability among the collected data (50–225 mm). WS-IS realized between a sprinkler system (SG, SS or CP) and a localized system (SD or SSD) markedly decrease when soil WHC increases. Highest WS-IS (25–70%) are observed in soils with low WHC (less than 75 mm). On the contrary, WS-SP do not clearly seem to be influenced by WHC (Figure 5b). The analysis

of variance presented by Serra-Wittling et al (2019) confirms that the effect of WHC is significant on WS-IS, but not on WS-SP. Indeed, the higher the WHC, the higher the volume of irrigation water is stored in the soil, and the less the volume of irrigation water is lost by drainage. Thus, soils with low WHC irrigated with sprinkler systems applying large water amounts have the greatest potential for water saving (WS-IS) when switching to localized systems applying lower doses. By contrast, WHC has basically no influence on the information provided by soil probes used for irrigation scheduling. Therefore, WS-SP does not depend on WHC. From on-farm studies, Ayars et al (2015) mention that the extent of water savings is field specific and depends, among others, on soil water holding capacity.

3.2. Assessing potentially achievable water savings

A referential of achievable water savings between two irrigation systems could be established (Table 2). Values on the diagonal relate to the renewal of a system to the identical, i.e. the change of an old one with a new one. For more specific or complex situations, instructions for use are the following:

- Temporal or spatial succession of crops. If crops differ from one year to the next (e.g. field crops following vegetables for a spray gun), or if the same system is used concurrently for different crops (e.g. field crops and vegetables under different sectors of a center pivot), then consider the most water consuming crop (highest annual required volume per hectare).
- Two systems simultaneously used on the same plot (e.g. center pivot and surface drip to cover the plot corners), then consider the most consuming equipment.
- Two systems successively used on the same plot (e.g. hose reel to favour seed emergence after sowing then subsurface drip), then consider the system used the longest over the cropping season.
- Complementary device to save water (e.g. jet-breaking systems or adjustable angles on a spray gun), then consider supplemental saving of 5 to 10%.

Likewise, a referential of potentially attainable water savings by using soil probes for irrigation scheduling has been set up (Table 3).

Both referentials can be useful as guidelines to assess ex ante the water savings to be potentially expected when shifting from an existing irrigation system to another one for a given crop, or when adopting soil probes for irrigation scheduling. They may also help public authorities to assess potential reduction of water withdrawal for irrigation at the regional or basin scale. Moreover, they may provide information to funding institutions and regulatory bodies, like the European Union through the European Agricultural Fund for Rural Development (EAFRD), to direct subsidies towards the most relevant equipment in terms of water saving potential

Table 2. Potential water savings achievable by changing irrigation system (changing from system 1 to system 2). Values on the diagonal relate to the renewal of a system to the identical (from an old one to a new one).

FIELD CROPS

Water saving (%) ➔	System 2				
	Spray gun	Solid set	Low pressure center pivot or lateral move	Surface drip	Subsurface drip
System 1					
Spray gun	10	10	5 - 20*	10 - 20*	15 - 35*
Solid set	--	10	5 - 20*	15 - 25*	20 - 25*
Low pressure center pivot or lateral move	--	--	5 - 10	5 - 15	10 - 25
Surface drip	--	--	--	10 - 20	15 - 20

Subsurface drip	--	--	--	--	10 - 20
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PERENNIAL CROPS

Water saving (%) ↔	System 2				
System 1	Sprinkler overhead irrigation	Sprinkler for irrigation under foliage	Microsprinkler for irrigation under foliage	Surface drip	Subsurface drip
Sprinkler overhead irrigation	10	10	15 - 30*	20 - 35*	25 - 35*
Microsprinkler for irrigation under foliage	--	--	10 - 20	15 - 25	15 - 30
Surface drip	--	--	--	10 - 20	5 - 15
Subsurface drip	--	--	--	--	10 - 20

VEGETABLES

Water saving (%) ↔	System 2		
System 1	Solid set	Microsprinkler	Surface drip
Solid set	10	5 - 10*	5 - 15*
Microsprinkler	--	10 - 20	10 - 30
Surface drip	--	--	10 - 20

* Increase upper and lower limits of the interval by 5% in windy areas.

Table 3. Potential water savings achievable by using soil probes for irrigation scheduling for different crop types.

Water saving (%)	Tensiometric or capacitive probes
FIELD CROPS	15 - 40
PERENNIAL CROPS	10 - 20
VEGETABLES	15 - 40

3.3. Modelling irrigation efficiency in corn crops

Observed and simulated yields

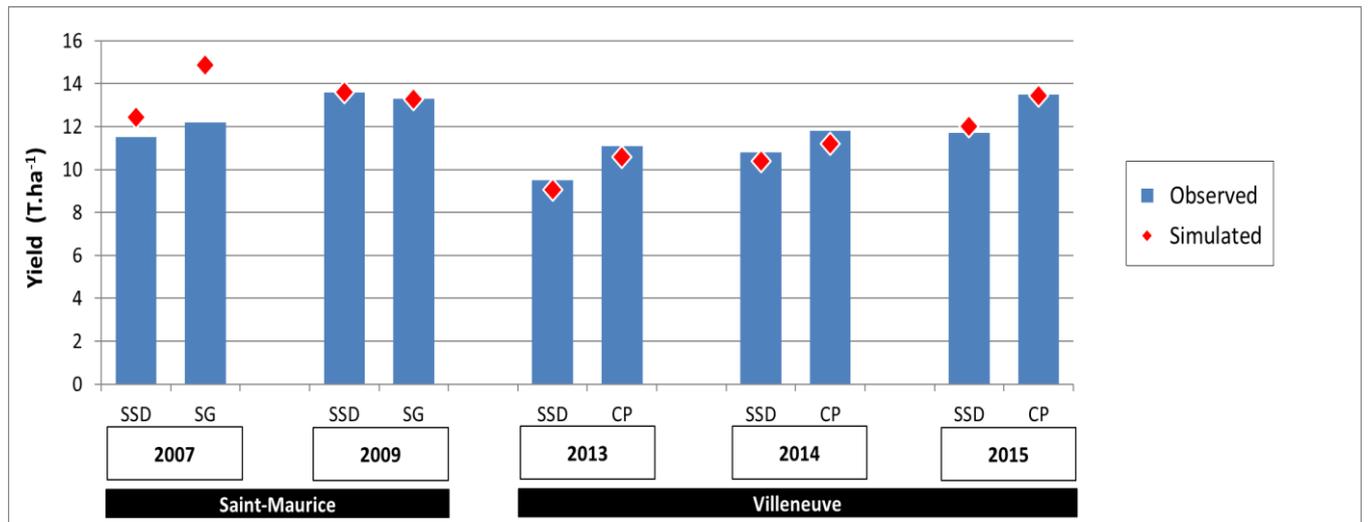


Figure 6. Dry yield observed and simulated with Optirrig model for corn irrigated with different systems at Saint-Maurice-de-Gourdans and Villeneuve-de-Marsan. SG: spray gun; CP: center pivot; SSD: subsurface drip.

At Saint-Maurice, yields with SG irrigation ranged between 12.2 and 13.3 T.ha⁻¹ and with SSD between 11.5 and 13.5 T.ha⁻¹. At Villeneuve, observed yields with CP varied between 11.1 and 13.5 T.ha⁻¹, and with SSD between 9.5 and 11.7 T.ha⁻¹. Simulated yields are very close to the observed yields (Figure 6), except for St-Maurice in 2007 where yield is over estimated by the model for SG irrigation. This confirms that Optirrig can be used for the estimation of water volumes and their distribution.

Observed water savings

Just looking at the total irrigation amounts on Figure 7, it can be noticed that total water supply over the cropping season is systematically reduced in SSD compared to sprinkler irrigation (CP or SG) for all years studied. At Saint-Maurice observed water savings (WS-IS) between SG and SSD reached 63% in 2007 (humid year, HD=1.30) and 18% in 2009 (dry year, HD=2.92), following the general trend described above that water savings allowed by localized systems decrease when HD increases. At Villeneuve, WS-IS between CP and SSD were 24%, 21% and 37% in 2013 (HD=1.32), 2014 (HD=1.65) and 2015 (HD=1.70) respectively. Unlike at Saint-Maurice, no relationship could be observed between WS-IS and HD.

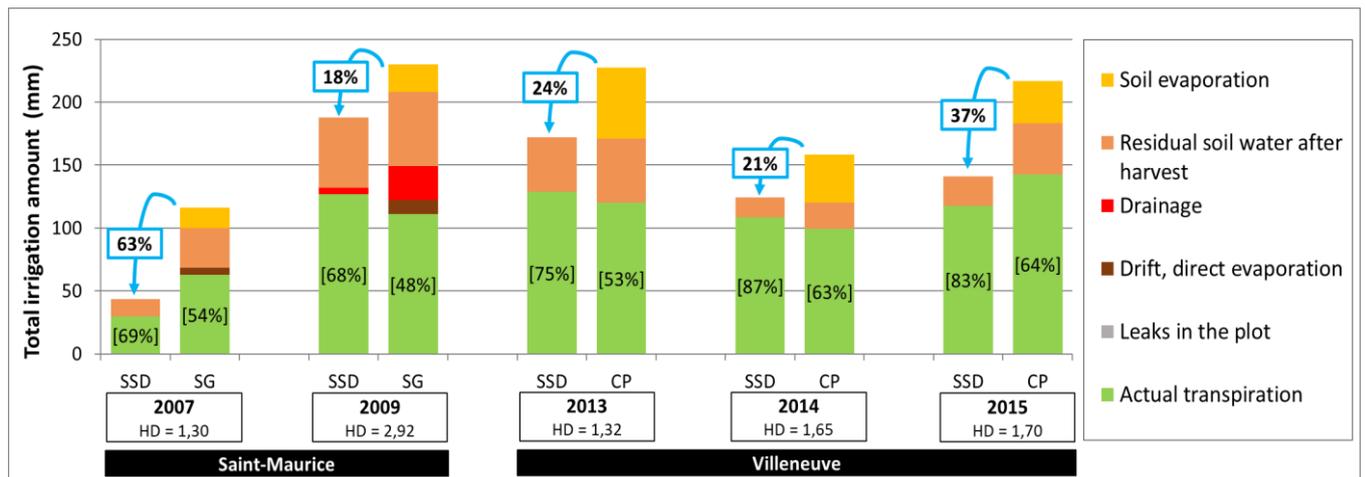


Figure 7. Distribution of irrigation water amounts between actual crop transpiration and different losses at the plot level at Saint-Maurice-de-Gourdans and Villeneuve-de-Marsan. SG: spray gun; CP: center pivot; SSD: subsurface drip; HD: hydric deficit (E_{To}/P). Losses through leaks in the plot are arbitrarily assumed to be zero. Bracketed percentages [%] indicate the part of irrigation water actually transpired by the crop, i.e. the global irrigation efficiency. Percentages in blue squares indicate the water saving (WS-IS) observed between sprinkler and localized system.

Simulated Irrigation efficiency and water losses

Optirrig model simulates the part of irrigation water actually absorbed and transpired by the crop, and distributes the different amounts of irrigation water losses (detail of histogram columns on Figure 7). It allows calculating the overall irrigation efficiency, i.e. the share of irrigation water transpired by the crop, which varies between 48% and 54% for SG (Saint-Maurice), 53% and 64% for CP (Villeneuve), and 68% to 87% for SSD (Saint-Maurice and Villeneuve). This is consistent with the fact that SG, CP and SSD are known to be ranked by increasing global efficiency. Observed values for SG are somewhat lower than those reported by Ghinassi (2012) (63 to 88%) because the author calculated irrigation efficiency with the crop evapotranspiration as numerator instead of actual crop transpiration as we did. Observed values for SSD are in accordance with those found by Lozano et al (2016) under plastic tunnels (58 to 81%). The authors also calculated irrigation efficiency with the crop evapotranspiration as numerator, but as plant beds were covered with plastic film, so soil evaporation could be considered as null and evapotranspiration equaled crop transpiration.

Irrigation water lost by direct evaporation in the air and wind drift was arbitrarily fixed at 5% of the total amount of water entering the plot for SG and 0% for CP and SSD. Losses through leaks in the plot were assumed to be zero. With SG, losses by soil evaporation represent 16 mm in 2007 and 22 mm in 2009, i.e. respectively 9% and 14% of the total water entering the plot. With CP, they are 56 mm, 38 mm and 34 mm in 2013, 2014 and 2015 respectively, i.e. 24%, 24% and 15% of the water entering the plot. No drainage occurred with CP and almost no drainage with SSD except 5 mm at Saint-Maurice in 2009. On the contrary, drainage is an important irrigation water loss with SG in 2009 (27 mm) as it represents 11% of the total applied water, or 22% of the total irrigation water losses. Drainage is more important with SG as applied water amounts (30-35 mm in 2009) are higher than with SSD (3.1-4.6 mm in 2009). The major irrigation water losses are the amounts of water stored in the soil at harvest. It ranks between 13 mm and 59 mm, representing 35 to 55% of the CP total losses, 50 to 53% of the SG total losses and almost 100% of the SSD total losses. This final irrigation water stock in soil will stay unused, as no crop will be seeded directly after corn in both case studies. For the water supply of the following crop, it can be assumed that the winter rainfall will be sufficient to ensure replenishing of the soil reserve, so that application of these irrigation volumes could have been avoided.

Optirrig simulation helps to understand where observed water saving (WS-IS) come from, as these originate in the reduction of losses between two systems at the plot level. WS-IS between sprinkler systems (SG or CP) and SSD result from complete suppression of losses by direct evaporation/drift and soil evaporation, and reduction of losses by drainage and excessive storage losses. These losses are

inherent to sprinkler systems and are called “technical losses” as they depend on the type of the technology used (Cheviron et al, 2020). Direct evaporation/drift are linked with jet atomization in the air, soil evaporation with soil surface wetting, drainage and excessive storage at harvest with large water doses applied.

From the simulations, it is also obvious that additional savings could have been realized with SSD by suppressing drainage (2009 at Saint-Maurice) and with both sprinkler and SSD by reducing residual soil water stock at harvest. Reducing residual water stock for SSD at Saint-Maurice would have increased water savings from 63% (observed) to 74% (potentially achievable) and from 18% (observed) to 43% (achievable) in 2007 and 2009 respectively. At Villeneuve, it would have increased savings from 24% (observed) to 43% (achievable), from 21% (observed) to 37% (achievable) and from 37% (observed) to 47% (achievable) in 2013, 2014 and 2015 respectively. Drainage and residual water stock are “tactical losses”, depending on how the technology is used, and related to irrigation management and scheduling. Drainage can be decreased by delaying irrigation after a significant rainfall. Excessive irrigation water storage in the soil at harvest could be prevented by reducing or suppressing the last irrigation event(s). Typically, the use of soil probes for irrigation scheduling, as described in the above sections, can reduce drainage and residual water stock, thus decrease losses. Wind drift with sprinkler irrigation, which can be limited by avoiding windy days or hours, is also a tactical loss. It should be noted that one kind of loss may have both technical and tactical origins.

The reduction of technical and tactical losses is the key to saving water and thus to improving efficiency at the plot scale. It should be noted that water savings arise most often from a combination of levers that depend on the context, so that there is no one-size-fits-all solution (GAO report, 2019). Water-efficient technologies (irrigation systems and scheduling tools) are one way to save water, but numerous other measures exist, such as water-saving cropping practices including, among others, landscaping to better valorize rainwater, crop management (drought resistant species or varieties, avoidance strategy to escape drought period) and soil management (no-tillage, mulching to reduce soil evaporation, weeds’ management to decrease water consumption, organic matter input to increase soil water storage) (Stewart and Lal, 2018; Page et al, 2020)

4. Conclusion

Our study was intended to analyse the water savings achieved and achievable at the plot scale through irrigation systems modernization, i.e. adoption of a more efficient irrigation system or of soil probes for irrigation scheduling. Results highlight that:

- Achieved irrigation water savings are highly variable, ranging from 0% to more than 70% and thus are not generalizable;
- Water savings obtained from localized irrigation systems significantly decrease when the hydric deficit of the cropping season increases and when soil water holding capacity is high;
- Water savings obtained from irrigation scheduling using soil probes do not seem to be influenced by hydric deficit, soil water holding capacity or soil probe type;
- A referential of potentially achievable water savings through the change of irrigation equipment and/or irrigation management could be established;
- The modelling approach with Optirrig allows (1) understanding the origin of observed water saving between two irrigation systems by quantifying the reduction of various technical losses, and (2) assessing additional potentially achievable irrigation water savings (reduction of tactical losses).

From a climate change perspective, it is important to keep in mind that water savings potentially achievable by switching from sprinkler to localized technology may be limited, even impossible, in extremely dry years. On the contrary, scheduling irrigation with soil probes may offer potential water savings that are less dependent on climatic conditions. Therefore, to promote a better irrigation efficiency at the plot scale, and thus water savings, it would seem advisable that, along with investments in water saving equipment, the improvement of irrigators’ practices, in particular irrigation-scheduling tools, should also be encouraged.

Finally, it is necessary to remember that water savings at plot level do not necessarily imply long-term water savings at the basin scale (Van der Kooij et al, 2013; Grafton et al, 2018). Indeed, the ability of

water saving technologies to achieve water conservation at the basin scale depends on farmers' individual responses to increased irrigation efficiency and on the institutional environment in which they operate (Perez-Blanco et al, 2020). The adoption of more efficient irrigation equipment often leads to increased water withdrawal due to changes in crop choices and crop rotation patterns, or to the extension of irrigated area. This is the so-called "rebound effect" (Pfeiffer and Lin, 2014; Berbel et al, 2015). To achieve reductions in water extractions at the basin level, improvements in irrigation efficiency has to be simultaneously linked with measures that decrease the quantity of water that farmers are allowed to extract (Koech and Langat, 2018).

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