Modernization of irrigation systems in France: what potential water savings at plot level?

Claire Serra Wittling, Bruno Molle, Bruno Cheviron

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What is the real potential for water savings at plot level resulting from the change of irrigation equipment or the adoption of management tools in a given context? To answer this question, the authors of this article have compiled more than ninety-three references of experimental water consumption trials representative of a wide range of of soil and climate conditions and crops in metropolitan France. Their results show that the water savings potentially achievable by switching from sprinkling to a localised irrigation system are limited, if not impossible, in very dry years. On the contrary, irrigation control using soil water status sensors allows water savings that are less dependent on climatic conditions.

What strategies for water saving in irrigation?

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, it supports investments in efficient irrigation equipment via the European Agricultural Fund for Rural Development (EAFRD). In this context, "an investment in an improvement to an existing irrigation installation or element of irrigation infrastructure shall be eligible only if it is assessed ex ante as offering potential water savings of a minimum of between 5% and 25% according to the technical parameters of the existing installation or infrastructure" (European Union (2013), Article 46, point 4).

Water savings can be achieved by reducing irrigation water losses, whose definition and estimation vary among approaches (Seckler et al., 2003; Jensen, 2007; Perry, 2007; Lankford, 2012; Van Halsema and Vincent, 2012). The first approach, linked with the concept of "classical irrigation efficiency", focuses on the ratio of water beneficially used by the crop (evapotranspiration) to the water delivered. The second one, called the "neo-classical" approach, takes into account the part of delivered water potentially available for downstream reutilization. The classical approach is appropriate at plot scale and considers that water leaving the plot is lost (Hsiao, 2007), whereas the neoclassical one is relevant for water resource management at the basin scale, as it values the reuse of return flow, which is useful for the monitoring of water table levels (Richter et al., 2017).

In the above-mentioned European regulatory context, water savings are basically considered at plot or farm scale, in keeping with the "classical efficiency" approach. In this case, the entire irrigation water course at plot level can be described as a "cascade scheme" (Serra-Wittling and Molle, 2017) divided in 6 steps from plot entry to plant roots: water entering the plot, applied water (i.e. at nozzle or dripper exit), water reaching the soil surface, water stored in the root zone, water actually evapotranspired and water absorbed and actually transpired that participates to crop yield formation (Figure ❶). Between each step, irrigation water losses can occur, namely leaks from equipment, direct evaporation in the air and wind drift during sprinkler irrigation, run-off and drainage related to excessive or non-uniform application, residual water in the soil after harvest representing excessive water storage, weed transpiration, soil evaporation (for a comprehensive review, see Hsiao et al., 2007). Irrigation global efficiency is then defined as the ratio of the transpired irrigation water to the irrigation water entering the plot.

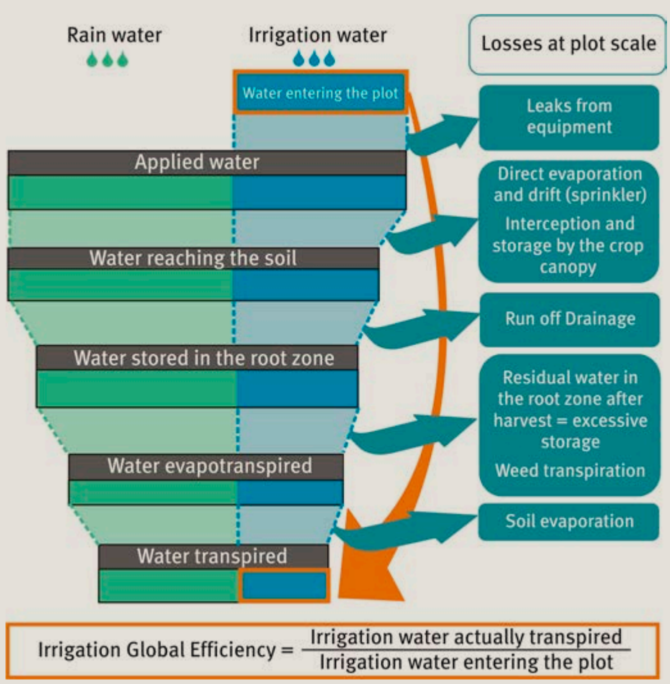
There are several types of levers used to save water by limiting irrigation water losses (BIO Intelligence Service, 2012; Jensen et al., 2014) including soil and crop management (no-till farming, mulching, weeds' management), as well as the improvement of irrigation technology (efficient irrigation application) and management (scheduling, deficit irrigation).

Irrigation upgrades at the technology level can be achieved by adding some devices to an existing system. For instance, a variable rate irrigation system (VRI) can be adapted to center pivots (Zhao et al., 2017) or a controller can be used to manage sprinkler rotation speeds on a hose-reel machine (Ghinassi and Pezzola, 2014). Another way to take advantage of technology is to adopt systems that are more efficient, i.e. by switching from flood or sprinkler irrigation to localized irrigation (surface drip, subsurface drip or microsprinkler). All localized systems are likely to eliminate drift and direct evaporation normally occurring during sprinkler irrigation. They also reduce run-off and drainage, as they lessen the amounts of water applied (typically near yet below soil saturation), allow better control of these amounts and deliver lower rates (hopefully lower than soil saturated hydraulic conductivity). Drip irrigation also eliminates interception by the canopy. Subsurface drip irrigation drastically reduces soil evaporation (Bonachela et al., 2001). Lastly, increasing the uniformity of the spatial distribution of irrigation also contributes to greater efficiency and water loss reductions, except in specific conditions (noticeable slopes, uneven soil depths or types) where it is better to deliver different doses to different parts of the plots. Therefore, in the general case, localized irrigation systems allow water savings only if satisfactory uniformity is achieved. Here are some commonly adopted 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):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).

Improvements that can be made in irrigation management include irrigation timing (daytime vs nighttime) (Molle et al., 2012; Cavero et al., 2016), regulated deficit irrigation (Geerts and Raes, 2009) and irrigation scheduling. The latter consists in adjusting irrigation frequency and quantities based on an irrigation strategy optimized with models (Evett and Tolk, 2009; Li et al., 2018; Malik et al., 2019, among many others), or on climatic conditions and plant (Jones, 2004) or measured soil water status. The most commonly used sensors to monitor soil water status are capacitive probes (Evett et al., 2012) and tensiometric probes (Bianchi et al., 2017). Soil probes are used to schedule irrigation according to actual soil water status, thus avoiding over-irrigation and, in turn, reducing run-off, drainage, and residual soil water after harvest.

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 aim of this study was to evaluate irrigation water savings achievable by switching from sprinkler to localized irrigation system or by using soil hydric status probes. For this purpose, we used the French metropolitan context as a case study and compiled all available studies conducted in France. We chose to focus on water savings achieved through the change in the irrigation equipment used or the adoption of soil probes for irrigation scheduling. We analysed how these water savings are influenced by the climatic context. Moreover, a modelling approach using the Optirrig crop model was carried out to quantify irrigation water losses and irrigation global efficiency at plot level.

❶ Steps of the water course at plot level and irrigation water losses



Methodology: collecting water savings references

Data collection

We compiled all available studies, conducted on the French metropolitan territory in the past 30 years, which enabled us to compare water consumption either between two different irrigation systems (sprinkler or localized system), or between two different scheduling modes (without and with soil probes), but always within the same context (same year, same soil, same crop). All these studies are based on experimental field trials carried out by chambers of agriculture, technical institutes, research institutes, experimental stations, or regional water management organizations. They were conducted either in experimental stations or by farmers supervised by an irrigation technical advisor. The data produced by these studies are most often unpublished and are found in grey literature reports. They originate from 25 different locations, mainly from French regions with the greatest irrigated surface areas (Figure ❷), and refer to field crops, fruit and vegetable production. A total of 93 records of irrigation water consumption at plot scale was collected. 70 records detail the comparison of two irrigation systems: a sprinkler system (reel machine, moving lateral, center pivot or solid set) and a localized system (surface drip, subsurface drip or microsprinkler). 23 records compare the water consumption of two scheduling modes: without and with soil probes. None of the experiments refers to the use of surface irrigation methods, as they are no longer widely-used in France. Each record is used to assess the water saving achieved between the highest water consuming system and the lowest water consuming one. We selected only data describing water savings achieved without significant yield or quality loss: a yield reduction of up to 10% was tolerated. The entire database is accessible in the article of Serra-Wittling et al. (2019).

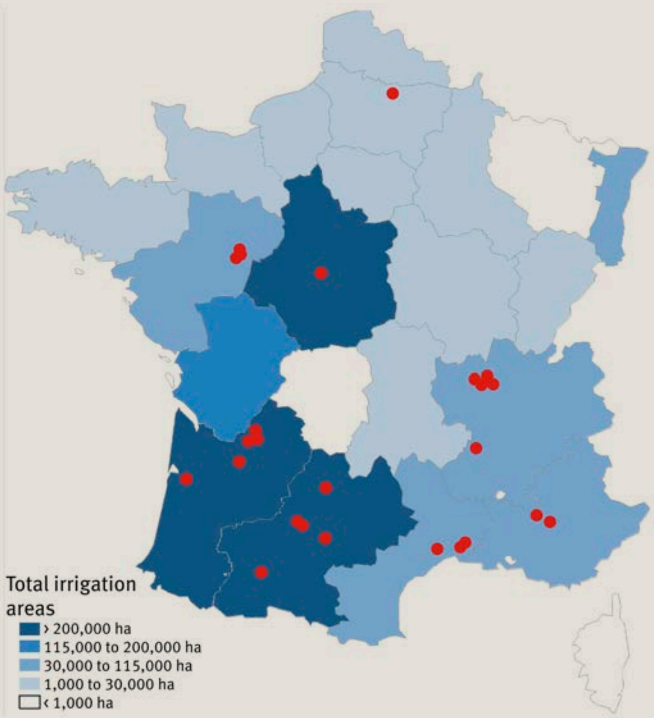
Data base creation

Each record contains general data concerning the agro-pedo-climatic context, specific data describing both compared situations (two different irrigation systems or two different scheduling modes, i.e. without and with soil sensor), the associated irrigation water amounts and yields, as well as variables calculated from the previous raw data.

General data

Year, location, soil water holding capacity (WHC), crop type (field crop, vegetable, fruit production), cumulated precipitation (P) and Penman-Monteith reference evapotranspiration (ETo) during the cropping season. P and ETo were obtained either from the meteorological station on the experimental site itself, or from the nearest meteorological station of INRAE (French National Research Institute for Agriculture, Food, and Environment) or Meteo France. P and ETo are cumulated during the cropping season, i.e. from the mean sowing date (or planting or fruit set) to the mean harvest date.

❷ Irrigated areas in France (2010) and location of the 25 experimental sites where data were collected.



Specific data allowing the comparison of two irrigation situations

Irrigation systems 1 and 2 are compared (system 1 being the most water consumptive, and system 2 the least consumptive). In all cases, irrigation system 1 is a sprinkler system (hose reel machine, lateral move, center pivot or solid set system) and irrigation system 2 is a localized irrigation system, either based on surface drip (SD), subsurface drip (SSD) or microsprinkler (MS) setups. Two scheduling systems are compared as well. The first one is based on either traditional farmer practices, weekly irrigation recommendation bulletins, or maximal evapotranspiration (MET) evaluations, and does not use any scheduling device. The second one employs soil sensors (tensiometric or capacitive probes) to adjust the irrigation dose to soil moisture content. For each irrigation or scheduling system, the total amount of irrigation water applied during the cropping season with system 1 (Irr1) and system 2 (Irr2) are recorded, together with the associated yields.

Calculated variables

The hydric deficit of the cropping season (HD, unitless) is calculated as HD = ETo / P, where ETo (mm) s 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 are therefore not considered in this study. HD should be considered as an indicator of climatic drought, but not of irrigation requirement.

Water saving (WS in %) obtained when using system 2 vs system 1, or when using a soil sensor vs no soil sensor, is evaluated as [(Irr1 – Irr2) / Irr1] x 100, where Irr1 (mm) and Irr2 (mm) are the total amounts of irrigation water applied during the cropping season with system 1 and 2 respectively. We distinguish between the water savings obtained when comparing two irrigation systems (WS-IS) and those obtained when comparing two soil probes (WS-SP).

Modelling water losses

Optirrig crop model

The recently developed "Efficiency" module of Optirrig crop model allows simulating the irrigation water volumes at each step of irrigation water course from the canal to plant roots. In this study, it was used at plot level (see also the article of Cheviron et al., 2020, in this issue). It evaluates the global irrigation efficiency (ratio of transpired irrigation water to irrigation water entering the plot) as well as the successive volumes of irrigation water lost from the plot entry to the roots (direct evaporation and wind drift during sprinkler irrigation, drainage, soil evaporation and residual soil water after harvest).

A study case

The experimental trial was conducted on corn, in 2009, on a farm plot in the Ain plain (30 km east of Lyon, France), to study. The alluvial soil has a water holding capacity of 60-80 mm. Irrigation was scheduled with tensiometers. The sprinkler system was a hose reel machine with pipe diameter of 100 mm and pipe length of 400 m. During the cropping season, there were 7 irrigation events with water amounts ranging from 30 to 35 mm. The localized system was subsurface drip (SSD) with emitter spacing of 30 cm, flow rate of 1.14 l.h-1, drip lines lateral spacing of 150 cm and drip line depth of 50 cm. 55 irrigation events from 2.5 to 3.75 mm were performed. Irrigation amounts were monitored for both systems during the season, as well as yields. It was assumed that no irrigation water loss occurred in the plot, so that all water entering the plot flow out from nozzle or dripper. Lost irrigation water amounts were simulated with the "Efficiency" of Optirrig.

Résults and discussion: evaluating strategies for water savings

Water savings achieved with irrigation systems (WS-IS)

As shown on figure ❸, water saving between two irrigation systems (WS-IS) that was observed using surface drip (SD), subsurface drip (SSD) or microsprinkler (MS), compared to a sprinkler irrigation system, ranges from 0% to 77%, which evidences high variability.

Localized irrigation systems (SD, SSD or MS) can, to a greater or lesser extent, help reduce the amount of water applied during the cropping season compared to sprinkler systems (spray gun, center pivot, solid-set). These water savings are explained by the higher application efficiency of localized systems that very likely reduce irrigation water losses occurring with sprinkler irrigation resulting from drift and direct evaporation, canopy interception, run-off, drainage and soil evaporation. Water savings can also be attributed to the more efficient use of rainwater with localized systems. Indeed, considering that the interval between sprinkler irrigations varies between 3 and 10 days (depending on region, climate, soil), and that the weather forecast is much less accurate beyond 3-4 days, rainfall can occur between two sprinkler irrigations, thus leading to irrigation water waste.

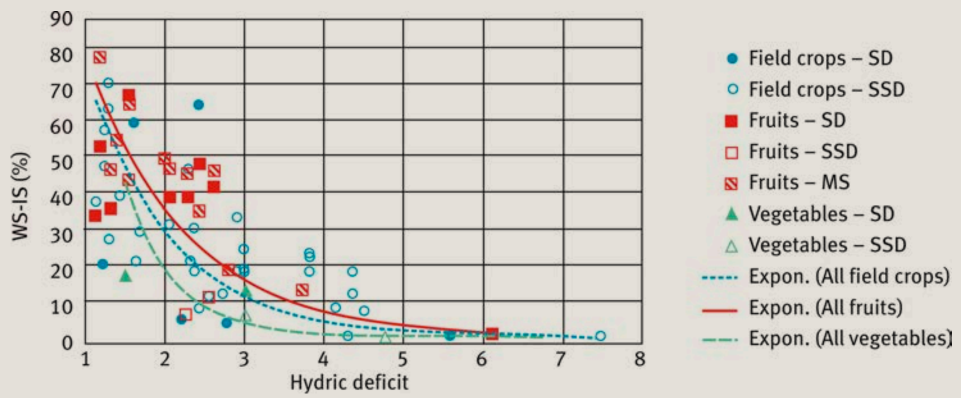
WS-IS (%) tends to decrease when hydric deficit increases (Figure ❸). It appears that, for a hydric deficit value exceeding 4.5, WS-IS always approaches 0%, regardless of the irrigation system or the crop type. This can be explained by the reduction in drainage losses occurring during sprinkler irrigation 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 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 amounts of water are applied daily. In dry years, all the irrigation water contributes to the soil water reserve replenishment so that no loss occurs and global irrigation efficiency of the sprinkler systems increases and draws near to that of localized systems, thus reducing the water savings observed between both systems.

Water savings achieved with soil probes (WS-SP)

In all cases, water amounts are lower when irrigation is managed with soil probes. Observed WS-SP varies between 8% and 68% (Figure ❹). Indeed, soil probes allow real-time decisions that complement scheduling strategies, where changes to irrigation dates and doses can be made according to the actual soil water status. This results in a reduction in over-irrigation and thus in losses due to run-off, deep percolation and residual soil water after harvesting. Soil probes may also help to optimize rainfall use, as irrigation can be started later in the season and stopped earlier. In sprinkler irrigation, the first, and sometimes also the last irrigation of the season, can be cancelled, which leads to consistent water saving.

Contrary to WS-IS, WS-SP does not seem to depend on climatic conditions as HD has no significant effect on WS-SP. 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

❸ Water saving (WS-IS) observed between a sprinkler system and a localized irrigation system, according to the hydric deficit of the cropping season. Exponential curves (Expon.) for each crop type. SD: surface drip, SSD: subsurface drip, MS: microsprinkler.



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).

Where do the observed water savings come from? A study case

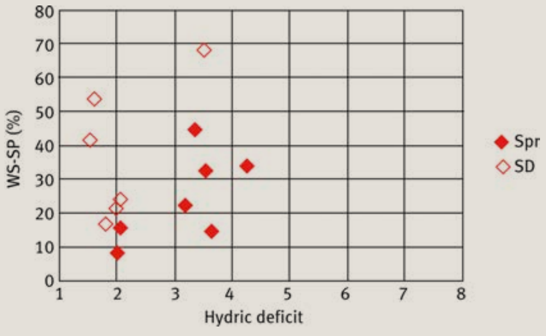
Amounts of irrigation water applied are 230 and 153 mm for sprinkler and SSD respectively, so that SSD allows 34% water saving compared to sprinkler (WS-IS) (Figure ❺). Corn yield obtained are equivalent for both systems: 13.3 and 13.1 T.ha-1 for sprinkler and SSD respectively.

Modelling with Optirrig allows quantifying the part of irrigation water actually used for crop transpiration and the lost volumes. The actual transpiration represents 49% of the total irrigation water for the sprinkler system and 68% for SSD, confirming that SSD has a much better global irrigation efficiency (nearly 20% higher) than the hose reel machine, due to the reduction of water losses with SSD.

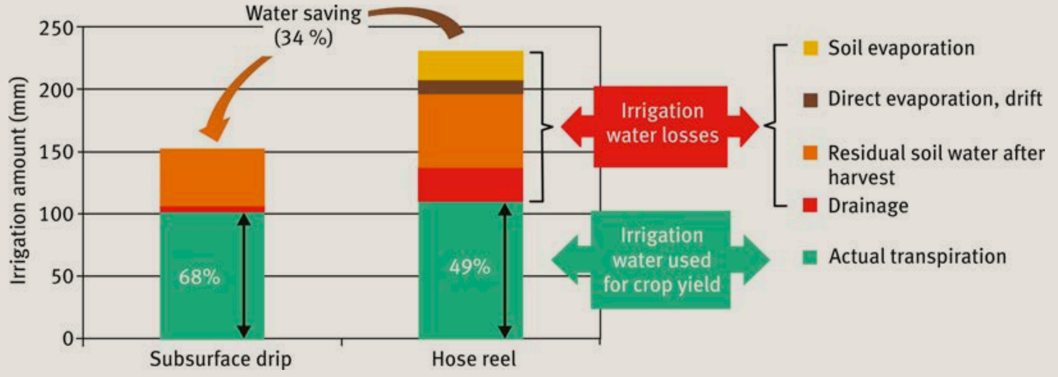
With the hose reel machine, irrigation water lost by direct evaporation in the air and wind drift was arbitrarily fixed at 5% of the total amount of water entering the plot (Molle et al., 2012). On principle, these losses do not occur with drip irrigation as the entire water amount flowing out of the emitter is supposed to reach the soil. Soil evaporation does not occur with SSD as irrigation water applied at 50 cm depth cannot evaporate from soil. With the hose reel machine, this loss represent 22mm, i.e. 9% of the water entering the plot. The major irrigation water loss is the water stored in the soil at harvest: 59 mm with sprinkler and 46 mm with SSD, that is 50% of the total losses with sprinkler and 94% for SSD. This final water stock in soil will stay unused, as no crop will be seeded directly after corn. 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. Drainage is another important irrigation water loss with the hose reel machine (27 mm) as it represents 11% of the total applied water, or 22% of the total irrigation water losses. Only 3 mm irrigation water are lost by drainage with SSD. Drainage is more important with sprinkler irrigation as applied water amounts (30-35 mm) are higher than with SSD (2.5-3.75 mm).

Some of the above listed losses of irrigation water are linked with the irrigation technology itself and depend on the type of system used (sprinkler or localized). They are called "technical losses". Direct evaporation or wind drift and soil evaporation are only related to sprinkler irrigation. Losses by drainage and excessive storage in the profile are higher with sprinkler irrigation as the applied water amounts are larger. Other losses (called "tactical losses") are related to the irrigation management and scheduling (dates and doses). Wind drift with sprinkler irrigation can be limited by avoiding windy days or hours. Delaying irrigation after a significant rainfall should reduce drainage losses. Excessive irrigation water storage in the soil could be prevented by reducing or suppressing the last irrigation event(s). Reducing water losses, and thus saving water with SSD compared to sprinkler irrigation, originate both in technical and tactical improvements.

❹ Water saving realized by using soil probes (WS-SP) to schedule irrigation in open field conditions, according to the hydric deficit of the cropping season. Spr: Sprinkler irrigation, SD: surface drip



❺ Simulation of irrigation water amounts transpired by the crop or lost for corn with subsurface drip (SSD) or sprinkler irrigation (hose reel machine).



Conclusion

This study compiled all available field studies conducted on the French metropolitan territory over the past 30 years, concerning water savings achieved with localized systems (surface drip, subsurface drip or microsprinkler) compared with sprinkler systems (reel machine, lateral move, center pivot or solid set system), as well as with scheduling based on soil probes (tensiometric or capacitive probes) compared with traditional water balance management. A modelling approach carried out on a study case allowed to quantify the reduction of irrigation water losses contributing to the observed water savings.

Our work shows that:

• Localized irrigation systems, as well as soil probes, are very effective solutions that can be used to save water at plot scale and thus increase irrigation water productivity. However, it is not reasonable to generalize values on water savings, as they are highly variable and may depend on several factors.

• Reducing water losses, and thus saving water with localized systems compared to sprinkler systems, originate both in technical and tactical improvements. Therefore, to promote water savings, it would seem advisable, that along with investments in water saving equipment, the improvement of irrigators' practices and, in particular irrigation-scheduling tools, should also be encouraged.

• Water savings obtained with localized irrigation systems are highly dependent on climatic conditions, whereas those obtained with soil probes are not. This main feature should be considered carefully from a climate change perspective. For the purpose of water saving and water extraction limitation, it is important to keep in mind that water savings potentially achievable by switching from sprinkler to localized irrigation system are optimal in conditions with moderate hydric deficit. They may be limited, even impossible, in extremely dry years. On the contrary, managing irrigation with soil probes may offer potential water savings that are less dependent on climatic conditions.

Finally, it is important to remember that water savings at plot level do not necessarily imply long-term water savings at the territory scale (Grafton et al., 2018). 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, improvements in irrigation efficiency has to be simultaneously linked with measures that decrease the quantity of water that farmers are allowed to extract. ■

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Further reading...

BIO INTELLIGENCE SERVICE, 2012, Water saving potential in agriculture in Europe: findings from the existing studies and application to case studies. Final report prepared for European Commission DG ENV, 234 p., https://ec.europa.eu/environment/water/quantity/pdf/BIO_Water%20savings%20in%20agiculture_Final%20report.pdf

HSIAO, T.C., STEDUTO, P., FERERES, E., 2007, A systematic and quantitative approach to improve water use efficiency in agriculture, *Irrigation Science*, vol. 25, p. 209-231, https://link.springer.com/content/pdf/10.1007/s00271-007-0063-2.pdf

SERRA-WITTLING, C., MOLLE, B., 2017, Évaluation des économies d'eau à la parcelle réalisables par la modernisation des systèmes d'irrigation. Rapport d'étude réalisée avec le soutien du Ministère de l'Agriculture et de l'Alimentation, IRSTEA, 149 p., http://www.g-eau.fr/index.php/fr/umr-geau/actualites/item/758-etude-irstea-2017-sur-l-evaluation-des-economies-d-eau-potentielles-a-la-parcelle-realisables-par-la-modernisation-des-systemes-d-irrigation-c-serra-wittling-et-b-molle

SERRA-WITTLING, C., MOLLE, B., CHEVIRON, B., 2019, Plot level assessment of irrigation water savings due to the shift from sprinkler to localized irrigation systems or to the use of soil hydric status probes. Application in the French context, *Agricultural Water Management*, vol. 223, 105682, https://hal.inrae.fr/hal-02609656/document

Additional bibliography

BERBEL, J., GUTIÉRREZ-MARTÍN, C., RODRÍGUEZ-DÍAZ, J.A., CAMACHO, E., MONTESINOS, P., 2015, Literature review on rebound effect of water saving measures and analysis of a Spanish case study, *Water Resources Management,* vol. 29, p.663-678.

BIANCHI, A., MASSERONI, D., THALHEIMER, M., OLIVERA DE MEDICI, L., FACCHI, A., 2017, Field irrigation management through soil water potential measurements: a review, *Italian Journal of Agrometeorology*, n° 2, p. 25-38.

BONACHELA, S.F., ORGAZ, F., VILLALOBOS, F.J., FERERES, E., 2001, Soil evaporation from drip-irrigated olive orchards, *Irrigation Science*, vol. 20, p. 65-71.

CAVERO, J., FACI, J.M., MARTÍNEZ-COB, A., 2016, Relevance of sprinkler irrigation time of the day on alfalfa forage production, *Agricultural Water Management*, vol. 178, p. 304-313.

EUROPEAN UNION, 2013, Regulation (EU) No 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC), No 1698/2005, *Official Journal of the European Union L,* n° 347, p. 487-548.

EVETT, S.R., SCHWARTZ, R.C., CASANOVA, J.J., HENG, L.K., 2012, Soil water sensing for water balance, ET and WUE, *Agricultural Water Management*, vol. 104, p. 1-9.

EVETT, S.R., TOLK, J.A., 2009, Introduction: Can water use efficiency be modeled well enough to impact crop management?, *Agronomy Journal*, vol. 101, p. 423-425.

v**GEERTS, S., RAES, D.,** 2009, Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas, *Agricultural Water Management,* vol. 96, p. 1275-1284.

GHINASSI, G., PEZZOLA, E., 2014, *Controlling sprinkler rotation speed to optimize water distribution uniformity of travelling rain guns*, 2014 ASABE and CSBE/SCGAB Annual International Meeting, Montreal, Quebec Canada, July 13-16, 2014.

GRAFTON, R.Q., WILLIAMS, J., PERRY, C.J., MOLLE, F., UDALL, B., GARRICK, D., RINGLER, C., WHEELER, S.A., ALLEN, R.G., WANG, Y., STEDUTO, P., 2018, The paradox of irrigation efficiency. Higher efficiency rarely reduces water consumption, *Science*, vol. 361, p. 748-750.

HOWELL, T.A., 2003, Irrigation Efficiency, *in:* STEWART, B.A., HOWELL, T.A. (Eds.), *Encyclopedia of Water Science*, Marcel Dekker, New York, p. 467-472.

JENSEN, C.R., ORUM, J.E., PEDERSEN, S.M., ANDERSEN, M.N., PLAUBORG, F., LIU, F., JACOBSEN, S.E., 2014, A short overview of measures for securing water resources for irrigated crop production, *Journal of Agronomy and Crop Science*, vol. 200, p. 333-343.

JENSEN, M.E., 2007, Beyond irrigation efficiency, Irrigation Science, vol. 25, p. 233-245.

JONES, H.G., 2004, Irrigation scheduling: advantages and pitfalls of plant-based methods, *Journal of Experimental Botany*, vol. 55, p. 2427-2436.

LANKFORD, B., 2012, Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency, *Agricultural Water Management,* vol. 108, p. 27-38.

LI, J., 2018, Increasing crop productivity in an eco-friendly manner by improving sprinkler and micro-irrigation design and management: A review of 20 years' research at the IWHR, China, *Irrigation and drainage*, vol. 67, p. 97-112.

MALIK, W., ISLA, R., DECHMI, F., 2019, DSSAT-CERES-maize modelling to improve irrigation and nitrogen management practices under Mediterranean conditions, *Agricultural Water Management*, vol. 213, p. 298-308.

MOLLE, B., TOMAS, S., HENDAWI, M., GRANIER, J., 2012, Evaporation and wind drift losses during sprinkler irrigation influenced by droplet size distribution, *Irrigation and drainage*, vol. 61, p. 240-250.

PERRY, C., 2007, Efficient irrigation; inefficient communication; flawed recommendations, *Irrigation and drainage*, vol. 56, p. 367-378.

PFEIFFER, L., LIN, C.Y.C., 2014, Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence, *Journal of Environmental Economics and Management*, vol. 67, p. 189-208.

RICHTER, B.D., BROWN, J.D., DIBENEDETTO, R., GORSKY, A., KEENAN, E., MADRAY, C., MORRIS, M., ROWELL, D., RYU, S., 2017, Opportunities for saving and reallocating agricultural water to alleviate water scarcity, *Water Policy*, vol. 19, n° 5, p. 886-907.

SECKLER, D., MOLDEN, D., SAKTHIVADIVEL, R., 2003, The concept of efficiency in water resources management and policy, *in:* KIJNE, J.W., BARKER, R., MOLDEN, D. (Eds.), *Water productivity in agriculture: Limits and opportunities for improvement*, CAB International.

VAN HALSEMA, G.E., VINCENT, L., 2012, Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism, *Agricultural Water Management*, vol. 108, p. 9-15.

ZHAO, W., LI, J., YANG, R., LI, Y., 2017, Yields and water-saving effects of crops as affected by variable rate irrigation management based on soil water spatial variation (in Chinese, with English abstract), *Transactions of the Chinese Society of Agricultural Engineering*, 33, p. 1-7.

Field sprinkler irrigation.