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Irrigation in the age of agriculture 4.0: management, monitoring and precision

A irrigação na era da agricultura 4.0: manejo, monitoramento e precisão

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ABSTRACT - Technological evolution is essential to make irrigated agriculture more efficient in the use of water. Thus, this review article aims to contextualize irrigation in the age of agriculture 4.0 in order to address how these new technologies are impacting the rational use of water. With regard to the automation of irrigated systems, irrigation efficiency with moisture sensors, applications using smartphone, controllers and fertilizer injectors, as well as how their operation can promote irrigation, was addressed. Regarding irrigation management, the use of remote sensing as an option to determine crop evapotranspiration was contextualized, listing the types of spectral bands and sensors used to collect images (orbital, aerial and terrestrial), in the monitoring of crop water status. The importance of data collection in the delineations of management zones for precision irrigation and what possible advances can still be achieved with regard to obtaining and analyzing data were also discussed. Finally, it is concluded that, despite the high efficiency of automated irrigation systems, information of soil, climate and plant attributes obtained through the range of data provided by sensors will be responsible for mitigating the global impacts caused by irrigated agriculture in the near future, since this information can enhance irrigation, with maximum efficiency, thus reducing water consumption by agriculture.

Key words: Precision agriculture. Internet of things. Remote sensing. Management zones.

RESUMO - A evolução tecnológica é imprescindível para tornar a agricultura irrigada mais eficiente no uso da água. Sendo assim, esse artigo de revisão visa contextualizar a irrigação na era da agricultura 4.0 de forma a abordar como essas novas tecnologias estão a impactar no uso racional da água. No que concerne a automação de sistemas irrigados abordou-se a eficiência da irrigação com auxílio de sensores de umidade, aplicativos com uso de smartphone, controladores e injetores de fertilizantes e como o funcionamento destes pode promover a irrigação. Com relação ao manejo da irrigação, o uso do sensoriamento remoto como opção para determinação da evapotranspiração da cultura foi contextualizado, relacionando os tipos de bandas espectrais e sensores utilizados para a coleta de imagens (orbital, aéreo e terrestre), no acompanhamento do status hídrico da cultura. Versou-se também sobre a importância da coleta de dados nas delimitações das zonas de manejo para a irrigação de precisão e quais os possíveis avanços ainda podem ser alcançados no que concerne a obtenção e análise de dados. Por fim, conclui-se que, apesar da alta eficiência dos sistemas de irrigação automatizados, informações oriundas dos atributos do solo, clima e planta obtidas através da gama de dados fornecidos por sensores, serão responsáveis pela mitigação dos impactos globais ocasionados pela agricultura irrigada no futuro próximo, já que estas informações podem potencializar com máxima eficiência, a irrigação de precisão, reduzindo assim o consumo de água pela agricultura.

Palavras-chaves: Agricultura de precisão. Internet das coisas. Sensoriamento remoto. Zonas de manejo.

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INTRODUCTION

Global projections indicate that demand and conflicts for water and energy tend to increase significantly in the coming years, because of, among other reasons, exaggerated population growth, environmental degradation caused by anthropic factors, and climate change that generate extreme meteorological phenomena, and these factors also pose risk to global agriculture (FAO, 2011). In view of this, technological evolution is essential to make irrigated agriculture more efficient in the use of water and inputs (CHAUHDARY *et al.*, 2020; SANTAELLA *et al.*, 2013).

In this context, several techniques have emerged to assist in the agricultural production process, especially with regard to irrigation, such as satellite navigation, sensor network, network computing, ubiquitous computing and sensitive computing, use of programming, creation of applications (SOUZA; CONCHESQUI; SILVA, 2019), among others, thus enabling information to be managed through the internet of things (IoT), hence helping to monitor and understand more quickly emerging situations in agricultural areas, obtaining an informed decision-making with various types of information (AQEEL-UR-REHMAN; SHAIKH, 2009), leading the world to the path of precision agriculture (PA).

PA has arrived offering a multitude of advantages with high potential related to sustainability, yield, better product quality, lower environmental impact and greater profitability. Among other purposes, it seeks to improve the quality of life aiming at food security and rural economic development. PA uses an approach with scientific and modern validation, combined with conventional knowledge and information technologies for an intelligent agricultural production (SHIRATSUCHI *et al.*, 2014).

In this path of PA, the main technological advances in irrigation and fertigation refer to the use of irrigation systems and modern injection equipment, which promote the most efficient application of water and fertilizers, and that allow the entire process to be optimized through automation in the use of technological information with data collection informed by IoT for each specific area of the properties, thus defining differentiated management zones for higher efficiency in the use of water and fertilizers (INCROCCI; MASSA; PARDOSSI, 2017).

For irrigation management, remote sensing (RS) presents itself as an option and can be used to estimate crop evapotranspiration rate (REYES-GONZÁLEZ *et al.*, 2018; MOKHTARI *et al.*, 2019), water deficit (VIRNODKAR *et al.*, 2020), and consequently propose an adequate irrigation schedule of how much and when to irrigate, or employing techniques of variable-rate irrigation (VRI) based on the values of vegetation indices (O'SHAUGHNESSY *et al.*, 2019; BHATTI *et al.*, 2020) obtained through remote sensors. Data collection is performed through remote sensors that capture the reflectance of plants without direct contact with the target, making RS an alternative of non-destructive method to indirectly measure the water status of plants, for example.

Thus, this review article aims to contextualize irrigation in the age of agriculture 4.0, through a literature review, in order to address how these new technologies are impacting the rational use of water in agriculture, also bringing the main technological trends used in this area.

AUTOMATION OF WATER AND NUTRIENT MANAGEMENT IN IRRIGATED AGRICULTURE

Knowledge on the contents of water and nutrients in the soil and on their dynamics in time and space is necessary for the proper management of irrigated agriculture. Soil water content varies with rainfall, irrigation, drainage and evaporation, as well as with cultural practices and soil conditions. In this context, there must be technologies that complement each other and be able to measure the water content in the soil instantaneously, accurately and continuously, provide answer to the basic question "when and how much to irrigate?" and, if possible, masterly execute the decision-making process (GAVA; SILVA; BAIO, 2016; SOUZA *et al.*, 2016a).

Constantly monitoring soil moisture and electrical conductivity makes it possible to calculate the amount of water and the appropriate time for its application. In addition, the automation of systems makes it possible to manage these data and perform functions through the internet of things (IoT).

IoT is the communication between equipment (engines, tractors, agricultural greenhouses, sensors and others equipped with embedded technology) via connection with a wireless network capable of gathering, transmitting and exchanging data. It is considered an extension of the current computer network, which enables equipment to receive commands remotely and be used as service providers, paving the way for numerous possibilities in agriculture.

IoT is the present and future of the computer network in which devices relate to other devices and users. In this context, the devices tend to take control of a series of common day-to-day actions, without the obligation for users to be fully dedicated to the command of decisions (SANTAELLA *et al.*, 2013).

Domínguez-Niño *et al.* (2020) successfully used capacitance sensors to provide automated feedback to the programming algorithm for soil water management (Figure 1). In this study, the authors show the feasibility of automated sensor-based irrigation programming in apple orchards. The algorithm, based on the water balance approach and locally tuned through sensor feedback, provided accurate doses of irrigation throughout the cropping season, adapting to climatic conditions and to the crop growing season.

Kamienski and Visoli (2018) suggest a platform for precision irrigation based on IoT, for which two scenarios are presented to test the platform: Matopiba (Bahia) and Espírito Santo do Pinhal (São Paulo). For the pilot scenarios, an overview of the platform, its architecture and computational platform and the development process based on scenarios adopted in the projects are presented.

In another study using sensors to automate irrigation management, Souza; Conchesqui and Silva (2019) present a proposal for a semi-automatic system with devices that are available on the market (Figure 2).

The authors used Parrot Flower Power® capacitance sensors, which can measure not only soil moisture, but also the intensity of solar radiation, soil temperature, air temperature and the need for fertilization. In this study, to effect the semi-automation, programming procedures were carried out in the irrigation controller GreenIQ® (Figure 3A), which performed estimates of soil moisture through capacitance sensors via Bluetooth.

Soil moisture estimates were analyzed by the GreenIQ® application via smartphone, informing the user through the local wireless network about suggestions of when and how much to irrigate, also offering meteorological data to assist in the user's decision making (Figure 3B). In addition, the GreenIQ® semi-automatic controller was connected to an Alexa® personal assistant from Amazon® for the voice interface of the irrigation management programming commands (Figure 3C).

The GreenIQ® controller can operate automatically, making all decisions of how much and when to irrigate, but this function was adjusted to semi-automatic. In this module, the system waits for confirmation to irrigate, so the operator can confirm via voice command with the digital assistant or simply through the application on the smartphone.

The authors were able to conclude that the semi-automatic irrigation system showed agility and accurate, which promotes a reduction in labor as there is no need for manual readings of sensors in the field and an increase in the amount of information provided to decide how much and when to irrigate without even the need to be present in the field. Also, the tests proved the system is efficient. It was possible to perform irrigation programming through voice commands. In addition, voice commands ended up being less attractive, because it is necessary to go to the

Figure 1 - Schematization of the automated soil water management system (DOMÍNGUEZ-NIÑO *et al.*, 2020)

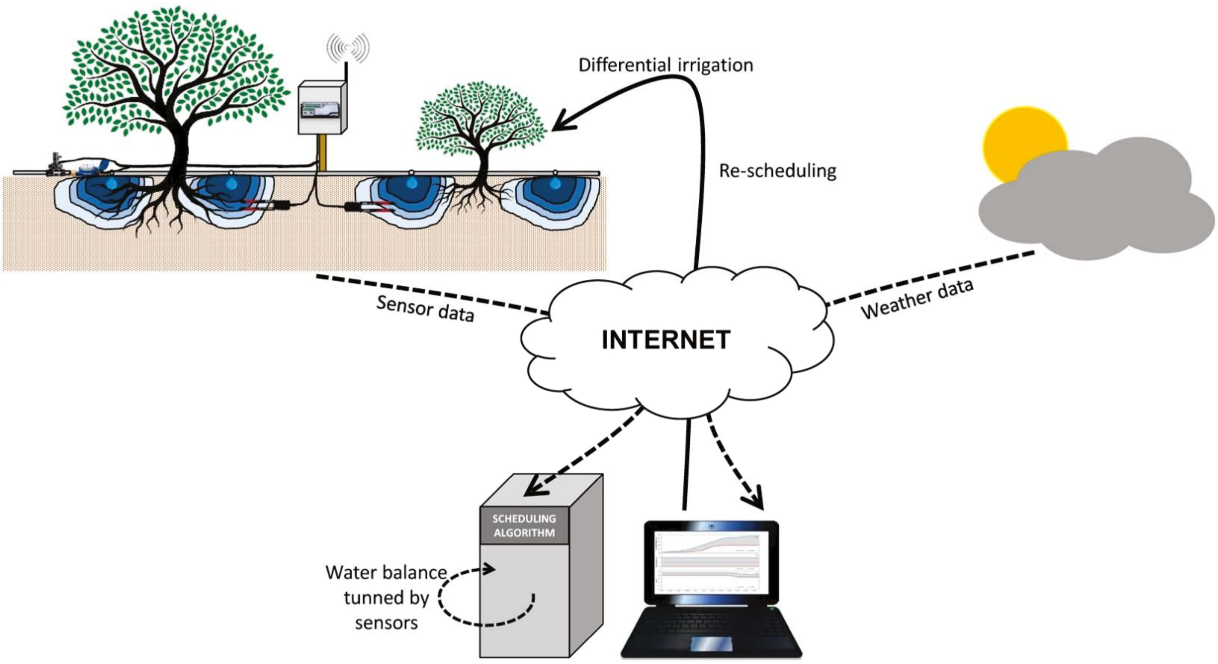
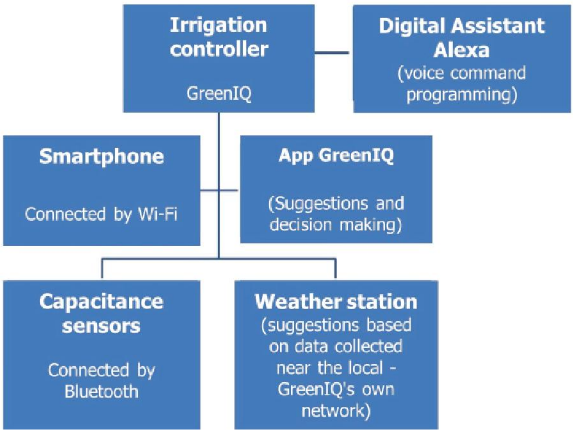


Figure 2 - Organization chart for the operation of the semi-automatic irrigation management system (SOUZA; CONCHESQUI; SILVA, 2019)



agricultural greenhouse to program the irrigation, while when using only the GreenIQ® semi-automatic controller, the irrigation programming can be done from any location with wireless network signal via smartphone.

Sensors in the management of soil water and nutrients

With regard to the monitoring of water and nutrient contents in the soil, direct or indirect methods can be employed to provide an accurate response, which helps to keep the soil always at a sufficient level of water and nutrients for plant growth (RAMOS *et al.*, 2014). The difference between the methods is the way they are applied, the equipment used and the response time.

To overcome the obstacles of the direct method, indirect methods that work with physical properties of the soil to estimate its moisture and electrical conductivity have emerged. In this case, Ramos *et al.* (2014) explain that the use of more sophisticated devices to apply these indirect techniques, despite enabling several types of measurement and with a shorter response time, also require a higher cost due to the acquisition of equipment.

Among the sensors currently used, according to Souza *et al.* (2016b), Time Domain Reflectometry (TDR) and Capacitance emit electromagnetic waves at a specific frequency in conductive rods inserted into the soil to evaluate the interference of water on the propagation of electromagnetic pulses.

There are two possibilities for the use of electromagnetic techniques to measure soil moisture and electrical conductivity with respect to the frequency of operation of the device. In the first one, the frequency of operation fluctuates among values below 100 MHz, called capacitance sensors, also called frequency domain reflectometry (FDR), while in the second one the device operates at a frequency of approximately 1.2 GHz, called TDR (SOUZA *et al.*, 2016a).

These frequencies polarize the dipoles present in the soil and the phenomenon is responsible for the effect of water (dipole) on the propagation velocity of the electromagnetic wave. However, the capacitance, through a reduction in the operating frequency, enables the use of frequencies below 100 MHz, which interferes in the polarization of ions (Figure 4).

This reduced frequency leads to lower cost, which provides better conditions for the acquisition of capacitance sensor when compared to TDR sensor. It is also believed that the use is not consolidated among farmers and researchers, due to the absence of information describing its limitations, especially regarding the need for a calibration for each type of soil.

The devices used in the TDR are a high-precision oscilloscope (ZHANG *et al.*, 2017), a battery and probes composed of coaxial cables, stainless steel rods and epoxy resin head, Figure 5A.

Figure 3 - A) Equipment used: GreenIQ® controller; B) Graphical interface of the soil irrigation management application and C) Alexa® personal assistant from Amazon® (SOUZA; CONCHESQUI; SILVA, 2019)

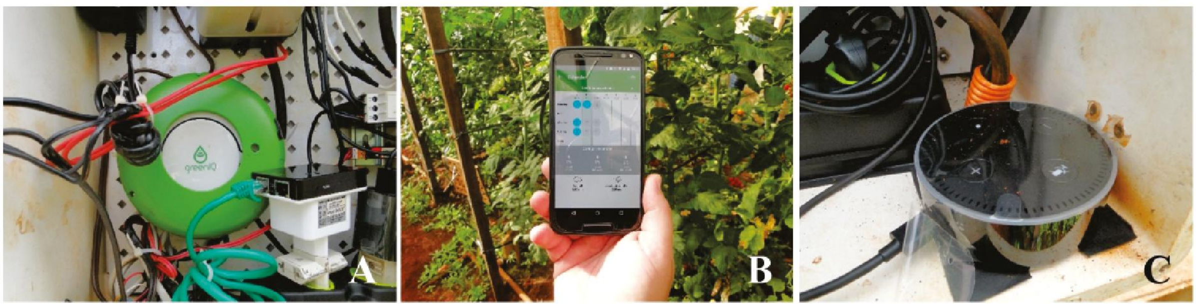
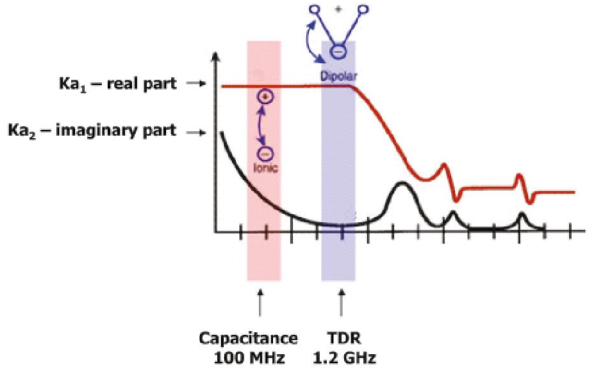


Figure 4 - Comparison of the real and imaginary dielectric constants for the composition of the apparent dielectric constant for different techniques (TDR and capacitance) in a saturated soil (SOUZA *et al*., 2016a)



According to Souza *et al*. (2016b), TDR and capacitance sensor can measure the soil water content through the propagation velocity of electromagnetic pulses, correlating this velocity with the soil dielectric constant (Ka_1). In the air this constant is equal to 1, in solid media it is between 3 and 5, and in the water it is equal to 81 (PAVÃO; SIMIONE; SOUZA, 2017). Considering the soil-water-atmosphere system, the apparent dielectric constant (Ka_2) of the soil is measured, which, in addition to Ka, also takes into account the losses for the surrounding environment (SOUZA *et al*., 2016a). The effect of the sampled medium on the propagation of the electromagnetic wave is transformed into Ka through the equation presented by Hook; Livingston (1995):

$$Ka = \left(\frac{\Delta X}{Vp.L} \right)^2 \qquad (1)$$

where,

ΔX - Distance traveled by the electromagnetic wave, m;

Vp - Propagation velocity, 0.99 (99% c);

c - Velocity of light, 3×10^8 m s^{-1};

L - Rod length, m.

Figure 5B shows the correlation between the reflection coefficient and the distance traveled, which makes it possible to identify the beginning and end of the propagation of the electromagnetic wave on the probe rod and, consequently, to calculate Ka. The generic TDR probe must comply with questions in its construction for the perfect identification of the distance traveled, Figure 5C (SOUZA *et al*., 2006b).

The possibility of adopting the TDR technique not only in the soil with obtaining of water and nutrient contents, but also in media such as the plant itself for monitoring the xylem solution is another attraction (NADLER *et al*., 2006; PAVÃO *et al*., 2014). Calibration arises from the fact that the equation developed by Topp; Davis and Annan (1980) is used as the standard, and it has limitations when applied in soils with high organic matter content, high salt concentration and presence of iron oxides, as most soils in the Brazilian territory (SOUZA *et al*., 2016a).

However, the use of TDR is limited by its price of acquisition, for both the probes and the device, which requires accurate electronics to generate the electromagnetic pulses (Table 1).

Capacitance is called as such, because its probes function as electric capacitors, which store energy, consisting of two charged coaxial plates, one positive and the other negative. These plates are placed in the soil, which

Figure 5 - A) Tektronix 1502 C reflectometer and WinTDR graphical interface; B) Monitoring of the electromagnetic wave propagation, where: X_1 is the beginning and X_2 is the end of the probe rod; and C) Detailing of TDR probe (SOUZA *et al*., 2006a; SOUZA *et al*., 2006b)

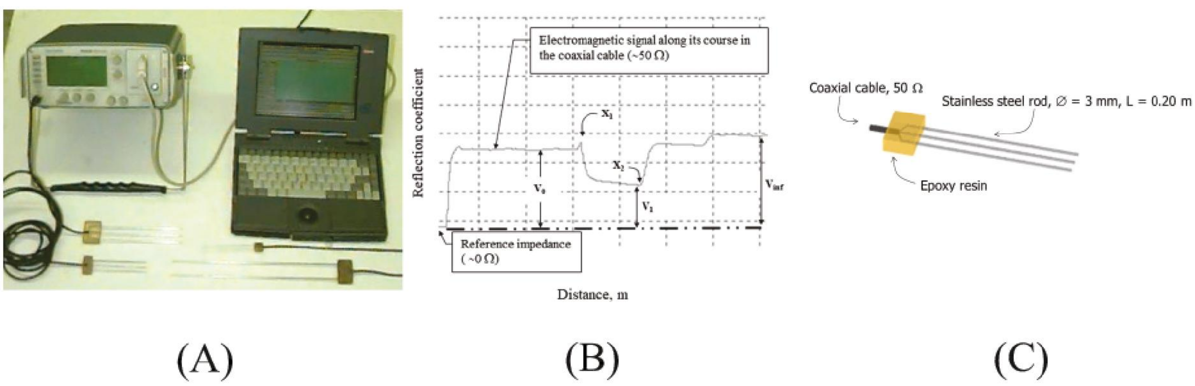


Table 1 - Comparison of minimum cost for operation between different TDR devices (adapted from ROBINSON *et al.*, 2003)

TDR	Tektronix 1502	Easy Test	Soil moisture mini Trase	ESI MP - 917	TDR 100	Soil moisture Trase	Trime FM2
Cost (US$)	116,95.00	4,707.00	6,895.00	5,350.00	3,650.00	9,550.00	4,370.00

functions as a dielectric material, separating the plates and preventing the passage of electric current between them. When one of the plates is electrified, there is an expansion of the electromagnetic field through the oscillation of the capacitors, which polarizes the water molecules present in the soil; the higher the water content in the soil, the lower the amount of energy accumulated on the surface of the probe (SOUZA *et al.*, 2016a).

Some capacitance devices do not use Ka for their moisture estimates. These devices calculate the relative frequency (RF) (SOUZA *et al.*, 2016a), which is converted into soil moisture (m^3 m^{-3}) for each type of soil using a calibration equation, suggested by the manufacturer or constructed by the user himself.

The RF aims to offer an option of correlation with water in the soil without the effect of the imaginary part (Ka_2) on the composition of Ka in the soil (Figure 1). Ka_2 is the result of the alteration of the dielectric medium by the presence of free ions and variations in temperature. Ka is composed of the sum of Ka_1 (real part) plus Ka_2, which is very effective at operating frequencies below 100 MHz (SOUZA *et al.*, 2016a). RF is defined by the following equation:

$$RF = \frac{(F_a - F_s)}{(F_a - F_w)} \quad (2)$$

where,

F_a - frequency count of the probe in the air;

F_s - frequency count of the probe in the soil;

F_w - frequency count of the probe immersed in water.

Electromagnetic techniques for agriculture management

Many experiences are described in the literature for the management of fertigated agriculture using electromagnetic techniques. Mendonça *et al.* (2020) present results that bring an interesting discussion about the possibility of using 25% of the available water capacity (AWC) for grape tomato under subsurface drip irrigation. In this study, 3 limit values of moisture were tested for irrigation management, which were monitored daily by the TDR, being 0.33, 0.29 and 0.25 m^3 m^{-3}, respectively equivalent to 100, 75 and 50% of soil AWC. Deficit irrigation of 75% AWC was the most indicated, resulting in 471 mm of applied water depth, which corresponds to 36% of the 100% AWC depth, promoting the same quality and quantity of fruits.

The main disadvantage is the need for calibration for the different tropical soils, as the presence of high levels of clay, iron oxide and organic matter can directly interfere in the measurements. As already mentioned, the techniques require water polarization for reliable measurements of the behavior of the propagation of the electromagnetic wave in the soil, which may move in a way that suggests that there is no storage because water is not free in the soil. This phenomenon is common in soils with adsorption accentuated by the increase in the specific surface of the particles, but does not compromise the management of soil water and nutrients, provided that the storage range that will be explored by the plant is defined and a specific calibration is performed under laboratory or field conditions.

Calibrations under laboratory conditions are more limited as they use disturbed soil samples, whereas calibrations under field conditions are more laborious because they involve the need to open soil pits. The literature reports a wide variety of studies on calibration for the different techniques of capacitance and TDR probes (CHEN *et al.*, 2019). An equation representing a specific calibration between the Ka or RF ratio and soil moisture can hardly be used accurately for another type of soil (SOUZA *et al.*, 2013).

Berça; Mendonça and Souza (2019) used TDR probes to monitor the effect of sugarcane straw as mulch on the distribution and storage of fertigated water and nutrients in cabbage. These authors concluded that the use of organic mulch did not interfere in cabbage yield and promoted savings of up to 28.1 mm (14.5%) in the water depth used.

About FDR, Bello; Tfwala and Rensburg (2019) suggest the use of automated sensors for irrigation management through continuous monitoring of water absorption by plants. In addition to the use of the electromagnetic technique for the management of fertigation, it can also be used in the mapping of the solution in the analyzed profile by correlation with geostatistics. This is what happens, for example, in the use of SURFER software, from the company Golden Software.

According to Golden Software (2017), SURFER is a program based on data interpolation for the construction of two-dimensional and three-dimensional grids that can be used by geologists, archaeologists, engineers, oceanographers, biologists, climatologists and other professionals. Examples of the varied applications of SURFER are the studies of Grecco; Bizari and Souza (2016) and Souza and Matsura (2004) in the spatial and temporal characterization of patterns of water and solute distribution in the soil, Figure 6.

Efficiency and technological advances in fertigation

Fertigation is a technique of fertilizer application via irrigation water, whose main advantages are the increase in yield and quality of food and the reduction of costs with labor and fertilizers. Despite these and other advantages, investment and skilled labor are required to carry out management properly (INCROCCI; MASSA; PARDOSSI, 2017).

The main technological advances in irrigation and fertigation refer to the use of irrigation systems and more modern injection devices, which provide the most efficient application of water and fertilizers, besides enabling the whole process to be optimized through automation.

One of the major technological advances in fertigation is the possibility of using sensors and remote control through the IoT technology. In high-tech automatic systems, the equipment can be used in harmony with agriculture. This means that sensors in the soil to collect EC and pH data, for example, can be used to adjust injection systems in real time.

Although current technology enables a high efficiency of fertigation in any method of pressurized irrigation, the localized method is the one that has the greatest benefits, especially for regions with scarcity of water resources. Localized irrigation, besides reducing nutrient losses for applying them close to the roots, is the one that best adjusts to the water saving strategies. In addition, it allows safer use of wastewater, an activity that is being used in almost all the world and tends to expand more and more (NARAIN-FORD *et al.*, 2020).

The current technological advance has facilitated access to more sophisticated equipment, which allows controlling the EC and pH of the solution automatically and/or applying the nutrient solution at a constant concentration and in several sectors at the same time. Dosing pumps and automatic fertigation systems are some examples (Figure 7).

This device offers a complete possibility for precise fertigation, as it makes it possible to inject and dose nutrient solutions proportionally (regardless of pressure variation), keeping them within the ideal ranges of EC and pH (CARRIJO *et al.*, 2001). In addition, it can be easily automated and used simultaneously in various sectors. Despite the advantages, this device is expensive, needs power to operate, lacks skilled manpower to operate and requires continuous inspection and maintenance. The operating principle may vary according to the manufacturer. In general, the device is able to inject into the main irrigation pipe various fertilizers and acids, from a single homogeneous solution contained in mixing chambers.

The suction of fertilizers and acid in the dosing channels can be done through Venturi injectors, centrifugal pumps or dosing pumps. Especially when the injection is done through Venturis, an auxiliary booster pump is required to create the pressure difference for suction. This auxiliary pump enables the use of Venturis with high suction capacity and low consumption of motive flow. The form of installation can be inline (Figure 8A) or in two bypass configurations (Figure 8B and 8C).

Head losses are lower in bypass installation, especially when the device is connected before and after the irrigation pump. In this scheme, the irrigation pump can serve as a dosing booster pump. The operation of this type of device is based on the programming of a control panel (Figure 9).

The options available in the panel, which vary according to the manufacturer, makes it possible for example to register and select formulations (nutrient solutions) specific to a given crop, to adjust the EC or pH of the solution to a desired value (via algorithms), to choose independent settings for each sector to be fertigated, to enable alarms for maximum and minimum values of EC and pH, among other options. Fertigation can be initiated from an irrigation controller and, depending on the model, it is also possible to control irrigation.

The maintenance of this system is usually performed at short intervals (daily, weekly, others) and involves several procedures such as cleaning filters (fertilizer and supply water), inspection for water and fertilizer leaks, calibration of the sensors of EC, pH etc.

Automation has enabled higher efficiency in the use of resources, due to greater control of activities. The application of water and fertilizers in the right quantity and at the ideal time, the reduction in pump actuation and the lower human intervention have promoted greater yield and saving of water, energy, fertilizers and labor, among other advantages. Some studies show that the use of modern irrigation and fertigation systems can increase yield and/or reduce environmental costs and impacts (CHAUHDARY *et al.*, 2020; KASSING; SCHUTTER; ABRAHAM, 2020).

Figure 6 - Soil moisture profiles (m^3 m^{-3}) for drip irrigation with flow rates of 2 and 4 L h^{-1} (SOUZA; MATSURA, 2004)

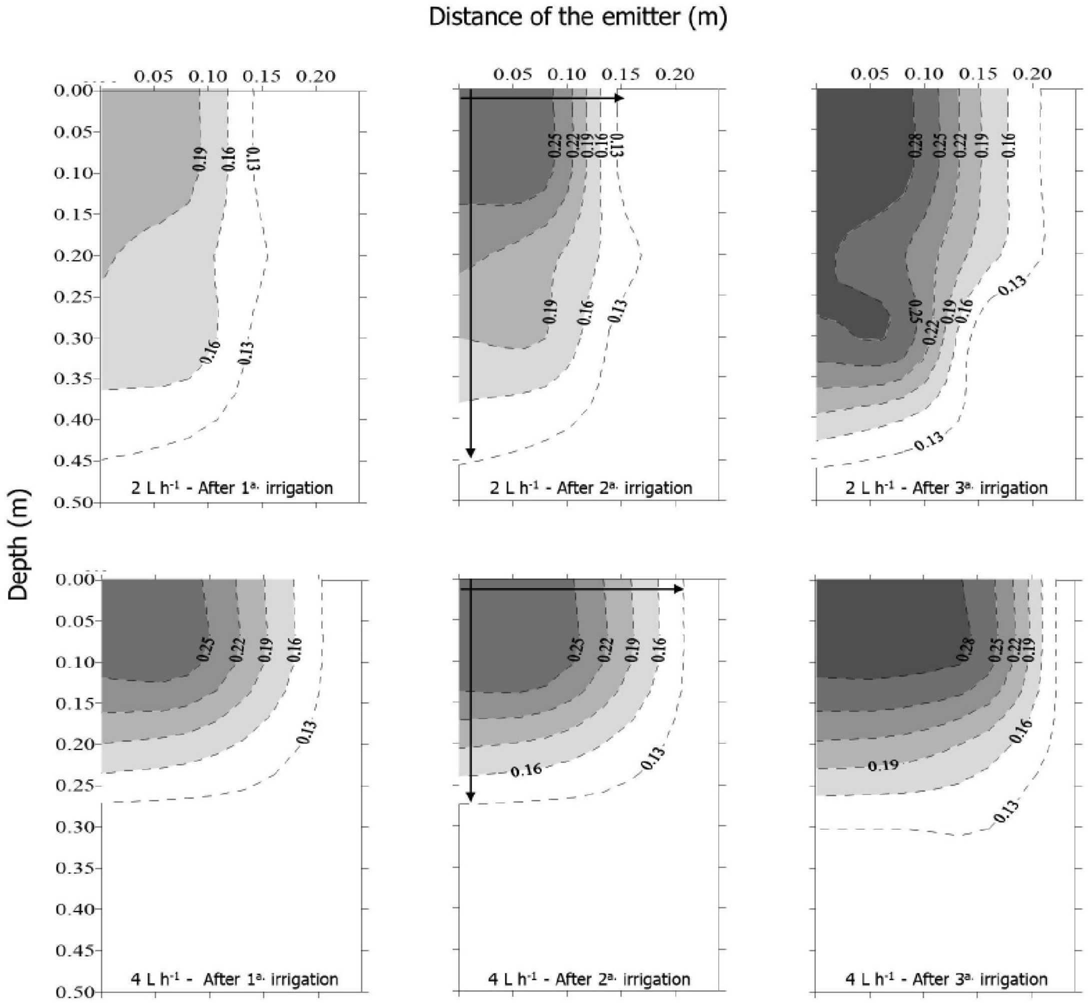
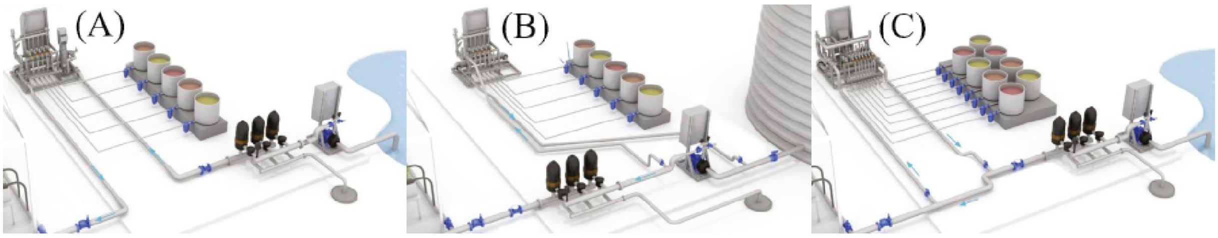


Figure 7 - Hydraulic dosing pump (A) and automatic fertigation system (B)

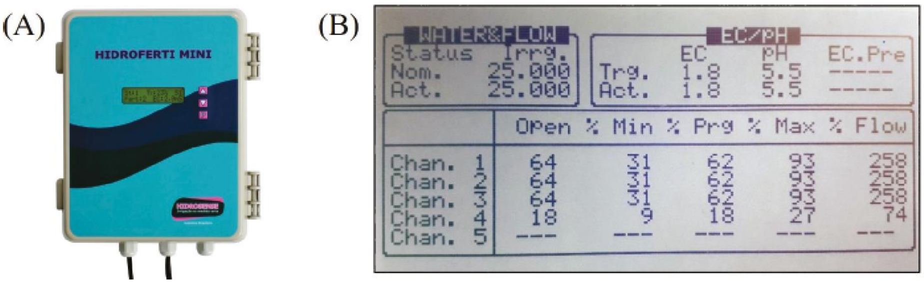
Source: gavish.intercallchat.info and cannapro.com

Figure 8 - Installation schemes for a NetaJet automatic fertigation system: inline (A), and in bypass with the system connected before and after the irrigation pump (B) and after the irrigation pump (C)



Source: netafim.com

Figure 9 - Fertigation controller panel (A) and detail of the program interface (B)



Source: hidrosense.com.br

Considerations on fertigation management - case of irrigating communities with pressurized distribution networks

If the fertilizer distribution scale is expanded and the injection is performed in community systems or systems that supply different plots / users, through a pressurized network with a high number of hydrants, the problem of obtaining a good uniformity becomes more complex. This is the case in regions such as the Mediterranean, where there are problems with water supply both spatially and temporally. A common solution in the search for improved water management is the construction and management of collective irrigation infrastructures. For this, on many occasions they are constructed in irrigating communities (association of water users). Through these community structures, the goal is to improve the abstraction and distribution of water, from the points of view of both water and energy efficiency.

In Spain, the irrigated area in 2019 is estimated at 3.83 million ha, of which more than 76% are drip systems (53%) and sprinkler systems (23%) (ESYRCE, 2019). Such distribution is due to a modernization process, promoted by public administration, combining public and private resources (TARJUELO *et al.*, 2015). On the other hand, at least 80% of this entire irrigated area is maintained under community irrigation structures. Therefore, most of them are pressure irrigation networks that have some kind of automation system and control of irrigation, and many of them have community fertigation systems (GARCIA, 2018).

Collective fertigation is even more justified when there are major monocultures with homogeneous fertilizer needs and the average dimension of the exploitation of each producer is small, with paradigmatic cases such as the Valencian community, where traditionally the average dimension of the plot is very small (less than 1 ha) and citrus monoculture is dominant (ORTEGA-REIG *et al.*, 2017).

The way to operate the necessary infrastructure and manage fertigation is varied and will depend greatly on the degree of automation and management of the network. First, the way water is distributed will be decisive; for example, if the network operates on demand (organization with total flexibility), where each user can freely open the water output of its plot, the fertilizer flow injected must be continuous and proportional to the flow transported by the main network. In this situation, the injector device must consist of electric injectors, preferably centrifugal type, where the solution flow will be adjusted by modifying the speed of rotation of the pump. For this, it will be necessary to use a frequency variator for the pump motor, operated under the pulse transmitter of the meter or the electronic flow meter, located in the main pipe of the distribution network. If this is the operating scheme, the solenoid valves are not required at the different outlets in the field, since it is not the end user who performs the opening and closing operation.

If the network distributes water in fixed sectors or shifts (rigid organization) and each plot has the same irrigation time determined by the network managers, the collective injection can be programmed in a more rational and fractionated manner, distributing the times for cleaning and application of each fertilizer. However, in this case, a much higher degree of automation is required, and it is necessary to equip all multi-user hydrants with solenoid valves. In this case, the injection devices that can be used are enlarged, although electric injectors are always more interesting for community networks, with piston pumps giving good results in this condition.

However, the introduction of new crops in the irrigation sectors, which have different water or fertilizer needs compared to monoculture, implies not applying the same treatment for all plots. Another important change arises when many of the plots are used for organic cultivation, which implies washing of the network of substances that are not compatible (GENERALITAT VALENCIANA, 2020).

Under these new conditions, the options of on-demand irrigation systems are no longer viable for a correct distribution of fertilizers, and it is almost mandatory that the control of irrigation and fertigation times be fully organized by network managers and not by end users. Jiménez-Bello *et al.* (2011) studied the behavior of the water distribution network and the behavior of fertilizer evolution for each hydrant, analyzing how irrigation programming conditioned the time of fertilizer application in each plot.

It is possible to establish a methodology, by means of an EPANET model (ROSSMAN, 2000), that homogenizes irrigation times if there are users who do not want fertigation. Likewise, if the network is dependent on energy for pressurization, it is possible to establish strategies to ensure adequate fertigation times. An interesting conclusion of this model is that, if there are hydrants/plots that do not want community fertigation, it is difficult to ensure that no amount of chemical reaches them, while maintaining the correct time of fertilization.

Other complementary measures are defined for this management, thus requiring the sectorization and hydraulic regulation of the network, which includes monitoring by means of EC and pH sensors in the head control, before and after injection and in critical hydrants of the network, to monitor and verify the appropriate dosage of fertilizer. In addition, for the injection of products with high added value and at low concentrations, it is necessary to design, besides the main heads, product injection hydrants in strategic points of the network, to reduce travel times and optimize the application of the products (GENERALITAT VALENCIANA, 2020).

IRRIGATION MANAGEMENT USING REMOTE SENSING

In order to provide spectral and spatial information during the crop season, remote sensing (RS) has been widely applied in the monitoring of the temporal and spatial variability of agricultural crops in recent years. Among the activities in agriculture, RS is being widely applied in the field of irrigation for a more efficient water management. In RS, data are obtained by means of sensors that capture the reflectance of plants without direct contact with the target, making RS an alternative of a non-destructive method to indirectly measure the water status of the plants, for example.

However, it is worth pointing out that the effective monitoring of crops using RS depends on the type of platform on which the sensor will be embedded as well as on the level of collection (orbital, aerial and terrestrial), and spatial, spectral, radiometric and temporal resolutions may interfere with monitoring (BERNI *et al.*, 2009). Thus, we will briefly discuss the use of RS for irrigation management, which can be employed to estimate the evapotranspiration rate (REYES-GONZÁLEZ *et al.*, 2018; MOKHTARI *et al.*, 2019), water deficit (VIRNODKAR *et al.*, 2020), and consequently propose an adequate irrigation schedule of how much and when to irrigate, or using variable-rate irrigation (VRI) techniques based on the values of vegetation indices (O'SHAUGHNESSY *et al.*, 2019; BHATTI *et al.*, 2020).

Estimation of water status

Among the spectral bands used in the monitoring of irrigation management, the thermal band, in the infrared region, is the one that has a direct correlation with the estimate of plant water status, as water status is based on leaf temperature, which is inversely proportional to stomatal opening and transpiration (FUCHS, 1990), being commonly used to calculate the crop water stress index (CWSI). Thermal sensors capture leaf temperature changes more easily, indicating variations in water status and stomatal conductance, which consequently may result in yield gains, which can reach up to 30% (LOPES; REYNOLDS, 2010) when irrigation is adjusted based on these parameters.

Despite not compromising the use in agriculture, the application of thermal images has some limitations, such as the high cost of cameras (KHANAL *et al.*, 2017) and low resolution of images (satellites or unmanned aerial vehicle - UAV), which can cause the extraction of mixed pixel (JONES; SIRAULT, 2014). However, despite these limitations, several applications of thermal images and UAV, including their use in water status estimation, are presented by Messina and Modica (2020).

Due to the low spectral resolution of thermal images, several vegetation indices (VI) that use the visible and near infrared (NIR) bands have been proposed as an alternative in the monitoring of crop water stress, mainly in the estimation of leaf water potential (LWP) and stomatal conductance. VIs that use visible and NIR bands in their composition are able to detect physiological changes in the photosynthetic apparatus, such as increased degradation of chlorophylls, carotenoids and xanthophylls, which consequently reduces leaf reflectance, besides reducing stomatal opening under water stress conditions (ZARCO-TEJADA *et al.*, 2013).

Estimating LWP by means of RS increases the capacity of analysis in a commercial area (COHEN *et al.*, 2015), which consequently makes it possible to generate spatial variability maps of the plantation based on the indices that estimate water stress. In addition, it makes it possible to monitor variations in water use by the crop, increasing the accuracy in irrigation management (COHEN *et al.*, 2015; QUEBRAJO *et al.*, 2018).

The normalized difference vegetation index (NDVI), developed by Rouse *et al.* (1974), is the most usual among the VIs that have a structural correlation with plant water stress, that is, VIs with good correction with variations in stomatal conductance and LWP. Other VIs, such as renormalized difference vegetation index - RDVI (ROUJEAN; BREON, 1995), and optimized soil adjusted vegetation index - OSAVI (HABOUDANE *et al.*, 2002), have also been pointed out as an alternative for monitoring water stress, especially when the vegetation cover is low and, consequently, soil reflectance interferes in the values of the vegetation pixels. This is one of the main advantages in the use of these VIs, especially when using satellite images.

In addition to these VIs that use only the visible spectrum, the normalized difference water index - NDWI (GAO *et al.*, 1996) can be used as an alternative to estimate LWP, as it is generated from the combination of wavelengths in the NIR and shortwave infrared (SWIF) ranges. So, this VI can capture changes in reflectance due to changes in the internal structure of the leaf through the NIR, as well as changes in leaf water content through the SWIF (IHUOMA and MADRAMOOTOO, 2017). Consequently, these factors make it a potential option to manage the LWP and irrigation of crops.

Estimation of Evapotranspiration (ET) and Crop Coefficient (kc)

Crop irrigation schedule around the world is based on ET estimation, which considers the kc of crops at each stage of development. Estimating ET is essential to manage irrigation and make efficient use of water. There are different ways to estimate ET, either directly (weighing lysimeter and soil water balance) or indirect (pan evaporation, atmometer, Bowen ratio energy balance system (BREBS), eddy covariance (EC), scintillometer, sap flow and remote sensing (ALLEN *et al.*, 2011; REYES-GONZÁLEZ *et al.*, 2017).

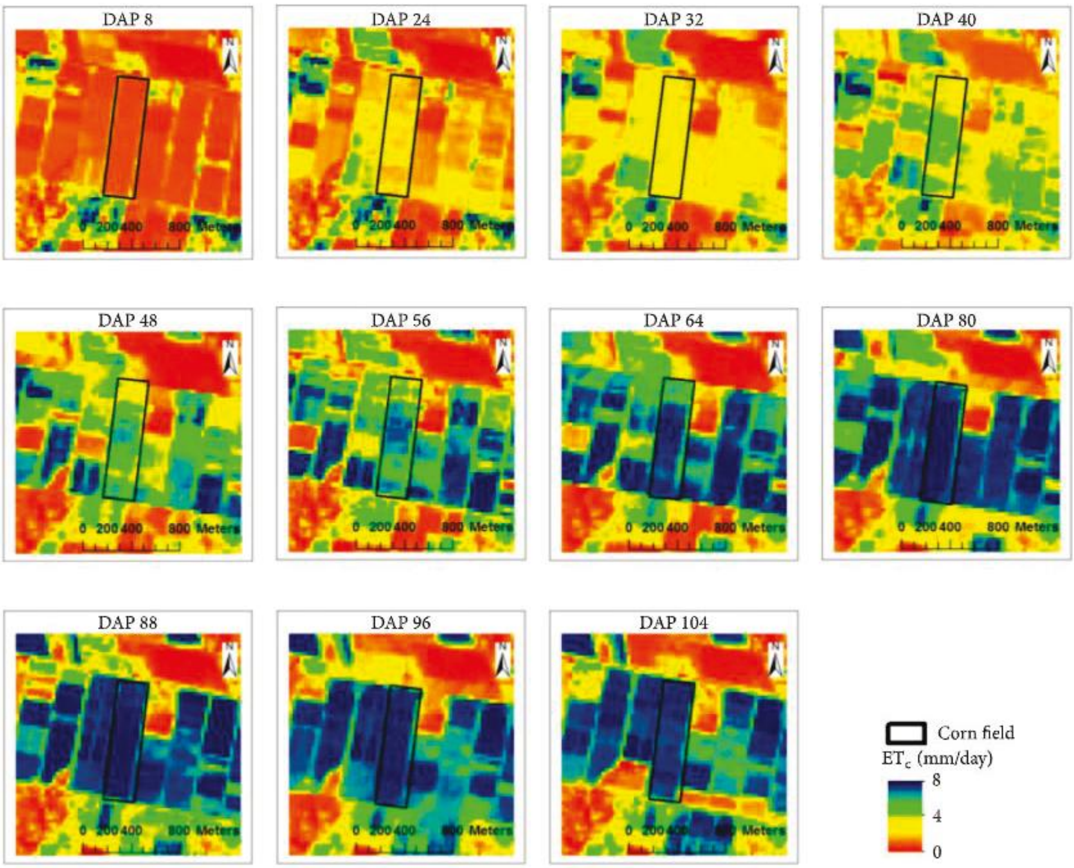
Due to the rapid growth and adoption of remote sensing and its ability to cover extensive areas, several researchers around the world have used satellite images to estimate ET, through mathematical models and VIs, proposing irrigation schedule based on spatial variation of ET (FRENCH *et al.*, 2015; CHEN *et al.*, 2018; OLIVEIRA-GUERRA *et al.*, 2020).

Mapping evapotranspiration at high resolution using internalized calibration (MATRIC - ALLEN *et al.*, 2007), and the surface energy balance algorithm for land (SEBAL - BASTIAANSSEN *et al.*, 1998), from which the former is derived, are the most used models to estimate ET in various crops. These models combine visible spectral, NIR and thermal bands together with meteorological data to empirically estimate spatial variations of hydrometeorological parameters useful for water management and use, especially irrigation management (SANTOS *et al.*, 2008; REYES-GONZÁLEZ *et al.*, 2017; FRENCH *et al.*, 2015; ANDERSON *et al.*, 2012).

Among the main advantages of using RS to access ET is that, through the construction of spatial variability maps of ET using VIs, it is possible to visualize and identify spatial variations within the same area, whereas the use of only local weather stations does not have such a dimension of variability. This advantage allows making better decisions and understanding the dynamics of water consumption by crops over time. Estimating ET by means of RS can reduce by up to 18% the amount of water destined for irrigation, taking NDVI as an irrigation management parameter (REYES-GONZÁLEZ *et al.*, 2018). In addition, through spatial and temporal analysis it is possible to verify the water requirement in each stage crop development (Figure 10).

Using satellite images (Landsat) to extract the reflectance values and calculate the NDVI, linear models showed the relationship of Kc estimated by NDVI with the reference values stipulated by FAO-56 for grass

Figure 10 - Temporal and spatial ETc calculated using NDVI from Landsat 7 and Landsat 8 images for silage corn crop. Lighter values indicate lower water requirement and darker values indicate higher water demand. (Adapted from REYES-GONZÁLEZ *et al.*, 2018)



(kc = 1.5507*NDVI - 0.0229) and for alfalfa (kc = 1.1981*NDVI - 0.1002) in the Lagunera region, Mexico (REYS-GONZÁLEZ *et al.*, 2018). Similarly, but using MODIS images, Kamble *et al.* (2013) developed a linear model (kc = 1.457*NDVI – 0.1725) for corn crop in which NDVI variations are related to Kc variations of the crop during its growth cycle, mainly in irrigated areas.

However, it is important to emphasize that the estimation of kc using VI may vary in space and time, especially due to variations in the cropping system and agroclimatic characteristics of each region, so the values estimated for a crop in a given region may not be applicable for other growing regions (VANINO *et al.*, 2015; VILLAGRA *et al.*, 2014), which makes it necessary to analyze and develop local methods that are functional for each region. Despite this geospatial limitation, the use of RS techniques to assist in irrigation programming may be more accurate than fixed values in the literature (VANINO *et al.*, 2015), such as those pre-established by FAO-56. This is because the methods that use RS consider the spatial variability of the crops, which allows different managements and consequently better water use.

PRECISION AGRICULTURE: MANAGEMENT ZONES FOR DIFFERENTIATED OR VARIABLE-RATE IRRIGATION

In conventional agriculture, the heterogeneity present in an agricultural production area is not considered, and average values of soil and plant attributes, representative of this same area considered as uniform, are taken into account for decision-making regarding the performance of an agricultural practice, usually related to the application of an input (fertilizer, soil amendments, seed, water, pesticide etc.), soil sampling, plant sampling and harvest.

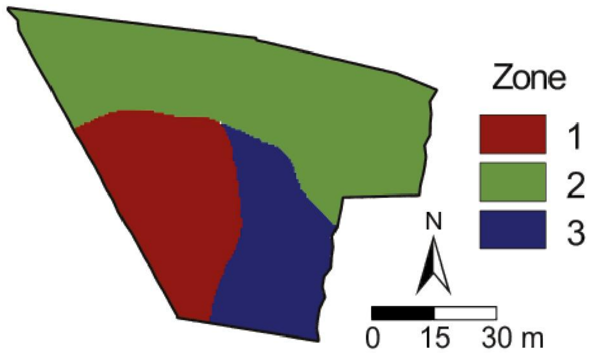
However, from the end of the 1980s, the performance of agricultural practices in a specific way with local conditions of cultivation became an object of interest (ARSLAN; COLVIN, 2002), that is, precision agriculture (PA). Thus, the variability between the various parts of an agricultural area began to be considered in the performance of agricultural management, which led to the need to perform an agricultural practice uniformly in one sub-area, but in a differentiated way in relation to another sub-area. Each sub-area that receives a specific management is defined as a management zone (MZ).

The heterogeneity present in an agricultural field is caused by the spatial and temporal variation of several factors such as climate, topography and biological activity (CÓRDOBA *et al.*, 2013), or even, MZ is a sub-region that is relatively homogeneous in terms of soil and topography attributes (ROUDIER *et al.*, 2008; HAGHVERDI *et al.*, 2015), and for which a specific application rate should be used (ROUDIER *et al.*, 2008). Thus, there may be a reduction of resources used and optimization of yield (SCHEPERS *et al.*, 2004). Therefore, delineating the MZ is a critical problem due to the varied situations of heterogeneity encountered in agriculture and the purpose for its application.

When the temporal-spatial variation of the area to be irrigated is significant, the application of water at variable rate or in a differentiated way by an irrigation system can improve water use efficiency and crop yield. Conventional irrigation management, without considering such variability, helps to define the moment and how much to irrigate, while variable-rate irrigation can help improve the definition of how much and where to irrigate. The methods for delineating MZ may vary according to the data used and the techniques used for this. Embedded sensors, proximal remote sensing, and orbital sensors can aid in field data collection. Spatial and temporal resolution and accuracy vary depending on available data and influence the MZ delineation. Yield data only may not have a good potential for MZ delineation due to temporal variability. In practice, the knowledge that the farmers have about the conditions of their cropping area can also be very useful for choosing the most appropriate data for defining MZ for irrigation (HAGHVERDI *et al.*, 2015).

Knowledge on the spatial variability of water storage (Figure 11) facilitates the performance of the differentiated management of irrigation in the field, while the temporal stability of this attribute can identify, in the field, points that best represented the spatial average for the area. Furthermore, from this knowledge, it is possible to reduce the number of samples needed to estimate a representative average with high precision and to determine representative points of the area that can be used for soil water monitoring (LEMOS FILHO *et al.*, 2015; LEMOS FILHO *et al.*, 2016).

Figure 11 - Example of spatial variability of soil water storage in agricultural area



MZs can be defined based on one soil attribute, such as the available water at the effective depth of the root system of the crop, using geostatistical analysis (NASCIMENTO *et al.*, 2014), based on the particle-size composition of the soil as percentages of sand, silt and clay (OLDONI *et al.*, 2018), or based on various soil attributes, such as apparent electrical conductivity (ECa), particle-size composition, bulk density and available water (OLDONI; BASSOI, 2016), when the multivariate analysis fuzzy c-means clustering can be used to define the number of MZ. Jiang *et al.* (2011) used four soil attributes (saturation moisture, field capacity, permanent wilting point and bulk density) to characterize soil spatial variability and, through principal component analysis, obtained the delineation of two MZs, besides providing a means of verification as to the optimal number of soil samples to be obtained.

Despite the development already carried out and the knowledge already acquired regarding the use of MZ for the differentiated management of irrigation or water application at variable rate according to the variability found in the field, Smith and Baillie (2009) state that the commonly used meaning for the term precision irrigation addresses the application of water volume at the depth of the soil profile explored by the root system of plants and at the desired time, but uniformly, without taking into account the variability of the area, besides being also associated with the use of equipment and sensors for the practice of irrigation. Thus, the term precision irrigation is used incorrectly.

According to the International Society of Precision Agriculture (2019), PA is a management strategy that gathers, processes and analyzes temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production. Thus, the correct concept of the term precision irrigation, using the principles of precision agriculture, is more comprehensive, as it must involve differentiated irrigation as a function of the variability presented by the soil and plant and be adapted and applicable to all irrigation methods.

Nascimento *et al*. (2014) showed that it is possible to reduce the water depth applied by drip system in MZ with higher availability of water in the root zone of the crop, through the monitoring of soil water, and without reducing the yield of table grape. Vellidis *et al*. (2016) developed a variable-rate irrigation control system in a center pivot, based on soil moisture monitoring by sensors installed in MZs and that determined the differentiated application of water, which promoted a 30% saving of water and a similar peanut yield compared to that obtained under uniform irrigation management.

CONCLUSIONS

1 - To ensure the sustainability of irrigated agriculture, considering the future prospects, where water availability can be reduced due to anthropic actions in nature, the use of automated and high-precision irrigation systems is expected to increase significantly in the coming years, expanding with the advancement of technology;

2 - However, despite the high efficiency of these systems, information of soil, climate and plant attributes obtained through the range of data provided by sensors will be responsible for mitigating the global impacts caused by irrigated agriculture in the near future, since this information can enhance precision irrigation with maximum efficiency, thus reducing water consumption by agriculture.

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