ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20210416103500

Subject review

An Overview of Precision Irrigation Systems Used in Agriculture

Ivan Plaščak, Mladen Jurišić, Dorijan Radočaj, Milan Vujić, Domagoj Zimmer*

Abstract: The introduction of precision agriculture increased the efficiency of plant production, while simultaneously reducing the production cost. Precision irrigation can be considered as the combination of sensors, computer software and irrigation systems. Precision irrigation has reduced water consumption and increased yields, and thus increased economic profits. The development of new crop monitoring technologies in precision irrigation has been made possible by the imaging and analysis of real-time crop condition data. The aim of this study was to describe the present state and possibilities of precision irrigation in practice in the EU and Croatia. An overview of the current precision irrigation technologies, as well as its adaptive management to the decision-making in agricultural water management, represents a fundamental basis for future practical studies in precision irrigation.

Keywords: micro-irrigation/flooding; precision agriculture; rainfall irrigation/flooding; sensors; simulation; surface irrigation/flooding

1 INTRODUCTION

The application of irrigation systems in agriculture in Europe is near 30%, while in Croatia it is only about 2% [1]. The available water levels are in constant decline in the world, which urges for the accurate determination of the exact amount of water required by the crops during the growing season. Precision agriculture is defined as the technology based on the identification and management of variabilities within the agricultural field for optimal profitability, sustainability and protection of land resources [2]. The advantages of precision agriculture in terms of economic and environmental benefits are in the reduced use of water, fertilizers, herbicides and pesticides [3]. One of the most important areas in which precision agriculture is applied is the management of soil properties heterogeneity, which is crucial for most agrotechnical operations [4]. Precision irrigation requires the possession of soil-related information such as: texture, water capacity, moisture and crop water demand at certain growth stages. The procedures within precision irrigation are supported by technical components, such as sensors and computer processing software.

In the water the soil is bound to the soil particles with the force that the root system must overcome during the water absorption. Therefore, water in the soil is divided into accessible (free) and inaccessible (bound). The forces that hold water along the soil particles are the moisture tension (surface, hydrostatic and gravitational forces), and the osmotic pressure of the water soil phase [5]. In [6], on agricultural lands that do not have enough water for crop production during their partial or full growth period, water should be artificially applied. All operations which include the man-made and artificial increase of the soil water content with the aim of crop production are considered as irrigation.

Author [7] stated that thermal remote sensing used for the determination of crop water content is based on the emitted radiation of the plant in relation to the temperature difference between the leaf and stem. It significantly varies with air temperature and evapotranspiration intensity. The best method for determining soil moisture in potato cultivation were studied in research of [8]. The authors noted the efficiency of watermark tensiometers for that application. However, they emphasize the need for a calibration curve in order to relate the values of pressure (kPa or cbar) and volume of soil water content (vol%) to the current soil moisture. The same authors stated that Aquaterr sensors were sensitive to changes in soil temperature and therefore do not recommend their use in potato cultivation. According to [9], the efficiency of watermark sensors depends on weather conditions. The depth of sensor placement should not be the same in average climatic years and in years with extreme weather conditions. Authors [10] measured soil water content on five soil types with the help of electrical conductivity, and the influence of the change in the amount of water for future soil mapping was confirmed, similar to measures of [11]. Many authors [5, 12] divided the irrigation systems into three fundamental methods: surface irrigation/flooding, rainfall irrigation/flooding and micro-irrigation systems.

2 THE DEVELOPMENT OF PRECISION IRRIGATION

Research related to precision irrigation began in the United States in the early 1990s. The research was largely based on the modification of mobile irrigation systems that are able to cover a large area and apply a diverse amount of water. Such systems were controlled using the input spatial data [13]. Various procedures have been evaluated to implement valve control to achieve the desired application of irrigation rates. It was concluded that due to the cost and complexity of these systems, economic feasibility depends on large agricultural production and does not pay off for small farmers [14]. The number of studies by European researchers regarding precision irrigation increased in the 2000s and emphasis was placed on the purpose and performance of spatially variable irrigation rates [15-19].

The studies conducted by [20] and [21] included the application of an infrared thermometer mounted on a rain wing. These pivot systems were used for the data collection of soil temperature and plant surface temperature for the development of automatic irrigation. Authors [20] concluded that the method of modeling the dynamics of crop cover temperature can be cost-efficient. Due to the low cost and simplicity of the method, this method became accessible for smaller farmers as well.

Additional research conducted in Europe, according to authors [15], focused on variations in yields due to uneven irrigation. In New Zealand, authors [22] investigated water savings and the economic benefits of precision irrigation using pivot systems. Common features of these studies include: the emphasis on system design and control to obtain spatially diverse applications; the use of global navigation satellite system (GNSS) for irrigation control using previously created soil maps; and differential irrigation in the areas from 40 to 100 m^2. Authors [16] focused on the development and testing of digital control systems that use an embedded computer to process and apply transmitted radio waves. They used the low-energy precision application (LEPA) system on the pivot irrigation system. It was concluded that pivot systems and LEPA can be corrected for the application of spatially different irrigation. The common precision irrigation strategy was to change the amount of water rates, and thus the depth of water application. Precision irrigation relies on the development of the appropriate irrigation management systems based on the data collected about the crop requirements for water and nutrients in real-time.

The notion of spatially variable irrigation is based on the hypothesis that each plant requires a non-uniform amount of water due to the difference in root system depth. The yield is maximum if each plant receives the exact amount of water it requires, considering the within-field heterogeneity [16].

The primary objective of precision irrigation is to optimize the amount of water in the entire agricultural field. Variable-rate irrigation in specific locations can achieve significant water savings [14]. According to authors [19], variable-rate can produce water savings in the range from 10 to 15 % compared to the conventional methods. Authors [23] even estimated that the potential water savings using precision irrigation can reach about 25 %.

Authors [24] observed that the potato yield using the pivot systems based on the spatially variable irrigation systems can increase the yield from 4 to 6 %. Crop modeling and spatially variable irrigation have proven to be essential and effective means of yield management. Two authors [25] used the CERES model to model maize crops and the feasibility of maize irrigation. Spatially variable irrigation also resulted in higher maize yields. However, in some instances, multiple authors [26-28] pointed to the fact that such a system might not be profitable for small farmers.

3 PRECISION IRRIGATION METHODS AND SYSTEMS

3.1 Surface/flooding Irrigation

The rirmod irrigation model has been accepted as a standard for the evaluation and optimization of surface furrow irrigation in Australia [29]. It is based on solving full hydrodynamic equations and its accuracy is determined only by input parameters. This model uses real-time irrigation data and creates irrigation statistics for future use. Using the Winsrfr model and the aim model, many authors [30, 31] used approximate hydrodynamic equations and their accuracy was determined only for individual situations.

Real-time automation and adaptability control produced quality results for managing infiltration time variability. According to authors [32], this procedure ensures greater efficiency of irrigation compared to traditional irrigation estimates, allowing significant labor savings. The real-time control system monitors the water movement along the furrow. It determines the characteristics of soil absorption through the simulation procedure and therefore modifies the input variables (water flow and moment of irrigation cessation). If the set irrigation parameters are continuous and change automatically, it means that the irrigation system is adaptable to the conditions in the field.

AWMA Pyt Ltd, is an Australian company that developed the aquator system for automatic and remote control of water resources. Operations assigned via aquator are transmitted by a device that is most commonly mounted on the base station roof. The control openings have built-in receivers and are powered via solar panels. Reverse remote reading was developed by authors [33] as an alternative contact sensor that serves to monitor the progress of water entry into the furrows and allow automatic control of water flow. The camera is located at the field boundary and images water flowing down the furrow during irrigation. The images are analyzed by a computer system to calculate the actual position of the incoming water.

Authors [32] laid the foundations for the practical control of furrow irrigation in real-time. The proposed system includes: automatic start of inflow into furrows and its measurement; measuring the water flow through the furrows; real-time assessment of soil infiltration and soil moisture deficiency; real-time simulation and optimization of interruption time and automatic shutdown of inflow at the set time. The system performs all procedures without user interaction.

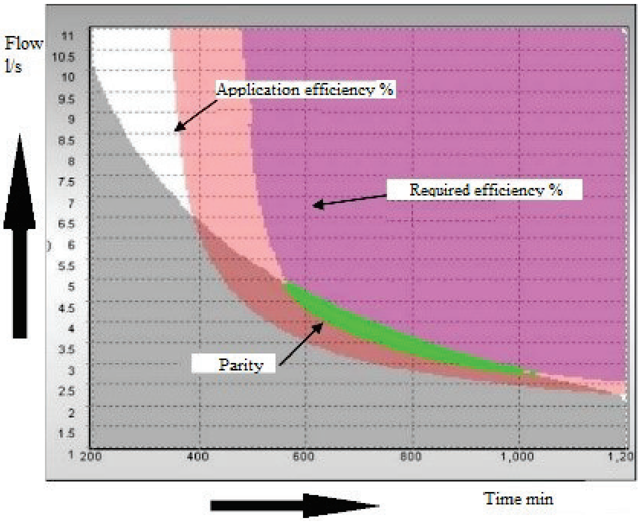


Figure 1 IrriPro optimization screen [34]

Decision-making software is an important segment for such a system and includes: continuous flow measurement using pressure measurement in the supply system; earlier soil characterization by determining the soil type; and the probability of water infiltration into the soil. The IrriPro software package was developed to extend the hydraulic modeling of a single furrow or an entire field. It uses hydrodynamic equations and multiple simulations for each furrow in the field and combines the results to create 2D networks of applied depths (Fig. 1 and 2). It then determines the flow rate and the end time of the flow in order to achieve maximum effect.

Fig. 1. represents an example of the IrriPro optimization screen, which lists the parameters for multiple furrows in the entire field. The green area indicates the zone of optimal performance. Fig. 2 shows the predicted irrigation end periods for 84 furrows, considering the heterogeneity of the furrows.

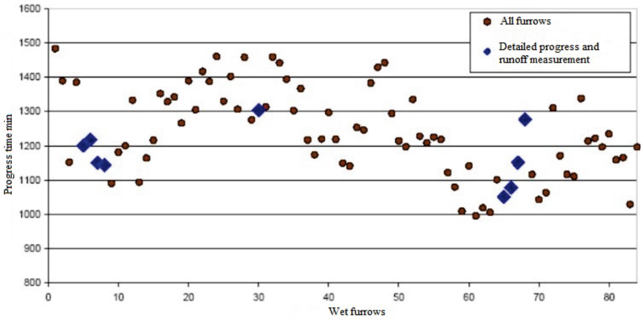


Figure 2 IrriPro predicted irrigation end periods [34]

3.2 Rainfall Irrigation

Simulations of rainfall irrigation/flooding models have been rapidly evolving over the last two decades. The computer software Space Pro includes the known templates for the purpose of selecting the size and spacing of the sprayers for the maximization of irrigation uniformity. This software relies on known parameters for each sprayer, such as the pressure and above ground height. The wind influence is usually neglected in the process, which impairs the efficiency of the sprayer [35]. Two main approaches are commonly used: a ballistic approach to calculate the flight path of individual water droplets; and an empirical approach involving extrapolation from measured parameters. These parameters include varying wind speeds and directions, pressure and droplet flight path.

Travgun is the model developed by authors [36], which uses the irrigation direction to calculate the wind-free pattern and to determine the six parameters used to adjust the wind impact pattern. The information obtained from the model is an estimate of the uniformity of irrigation application for any angle, distance, droplet flight path, wind speed and direction. The model does not predict irrigation depths at specific points in the field. The purpose of all models is to assess the uniformity of irrigation, the selection of appropriate nozzles and their spacing.

Of all irrigation systems, rainwater irrigation systems offer the greatest potential for uniform irrigation, as they are easily adaptable for spatially variable management. Significant progress has been made in the development of hardware to control the pivot system with the aim of achieving irrigation precision. According to authors [37], further development of decision-making tools in irrigation pivot systems is needed to achieve optimal irrigation accuracy.

A number of technologies for the variable water irrigation have been developed, classifying them as [16]: multiple discrete devices combined with a constant application rate to achieve irrigation depth; a fixed flow rate device with the possibility of rapid interruption to ensure a range of depth of irrigation application; and variable sprayers with time control. A control system has also been developed to control the irrigation speed for each individual sprayer. Key criteria in the development of these technologies include: ease of installation in existing commercial irrigation systems; adequate uniformity of water application within the management zone; compatibility with existing irrigation system equipment; reduction of robust electronics; two-way communication; and the possibility of future upgrade.

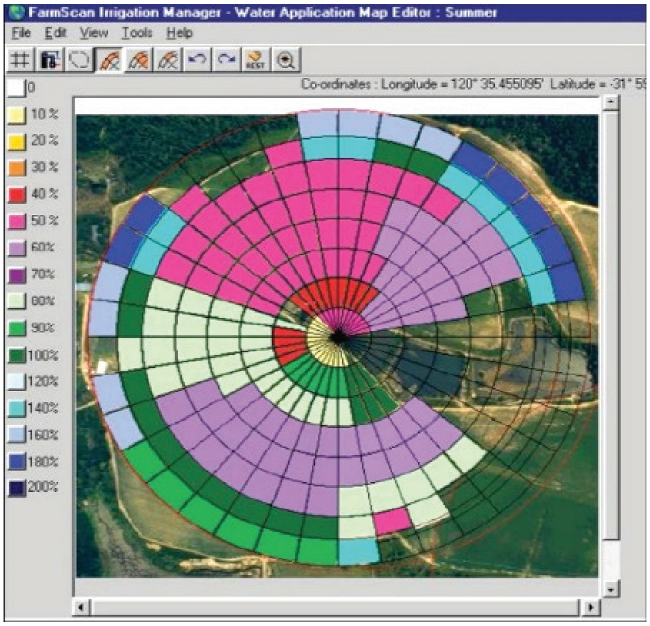


Figure 3 Farmscan irrigation rates [34]

To achieve higher precision of water application to a specific location, the exact locations of all elements for irrigation application must be known. To determine the center pivot locations, either multiple electronic compasses that continuously measure inconsistencies along the length of the system; or GNSS for positioning at one or more locations are used. The pivot devices for application with variable irrigation rates are currently commercially available technology. The farmscan 7000VRI is a system used to control the center pivot device [34]. The prescribed maps were created using a personal computer (Fig. 3). The application map separates the circular areas covered by the sprayer into circular clips with an angle of 2° to 10° and each clip is divided into segments. Irrigation installments per segment are variable values and it is possible to mark several or all segments for irrigation. The irrigation rates calculated in this way can easily be transferred to the controller. If irrigation rates are to be increased above 100 %, the sprayer will automatically slow down.

Farmscan system supports the creation of five irrigation rates. Up to 48 zones can be irrigated by adding auxiliary nozzles located along with the supports. The nozzles are grouped into blocks, and the blocks are controlled by the main line that is electronically controlled by a controller [34]. Farmscan irrigation management map divides the agricultural area into cells that are differently colored according to the percentage of water available to the crops. Since soils have different structures, varying water retention capacities and infiltration rations, irrigation rates may differ between different zones in one agricultural field [34]. Sensor systems can be more accurate than those based on maps due to access or data collection in real-time. Control systems that dynamically collect data using remote sensing or built-in sensors on the irrigation system are under development [38].

Automated irrigation control systems use sensors grouped in one location. This management method uses only the obtained soil properties data for irrigation planning and aims at crop uniformity in the field, without optimizing production in different parts of the field. However, the local microclimate, plant genetics and the occurrence of infestation/pests in crops can result in one area having a different yield compared to another. The system developed by authors [39] creates a soil map based on data obtained from neutron probes which provide soil moisture data and meteorological stations.

Most conventional irrigation systems are designed to operate with a constant flow in the system and pressure on the sprinklers. In precision irrigation, pivot irrigation systems use constant pressure but variable water flow. Possible solutions for variable water supply are multi-pump systems or the use of a variable speed pump [16].

3.3 Micro-Irrigation Systems

Micro-irrigation systems are designed for the exclusive irrigation of the zone in the plant proximity. The advantages of this approach are: irrigation of a smaller area, minimal water evaporation from the soil surface, reduced weed presence, and uniform water application in the root zone of the plant. A special advantage of micro-irrigation is the addition of a smaller amount of water at short irrigation intervals. This provides the ability to maintain soil moisture with a certain water deficit below the capacity of the field. It can be managed throughout the entire season or only its part, thus achieving greater irrigation efficiency and reducing irrigation costs. The efficiency of micro-irrigation can be higher than 90 % [40].

Water losses in micro-irrigation mainly occur by evaporation of water from the soil surface and outflow of water into the drainage. Evaporation losses are small due to the limited irrigation area and no standing water on the soil surface. The causes of possibly uneven irrigation in micro-systems are the length of the pipe, pressure oscillations and clogging of the applicator during its operation. The micro-irrigation system has a higher potential for widespread implementation compared to other systems. Management is easy and is usually automated based on time, soil moisture, or surrounding temperature [40].

Authors [41] used a system for monitoring the moisture in the root zone in viticulture and measured soil moisture in a closed-loop system. Authors [42] focused on the development of a spatially variable micro-irrigation system that enables the management of individual micro applicators (droppers) in an orchard. The basis of the research was a varying water supply for one or more individual trees located on a single pipeline. The focus was particularly set on designing an intelligent node of a micro-irrigation system that can individually manage applicators. This required the development of a physical network for energy distribution and communication between applicators and individual nodes along the irrigation line. Development was supported by software for managing the main controller, communication devices and individual micro applicator nodes. A total of 50 nodes were deployed. Each node consisted of a micro-controller and an electrical circuit. The solenoid valves individually controlled the water flow on each applicator. A pressure sensor was used to monitor the pressure in the applicators. The applicator controller provided information and stored data for the irrigation schedule. The laptop was used to transmit the irrigation schedule and access the sensor data on the pipeline regulator. The results showed that the micro-irrigation system can be configured for varying irrigation according to the individual needs of each plant [43]. Fig. 4. displays a micro-irrigation system with a wireless network.

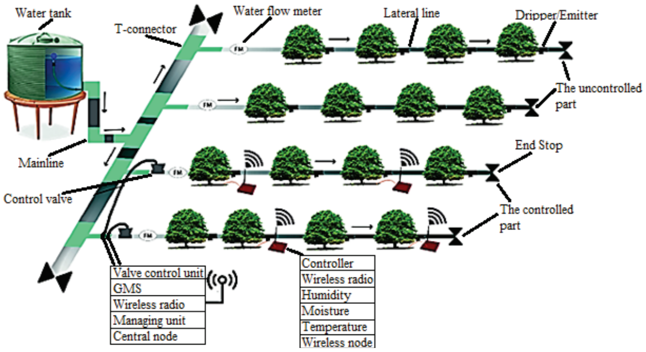


Figure 4 Micro-irrigation system [43]

That system operates on the principle of a wireless network. The sensor connected to the wireless node measures the soil moisture according to the set values and determined the irrigation starting period. The wireless controller measures soil moisture and temperature and using a built-in transmitter that sends information to the central node. The central node controls the solenoid valves and the node has a built-in receiver that receives information sent from the wireless node. The central node can be connected to a laptop, and can also be controlled via a mobile device using a GSM module. The controller in the central node processes the data according to the set values and thus manages the automatic micro-irrigation. Water pumps and associated solar panels for pumps can be installed on this system. It is possible to operate the controller via a mobile phone and to enter/export data obtained from the humidity sensor in real-time [43].

4 SENSORS AND METHODS OF DATA COLLECTION

The precision irrigation systems require accurate spatiotemporal data of soil and crop conditions in the field. They also require the ability to identify and quantify such data in order to apply appropriate irrigation. Various measuring devices for collecting data on soil moisture and plant water requirements are present. Spatial variability of the field can be measured: continuously (imaging in motion using a camera placed on pivot centers), discrete (point sampling of soil properties using soil moisture probes) and remotely (multispectral sensors mounted on unmanned aerial vehicles or satellites). A wide range of plant sensor technologies is available for the detection of plant stress. Crop monitoring technologies can be divided into two groups: contact sensors (provide detailed data for individual plants that are useful for understanding daily fluctuations) and remote (more suitable for collecting spatial data at the local or regional level and therefore more suitable for estimating spatial differences in plant loading and application in precision irrigation system). Such sensors typically measure plant responses associated with water intake, moisture evaporation, and plant growth rates. Variations in these measurements that indicate crop stress can be used in decision-making in precision irrigation. Crop sensors do not give any indication of water deficiency, so these methods should be used in combination with soil moisture measurements. Crop sensors typically have the ability to record and GNSS readings and can produce field measurement maps. There is also a wide range of satellite sensors from which data can be obtained for agricultural use [44-47].

4.1 Multispectral Sensors

Authors [44] noted that a wide range of sensors that can be used regardless of their distance to imaging object to measure the electromagnetic reflectance of the surface. Authors [45] provided a description of spectral bands that can be used to monitor soil variability. Data obtained in the spectral bands can usually be processed to highlight differences in crop conditions using the normalized difference vegetation index (NDVI). Various researchers have found a relationship between NDVI and crop coefficient for a wide range of crops. An alternative to using NDVI is to predict the actual evaporation of crops using remote energy balance research. According to [46, 47], both approaches support obtaining a large amount of data on crop water evaporation for irrigation management. Fig. 5. represents an example of the NDVI image in precision irrigation.

NDVI quantifies the vegetation by measuring the differences between the reflectance in the near-infrared band, NIR (which is strongly influenced by vegetation), and red band, RED (which is highly absorbed by vegetation). The NDVI was calculated according to formula (1) [48]:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}. \tag{1}$$

Healthy vegetation with high chlorophyll content reflects more near-infrared and green wavelengths compared to other wavelengths but absorbs more red and blue wavelengths. The result of the formula (1) creates the values in the number interval between –1 and +1. If they are low in the *RED* band and high in the *NIR* band, *NDVI* will result in a value close to 1 and vice versa [48]. Thus, in the example displayed in Fig. 5, green pixels indicate healthy and dense vegetation while red pixels indicate a crop under water stress.

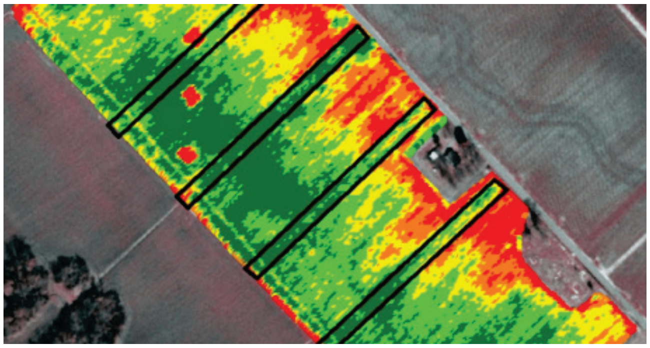


Figure 5 NDVI values for precision irrigation management [48]

Multispectral sensors are commonly implemented on satellites and unmanned aerial vehicles, which regularly achieve a higher spatial resolution [43]. In Fig. 6 an example of determining soil moisture and an irrigation map of the Ceres model is presented.

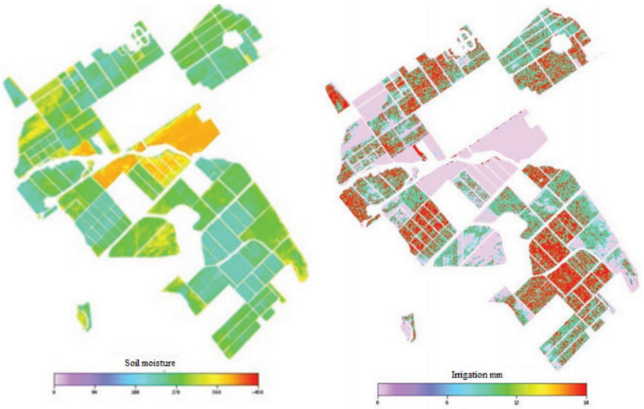


Figure 6 An irrigation map obtained using the Ceres model [34]

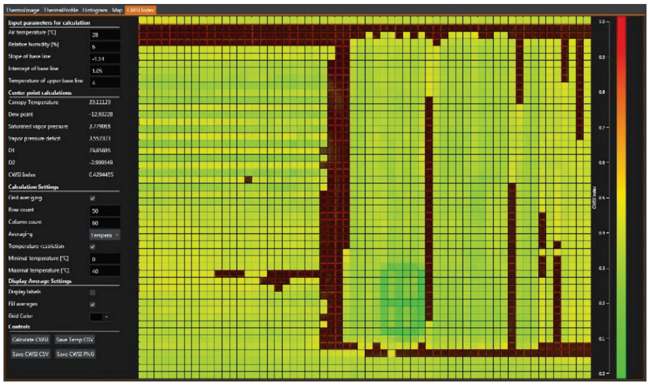
4.2 Thermal Sensors

Canopy cover temperature represents a relative measure of the water evaporation rate and indicates crop water stress. Infrared thermal cameras measure the radiation energy (temperature) of an object using thermal infrared wavelengths. The canopy cover temperature obtained by thermal sensors is compared with the crops without water stress for the calculation of crop water stress index (*CWSI*). *CWSI* is calculated according to formula (2) [34]:

$$CWSI = \frac{T_c - T_{wet}}{T_{dry} - T_{wet}}, \tag{2}$$

where: T_c represents vegetation temperature obtained from the thermal image; T_{wet} represents the lower temperature limit and T_{dry} represents the higher temperature limit. Thermal sensors and thermometers enable the creation of maps representing soil water content variations in the agricultural field. *CWSI* was developed in 1981 and was normalized to determine operates works on the principle of thermal infrared wavelengths and can be mounted on an unmanned aerial vehicle for aerial monitoring [50].

Fig. 7. displays the agricultural area divided into pixels with a *CWSI* value after imaging, which determines the amount of crop water deficiency. If the pixel value is 0, it indicates that the crop is not under stress and contains the optimal amount of water. If the pixel value is 1, the maximum crop water stress is present and the irrigation should be implemented or applied.



Input parameters for calculation
Air temperature [°C]: 28
Relative humidity [%]: 6
Slope of base line: -1.14
Intercept of base line: 1.05
Temperature of upper base line: 4

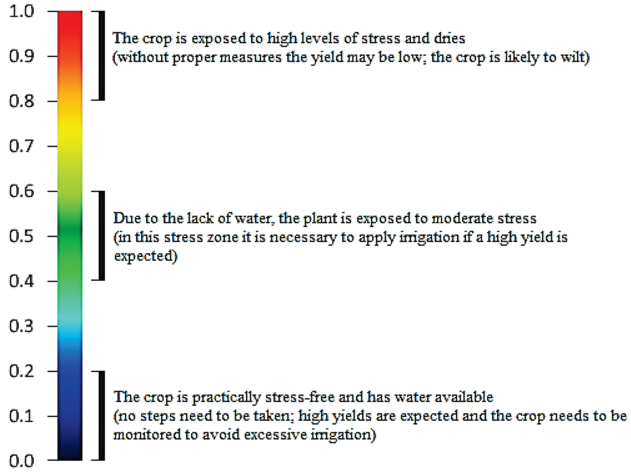
Center point calculations
Canopy Temperature: 39.11129
Dew point: -12.93228
Saturated vapor pressure: 3.779068
Vapor pressure deficit: 3.552323
D1: 29.85885
D2: -2.909549
CWSI Index: 0.4294455

Calculation Settings
Grid averaging: ☑
Row count: 50
Column count: 60
Averaging: Tempera
Temperature restriction: ☑
Minimal temperature [°C]: 0
Maximal temperature [°C]: 40

Display Average Settings
Display labels: ☐
Fill averages: ☑
Grid Color:

Controls

Figure 7 Display of *CWSI* values representing water stress after imaging [50]



The crop is exposed to high levels of stress and dries
(without proper measures the yield may be low; the crop is likely to wilt)

Due to the lack of water, the plant is exposed to moderate stress
(in this stress zone it is necessary to apply irrigation if a high yield is expected)

The crop is practically stress-free and has water available
(no steps need to be taken; high yields are expected and the crop needs to be monitored to avoid excessive irrigation)

Figure 8 Crop water stress scale [50]

Fig. 8. displays an example of a crop water stress scale [50]. Authors [38] noted the irrigation schedule for the controlled pivot system and the drop-by-drop systems were controlled by the temperature-time threshold (TTT) method. The TTT method includes infrared thermal cameras that continuously measure the temperature of the plant cover. If the cover temperature rose by a predetermined value in a certain time, irrigation would be started.

5 CONCLUSION

The combination of crop and soil monitoring with appropriate growth simulation models is the first step of precision irrigation. Upgrading these models with the control and optimization systems of each irrigation system completes the precision irrigation system. These procedures rely on the ability to manage variations in individual plants' water balance.

There is no best universal precision irrigation system. Moving towards precision irrigation requires a system that can adapt to the existing conditions. It also implies the idea that the system will succeed in achieving a certain goal, like maximum water utilization, maximum yield, or maximum profitability.

The four important steps for precision irrigation are data collection, data analysis, control, and system evaluation. Precision irrigation systems require accurate and updated spatial data obtained by field measurement and collected using a variety of imaging sensors. The obtained data are interpreted and analyzed by computer software to aid in decision making. Precision irrigation can potentially increase economic efficiency through optimal irrigation in each part of the field according to crop requirements and thus reduce costs.

According to available data in the Republic of Croatia, irrigation is not significantly developed and amounts to only 0.46% of the agricultural area (less than 10 000 ha). There are the most suitable soils for irrigation in Osijek-Baranja and Vukovar-Srijem counties. According to the available quality and quantity of water, Croatia can irrigate about 30% of arable land or about 600 000 ha.

6 REFERENCES

[1] Gereš, D. (2002). Sustainable use of water in Croatia and in Europe. *Građevinar, 54*(6), 345-353.

[2] Šimatović, J. (2012). Application of GIS systems in crop production - Precision Agriculture. *Bsc Graduation thesis*. Faculty of Agriculture Osijek, University of Josip Juraj Strossmayer in Osijek.

[3] Goovaerts, P. (2000) Geostatistical approaches for incorporating elevation into the spatial interpolation of rainfall. *Journal of Hydrology, 228*(1-2), 113-129. https://doi.org/10.1016/S0022-1694(00)00144-X

[4] Jurišić, M., Stanisavljević, A., Plaščak, I. (2010). Application of Geographic Information System (GIS) in the selection of vineyard sites in Croatia. *Bulgarian Jorunal of Agricutural Science, 16*(2), 235-242. https://www.researchgate.net/publication/267692739_Application_of_Geographic_Information_System_GIS_in_the_selection_of_vineyard_sites_in_Croatia

[5] Vukadinović, V. (2016). Soil, fertilization and yield. *Own edition*, Osijek.

[6] Mađar, S. & Šoštarić, J. (2009). *Irrigation of agricultural crops*. Faculty of Agriculture in Osijek.

[7] Mulla, D. J. (2013). Tventy five years of remote sensing in precision agriculture: Key advances and reaming knowledge gaps. *Biosystems Engineering journal, 114*(4), 358-371.

[8] Proulx, S., Sri Ranjan, R., & Klassen, G. (1998). Evaluation of soil moisture sensors in potato fields. *1998 North Central Region Intersectional Meeting, South Dakota,* 1-17. https://www.researchgate.net › download › nordak

[9] Marković, M. (2013). Influence of irrigation and nitrogen fertilization on yield and quality of maize (Zea mays L.) grain. PhD thesis. *Faculty of Agriculture in Osijek*, *University of Josip Juraj Strossmayer in Osijek.* https://drive.google.com/file/d/0B70wpjq3L39CaF9qc2x0SF9QQjQ/view

[10] Brevik, E. C., Fenton, T. E., & Lazari, A. (2006). Soil electrical condutivity as a function of soil water content and implications for soil mapping. *Precision Agriculture, 7,* 393-404. https://doi.org/10.1007/s11119-006-9021-x

[11] Huđek, J. (2014). Monitoring of soil moisture content with tdr device irrigation scheduling. *Master thesis*. Faculty of Agriculture in Osijek, University of Josip Juraj Strossmayer in Osijek.

[12] Pereira L. S. & Trout T. J. (1999.) Irrigation methods in: cigr handbook of agricultural engineering. Handbook. *American Society of Agricultural Engineers*. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjjxeaetdrwAhWYHuwKHWFWBp4QFjABegQIAxAD&url=https%3A%2F%2Felibrary.asabe.org%2Fcigr_handbook.asp%3Fconfid%3Dcigr1999&usg=AOvVaw2R0LvaornAcB42kLoJl_NU

[13] Evans, R. G., Han, S., Kroeger, M. W., & Schneider, S. M. (1996). Precision centre pivot irrigation for efficient use of water and nitrogen. *Precision Agriculture, Proceedings of the 3rd International Conference, Minneapolis, Minnesota,* 75-84. https://doi.org/10.2134/1996.precisionagproc3.c8

[14] Kincaid, D. C., Buchleiter, G. (2004). Irrigation, Site-Specific. *Encyclopedia of Water Science,* 1-4. https://doi.org/0.1081/E-EWS 120010137

[15] Al-Karadsheh, E., Sourell, H. & Krause, R. (2002.) Precision Irrigation: New strategy irrigation water management. *Conference on International Research on Food Security, Natural Resource Management and Rural Development, Deutscher Tropentag, Witzenhausen, 11-22.*

[16] Camp, C. R., Sadler, E. J., & Evans, R. G. (2006). Precision Water Management: Current Realities, Possibilities and Trends. *Handbook of Precision Agriculture. Binghamton, New York: Haworth Press.,* 153-183.

[17] Chavez, J. L., F. Pierce, F. J., Matthews, G. R., Elliot, T. V., Evans, R. G., & Kim, Y. (2006). Performance of a continuous move irrigation control and monitoring system. *2006 ASABE Annual International Meeting, Oregon,* 062163. https://doi.org/10.13031/2013.20733

[18] King, B. A., Stark, J. C., & Wall, R. W. (2006). Comparison of site-specific and conventional uniform irrigation management for potatoes. *Applied Engineering in Agriculture, 22*(5), 677-688. https://doi.org/10.13031/2013.22000

[19] Sadler, E. J., Evans, R. G., Stone, K. C., & Camp, C. R. (2005). Opportunities for conservation with precision irrigation. *Journal of Soil and Water conservation, 60* (6), 371-379.

[20] Peters, R. T. & Evett, S. R. (2004). Complete center pivot automation using the temperature-time threshold method of irrigation scheduling. *2004 ASAE/CSAE Annual International Meeting, Ottowa, Ontario, Canada,* 042196. https://doi.org/10.13031/2013.16409

[21] O'Shaughnessy, S. A., Evett, S. R., Coliazzi, P. D., & Howell, T. A. (2008). Soil water measurement and thermal indices for center pivot irrigation scheduling. *Irrigation Association Conference Proceedings Anaheim, California,* 23-33.

[22] Yule, I. J., Hedley, C. B., & Bradbury, S. (2008). Variable-rate irrigation. *12th Annual Symposium on Precision Agriculture Research & Application in Australasia, Sydney,* 24-26.

[23] Hedley, C. B. & Yule, I. J. (2009). Soil water status mapping and two variable-rate irrigation scenarios. *Precision Agriculture, 10*, 342-355. https://doi.org/10.1007/s11119-009-9119-z

[24] King, B. A., Wall, R. W., Kincaid, D. C., & Westermann, D. T. (2005). Field testing of a variable rate sprinkler and control system for site-specific water and nutrient application. *Applied Engineering in Agriculture, 21*(5)*,* 847-853. https://doi.org/10.13031/2013.19712

[25] DeJonge, K. & Kaleita, A. (2006). Simulation of spatially variable precision irrigation and its effects on Corn growth using CERES-Maize. *ASABE Annual International Meeting, St. Joseph, Michigan,* 062119. https://doi.org/10.13031/2013.20710

[26] Lu, Y. C., Sadler, J. E., & Camp, C. R. (2005). Economic feasibility study of variable rate irrigation of corn production in southeast coastal plain. *Journal of Sustainable Agriculture, 26*(3)*,* 69-81. https://doi.org/10.1300/J064v26n03_08

[27] Heerman, D. F., Hoeting, J., Thompson, S. E., Duke, H. R., Westfall, D. G., Buchleiter, G. W., Westra, P., Peairs, F. B., & Fleming, K. (2002). Interdisciplinary irrigated precision farming research. *Precision Agriculture, 3,* 47-61. https://doi.org/10.1023/A:1013374120356

[28] Almas, L. K., Amosson, S. H., Marek, T., Colette, W. A. (2003). Economic feasibility of precision irrigation in the northern Texas high plains. *Southern Agricultural Economics Association Annual Meeting. Mobile, Alabama,* 1-15.

[29] Gillies, H.M. (2008). Managing the effect of infiltration variability on the performance of surface irrigation. Dissrtacion. *Faculty of Engineering and Surveying, University of Southern Queensland.*

[30] Bautista, E., Clemmens, A. J., Strelkoff, T. S., Schlegel, J. (2009). Modern analysis of surface irrigation systems with WinSRFR. *Agricultural Water Management, 96*(7)*,* 1146-1154. https://doi.org/10.1016/j.agwat.2009.03.007

[31] Austin, N. R., Prendergast, J. B. (1997). Use of kinematic wave theory to model irrigation on cracking soil. *Irrigation Science, 18*, 1-10. https://doi.org/10.1007/s002710050038

[32] Khatri, K. L., Smith, R. J. (2006). Real-time prediction of soil inflitration characteristics for the managment of furrow irrigation. *Irrigation Science, 25,* 33-43. https://doi.org/10.1007/s00271-006-0032-1

[33] Lam, Y., Slaughter, D. C., Wallender W. W., Upadhyaya, S. K. (2007). Machine vision monitoring for control of water advance in furrow irrigation. *Transactions ASABE, 50*(2)*,* 371-378. https://doi.org/10.13031/2013.22628

[34] Smith, R. J., Baillie, J. N., McCarthy, A. C., Raine, S. R., & Baillie, C. P. (2010). Review of Precision Irrigation Technologies and theri Application. *Toowoomba, Australia: National Centre for Engineering in Agriculture University of Southern Queensland Toowoomba,* 1003017/1.

[35] Cape, J. (1998). Using software to review sprinkler performance. *Irrigation Australia, 13*(3)*,* 18-20.

[36] Smith, R. J., Gillies, M. H., Newell, G., & Foley, J. P. (2008). A decision support model for travelling gun irrigation machines. *Biosystems Engineering, 100*(1)*,* 126-136. https://doi.org/10.1016/j.biosystemseng.2008.01.004

[37] McCarthy, A. C., Hancock, N. H., & Raine, S. R. (2010). VARIwise: A general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale. *Computers and Electronics in Agriculture, 70*(1)*,* 117-128. https://doi.org/10.1016/j.compag.2009.09.011

[38] Peters, R. T. & Evett, S. R. (2006). A fully Automated Center Pivot Using Crop Canopy Temperature. *USCID Water Managment Conference*, *Boise, Idaho*, 139-148.

[39] Evans, R. G., Kim, Y., & Iversen, W. M. (2007). Evaluation of closed-loop irrigation control with wireless sensor network.

2007 ASABE Annual International Meeting, Minneapolis, Minnesota, 072248. https://doi.org/10.13031/2013.23374

[40] Evett, S. R., Peters, R. T., & Howell, T. A. (2006). Controlling water use efficiency with irrigation automation: cases from drip and center pivot irrigation of corn and soybean. *Southern Conservation Systems Conference, Amarillo TX,* 57-66.

[41] Capraro, F., Patino, D., Tosetti, S., & Schugurensky, C. (2008). Neural network-based irrigation control for precision agriculture. *IEEE International Conference on Networking, Sensing and Control, Sanya, China,* 357-362.

[42] Coates, R., Delwiche, M., & Brown, P. (2006). Design of a system for individual microsprinkler control. *Transactions of the ASABE, 49*(6), 1963-1970. https://doi.org/10.13031/2013.22276

[43] Barman, A., Neogi B., & Pal, S. (2020). Solar-Powered Automated IoT-Based Drip Irrigation System. *IoT and Analytics for Agriculture. Studies in Big Dana, Springer, Singapore,* 27-49. https://doi.org/10.1007/978-981-13-9177-4_2

[44] Bastiaanssen, W. G. M., Molden, D. J., & Makin, I. W. (2000). Remote sensing for irrigated agriculture: examples from research and possible applications. *Agricultural Water Management, 46(2),* 137-155. https://doi.org/10.1016/S0378-3774(00)00080-9

[45] McBratney, A. B., Mendonca Santos M. L., & Minasny, B. (2003). On digital soil mapping. *Geoderma, 117*(1-2), 3-52. https://doi.org/10.1016/S0016-7061(03)00223-4

[46] Gowda, P. H, Senay, G. B., Howell, T. A., & Marek, T. H. (2008). Lysimetric Evaluation of Simplified Surface Energy Balance Approach in the texas high plains. *Applied Engineering in Agriculture, 25*(5), 665-669. https://doi.org/10.13031/2013.28855

[47] Chavez, J. L., Gowda, P. H., Howell, T. A., & Copeland, K. S. (2009). Radiometric surface temperature calibration effects on satelite based evapotranspiration estimation. *International Journal of Remote Sensing, 30(9),* 2337-2354. https://doi.org/10.1080/01431160802549393

[48] Precision Agriculture (2018). NDVI and satellite crop monitoring. Retrieved from https://precisionagricultu.re/ndvi-and-satellite-crop-monitoring/

[49] Hossain, B. (2008). EM38 for measuring and mapping soil moisture in a cracking clay soil. *PhD Thesis*. University of New England, Armidale.

[50] Medicas (2020). Thermal screening of diseases. Retrieved from https://www.workswell-thermal-camera.com

Authors' contacts:

Ivan Plaščak, PhD, Associate Professor
Faculty of Agrobiotechnical Sciences Osijek
Vladimira Preloga 1, 31000 Osijek, Croatia
iplascak@fazos.hr

Mladen Jurišić, PhD, Full Professor
Faculty of Agrobiotechnical Sciences Osijek
Vladimira Preloga 1, 31000 Osijek, Croatia
mjurisic@fazos.hr

Dorijan Radočaj, MSc, Assistant
Faculty of Agrobiotechnical Sciences Osijek
Vladimira Preloga 1, 31000 Osijek, Croatia
dradocaj@fazos.hr

Milan Vujić, MSc
Faculty of Agrobiotechnical Sciences Osijek
Vladimira Preloga 1, 31000 Osijek, Croatia
vujic.milan94@gmail.com

Domagoj Zimmer, PhD, Postdoc
(Corresponding author)
Faculty of Agrobiotechnical Sciences Osijek
Vladimira Preloga 1, 31000 Osijek, Croatia
dzimmer@fazos.hr