EVALUATION OF AN AUTOMATIC CONTROL SYSTEM WITH DRIP IRRIGATION SYSTEM SHOWING POOR HYDRAULIC PERFORMANCE
/

تقييم نظام تحكم أوتوماتيكي مع نظام رى بالتنقيط ذو أداء هيدروليكي ضعيف

Moataz Elnemr
Department of Agricultural Engineering, Faculty of Agriculture, Damietta University / Egypt
Tel: +201062084800; E-mail: moknemr@du.edu.eg

ABSTRACT

A field experiment was conducted with the purpose of testing and evaluating the use of a closed-loop, real-time control system which was developed by (Elnemr M.K., 2017) for application to a poor hydraulic performance drip irrigation system with sandy loam soil cultivated with cucumber crop. This control system collects soil moisture data through three sensors distributed along each third of the lateral. The control system was based on calculating the average soil moisture content (MC) of the three readings and using it as an indicator to start or stop irrigation process according to the requirements of the plant. The control system will start the pump after the depletion of allowed MC percentage of available water which is one of the required inputs to operate the control system. The irrigation process continues until reaching the field capacity (FC) value. The study compared two management methods for the irrigation system. First one was using the proposed control system (Au_m) and the other one was manual operation based on calculating water requirement from climatic data (Cl_m). Using the proposed control system led to increase cucumber crop production by 23.8% of Cl_m productivity. The control system led to save water and seasonal irrigation time. This led to increase water productivity and energy use efficiency of Au_m if compared to Cl_m by 41.71% and 110% respectively. Despite the added cost to the irrigation system because of the control system, the benefit/cost ratio for Au_m was higher by 24.39% due to the decrease in energy and labour costs in addition to the increase in crop production. The study recommended using the researched control system with drip irrigation systems which show poor hydraulic performance to reduce negative effects on crop production and to reach more efficient use for both water and energy with keeping the opportunity to increase benefit/cost ratio. Further studies should be done on the system with drip irrigation system that work under acceptable ranges of hydraulic performance. Also, further studies should be done to investigate the most effective and suitable distribution of the sensors along lateral.

ملخص

تم اجراء تحربة حقلية بغرض اختبار وتقييم استخدام نظام تحكم أوتوماتيكي من نوع الحلقة المغلقة والوقت الحقيقي تم تطويره بواسطة النمر (2017) للتطبيق على نظام رى بالتنقيط ذو أداء هيدروليكي ضعيف في تربة رملية لومية مزروعة بمحصول الخيار. يقوم النظام بتجميع بيانات المحتوى الرطوبي للتربة من خلال توزيع ثلاث حساسات للرطوبة داخل التربة على طول الخط الحقلي بحيث يكون كل منها في أحد اثلاث الخط. يعتمد نظام التحكم على حساب متوسط الرطوبة للقراءات الثلاث واستخدامها كمؤشر لبدء عملية الرى أو ايقافها طبقاً لاحتياجات النبات. يقوم النظام بتشغيل طلمبة الرى عند استنفاذ نسبة الرطوبة المسموح بها من الماء الميسر والتي هى أحد مدخلات تشغيل نظام التحكم وتستمر عملية الرى حتى الوصول للسعة الحقلية وهى نقطة ايقاف التشغيل. قارنت الدراسة .بين طريقتين لإدارة نظام الرى الأولى باستخدام نظام التحكم المقترح والأخرى تشغيل النظام بشكل يدوي اعتماداً على حساب الاحتياجات المائية من خلال البيانات المناخية. أدى استخدام نظام التحكم المقترح إلى زيادة في محصول الخيار بنسبة بلغت 23.8% مقارنة بإنتاجية المعاملة المدارة اعتماداً على البيانات المناخيةً .كما أدى الاعتماد على نظام التحكم الى توفير في مياه وزمن الرى خلال الموسم. ادى ذلك الى زيادة انتاجية المياه بنسبة 41.71% مع زيادة في كفاءة استخدام الطاقة بنسبة 110% مقارنة بالتشغيل اليدوي.بالرغم من زيادة تكاليف نظام الرى نتيجة استخدام نظام التحكم الا أن هناك زيادة في نسبة العائد الى التكاليف بمقدار 24.39% لمعاملة التحكم الأوتوماتيكي مقارنة بالتشغيل اليدوي نتيجة تقليل تكلفة العمالة والطاقة بالإضافة لزيادة المحصول. أوصت الدراسة باستخدام نظام التحكم المقترح لتجنب الآثار السلبية للأداء الهيدروليكي الضعيف من ناحية الحفاظ على الانتاجية في مستواها الطبيعي واستخدام المياه والطاقة بشكل أكثر كفاءة مع الحفاظ على فرصة زيادة نسبة العائد/ التكاليف. وأوصت الدراسة بإجراء مزيد من التجارب لتحديد التوزيع الأمثل لأجهزة الاستشعار الخاصة بنظام التحكم وعددها الأمثل على طول الخط الحقلي للوصول لأفضل أداء ممكن للنظام المقترح.

INTRODUCTION

Scarcity of water worldwide created a competition between all water resources consumers (*FAO, 2013*). Agriculture is the main source of people food and one of the main consumers of water resources. Increasing water use efficiency beside energy saving in agriculture has been a big concern. Trickle irrigation systems including drip irrigation are highly recommended for saving water and increase water use efficiency (*Luquet et al., 2005*). Actual field practices with drip irrigation may affect reaching the goals of improved saving water and crop production (*Lankford B., 2012; van der Kooij et al., 2013*). Sometimes, drip irrigation system users may suffer from poor hydraulic performance of the system due to poor design or management as well as they may have to use cheaper system components if they can't afford the capital needs. Inexperienced users will also suffer from their inability to operate their irrigation systems in an optimum way in addition to their low skills in system performance monitoring. Using decision support systems and automatic control introduces applicable solutions to avoid the negative impacts which may result from the existence of one or all of poor design, management, and operation. Such improved management utilities when used with different crops as a monitoring tool (*Zhang et al., 2013*) will be useful for increasing irrigation efficiency (*Smarsly K., 2013*). Prediction of water needs is a key issue to the automatic control systems to reach success and effective scheduling. Generally, the main two ways of data processing in control systems are open-loop and closed-loop technics. Open-loop control systems miss the feedback data about soil moisture in the root zone which may change the irrigation scheduling strategy. Open-loop control systems technique was used by (*Smith M., 2000; Zwart and Bastiaanssen, 2004; Giusti and Marsili-Libelli, 2015*) to reduce the prediction of the water needs resulted from climatic data but they were unable to achieve this. Using closed-loop control systems and using sensors to collect data is the key to successive irrigation management in main extensive crops (*Ruíz-García et al., 2009*). Studies made by (*Kim et al, 2008, Kim et al, 2009; Pfitscher et al., 2012*), pointed out the importance of using real time, closed-loop automatic control to improve the performance of irrigation systems including efficient water and energy use. Despite the possibility of real time monitoring through the automatic control systems for the soil moisture, the distribution of soil moisture along laterals was not approached in most of the control systems presented. The more accurate data received by soil moisture sensors, the easier to access successful management through the irrigation control system. Hydraulic performance describes how uniform is the distribution of flow rates along the lateral. Irrigation uniformity plays an essential role to increase crop production, water use efficiency, and net profits (*Li and Kawano, 1996; López-Mata et al., 2010*). If there is a high variation between flow rates along the lateral, it will be hard to choose the point(s) which describe real soil moisture content accurately to decide the right scheduling strategy by the control system. This study aims to evaluate the implication of a real-time, closed-loop control system developed by (*Elnemr M.K., 2017*) with drip irrigation system working under poor uniformity conditions to investigate the effect of using the mentioned control system on water and energy use efficiency under such conditions besides making an economic evaluation to its use effect on net profits generated by the added cost.

.

MATERIALS AND METHODS

The field experiment location was 31.41º N, 31.75º E in Kafrelbatikh city, Damietta Governorate, Egypt on cucumber crop (*Sahim F1*) with sandy loam soil. Seeds planting started at 1/3/2019. Seeding rate was 3 seeds/pore then it was reduced to 1 plant/pore after germination. Area dimensions were 20m width, 40m long. 5-share chisel plough was hitched to 60hp tractor to achieve the required soil fragmentation. Amounts of 750-800-600 kg.ha^{-1} of Ammonium sulphate, Single Superphosphate, and Potassium sulphate, respectively, were scattered on the soil surface on three stages which were vegetative development, flowering, and fruit development. Soil surface levelling was carried out using a scraper to maintain the horizontal level of the soil at zero level. Table 1 illustrates some physical properties of the soil in the experimental site.

Table 1

Physical properties of experiment soil

Depth, cm	Soil particles size distribution			Texture	Field capacity, %	Wilting point, %
	Clay,%	Silt,%	Sand,%			
0-15	18.50	1.50	80.00	Sandy loam	19.48	9.06
15-30	19.13	2.52	78.35	Sandy loam	17.05	8.79
30-45	15.93	1.99	82.08	Sandy loam	16.69	7.05
45-60	17.05	2.01	80.94	Sandy loam	18.29	7.44

Drip irrigation network was divided into two parts, each of them performing one treatment. The difference between the two treatments was managing on/off decision for pumping water. First part was managed using the automatic control system (Au_m), second one was managed basing on climate data and operated by irrigation system operator (Cl_m). Three laterals were established to act three replicates of each treatment. As shown in Figure 1, drip irrigation system consisted of 1 HP centrifugal electric pump that suctions water from water basin 0.6 m³ which was always filled with fresh water to assure the existence of water when the control system operates the pump. The pump was connected to the water basin by a *PVC* pipe with 2.5 cm inner diameter. Manifold was a *PVC* pipe with 6.3 cm inner diameter. Built in emitters were used in laterals having 16 mm inner diameter and 20m length. Emitters were 50cm spacing along each lateral and the space between laterals was 1.5m. All laterals' inner diameter was 16mm. The pump was connected to the control system through a cable to permit the electric current to switch the pump on. Operating pressure head was measured using a pressure gauge fitted on the manifold.
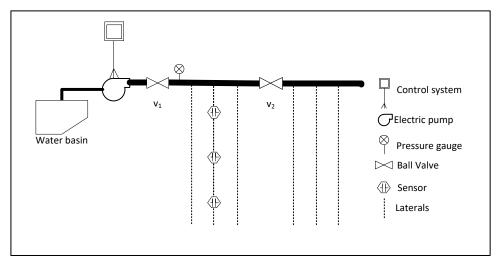

Fig.1 - Irrigation network and field experiment layout

Water inlet to the two parts was controlled by two valves which were marked V_1 and v_2 in Figure 1. V_1 was always open. V_2 was opened just with the need to irrigate (Cl_m) treatment. All the laterals started with T-shape valves with the same diameter of the laterals. Water flow to automatically controlled laterals was prevented during the irrigation of the other treatment by closing the T-shape valves. The control system has the ability to operate the pump at any time decided by the user for any required duration. This feature was used to irrigate the (Cl_m) treatment. After finishing irrigating the second part, the system was turned to automatic mode to control the first part basing on soil moisture data. Irrigation interval for Cl_m was 72h.

The used control system was developed by (*Elnemr, M.K., 2017*). Control system components, sensors calibration, and design considerations were shown in (*Elnemr M., 2019*). The designed algorithm of the control system was based on collecting soil moisture content data from the soil under three emission points along each third of lateral length to consider flow rate variation between emitters. The evaluated control system was recommended to be used with the poor hydraulic performance trickle irrigation systems. The average of the three collected values of soil moisture content was used to express the soil moisture content value (*MC*) which will be used to manage the irrigation system.

The system should be fed at the beginning of irrigation network installation with three values namely soil field capacity (*FC*), and permanent wilting point *(PWP)* which are related to soil properties, in addition to moisture allowed depletion (*MAD*) which is directly related to crop type. All these inputs were entered to the system as percentages with two digits accuracy. The values of *FC* and *PWP* used in the experiment were 17.9% and 8.1% respectively. These values are the average of the four values related to these constants as listed in Table 1.

MC_{on} is the soil moisture content at which the control system will give the decision of starting the pump; it will be calculated according to the following equation:

$$MC_{on} = (FC - PWP)(1 - \frac{MAD}{100}), [\%] \tag{1}$$

The control system was designed to start irrigation process when the soil moisture content reaches the allowed percentage of available water and stop the water pumping after reaching the *FC*. Corresponding values resulted from sensor calibration of *FC* and *PWP* were fed to the system. Values of FC and PWP shown in Table 1 were used. *MAD* value was 25% for cucumber as a shallow rooted crop (*Phocaides A., 2007*).

The first and second thirds length were 7m and last third was 6m long. Sensors were located under the middle emitter of each third after assuring it is unclogged. Each sensor was put at 20 cm depth as recommended by (*Rivera et al. 2012*). Sensors were connected to the control system through shielded cable which had three ends, two for negative and positive electrodes and the third one for sending the signal.

Primary field experiments were carried out to choose the operating head that would reflect poor hydraulic performance for the irrigation system. Uniformity coefficient parameter (*UC*) was selected to evaluate the system performance with four operating pressure heads which were 5, 8, 10, 20m of water. *UC* values under different pressure heads were calculated using the spread sheet developed by (*El-Nemr M.K., 2012*). Flow rates of 20 emitters from a certain lateral were collected in 250 ml capacity cans. Flow rates were collected at once by operating the system for 2 minutes and the resulted water volume was calculated in l/h. Obtained *UC* values and their evaluation referring to (*ASAE, 1997*) are listed in table 2. Referring to *UC* values, the operating pressure 8m was used during the experiment as the evaluation of uniformity is poor.

Table 2

Values of *UC*, %

Pressure head [m]	*UC* [%]	Evaluation
5	48.14	Unacceptable
8	65.20	Poor
10	85.95	Very good
20	90.27	Excellent

Crop water requirements for the climatic data-based part of the experiment were calculated according to (*FAO, 1998*). CLIMWAT program (*FAO, 1993*) was used to obtain daily reference evapotranspiration (ET_o) values from Damietta meteorological station (31.25⁰ N and 31.49⁰ E) which covers the experimental area. The Crop coefficient values were 0.6, 1, and 0.75 for the initial, crop development, mid-season, and late-season growing periods (*Phocaides A., 2007*).

Picking started when cucumber fruit reached the acceptable marketing size (the length of cucumber was 10-14 cm and/or 2 cm diameter). After finishing the growing season, average of three replicates was used to describe the total productivity of each treatment.

Water productivity (W_p) has been used to describe the relationship between cucumber crop production and the total amount of water used. It was determined in kg m^{-3} by applying the following equation:

$$W_P = \frac{Y}{W_a} \quad [kg/m^3] \tag{2}$$

where *Y*= Crop yield, [kg], W_a= Amount of applied water, [m³].

Energy use efficiency (*EUE*) indicator was used to express the relationship between crop productivity (kg) and energy consumption (kWh) as follows:

$$EUE = \frac{Crop\ productivity}{Energy\ consumption} \quad [kg / kWh] \tag{3}$$

The pump brake power was calculated according to Equation 4.

$$BP = \frac{P_w}{\eta} \quad [kW] \tag{4}$$

where: *BP*= engine brake power, [kW]; P_w= water power, [kW];

η= Pump efficiency which was taken 0.70.

$$P_w = Q \cdot H_t \cdot \omega \quad [kW] \tag{5}$$

where:

Q= required discharge at the network, [m³/h]; H_t= total head, [m]; ω = water specific weight, [kg/m³].

$$H_t = H_f + H_s + H_e \quad [m] \tag{6}$$

where: H_f=friction loss, [m]; H_s =static suction head, [m]; H_e =emitter operating pressure head, [m].

The suction static head was neglected because the water suction level in the water basin and pump water inlet was nearly at the same level. Hazen-Williams formula (*Hazen and Williams, 1920*) was used to calculate the friction loss for the manifold and laterals.

$$H_f = \frac{10.67 Q^{1.85}}{C^{1.85} . d^{4.87}} L \quad [m] \tag{7}$$

where: d = inside pipe diameter in m, L= Length of the pipe in m, Q=Total flow rate m^3.h^{-1}, C= Formula constant which was 150 for both *PVC* and *PE* pipes.

Minor friction losses were assumed 10% of the total friction loss (*El-Gindy et al., 2001*). Energy consumption was calculated by multiplying the calculated power requirement in the total operation time per season for each treatment. Average of emitters flow rates was used to calculate the operation time for the climatically based part. The control system was provided with a time recorder to record total operation hours done by the system.

The total annual cost per hectare for the growing season was calculated referring to *Buchanan, et al. 2002* based on the Egyptian market information for the year 2019. Required cost data were collected in Egyptian pound (*EGP*) as a unit of price then converted to *US$* which had average price 17.39 *EGP* during experiment time. Total cost equalled the summation of total annual fixed and variable costs. Fixed costs included depreciation of network components, interest, and taxes and insurance costs. The depreciation costs of the different irrigation network components were calculated according to Equation 9:

$$Depreciation \; cost = \frac{Asset \; cost - Re \, sidual \; value}{Useful \; life \; of \; the \; asset} \quad [US \, \$] \tag{8}$$

The variable costs included energy, labour, repair and maintenance, and additive costs including pesticides, seeds, fertilizers, land rent, and transportation. The residual value of an object was assumed 10% of the price of new object case. The automatic control system cost was 466.06 *US$* with 5 years useful life. Life span of the pump and network components was assumed 10 years. The interest value was 13.5% while taxes and insurance were 2% of the original asset cost of an object. Energy cost (0.04 US$/ kWh). Labour fees were 5.75 US$/day/person for 8 hours working day. Repairs and maintenance costs were assumed to equal the depreciation cost. Profit of cucumber crop per kg was 0.29 *US$*. The benefits-cost ratio *(B/C)* was used to describe the final crop profitability for the farmer.

RESULTS

Picking process finished on 11/5/2019. Using automatic control led to increase cucumber production by 23.80% if compared to the production of (*Cl$_m$*). Production of (*Au$_m$*) reached 15.81 Mg.ha^{-1} while production of (*Cl$_m$*) was 12.77 Mg.ha^{-1}. This increase in production reflects the better management achieved by the control system for applying water in the most suitable times. Also, the ability of the control system to use the average *MC* from three points to make the necessary scheduling strategy shared in avoiding deficit or over irrigation which may result in poor uniformity.

Water productivity of (*Au$_m$*) was 9.75 kg m^{-3} while it reached 6.88 kg m^{-3} for (*Cl$_m$*). Increase in water productivity was 41.71% of water productivity at (*Cl$_m$*) treatment. (*Au$_m$*) also led to save 12.63% of water applied to *Cl$_m$*. Water productivity was directly impacted by the increase in crop productivity in (*Au$_m$*) in addition to saving water.

Using automatic control system led to increase energy use efficiency (*EUE*) if compared to (*Cl$_m$*) treatment. Energy use efficiency (*EUE*) for the treatment (*Au$_m$*) reached 76.09 kg/kW.h while it was 36.02 kg/kW.h for (*Cl$_m$*). Energy use efficiency (*EUE*) value is mainly related to both productivity and operation time. (*Au$_m$*) gave the opportunity to improve energy use efficiency (*EUE*) by adjusting operation time in addition to the increase in cucumber productivity.

Table 3 shows the costs of cucumber production and the total profits. Total fixed cost of (*Au$_m$*) was higher than the (*Cl$_m$*) because of the costs of the automatic control system. Labour cost was lower for (*Au$_m$*) because there was no need for persons to turn the system on and off. Also, the energy cost was lower for (*Au$_m$*) because of the more adjusted operation time which was lower than the seasonal operation time of (*Cl$_m$*). The reduction in energy and labour costs led to reduce the total costs of (*Au$_m$*) treatment despite the increase in irrigation network costs generated by the costs of the automatic control system.

The total profits of (Au_m) were greater than the profits of Cl_m. These results led to increase in *B/C* ratio of (Au_m) by 24.39% if compared to (Cl_m) treatment. (Au_m) treatment cost is expected to decrease if the control system manufacturing turned to mass production.

Table 3

Annual costs and benefits/cost ratio of the treatments, US$/ha

	Cl_m	Au_m
Depreciation	43.90	84.72
Interest	36.22	70.83
Taxes and insurance	9.76	19.08
Total fixed costs	89.88	174.63
Energy	57.02	33.58
Labour	198.70	93.15
Repairs and maintenance	43.90	84.72
Additives	305.03	305.03
Total variable cost	604.66	516.48
Total cost	694.54	691.11
Benefits	3703.30	4584.90
B/C ratio	5.33	6.63

Using the proposed control system led to increase crop productivity, save water, and decrease seasonal operation time. All these effects were followed by increasing water production (W_p) and energy use efficiency (*EUE*). Despite the poor hydraulic performance of the system which was expected to decrease production, the total productivity with (Au_m) reached the limit of cucumber productivity per hectare in Egypt (*Zaki M., 1992*) and the world average which is 15 Mg/ha. The decrease in crop production in (Cl_m) is mainly related to the poor hydraulic performance and unequal amounts of water applied along laterals. This means that the design considerations of this control system led to avoid over and deficit irrigation of the plants along the lateral. Results also clarified that basing on soil and crop data in the proposed control system led to increase water production (W_p) and helped to reach better scheduling which is in agreement with the studies made by (*Dukes et al. 2007; Elmarzaky et al., 2011; Venkatapur and Nikitha, 2017*) on closed-loop control systems. The proposed control system can be improved to be compatible with renewable energy sources like solar energy to keep real-time monitoring for the soil moisture content to avoid losing data because of any issues related to possible electric current absence. Future experiments should include investigating the introduced control system use with acceptable ranges of hydraulic performance. Also, future work can include choosing the best distribution for the sensors along laterals and the effect of increasing the number of monitoring sensors.

CONCLUSIONS

Field experiment was carried out to investigate the effect of a closed-loop real-time control system which was developed by *Elnemr M.K., 2017* on cucumber crop production, water productivity, and energy use efficiency with poor hydraulic performance drip irrigation system. The control system was designed to manage irrigation system basing on collecting soil moisture data through sensors which were located in each third of the lateral. The average of the three readings was used as the soil moisture content which will decide the irrigation needs. The control system will start the pump when the soil moisture content reaches the allowed depletion of available water. Irrigation process will stop after reaching soil field capacity. The automatic control management was compared to climatic data-based management. Irrigation management with the control system led to increase crop production, water productivity, and energy use efficiency compared to the other management method. Despite the poor hydraulic performance of the irrigation system, the automatic control management kept the productivity of cucumber at the known limits per unit area.

As a result, there was an increase in water production (W_p), and energy use efficiency (*EUE)* due to the saving in water and operation time. Using the control system also led to increase the *B/C* ratio compared to (Cl_m) due to increase in crop production with decreasing both labour and energy costs. It is recommended to use the introduced control system with drip irrigation systems which show poor hydraulic performance to reduce negative effects on crop production and to reach more efficient use for both water and energy.

REFERENCES

[1]   ASAE (1997), American Society of Agricultural Engineers, Engineering Practice Standard EP 458: *Evaluation of Micro Irrigation Systems*, St. Joseph, Michigan. USA1997.

[2]   Buchanan R.J., Cross T.L., (2002), *Irrigation Cost Analysis Hand Book*, Agricultural Extension Service, The University of Tennessee. PB1721.

[3]   Dukes M.D., Muñoz-Carpena R., Zotarelli L., Icerman J.; Scholberg J.M., (2007), Soil moisture-based irrigation control to conserve water and nutrients under drip irrigated vegetable production. Studies of the unsaturated soil Zone (*Estudios de la Zona No Saturada del Suelo).* Vol. 8:229-236.

[4]   El-Gindy, A.M., Abdelaziz A.A., Soliman A.A., (2001), *Irrigation and Drainage Networks Design*, Ain Shams University, Egypt.

[5]   El Marazky M.S., Mohammed F.S, Al-Ghobari H.M., (2011), Evaluation of Soil Moisture Sensors under Intelligent Irrigation Systems for Economical Crops in Arid Regions. *American Journal of Agricultural and Biological Sciences,* vol.6 (2): 287-300.

[6]   El-Nemr M.K., (2012), An Interactive Spreadsheet for Drip Irrigation System Uniformity Parameters Evaluation. *International Journal of Agriculture Sciences*, 4(4):216-220.

[7]   Elnemr M., (2019), Prototype of a control system for trickle irrigation systems considering distributors' flow rate variation. *International Journal of Water Resources and Environmental Engineering*, 11(5): 83-90.

[8]   Elnemr M.K., (2017), Automatic control system for poor hydraulic performance trickle irrigation systems. Egypt patent Dec. 24 2166/2017.

[9]   FAO (1998), Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements, *FAO Irrigation and Drainage Paper 56*.

[10]   FAO (2013), AQUASTAT Database. *Food and Agriculture Organization of the United Nations*, http://www.fao.org/nr/water/aquastat/data/query/results.html (accessed 30 December 2013).

[11]   Giusti E., Marsili-Libelli S., (2015), A fuzzy decision support system for irrigation and water conservation in agriculture. *Environmental Modelling and Software.* 63:73–86.

[12]   Hazen A., Williams G.S., (1920), *Hydraulic Tables*, 3rd ed., John Wiley and Sons, New York.

[13]   Kim Y., Evans R.G., (2008), Remote Sensing and Control of an Irrigation System Using a Distributed Wireless Sensor Network. *IEEE Transactions on Instrumentation and Measurement*, 57(7): 1379-1386.

[14]   Kim Y., Evans R.G., Iversen W.M., (2009), Evaluation of Closed-Loop Site Specific Irrigation with Wireless Sensor Network. *Journal of Irrigation and Drainage Engineering*, ASCE, January-February 2009:25-31.

[15]   Lankford B., (2012), Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency. *Agricultural Water Management.* 108:27–38.

[16]   Li J., Kawano H., (1996),The areal distribution of soil moisture under sprinkler irrigation. *Irrigation Sciences.* 32:29-36.

[17]   López-Mata E., Tarjuelo J.M., De Juan J.A., Ballesteros R., Domínguez A., (2010), *Agricultural Water Management*, 98: 190-198.

[18]   Luquet, D., Vidal A. , Smith M., Dauzat J., (2005), More crop per drop: how to make it acceptable for farmers?. *Agricultural Water Management.* 73:108–119.

[19]   Pfitscher L.L., Bernardon D.P., Kopp L.M., Heckler M., Behrens J., Montani P.B, Thome B., (2012), Automatic control of irrigation systems aiming at high energy efficiency in rice crops. Devices, Circuits and Systems (ICCDCS), *8th International Caribbean Conference*, pp.1,4, 14-17 March 2012.

[20]   Phocaides A., (2007), *Handbook on pressurized irrigation techniques*. Food and agriculture organization of the United Nations, Rome / Italy.

[21]   Rivera D., Granda S., Arumi J.L., Sndoval M., Billib M., (2012), A methodology to identify representative configurations of sensors for monitoring soil moisture. *Environmental Monitoring and Assessment.* 184:6563–6574.

[22]   Ruíz-García L., Lunadei L.; Barreiro P., Robla J.I, (2009), Review of wireless sensor technologies and applications in agriculture and food industry: State of the art and current trends, *Sensors*, 9: 4728–4750.

[23]   Smarsly K., (2013), Agricultural ecosystem monitoring based on autonomous sensor systems. In: *Second International Conference on Agro-Geoinformatics*, pp.402–407 (IEEE).

[24]   Smith M, (2000). The application of climatic data for planning and management of sustainable rainfed and irrigated crop production. *Agricultural and Forest Meteorology*, 103: 99–108.

[25]   Van der Kooij S, Zwarteveen, M., Boesveld, H., Kuper, M., (2013). The efficiency of drip irrigation unpacked. *Agricultural Water Management*, 123:103–110.

[26]   Venkatapur R.B., Nikitha S., (2017). Review on Closed Loop Automated Irrigation System. *The Asian Review of Civil Engineering*, 6(1):9-14.

[27]   Zaki M, (1992), Production trends for fruit and vegetable crops in Egypt. In: Lauret, F. (ed.). Fruits and vegetables in the Mediterranean economies (Les fruits et légumes dans les économies méditerranéennes). *Proceedings of the Chania conference.* Montpellier: *Mediterranean Options: Series A. Mediterranean Seminars*; n.19 (Options Méditerranéen nes: Série A. Séminaires Méditerranéens; n.19), CIHEAM, 1992, p. 147 -150.

[28]   Zhang, X., Zou H., Zhang N., Li Y., Yang Y, (2013), The research and applications of agricultural automation based on Internet of things. *WIT Transactions on Information and Communication Technologies.* 46: 111–119.

[29]   Zwart S.J., Bastiaanssen W.G., (2004), Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water management*, 69:115-133.