Educational Electronic Analog of the Mechanisms of the Water Table Management Modes Using Arduino Uno

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ABSTRACT

The objective of this research study is to use Arduino Uno Microcontroller for the design of an educational electronic analog to be used inside the classroom for teaching water table management modes in drainage engineering. The educational analog of this study simulates the mechanisms of controlling the drainage and subirrigation water management modes. The mechanisms of the modes are entirely based on mathematical equations simulated by the microcontroller who controls the analog and digital readings of a rainfall sensor, a capacitor for measuring the timely water table elevations during the management modes, a solenoid water valve and an irrigation water pump. A graphic Nextion display is used to simulate graphically an elegant 2D cross-sectional design of a typical drainage and subirrigation layouts. Three Nextion progress bars are used to simulate graphically the rainfall sensor, the water table levels of the management modes inside an observation well and the sump water levels of the pumped irrigation water. The calculations of the physical soil parameters of the management modes are based on the readings of the *RC* circuit of the analog. An SD card data logger controlled by Arduino is also used for data acquisition of the management modes. The graphical results of the examples, solved by the analog, showed complete exactness with the theory of controlling the mechanisms of the management modes. The visual artifact of the analog proved its influence among the students and, the worked examples solved by the analog proved its suitability as a teaching tool inside the class room.

Keywords Water Table Management, Subirrigation, Drainage, Arduino Uno

INTRODUCTION

The primary mechanism of the water table management is drainage, the removal of excess water to provide trafficable conditions for several different agricultural purposes. Lack of adequate rainfall can result in soil water deficit conditions. In some cases subirrigation through the drainage system, can be applied to raise the water table and supply crop water demands. The drainage outlet is blocked [9], and irrigation water is pumped into the drainage system to raise the water table to a depth that will directly supply crop water needs. However the outlet water level elevations can be lowered such that the system functions in the conventional drainage mode. In recent years, intelligent sensor techniques have achieved significant attention in soil and irrigation water management. Monitoring and control of soil and irrigation management systems using humidity, temperature, moisture and other related sensors are widely used in research and applications. Many available research papers show how moisture sensors are used to check the moisture levels in the field and to control the water supply of such irrigation fields. Monitoring of soil goodness by using Arduino has been proposed by so many researchers. Arduino together with the smart sensors controls and measures the quality (moisture, temperature, color, PH…) and effectiveness of soil. Soil monitoring systems are gaining importance as there is need to use water resources efficiently. Menon and Narasimha (8) developed an Arduino based detection technique for seepage failures like soil piping through embankments and landslides. Menon and Narasimha found that seeping water through embankments can be detected using low cost moisture sensors that can detect water presence. Taqwa et.al (10) proposed a low cost landslide early detection system based on the use of Ultra-sonic sensor for the detection of soil movement and an YL-69 soil moisture sensor for the detection of moisture levels. The study of Dipova (3) shows the design and development of a low cost open source data acquisition system for soil mechanics laboratories. In soil mechanics sensor readings are essential for many setups such as consolidation and triaxial tests. Most of the sensors used in soil mechanics are based on resistance change and according to Ohm's law, if the resistance changes, voltage output changes too. Dipova (3) used a position sensor (resistance proportional to position) of the type Linear Variable Differential Transformer (LVDT) which is an inductive type sensor and a very accurate device for measuring linear displacements. The paper of Azeez et.al (1) presented a system which can control the level of water in overhead tanks by employing an Ultra-sonic sensor connected to an Arduino Uno microcontroller and a relay which controls the on/off cycles of a water pump. A LabVIEW program is used to perform the necessary operations of the microcontroller board. The PC-based automated drip irrigation system designed by Elafou et.al (4) used a soil humidity sensor to open and close a solenoid water valve of the designed water circuit. The valve opens when the voltage reading of the sensor is 3.6 V (dry soil) and closes when the voltage reading is 1.8 V (wet soil). A computer-based prototype automation system has been developed at Michigan State University by Belcher and Fehr (2). The designed system provides a visual display in the office via modem and personal computer PC, and enables the user to input the desired water table elevation in each zone as a function of time, and stores operation data throughout the growing season. The system uses rainfall sensor, underground pipe drainage, and feedback of monitored water table level to control the on/off cycles of the irrigation pump. When it rains the system shuts off the irrigation pump and adjusts the flow restriction device in each zone as needed to hold the water table near the desired elevation. When the water table falls below the desired elevation, the system restricts drainage flow and activates the irrigation pump.

In this research study, an educational C-program describing the process of controlling a drainage and subirrigation water management modes by an Arduino Uno microcontroller has been designed and implemented. The program controls the analog readings of a rainfall sensor and an RC circuit for measuring the timely water table fluctuations of the management modes. The program also controls the on/off cycles of the water pump and the opening and closing of the solenoid water valve inside the collector pipe drain. When it rains the sensor shuts off completely the system and prevents any further activities. When the water table inside the observation well falls to a level very close to the drain interface, the solenoid water valve is closed and the water pump automatically start pumping water into the sump. The educational program uses an SD card data logger for the data acquisition of the rising and dropping water table levels. The analog readings of the capacitor (water table levels) are plotted graphically on the Nextion screen by two progress bars, one is used as an observation well and, the second is used as a water sump for subirrigation purposes. An accurate mathematical relationships relating the voltage readings of the capacitor, the soil physical parameters and, the analog time has been derived and used to solve the examples given in this paper. The graphical results of the examples, solved by the analog, showed complete exactness with the theory of controlling the mechanisms of the management modes.

THEORY

A- DRAINAGE MODE

Several investigators including Glover [6] have used the linearized form of the Boussinesq PDE to study the rate of water table drop. The maximum water table level (ht) midway between the drains at time (t) can be written as:

$$ht = \frac{4ho}{\pi} \sum_{n=1,3,.5,..}^{\infty} \frac{e^{-n^2\pi^2\left(\frac{\alpha t}{L^2}\right)}}{n} \sin\frac{n\pi}{2} \ldots\ldots\ldots\ldots\ldots (1)$$

Were,

ho = initial water table height, m

$\alpha = Kd/f$

K= soil permeability, m/d

d= distance between the drain interface and the impervious layer, m

f= specific yield of the soil layer

L=drain spacing, m

Glover [6] presented an approximation when **($\alpha t/L^2$)** values of equation (1) are greater than or equal to (0.05), and the approximation is:

$$ht = \frac{4ho}{\pi} * e^{-\pi^2 \frac{\alpha t}{L^2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots... (2)$$

Table (1) represents Glover's [6] tabulated dimensionless values of (ht/ho) of equation (2) for different values of ($\alpha t/L^2$).

Measurements of the water table levels are taken with respect to the drain interface. Equation (2) can be simulated by Arduino Uno using an RC circuit as shown in Figure (1). The capacitor discharge of the RC circuit [5], [7]; which is identical to the drop of the water table (ht) is given by the following equation:

$$vt = vo e^{\frac{-t}{RC}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (3)$$

If the (ho) value of the above equations equals (1) m., and the (vo) of "(3)," equals (5) volts, therefore, the head- voltage scale factor Sh will be (1 m hydraulic head = 5 volts in the analog) which simply means that Sh = 1/5 = 0.2. Knowing that the drawdown of the water table of equation (2) is mathematically similar to the discharge of the capacitor of the RC circuit of "(3),", therefore by letting:

$$ht = Sh * vt \ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots (4)$$

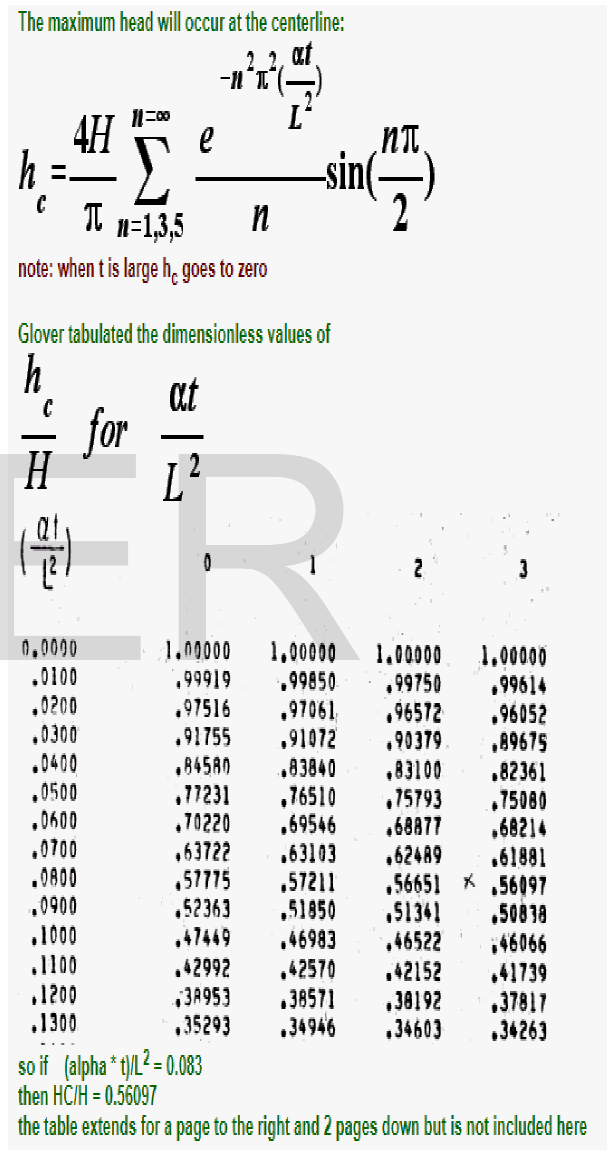
The following equation is obtained:

$$ht = 0.2 * 5 * e^{\frac{-tA}{RC}} \ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots (5)$$

Equation (5) describes the drawdown of the water table in the analog. The chosen (R) and (C) values in the analog are (10 K Ohm), and (100 µF) respectively, therefore the (R*C) value is (1) second. To determine explicitly the time (tA) of the analog as a function of the physical model parameter ($\alpha t/L^2$) of the drainage mode, the following equation is used:

$$tA = \frac{\pi^2 \alpha t}{L^2}(R)(C) - (R)(C)Ln\left(\frac{4ho}{0.2\pi vo}\right) \ldots\ldots\ldots (6)$$

The ($\alpha t/L^2$) parameter of equation (6) can be easily determined from equation (2) or from table (1) for any given ratio of (ht/ho).



The maximum head will occur at the centerline:

$$h_c = \frac{4H}{\pi} \sum_{n=1,3,5}^{n=\infty} \frac{e^{-n^2\pi^2(\frac{\alpha t}{L^2})}}{n} \sin(\frac{n\pi}{2})$$

note: when t is large h_c goes to zero

Glover tabulated the dimensionless values of $\frac{h_c}{H}$ for $\frac{\alpha t}{L^2}$

$(\frac{\alpha t}{L^2})$	0	1	2	3
0.0000	1.00000	1.00000	1.00000	1.00000
.0100	.99919	.99850	.99750	.99614
.0200	.97516	.97061	.96572	.96052
.0300	.91755	.91072	.90379	.89675
.0400	.84580	.83840	.83100	.82361
.0500	.77231	.76510	.75793	.75080
.0600	.70220	.69546	.68877	.68214
.0700	.63722	.63103	.62489	.61881
.0800	.57775	.57211	.56651	✕ .56097
.0900	.52363	.51850	.51341	.50838
.1000	.47449	.46983	.46522	.46066
.1100	.42992	.42570	.42152	.41739
.1200	.38953	.38571	.38192	.37817
.1300	.35293	.34946	.34603	.34263

so if (alpha * t)/L^2 = 0.083
then HC/H = 0.56097
the table extends for a page to the right and 2 pages down but is not included here

Table (1) Glover's dimensionless values of the approximate solution

The parameters (H) and (hc) of table (1) are (ho) and (ht) of this research paper.

B- SUBIRRIGATION MODE

In the case of subirrigation, the same analog setup can be used to simulate this scheme of water table management mode. In this mode the pumped water inside the sump moves from the sump to the soil through the collector and field drainage pipes. By moving upward, the water table rises and replenishes the root zone. Skaggs [9] developed an analytical solution for the water table rise in response to subirrigation. The maximum water table level (ht) midway between the drains at time (t) can be written as:

$$ht = yo - \frac{4yo}{\pi} \sum_{n=1,3,5..}^{\infty} \frac{e^{\frac{-n^2\pi^2 Kyot}{2fL^2}}}{n} \sin(\frac{n\pi}{2}) \ldots\ldots\ldots (7)$$

If only the first term of the series of "(7)," is considered as an approximation therefore, "(7)," can be written as:

$$ht = \left(yo - \frac{4yo}{\pi} e^{-\frac{\pi^2 Kyot}{2fL2}}\right) \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

(yo) of the subirrigation mode being equal to (ho) of the drainage mode.

The recharging of the capacitor of the RC circuit is used to study the subirrigation water table management mode. The capacitor recharge of the RC circuit which is mathematically identical to the rise of the water table; is given by the following equation [5], [7]:

$$vt = vo\left(1 - e^{\frac{-t}{RC}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Knowing that the water table rise of equation (7) is mathematically similar to the recharge of the capacitor of the RC circuit of "(9),", therefore by applying the same scaling factor of "(4),", the following is obtained:

$$ht = 0.2 * 5 * \left(1 - e^{\frac{-tA}{RC}}\right) \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Equation (10) represents the water table rise in the analog.

To determine explicitly the analog time (tA) of the rising water table as a function of the physical parameter ($Kyot/2fL^2$), the following equation can be used:

$$tA = -(R)(C)\left[1 - \frac{yo\left(1 - \frac{4}{\pi} e^{-\pi^2 \frac{kyot}{2fL^2}}\right)}{0.2vo}\right] \ldots\ldots\ldots (11)$$

Similarly, the ($Kyot/2fL^2$) parameter of "(11)," can be determined from "(8)," for any (ht/yo) value.

ANALOG CONSTRUCTION

The general outlook of the designed educational electronic analog is shown in Figure 1. The Figure clearly shows (A) the Nextion graphic display, (B) the irrigation water pump (C) the relay controlling the water pump (D) the relay controlling the solenoid valve inside the collector pipe, (E) the solenoid valve, (F) the capacitor of the RC circuit, (G) the SD card reader, (H) the rainfall sensor and, (I) the sliding SPDT switch. The Microcontroller Arduino Uno of the educational analog controls the analog readings of a rainfall sensor which is used for detecting the presence of rain. When it rains, the red LED of this sensor glows up and the sensor shuts off completely the system and prevents any further activities. The microcontroller also controls the analog readings of an RC circuit for measuring the timely water table fluctuations of the drainage and subirrigation management modes. The RC circuit is composed of a capacitor connected in series with a fixed resistor [5] [7]. An ultra-sonic sensor could have been used but this type of sensors unfortunately does not show any physical relationship with the soil properties whereas the capacitor of the RC circuit can very well represent the physical properties of a virtual soil layer of which the hydraulic drop or rise of the water table in the field is completely analogous to the discharge and recharge of the capacitor of the proposed RC circuit. To start the drainage mode, the sliding switch of the RC circuit is set to position (1) causing the capacitor to discharge, switching OFF the relay of the irrigation water pump and, switching ON the relay of the solenoid water valve inside the collector pipe to open the valve and, allow the water table inside the observation well

(Nextion progress bar) to fall gradually until it reaches zero level as shown graphically in Figure (2). During this process, a yellow LED glows up as an indicator of the drainage mode. The analog incorporates an SD card data logger controlled by Arduino; which is used for data acquisition of the management modes. A data file is used to save the data of the drainage management mode. By the end of this process, the yellow LED of the drainage mode and the solenoid water valve inside the collector pipe are switched OFF automatically as shown in Figure (3). To fill the concrete sump at the outlet of the collector pipe with irrigation water, the relay of the water pump activates automatically the irrigation water pump and a green LED glows up indicating the start of this process. When the water inside the sump reaches a maximum predefined level, the relay of the irrigation pump and the green LED are switched OFF automatically. The sliding switch is then set to position (2) which causes the capacitor to be recharged indicating the start of the subirrigation management mode as shown in Figure (4). During this management mode, the yellow LED glows up again and the water table starts rising gradually inside the observation well to its maximum (*yo*) level. The data of the rising water table (*ht*) are printed to the same data file of the drainage mode using the SD card reader. A written C-code which controls the operation of the two separate relays of the drainage and subirrigation modes is responsible for the automation of the operations of the solenoid water valve and the irrigation water pump.

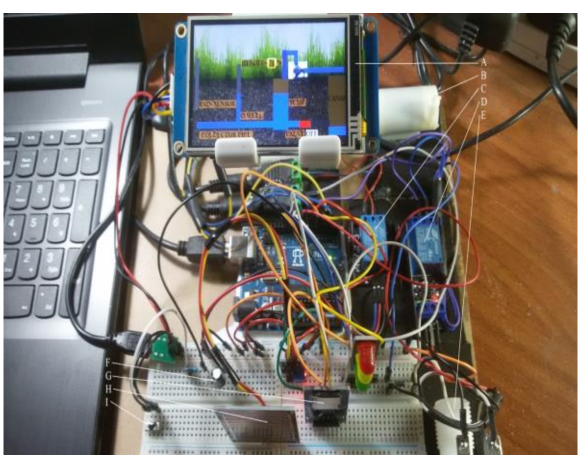


Figure 1 general outlook of the educational analog

Figure 2 the drainage mode of the analog

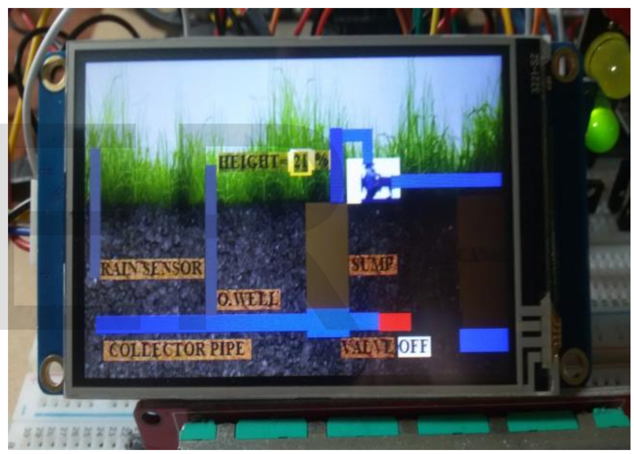


Figure 3 the start of filling the Sump with irrigation water (closed drainage valve)

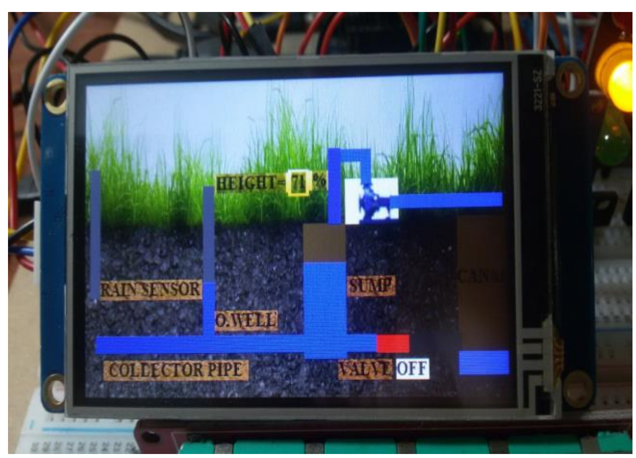


Figure 4 the subirrigation mode of the analog

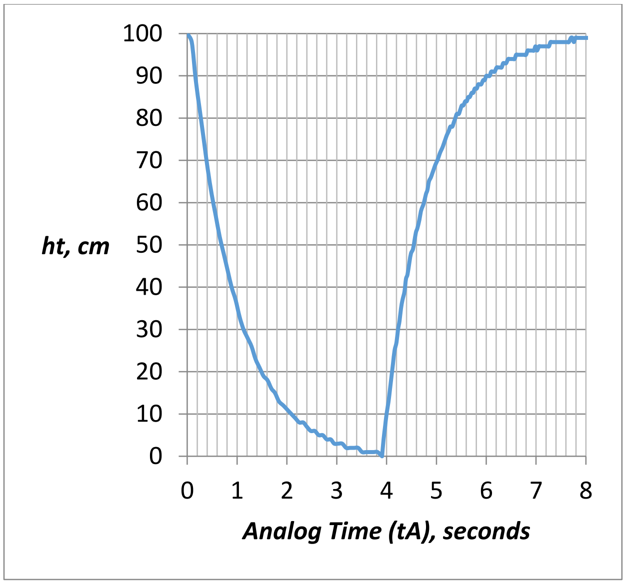


Figure 5 the graphical results of the drainage and subirrigation management modes

RESULTS AND DISCUSSION

The examples given in the manuscript are taken from different drainage and electrical engineering books. The GUI of the C- program, using Nextion display screen, starts with the analog readings of the rainfall sensor and, proceeds to read the capacitor of the RC circuit and other equipements of the designed analog according to the proposed management modes. Arduino Uno is the microcontroller used for the design of the analog.

WORKED EXAMPLE (1): With reference to the graphical results of Figure (5):-

(a) Use "(2)," to calculate the physical prameter ($\alpha t/L^2$) of the drainage mode when (ht) equals (0.5) m.

(b) Use "(6)," to calculate:the analog time (tA) for a water table drop (ht) equal to (0.5) m, knowing that (RC) = 1 second, (ho)=1 m and (vo)= 5 volts.. Check your answer with Figure (5).

(c) Check your the answer with the tabulated dimensionless values of Table (1).

SOLUTION:

(a) $\boldsymbol{ht = \frac{4ho}{\pi} * e^{-\pi^2 \frac{\alpha t}{L^2}}}$

$\boldsymbol{e^{-\pi^2 \frac{\alpha t}{L^2}}}$ **= (0.5*π)/4 =0.3927**

Taking natural logarithms of both sides gives:

($\alpha t/L^2$) =0.0947

(b) $\boldsymbol{tA = \frac{\pi^2 \alpha t}{L^2}(R)(C) - (R)(C)Ln\left(\frac{4ho}{0.2\pi vo}\right)}$

tA = 0.69308 sec.

(c) From Table (1), an ($\alpha t/L^2$) value of (0.093) gives (ht/ho) value of (0.5087) m.

WORKED EXAMPLE (2): If the soil of example (1) is under the subirrigation water management mode as shown in Figure (5):

(a) Use "(8)," to calculate the physical prameter ($Kyot/2fL^2$) of the soil when (ht) equals 0.5 m and (yo) equals (1) m.

(b) Use "(11)," to calculate the analog time (tA) for the water table to reach a height (ht) equal to (0.5) m, knowing that (RC) = 1 second, (ho)=1 m and (vo)= 5 volts.. Check your answer with Figure (5).

SOLUTION:

(a) $\boldsymbol{ht = \left(yo - \frac{4yo}{\pi}\, e^{-\frac{\pi^2 Kyot}{2fL2}}\right)}$

$\boldsymbol{e^{-\frac{\pi^2 Kyot}{2fL2}} = 0.3927}$

Taking natural logarithms of both sides gives:

($Kyot/2fL^2$) = 0.0947

(b) $\boldsymbol{tA = -(R)(C)\left[1 - \frac{yo\left(1 - \frac{4}{\pi} e^{-\pi^2 \frac{kyot}{2fL^2}}\right)}{0.2vo}\right]}$

tA = 0.69308 sec.

By checking the results of the worked examples of the drainage and subirrigation modes with Figure (5), it can be deduced that the derived mathematical (tA) relationships clearly defines the exactness of the derived relationships between the capacitor of the (RC) circuit which is used for water table level measurements and the physical parameters of the drainage and subirrigation modes. Notice the equality of the two physical parameters ($\alpha t/L^2$) and ($Kyot/2fL^2$) of the drainage and subirrigation modes which is true since the properties (***K, f, L, ho, yo***) of the soil are the same in both management modes. The ***RC*** circuit of the analog of this research study is very much related to the physics of the water table level fluctuations.

CONCLUSIONS

The focus of this study is to design an educational electronic analog based on an ***RC*** circuit to act as a sensor for measuring the fluctuations of the water table levels during the drainage and subirrigation water management modes. The virtual physical parameters ($\alpha t/L^2$) and ($Kyot/2fL^2$) which influences the measurements of the water table levels during drainage and subirrigation modes are found to be related mathematically to the analog time (***tA***) readings of the capacitor of the ***RC*** circuit. The equality of the values of the physical parameters ($\alpha t/L^2$) and ($Kyot/2fL^2$) of the drainage and subirrigation modes respectively, indicates that for the same physical properties of the virtual soil, the effect of the physical parameters should be similar whether the water table is rising as in the subirrigation mode or dropping as in the drainage mode.This equality is true since the physical properties (***K***) and (***f***) and the geometric properties (***ho***), (***yo***) and (***L***) are the same in both parameters.

The following points can be deduced from this research study:

1- The visual artifact of the constructed analog among the students was very influential.

2- The worked examples of the different management modes solved by the analog proved the suitability of the analog as a teaching tool inside the class room. The virtual environment of the Nextion C- program enabled better teaching by the lecturer and, better understanding by the students.

3- The design of the analog and the use of different electronic sensors, enabled the students to grasp the mechanism of the automated control of the drainage and subirrigation water management modes. The analog made the students quite interested in how drainage engineering is linked with electrical circuit designs.

4- The program proved to be very useful in teaching due to its simplicity of use, its elegant visual display and its correctness.

The important contribution that this paper has provided to the field of drainage engineering is the practical design of an educational analog by which the automation of the mechanisms of the drainage and subirrigation water management modes are fully and practically achieved inside the class room by the microcontroller Arduino.

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BIOGRAPHY

Faridoun Allawi is a retired professor in Soil and Water Engineering. In 1980, Allawi received his Msc in Soil and Water Engineering from Cranfield University of Technology, England and since then he was enrolled in teaching postgraduate and undergraduate engineering students. His main scientific interests are in the fields of hydro geological engineering and geometric modeling using interactive computer graphics.