EVALUATION OF A SENSOR-BASED PRECISION IRRIGATION SYSTEM FOR EFFICIENCY AND TO MONITOR AND CONTROL GROUNDWATER OVER-PUMPING IN OMAN

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Abstract

Oman is a country with a total area of 309,500 km^2. However, cultivable land in Oman is estimated to be less than 2%, which amounts to about 6100 km^2. More than 50 percent of the arable lands located in the northern coastal belt of Al Batinah region. The country with average annual rainfall around 100 mm, has limited natural fresh water resources and has been facing the serious problem of sea water intrusion into the scarce groundwater reserves due to undisciplined excessive pumping of groundwater for irrigation. Accomplishing this task, intelligent Energy & Water Meters were installed in selected farms to monitor and allocate groundwater quota and ensure sustainability of farming through controlled irrigation.

In order to implement this, it was decided to control/monitor groundwater pumping, while monitoring several field parameters such as soil moisture, EC and temperature. Since the farmlands are spread over the whole Batinah region of near 200 km stretch, it was decided to install the monitoring system in selected 40 farms with varying levels of control. This required remote monitoring of data, transmission of data and control commands to and from the remote stations to a central server computer, in order to make near real-time decisions based on the data and crop water requirement models to ensure safe pumping of ground water. It was also decided to implement sensor-based irrigation control instead of ET-based control systems for more precision.

The irrigation control system was designed around the PIC-182455 microcontroller and short range radio links based on Zigbee communication protocol. Each field module was planned to consist of a microcontroller programmed to access the sensors and acquire data, which will be transmitted to a central module that acts as the coordinator or the main node for the particular farm. The main node will transmit data to the server computer encapsulated as an SMS, over the cellular network. In order to achieve better reliability in operations, the database part of the project was made independent of the real time decisions taken to control the actuators by utilizing part of the intelligence of the microcontrollers. It was decided to program them to handle day to day measurements and take on-farm decisions based on the measured values and the model predicted values. In order to achieve this, it was necessary to derive model predicted values for the particular crop pattern in a particular farm and convert them to a look up table that can be fed to the on-board memory of the microcontroller device. The data collection environment was designed to be in MS Excel, while a GUI will be developed in MS Visual Basic to handle the communication and data transfer between the coordinator modules and the main server.

The developed prototype system could monitor at least five crops in a farm and could operate multiple solenoid valves in sequencing manner compensating with the capacity of

the main pump. Data file indicated the instantaneous irrigation status at any lateral in the farm and the same could be monitored through any mobile devices by accessing through relevant web link. In contrary to the commercially available systems, the develop system could be arranged for small and medium farms in Oman under site-specific manner.

Keywords: Precision irrigation, irrigation efficiency, sensor-based, wireless control, microcontroller.

1. **Introduction**

1.1 **General Introduction and Problem Identification**

Oman is having arid and semi arid climates with 100 mm average annual precipitation and with summer temperature reaching over 45^0C and, considered not suitable for intensive agriculture. While being a major source of employment, the agriculture sector in Oman has recorded an absolute value added to the economy to be about US$ 930 mln in 2010. About 13% of the country's population is considered to be actively engaged in agriculture related employment. However, a major limitation faced by Oman is its limited arable land, which amounts to only 7.07% of the total land area, and only about 10 percent of the total cultivable land is under productive agriculture. About 56% of the cultivated land is in coastal areas. Among these areas, the Batinah region which possesses over 320 km of coastal belt can be considered as the area where cultivation is most intense. Most of these area is irrigated by groundwater abstraction (MAF, 2013).

USGS (2013) and FAO, (2013) describe irrigation as the controlled application of water for agricultural purposes through manmade systems to supply water requirements not satisfied by rainfall. Examples of various irrigation methods used today can be listed as; Center-Pivot, Drip, Flood, Furrow, Gravity, Rotation, Sprinkler, Sub surface irrigation, Traveling Gun, Supplemental, and Surface irrigation (Thomson and Threadgill, 1987; USGS, 2013; FAO, 2013). As an semi-arid region, Oman's agriculture relies mainly on ground water abstraction. Table 1 shows the components of water balance in Oman, there was about 315 million cubic meters of water deficit to the water table in 2013 (Mott Macdonald, 2013). The deficit balance seems to be compensated by the seawater intrusion in the coastal belt. It is reported that agriculture uses 93% percent of the nation's renewable water, and the agricultural water use was 16% percent more than renewable supplies. In the recent years, Oman has experienced a reduction in agricultural productivity despite newly cultivated lands, especially because the loss due to salinization is higher than the added productivity through new lands (Alahkoon et al., 2013).

Table 1.1: Key components of water balance in Oman (Mott MacDonald, 2013)

Key Components of the Water Balance in Oman	MCM
Direct recharge	2397
Wadi recharge	240.4

Reservoir recharge	10.3
Urban recharge	77.1
Agricultural abstraction	-1546
Urban abstraction	-87.5
Capillary flux	-1414
Wadi flow	2511
External flow	-538.4
Storage	-173.3
Deficit	-315.8

The first major adverse effect of highly saline soils and irrigation water is the narrowing of crop choice, especially affecting cultivation of high value crops like vegetables. Due to the extreme climate conditions prevailing during the summer, farmers have been diverting to Greenhouse cultivation, including hydroponics which also consumes significant amount of water (MAF, 2013). The over pumping of ground water has become a serious effect causing many farmers to abandoned their farmlands in the coastal belt due to high salinity. Government imposed water quota system to prevent over pumping, however a sustainable solution could not be achieved so far.

Based on these facts, it is hypothesized that groundwater overdraft is the major driving factor towards higher salinity levels in the groundwater. This is further aggravated by sea water intrusion which has become glaringly visible in some of the coastal lands that have become uncultivable in the Al Batinah region (MAF, 2013).

1.2 Precision Irrigation Concept

It is well understood fact that traditional surface irrigation systems are designed based on the experience on climatic factors and the irrigation schedules that are set up considering the balance among the factors such as crop water requirement, evapotranspiration (ET), soil properties, etc.; can basically defined as ET-based irrigation. Considering the limitations in technology and energy needs, schedules are being prepared in selected frequencies. There is a possibility that irrigation can be over or under applied to some locations in the field.

In precision irrigation the water application is based on the site specific manner, applying right quantities, at right location and right time. Adaptation of technology is necessary in this case in which the monitoring, evaluation and instantaneous controlling become the mandatory parts. Smart irrigation is the modern term used in this regard in which smart controllers are being used for controlling the irrigation system evaluating the instantaneous needs in the filed. The definition given by the Irrigation Association (www.irrigation.org) states that “smart controllers” as controllers that reduce outdoor water use by monitoring and using information about site conditions (such as soil moisture, rain, wind, slope, soil, plant type, and more), and applying the right amount of water based on those factors (Dukes, 2012). The feedback of the monitored environmental factors which can also be of several forms are used in the control system.

Dukes et al. (2012) describe in detail, few different mechanisms used in modern irrigation scheduling systems. The first being the timer based automated irrigation system which has been found to apply 47% more water than the sprinkler systems that are not automated. This method uses fixed settings of the timers and irrigators that are not manipulated based on the actual water need or the environmental conditions (Dukes et al., 2012).

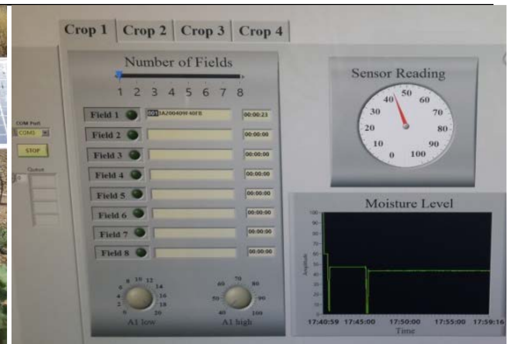
The second type of automated irrigation systems includes the soil moisture sensor based systems. Soil moisture based irrigation systems can be divided into two sub types; bypass and direct (IFAS Extension, 2008). The bypass type system works with timed application of water, however the information provided by the soil moisture sensor on moisture availability is used to bypass a certain water application event out of the series of timed events saving water. the direct on-demand type system's irrigation controller is activated based on the output of the soil moisture sensor. This system effectuates saving of water while guaranteeing immediate application of water once detecting a moisture deficiency through the sensor.

Considering the sever water shortage issues and consequently the increasing salinity problems in the arable land strip in due to ground water abstraction Oman, this research was aimed at researching the feasibility of implementing sensor-based precision irrigation systems in order to supply appropriate quotas of water to the farmers and also to monitor and control the groundwater abstraction. Experiments were developed to compare the benefits of Sensor-based irrigation systems over the existing ET-based system in terms of water use efficiency and other adaptation benefits according to the conditions in Oman.

2. **Materials and Methods**

2.1 **System Development**

The sensor-based smart irrigation systems are readily available in the market and many relevant research studies have been done in the past (Thomson and Threadgill, 1987; Abraham et al., 2000; Vellidis et al., 2008; Migliaccio et al., 2010; Dukes et al., 2012; Alahakoon et al., 2013). However, considering the need of capacity building and also to incorporate in the system the real conditions in Oman, an irrigation control system was designed around the PIC-182455 microcontroller and short range radio links based on Zigbee communication protocol. Figures 2.1.



(a)	(b)

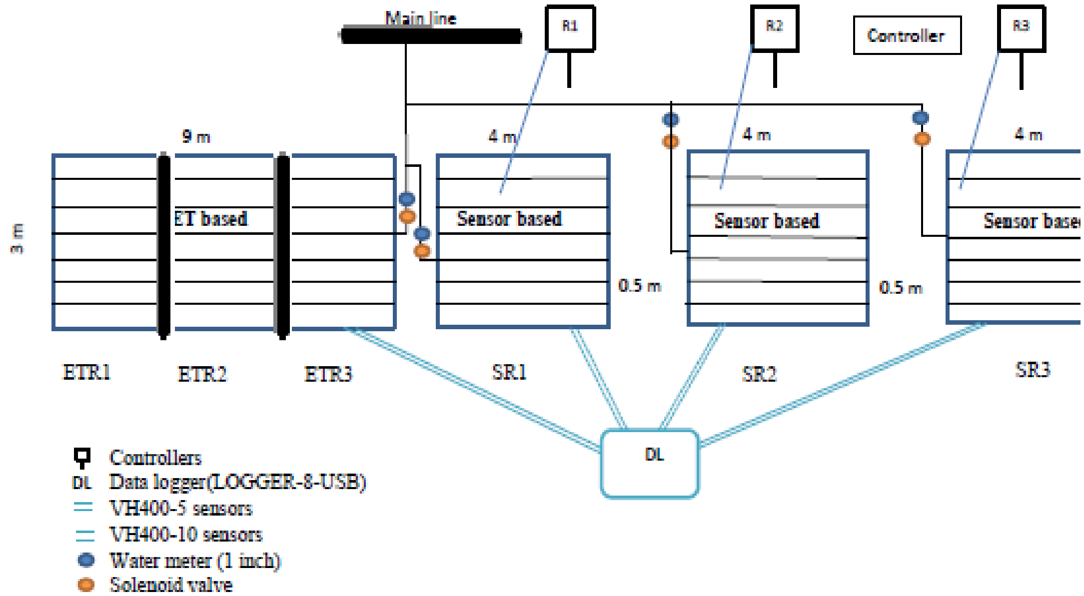
Figure 2.1: (a) Sensor based irrigation control system under preliminary testing; (b) Front-end window of the sensor-based irrigation control system with optional settings

2.2 **Experimental Method**

Prior to conduct experiments and implementation in Al-Batinah farms, a pilot study was conducted at the Agricultural Experimental Satiation (AES) of the Sultan Qaboos University (SQU) in Oman. Figure 2.2 shows the schematics of the experimental arrangement in the pilot study conducted at AES. Main goal of this experiment was to compare the performance of the ET-based and Sensor-based system and to calibrate and fine tune the system.

Four experimental plots were developed (Figure 2.2), the first for the ET-based irrigation system in which the irrigation was by timer controlled as per the ET models used by the AES crops. In order to theoretically estimate the evapotranspiration based and soil moisture based irrigation requirements, two analyses were done by developing models that can be used to simulate different field situations. One model was built around the FAO Penman-Monteith equation to estimate evapotranspiration (FAO, 1998). All meteorological parameters were fed in using recommended equations.

Three more field plots were set up for sensor based irrigation as three replications, for independently controlling irrigation based on moisture contents. The threshold levels were set up; field capacities between 18 and 29% moisture to on and off the solenoids valves. Okra crop was used in the experiment as early summer crop. In addition, at each control sensor location, two other moisture sensors were arranged, one at root-zone depth of 15 cm and another at 30 cm depth to independently monitor the moisture movement and to cross-check and to calibrate the precision of the controller sensor. The control-sensor data were recorded in a desktop computer through wire-less system and monitoring sensor data were downloaded from the field data loggers.



Depth of sensor	ET	Sensor R1	Sensor R2	Sensor R3
a-10		□		
a	•	•	• □	•
a+10				□
b	•	•	•	•
• - Sensor from data logger		□ - Sensor from controller		

Figure 2.2: Experimental arrangement for comparing the performance of Et-based and Sensor-based irrigation systems

3. **Results and Discussion**

The experiments conducted for calibration and quantifying for comparison are in progress and will be presented at the conference, and the simulated results are shown in Tables 3.1, 3.2 and Figures 3.1-3.2. Tables 3.1 and 3.2 show the environmental data used, the output of the Penman-Monteith model and the sample data and the output of soil moisture based model.

Table 3.1. Sample of important environmental data and output of the model based on FAO Penman-Monteith equation

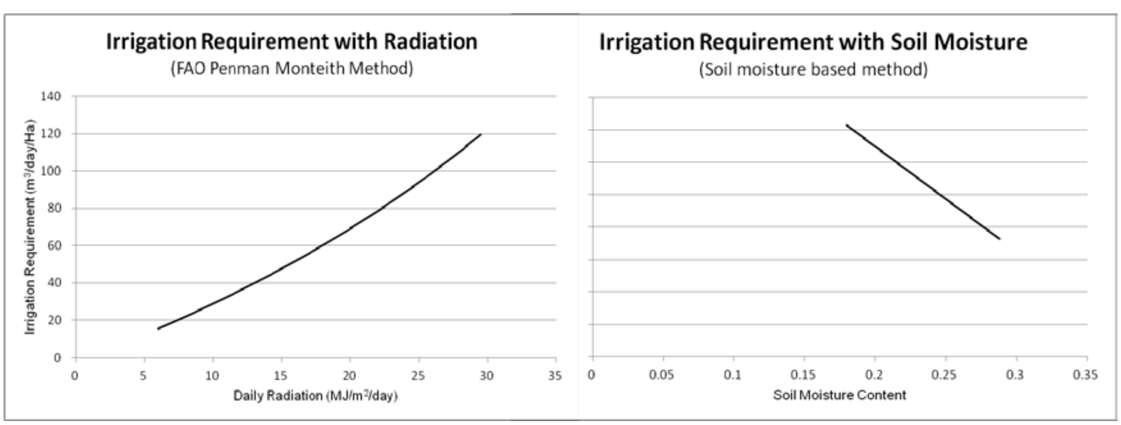
Monthly average daily maximum temperature (C)	Monthly average daily minimum temperature (C)	Monthly average daily wind speed (m/s)	Monthly average sunshine duration	Maximum daily RH	Daily extraterrestrial radiation	Day length	ET0 (mm/day)	Total requirement (m^3/day/Ha)
22.0	35.0	1.0	8.0	0.4	6.0	11.0	0.2	2.3
24.0	35.0	1.2	8.6	0.4	7.9	11.2	0.8	8.0
26.0	35.0	1.5	9.3	0.4	9.8	11.3	1.4	14.2
28.0	35.0	1.7	9.9	0.4	11.8	11.5	2.1	21.0
30.0	35.0	2.0	10.6	0.4	13.7	11.6	2.8	28.4
32.0	35.0	2.2	11.2	0.4	15.6	11.8	3.7	36.6
34.0	35.0	2.4	11.8	0.4	17.5	12.0	4.6	45.5

36.0	35.0	2.7	12.5	0.4	19.4	12.1	5.5	55.3
38.0	35.0	2.9	13.1	0.4	21.4	12.3	6.6	66.0
40.0	35.0	3.2	13.8	0.4	23.3	12.4	7.8	77.6
42.0	35.0	3.4	14.4	0.4	25.2	12.6	9.0	90.3
44.0	35.0	3.6	15.0	0.4	27.1	12.8	10.4	104.2
46.0	35.0	3.9	15.7	0.4	29.0	12.9	11.9	119.4

Table 3.2. Sample data and output of Soil Moisture based model

Field Capacity	Moisture Content	Bulk Density	Root Depth (cm)	Depth Needed (cm)	Total Requirement (m^3/day/Ha)
0.4	0.18	1.3	50	14.3	780
0.4	0.19	1.3	50	13.6	708.5
0.4	0.20	1.3	50	12.9	637
0.4	0.21	1.3	50	12.2	565.5
0.4	0.22	1.3	50	11.4	494
0.4	0.24	1.3	50	10.7	422.5
0.4	0.25	1.3	50	10.0	351
0.4	0.26	1.3	50	9.3	279.5
0.4	0.27	1.3	50	8.6	208
0.4	0.28	1.3	50	7.9	136.5
0.4	0.29	1.3	50	7.3	79.3

Figures 3.1 (a) and (b) show the simulated trends of two models; for the most critical parameter in each, the irrigation need for the FAO Penman-Monteith model and for the soil moisture based model. Figure 3.2 clearly shows that the irrigation requirement for soil moisture based irrigation system is much lower than the that of ET-based system. Figure also shows the simulated results for different segments of curves for 0.3 and 0.25 Field Capacity values.



(a) (b)

Fig. 3.1. (a) Variation of ET based irrigation water need with radiation; (b) Variation of Soil Moisture based irrigation water need with moisture content

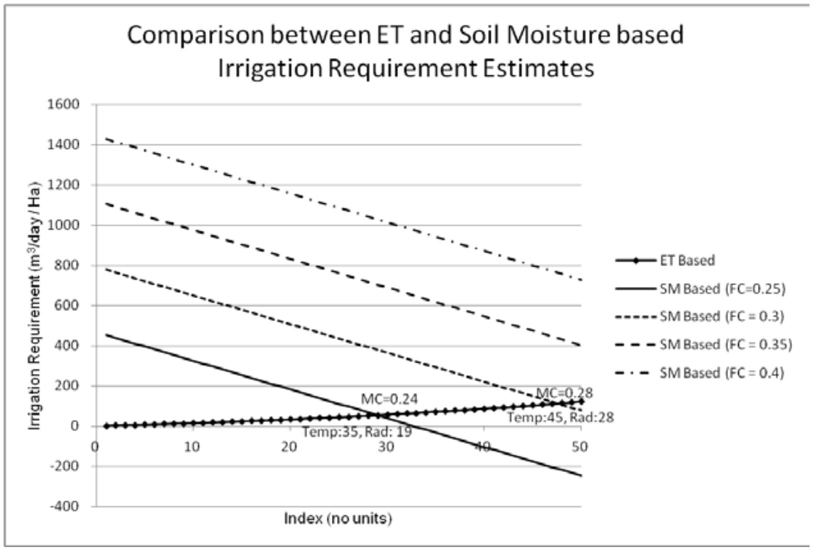


Fig. 3.2. Irrigation water requirement computed for different situations
(ET Based: Monthly average daily maximum temperature 22 – 47 (^{0}C), Monthly average daily wind speed 1 – 4 (m/s), Monthly average sunshine duration 8 – 16 (h), Daily extraterrestrial radiation 6 – 30 (MJ/m^2/day) Day length 11 – 13)
(Soil Moisture based: Moisture content: 18 – 29%, Field capacity: as indicated)

4. **Conclusive Remarks**

- Having high annual water deficit to the groundwater table lead to recommend the use of more efficient irrigation systems.
- Comparison of ET- and Sensor-based irrigation systems show that possibility of water saving by the sensor based system over the other (MC > 0.28 at Field capacity 0.3, and MC > 0.24 at Field capacity 0.25).
- The simulated results show that the sensor based smart irrigation systems deployed in the farms in this region must be designed to operate based on soil moisture as compared to the traditional ET based irrigation systems in order to achieve the best water saving.

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